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Key Points:
- Local time and vertical structures of the quasi-6-day oscillation (Q6DO) in the global ionosphere during the 2019 Antarctic SSW are examined.
- Unlike the climatological Q6DO that peaks only at 16 LT, the Q6DO peaks at 12 LT and 17 LT during this sudden stratospheric warming (SSW).
- Longitude shift of the two Q6DO peaks implies more than one quasi-6-day wave related perturbations are competing in the dynamo process.

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Abstract
This study investigates new characteristics of ionospheric modulations driven by quasi-6-day wave (Q6DW) burst following a rare Antarctic sudden stratospheric warming (SSW) in September 2019. Local-time and vertical variations of the amplitude and phase of quasi-6-day oscillation (Q6DO) in the ionosphere are examined by using data assimilation analysis of electron density from three-dimensional Global Ionosphere Specification (GIS). The maximum amplitudes of Q6DO are located symmetrically ±20° off the magnetic equator at ~12 LT, with a secondary peak at 17 LT. The amplitude of Q6DO weakens at 15 LT, with a sudden phase shift, suggesting multiple dynamo processes driving the Q6DO-related ionospheric variations. The altitude-latitude structure of Q6DO shows that the ionospheric modulations extend beyond the equatorial ionization anomaly, indicating the wind dynamo source regions at higher latitudes. A likely physical mechanism is discussed based on possible interactions of Q6DW and semidiurnal migrating tides leading to the dynamo modulation and phase differences.

Plain Language Summary
Sudden stratospheric warming (SSW) is an extreme meteorological phenomenon in the polar stratosphere, which usually occurs in the Northern Hemisphere. Numerous studies have shown that the SSW can significantly disturb the entire atmosphere from the troposphere all the way to the upper thermosphere and ionosphere. In September 2019, a rare and record-breaking SSW occurred in the Antarctic region, providing an opportunity to investigate the ionospheric variabilities connected to the Antarctic SSW, which is seldom explored. In this study, we present observations of the time evolution and vertical structure of quasi-6-day oscillation (Q6DO) in the ionosphere generated from the unusually large quasi-6-day wave (Q6DW) in the mesosphere and lower thermosphere. Our results show that the observed Q6DO behavior in the ionosphere is quite different from climatological characteristics in the local time and vertical structure, which indicates that the coupling mechanisms driving the ionospheric variability are complex due to the presence of Antarctic SSW.

1. Introduction
Sudden stratospheric warming (SSW) is a large-scale meteorological phenomenon in the winter stratosphere, characterized by a rapid increase in the polar stratospheric temperature by several tens of degrees with weakening or reversal of eastward zonal mean zonal flow. The warming is called “major” if the eastward zonal mean flow reverses to westward at 60° latitude and 10 hPa (~30 km) and “minor” if the zonal mean flow only decelerates without reversing (Matsuno, 1971; McInturff, 1978). The SSW is known to drive ionospheric variability through multiple mechanisms with different temporal scales. The most notable changes characterized by significant semidiurnal variations were found in the low-latitude ionosphere: for example, changes in equatorial vertical plasma drift (Chau et al., 2009, 2010; Fejer et al., 2010, 2011), equatorial electrojet (EEJ) (Fejer et al., 2010; Siddiqui et al., 2018; Vineeth et al., 2009; Yamazaki et al., 2012), and electron density and total electron content (TEC) (Goncharenko et al., 2010; Lin et al., 2013, 2019; C. H. Lin et al., 2012; J. T. Lin et al., 2012; Liu et al., 2011; Pancheva & Mukhtarov, 2011). Those changes are attributed to the modulation of tidal waves at ionospheric E-region altitudes (Fuller-Rowell et al., 2016; Pedatella et al., 2014, 2016; Pedatella & Liu, 2013).
Ionospheric responses to SSWs with longer temporal scales such as 2-, 5- to 6-, 10-, or 16-day variations in the F region have also been reported (Goncharenko et al., 2020; Mo et al., 2014; Patra et al., 2014), which are associated with planetary wave (PW) modulations. Quasi-6-day wave (Q6DW) is one of such robust and recurrent oscillations with maximum wind perturbations in the mesosphere and lower thermosphere (MLT), with periods of 5–7 days. The westward propagating Q6DWs with zonal wavenumber one is generally recognized as a manifestation of Rossby (normal) mode (1, 1). The Q6DW usually maximizes around equinoxes due to the critical layer and barotropic/baroclinic instability (Liu et al., 2004). Numerical simulations (Gan et al., 2016) predicted that the neutral wind oscillations due to the Q6DW in the E region dynamo (95–150 km) could reach a few tens of m/s. Additionally, secondary waves generated by nonlinear interactions between the Q6DW and migrating tides are also evident in the E region (Forbes & Zhang, 2017; Gan et al., 2017). These winds are large enough to modulate the zonal electric field in the E-region, thus modifying plasma drifts and generating quasi-6-day oscillations (Q6DO) in the F region electron density.

Due to weaker PW activity, SSWs are generally rare in the Southern Hemisphere (SH) compared to the Northern Hemisphere. However, an SSW event occurred recently in SH during September–October 2019. Though a minor warming, this Antarctic SSW broke several records in the SH stratosphere (Lim et al., 2020). The temperature increased by 50 K within a week and was likely caused by very strong PW activity in the SH stratosphere (Yamazaki et al., 2020, Yamazaki2020 hereafter). By using Aura satellite measurements, Yamazaki2020 reported an exceptionally strong Q6DW activity in the MLT during the SSW. The Q6DW amplitudes in geopotential height at middle latitudes are over 0.4 km, which is almost 3 times larger than the climatological Q6DW amplitude of 0.15 km. They reported consequent Q6DO signatures in the EEJ, electron density, and TEC in Swarm-B satellite observations at 11–14 local time (LT), but the Q6DO was somehow absent in Swarm-A orbits at 03–06 and 14–17 LT.

This different behavior observed by Swarm-A and B reflects that the ionospheric response to the Q6DW highly depends on LT. Note that the local time characteristic of Q6DO signatures in the ionosphere and their vertical and latitudinal distribution during SSWs were not examined previously, partly due to a lack of sufficient measurements. Further, the coupling mechanism between the Q6DW in the MLT and the ionosphere is not fully understood. In this study, we utilize a data-assimilation-based ionosphere product, which successfully captured the lunar and solar migrating modifications during the 2009 SSW (Lin et al., 2019), to investigate local time and altitude-latitude variations of Q6DO, attempting to resolve how the unusually intense Q6DW activity in MLT is coupled into the ionosphere during the 2019 Antarctic SSW.

2. Q6DO Retrieval Using GIS Electron Density

The ionospheric data (TEC/electron density) used in this study are from Global Ionosphere Specification (GIS) (Lin et al., 2015, 2017), which is an observational product based on the Gauss-Markov Kalman filter to assimilate the slant TECs from ground-based GPS receivers and space-based radio occultation receivers onboard the recently launched FORMOSAT-7/COSMIC-2 mission (Lin et al., 2020). GIS products have been verified by observing system simulation experiments (OSSEs), demonstrating that the data assimilation accurately reproduces the simulation truth (Lin et al., 2017). It is also validated by extensive ground-based ionospheric sounding observations (Lin et al., 2020). The domain of GIS used in this study consists of $5^\circ \times 2.5^\circ \times 20$ (km) grid in geographic longitude, ±60° magnetic latitude (MLAT), and altitude (100–1,000 km), with a time interval of 1 hr.

To extract the Q6DO of the ionosphere, a least-squares fitting method (e.g., Forbes & Zhang, 2017; Gu et al., 2014; Yamazaki, 2018) is adopted in the form given below to the observations (TEC′/Ne′):

\[
\text{TEC}^\prime (\lambda, \phi, t_{UT}) = \sum_{z=4}^{4} A_{\text{TEC}} (\phi, t_{LT}) \cos \left( \frac{\Omega}{1} t_{UT} - s \lambda + \phi_{\text{TEC}} (\phi, t_{LT}) \right) + \bar{A}_{\text{TEC}} (\phi, t_{LT})
\]

\[
\text{Ne}^\prime (\lambda, \phi, z, t_{UT}) = \sum_{z=4}^{4} A_{\text{Ne}} (\phi, z, t_{LT}) \cos \left( \frac{\Omega}{1} t_{UT} - s \lambda + \phi_{\text{Ne}} (\phi, z, t_{LT}) \right) + \bar{A}_{\text{Ne}} (\phi, z, t_{LT})
\]

where $\Omega$ is the angular speed of Earth’s rotation, $t_{LT}$ is the universal time, $\lambda$ is the longitude, and $s$ is the zonal wavenumber. Westward (eastward) propagating waves are denoted by wavenumbers $s < 0$ ($s > 0$).
Since the ionosphere varies dramatically during day and night, the observations at different local times are analyzed separately (00–23 LT) to reduce the aliasing from the diurnal variation. An 18-day temporal window in steps of 1 day was used for the fitting, and the amplitude $A$, phase $\phi$, and background zonal mean $\bar{B}$ are estimated as functions of MLAT $\phi$, altitude $z$, and local time $t_{LT}$. The wave period $\tau$ was considered for the range from 5.0 to 7.0 days in increments of 0.125 days, and the solution of $s = -1$ with the greatest $A$ is adopted in this study. The average period of Q6DW is $6.14 \pm 0.26$ days (Forbes & Zhang, 2017), which is well covered by the selected range. Further, a spectral analysis performed at 12 LT (when Q6DO has maximum amplitude) for the event peaked with a period of ~6 days, with $s = -1$ (figure not shown). Other modes with $s = -4$ to 4 were also fitted but yielded much smaller amplitudes.

### 3. New Characteristics of Ionospheric Responses to the Q6DW

We first examine the temporal variations of the Q6DO signatures extracted from GIS-TEC from August to December 2019. Figure 1a illustrates distinct Q6DO as a function of longitude and day-of-year (DOY) at 12 LT. The Q6DO activity enhances from the middle through the end of September and is most pronounced during DOY 260–280, coinciding with the time following the peak of the Antarctic SSW (gray lines). Figure 1b shows the latitudinal distribution of the absolute Q6DO amplitudes in TEC at 12 LT as a function of MLAT and DOY, demonstrating dramatic enhancements during this period. The responses rapidly grow from a narrow region near the peak of equatorial ionization anomaly (EIA) around ±20° MLAT to a broader...
and poleward region with maximum amplitudes reaching ~2.5–3 TECu around DOY 270, indicating the impact of a Q6DW burst in the MLT, consistent with Yamazaki2020. The local time versus DOY distribution of Q6DO in TEC at the southern EIA is presented in Figure 1c. This is the first time that the daily and local time variations of Q6DO of the ionosphere following an SSW are presented. The figure shows significant Q6DO in TEC with the strongest and secondary amplitudes occurring at 12 and 17 LT, respectively. Panels (a), (b), and (d) display Q6DO variations at 12 LT, which is the local time with the maximum amplitude according to panel (c).

Figures 1d and 1e show the relative amplitude, which is obtained by dividing the absolute amplitude by the background TEC. The relative amplitude is used to eliminate the influences of seasonal (Figure 1d) and diurnal (Figure 1e) variations of background ionosphere. Relative amplitude is more intimately related to the Q6DW amplitude in the neutral atmosphere (Gu et al., 2018; Yamazaki, 2018), while the absolute amplitude is influenced more by the ambient ionosphere. The strongest ionospheric Q6DO in the relative amplitude accounts for ~17% of the background TEC at 12 LT. Note that the peaks extend to poleward of EIA and span in a broader region than the absolute amplitude. The relative amplitudes of Q6DO also reveal prominent enhancements (>10% of the background) at all local times, except 04–07 LT, during DOY 260–280 (Figure 1e). These results indicate that the Q6DW activities in the MLT (refer to Figure 3d, Yamazaki2020) are able to perturb the ionosphere and drive Q6DO in TEC, throughout the daytime and nighttime, in this 20-day period.

We now turn our attention to understanding the MLAT versus local time distributions of Q6DO in TEC in Figure 2, focusing on DOY 270 when the Q6DO amplitude is largest. Peak amplitudes of Q6DO in Figure 2a are found symmetrically at about ±20° from the MLAT around 12 LT, with a secondary peak appearing around 17 LT at slightly lower MLAT. Note that the local time variation of Q6DO during daytime is not simply proportional to the background TEC variations shown in Figure 2b. Notably, the Q6DO amplitude diminishes around 15 LT, whereas the maximum background TEC occurs at 14 LT over ±17.5° MLAT.

The effective local-time period and latitudinal region for the Q6DW coupling into the ionosphere are clearly illustrated in the relative amplitude in Figure 2c, where the suppression in the afternoon around 15 LT between the two daytime peaks is more prominent in the relative amplitude. Besides, the symmetric Q6DO of EIA structure moves closer to the magnetic equator through midnight, indicating that the

Figure 2. MLAT-local time distribution of Q6DO in GIS-TEC on DOY 270. (a) Absolute Q6DO amplitude. (b) Zonal mean background TEC. (c) Relative Q6DO amplitude. (d) Initial phases of Q6DO in degrees where the absolute amplitudes ≥1 TECu. In panels (a) and (b), the white dashed lines indicate the occurrence time of maximum Q6DO and zonal mean at each MLAT.
vertical E × B drift perturbations could still sustain a certain magnitude at nighttime, except around 05–07 LT. Figure 2d presents the phases of Q6DO, and the color code represents the longitude where the contribution of positive perturbation from Q6DO is maximum. Here we present the phase in longitude so that we could identify the location of the peak oscillation intuitively. The local time variation depicts sudden changes in the phase (longitude) of Q6DO around 15 LT at EIA regions.

The reduction of Q6DO amplitudes at 15 LT in between the two peaks and the sudden phase shift (longitudinal shift of maximum oscillation) have not been reported previously. To further understand the local time and longitudinal variations, the Q6DO of TEC over both northern and southern EIA crests are plotted in Figure 3. The almost identical responses at both EIA crests demonstrate that the Q6DO are affected symmetrically by the Q6DW via modification of vertical E × B drift and plasma fountain. Figure 3 shows that the largest positive perturbation (peak of Q6DO) is located around 75°W with a magnitude of 3 TECu near noon. Nonetheless, the longitude of the Q6DO peak shows an abrupt shift, accompanied by a suppression of amplitude around 15 LT to a magnitude of 1.5 TECu with a shifted peak longitude at 0°W/E. Overall, the longitude of peak location follows the slope of theoretical Q6DO phase velocity given by \( \frac{\Omega}{\tau} \left( \frac{1}{\tau} + s \right) = -72 \text{ (deg/day)} \) in the local time frame, where \( \Omega = 360 \text{ (deg/day)} \), \( \tau = 6 \text{ days} \), and \( s = -1 \). The slopes indicated by the yellow and gray lines in Figure 3 well match with the longitude variations of the peak during 06–14 LT (daytime) and 17–19 (dusk) and 20–05 LT (night), except at 06, 15, and 20 LT.

We further examine the vertical-latitude structures of Q6DO in electron densities during maximum amplitude at 12 LT in the left panels (a)–(d) of Figure 4. Comparing Figures 4a and 4b, the Q6DO in the ionosphere exhibits two peaks at ~20° MLAT on both sides of the equator, which occur more poleward to the background EIA peaks at ~15° MLAT, also extend to higher altitudes. This is seen more pronounced in the relative Q6DO amplitude in Figure 4c. The regions where the Q6DO accounts for over 10% of the background electron density can reach ~50° MLAT and extend up to 700 km. The maximum Q6DO reaches ~25% of the background electron density and shows a field-aligned distribution. Moreover, from Figure 4d, the phases of Q6DO reveal nearly constant values along the same magnetic field line from equatorial to midlatitude regions (i.e., 150°E at the equator, 50°W at low latitude). These indicate that the source of the electron density variations comes from modifications of vertical E × B drift by the Q6DW, resulting in the symmetric field-aligned distribution of the modulation.

Finally, we compare the vertical structure of Q6DO at 15 LT when the dramatic suppression occurs, as shown in the right panels (e)–(h) of Figure 4. The Q6DO amplitudes are significantly suppressed in the middle- to high-latitude regions, with only ~15% of the background density over a narrow region of ±20°. As shown in Figure 4h, the phases of Q6DO are no longer field-aligned at the middle to high latitudes, indicating the weakening of the Q6DO in E × B.
4. Discussions

The GIS results described above demonstrate robust coupling between the MLT and the ionosphere during the 2019 Antarctic SSW event. The observed Q6DO amplitude (Figure 1c) is almost twice larger than the climatological annual maximum previously reported (Yamazaki, 2018). The results, for the first time, provide detailed local time variations of Q6DO in TEC during SSW, showing a peak response occurring at 12 LT followed by a period of diminished activity around 15 LT and a secondary peak around 17 LT (Figure 2). In contrast, previous climatology studies showed the strongest amplitudes of Q6DO in the afternoon during 14–16 LT, coinciding with the period of largest background ionosphere density (Gu et al., 2014, 2018; Yamazaki, 2018).
The local time variation reported here (Figures 2a and 2c) is consistent with the Swarm observation reported by Yamazaki2020 during the same event. They observed Q6DO signatures of EEJ and electron densities in Swarm-B around 12 LT, but not in Swarm-A measurements during 03–06 and 14–17 LT. Note that at 12 LT, the Q6DO amplitude is largest, while Swarm-A did not show Q6DO signatures because the observations coincided with the period of minimum amplitude. Our results thus clarify the observed difference between Swarm-A and B by showing the complete local time dependence of ionospheric response to the Q6DW burst in the MLT driven by 2019 SSW.

In addition to the amplitude of Q6DO in the ionosphere, the local time variations of phase (Figure 3) provide further insights into the coupling of Q6DW between the MLT and ionosphere during the SSW. The phase variations are usually not examined in detail but are used here to infer the temporal variability of the modulation and their source. The phase changes of the Q6DO at 06 and 20 LT could be interpreted as a transition of the dominant dynamo process between E and F regions. A similar phase shift at about 02 and 18 LT in the vertical E × B perturbations driven by the DE3 tidal wind was shown by Jin et al. (2008) due to the change of conductivity across the sunset terminator. There is usually a time delay of 2–4 hr for the TEC to reflect the E × B drift changes (e.g., Stolle et al., 2008; Venkatesh et al., 2015). However, the sudden phase changes at about 15 LT revealed in this study, which accompany a simultaneous decrease of amplitude (Figures 2 and 3), could not be interpreted as the transition from E to F region dynamo process. Additionally, based on the time delay in TEC responses mentioned above, the changes of Q6DO should be related to E × B variations that might occur before 15 LT, when the E region dynamo should still be dominant. Further, if there is only one wave source that contributes to the ionospheric Q6DO, the phase of Q6DO is expected to follow a westward tilted slope (yellow lines in Figure 3) during the entire daytime. Accordingly, the phase shift revealed in this study indicates that there are more than one dynamo disturbance sources driving the ionospheric variabilities associated with the Q6DW.

The vertical and latitude variations of Q6DO amplitudes and phases (Figures 4a–4d) give insight into the locations of these dynamo sources. The peak amplitude of Q6DO in electron density appears poleward of the EIA crests and extends to midlatitude, with coherent field-aligned phases. We speculate that the middle-latitude dynamo (Yue et al., 2012), in addition to the regular equatorial plasma fountain, may have played a role for the extension of Q6DO to midlatitude, with coherent field-aligned phases. We speculate that the middle-latitude dynamo (Yue et al., 2012), in addition to the regular equatorial plasma fountain, may have played a role for the extension of Q6DO to midlatitude. Yue et al. (2012) demonstrated that the electric field modulation by neutral wind dynamo is greater at midlatitude, and the resulting TEC oscillation still peaks at EIA (±25°) but extends to midlatitude. This implies the existence of tidal wind components at the midlatitude MLT region, where the meridional wind of the Q6DW is largest (Salby, 1981), and their contribution could be more significant at higher latitude through Pedersen current (Gan et al., 2017). The rapid transition of Q6DO characteristic by 15 LT with diminished amplitude and phases no longer being field-aligned beyond EIA crests (Figures 4e–4g) gives further evidence that there are more than one Q6DW-related dynamo disturbance sources located at midlatitude MLT and their possible interplay with each other. A plausible explanation for such multiple driving forces in modifying the dynamo process and producing the observed Q6DO variability is discussed below.

In a recent study by using whole atmosphere model simulations, Miyoshi and Yamazaki (2020) demonstrated that the nonlinear interaction between Q6DW and SW2 generates two westward propagating components, that is, s = −1 with a period of 13 hr and s = −3 with a period of 11 hr. Both child waves have the same longitudinal dependence as the Q6DW (westward-moving s = −1 structure with a period of 6 days) in a fixed local time frame and are exceptionally enhanced during this SSW event. As the phase and the altitude of the Q6DW might not necessarily be correlated to those of the child waves, the superposition of the dynamo process from these three Q6DW-related tidal waves could possibly produce local time variations of amplitude and phase shift (Figure 3) through constructive or destructive interference along local times. Further, the latitude structure of the Q6DW-modulated tidal wind components are mainly at midlatitude (Miyoshi & Yamazaki, 2020) and could explain the poleward shift in the location of Q6DO with respect to the EIA crests. In short, our observations of local time and altitude-latitude variations of Q6DO in the ionosphere show that the Q6DW effect to the ionosphere is complex and possibly related to the two child waves via Q6DW-tidal interactions. Further theoretical simulations to investigate their interplay using whole atmosphere models are required to elucidate the complex interactions.
5. Summary and Conclusions

The rare and strong Antarctic SSW that occurred in September 2019 has provided a unique opportunity to investigate the associated ionospheric variabilities. Using the GIS data-assimilation analysis, we are able to fully resolve latitude, height, and local-time dependent ionospheric responses to the Q6DW driven by SSW, which have never been investigated. Below, we summarize the major findings and conclusions drawn from this study.

1. The signature of Q6DO burst in the ionosphere variations is observed, following the Antarctic SSW. The largest Q6DO effect accounts for ~17% of background TEC and ~25% of electron density around the EIA region and extends to the middle to high latitude with ~10% magnitude of the background. The amplitudes are almost twice larger than the climatological value.

2. The absolute amplitude of Q6DO peaks at 12 and 17 LT and diminishes in between the two peaks at 15 LT, showing prominent local time and latitudinal dependence during the SSW, unlike earlier climatological studies. Notably, the SSW-driven Q6DO does not follow the diurnal variation of background electron density, which peaks a 14 LT, but exhibits its own characteristic variations.

3. From a fixed local time perspective, the sudden phase shift of Q6DO between the two peaks accompanied by a dramatic suppression of amplitude implies that there are more than one competitive sources driving the dynamo-electric field in the ionosphere. Secondary waves generated by nonlinear interaction between Q6DW and SW2 could be possible candidates with varying contributions to the ionospheric electron densities/TECs depending on which component is dominant at a given local time.

4. The vertical-latitude structure indicates that the primary source of the Q6DO-related dynamo electric field is located off the equator, poleward to the regular EIA driven by the equatorial plasma fountain. This could result from the different vertical-latitude structure of Q6DW and the wind fields associated with the secondary components from nonlinear interactions that affect the dynamo-electric field at different latitudes.

In conclusion, unique characteristics of Q6DO are found in the ionosphere during the rare Antarctic SSW, demonstrating robust coupling between Q6DW in the MLT and ionosphere. Unlike the climatological pattern in earlier studies, Q6DO in the ionosphere during the SSW reveals a strong local time variation, independent of the background density distribution. The observational evidence indicates the roles of competing multiple dynamo processes that couple Q6DW in the MLT and the ionosphere, manifesting as the phase changes and amplitude modulations of the electron density perturbations. As the Q6DO in the ionosphere could contribute as large as ~25% of the variability in the electron density at various local times, the effect is sufficiently significant to be considered when studying the solar-terrestrial and atmosphere coupling.

Data Availability Statement

The GIS data are available on Figshare (https://doi.org/10.6084/m9.figshare.13019126.v1). Alternatively, the GIS data could also be accessed from the National Cheng Kung University web-platform (http://formosat7.earth.ncku.edu.tw/). The institutional policy regulations require the researchers to sign-up for a free user account to access the data. Once logged in with the account, users can select GIS among the other available data products in the download menu. The MERRA-2 data (GMAO, 2015) are available at https://gmao.gsfc.nasa.gov/reanalysis/ (http://10.5067/A7S6XP56VZWS).

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