

The ionospheric total electron content and thermospheric winds during weak geomagnetic disturbances in January 2024

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Key Points:

- Weak geomagnetic disturbances cause remarkable ionospheric changes around the Weddell Sea Anomaly region.
- The thermospheric zonal winds showed huge changes during weak geomagnetic disturbances.
- The ionospheric total electron content disturbances were closely related to the thermospheric zonal winds and geomagnetic declination.

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Abstract: Geomagnetic activity is often ignored in understanding the ionospheric day-to-day variability during quiet times. The maximum daily mean K_p was 1.75 (maximum $K_{p3h} = 3.3$) on January 12–26, 2024. When the weak geomagnetic activities were enhanced, the ionospheric total electron content (TEC) decreased remarkably from the post-midnight to dawn sectors around the Weddell Sea Anomaly region (0°–90°W and 60°–80°S), and the disturbance amplitude attained ~20 TEC units around 4 local time. Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) satellite observations showed that the middle-latitude zonal winds became more westward, with the disturbance amplitude exceeding ~120 m/s in the post-midnight sector as the weak geomagnetic activity intensified. The interplanetary magnetic field B_z and B_y might jointly modulate polar convection to cause the changes in thermospheric dynamics. Zonal wind associated with the geomagnetic declination could almost account for the TEC oscillation around the Weddell Sea Anomaly. Results of this study indicate that weak geomagnetic disturbances during quiet times can cause huge ionospheric changes via dynamic processes and cannot be ignored.

Keywords: ionospheric total electron content; thermospheric zonal wind; weak geomagnetic disturbances

Plain Language Summary

The ionospheric day-to-day variability remains an important unresolved issue because of its coupling with the solar radiation, the solar wind–magnetosphere, and the lower atmosphere. As used in many previous studies, $K_p < 3$ can be often regarded as geomagnetically quiet times. The ionospheric changes during quiet times are known to be due mostly to the lower atmospheric forces. We give clear evidence that the ionospheric total electron content (TEC) and thermospheric zonal winds show significant disturbances in the post-midnight sector as a result of weak geomagnetic disturbances (maximum daily mean $K_p < 1.75$). The disturbance amplitudes of the TEC and zonal wind can attain ~20 TEC units (TECu) and ~120 m/s during weak geomagnetic disturbances. These show potentially important roles of geomagnetic disturbances during quiet times in generating the observed day-to-day

variations in thermospheric winds and ionospheric plasma. This study suggests that we should consider the ionospheric changes resulting from extremely weak geomagnetic activity rather than simply believing that quiet time geomagnetic activity cannot cause ionospheric disturbances.

1. Introduction

The ionospheric day-to-day variability remains an important unresolved issue because of its close coupling with the solar radiation, the solar wind–magnetosphere, and the lower atmosphere (e.g., Forbes et al., 2000; Rishbeth and Mendillo, 2001; Fang TW et al., 2013, 2018; Liu HX et al., 2021; Zhang RL et al., 2024a). Researchers have revealed ways the geomagnetic activity affects the ionosphere by studying the ionospheric changes during individual large ($K_p > 5$) storms (e.g., Prölss, 1995; Mendillo, 2006; Zhang RL et al., 2024b; Astafyeva et al., 2025) and recurrent geomagnetic activity and periodic high-speed solar wind streams (e.g., Lei JH et al., 2008; Liu J et al., 2010; Tulasi Ram et al., 2010; Deng Y et al., 2011; Moraes-Santos et al., 2024; Li QH et al., 2025).

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As used in many previous studies, $K_p < 3$ can be regarded as geomagnetically quiet times. In this case, the energy input from the solar wind and the magnetosphere is relatively limited, and the structure and variability of the ionosphere are largely modulated by processes in the lower atmosphere. How the lower atmosphere affects the ionosphere is often studied during geomagnetically quiet times (e.g., Zhang SR et al., 2005; Huang FQ et al., 2020; Kuai JW et al., 2021; Aa et al., 2023) or during remarkable meteorological processes with no robust geomagnetic disturbances, such as sudden stratospheric warming events (e.g., Chau et al., 2009, 2012; Goncharenko et al., 2010, 2021; Zhang RL et al., 2022), which has enriched our understanding of the atmosphere and ionosphere coupling.

However, the geomagnetic activity still keeps weak disturbances even during quiet times (Chen YD et al., 2014). Weak geomagnetic activities occur very frequently, yet the ionospheric responses to weaker geomagnetic activities have received less attention. One reason is that it is usually difficult to isolate the influences of weaker geomagnetic activities from the complex day-to-day ionospheric variability because of the combined effects of solar irradiance, geomagnetic activities, and waves propagating from the lower atmosphere (Rishbeth and Mendillo, 2001). Although it is difficult to observe the effects of weaker geomagnetic activities, these can be identified under some specific conditions. Cai XG et al. (2020, 2022) showed strong and long-lasting variations in the dayside thermospheric column density ratio of atomic oxygen to molecular nitrogen ($\Sigma O/N_2$) at the low and middle latitudes during weak geomagnetic activity with a maximum K_p of 2.3 during a solar minimum. Zhai CZ et al. (2023) showed a 30%–40% depletion in the ionospheric total electron content (TEC) and the topside ionospheric electron density over the Western Atlantic and Northeast American regions during a weak geomagnetic activity event (maximum $K_p = 2.3$) in June 2019. Li WB et al. (2023, 2024) applied deep learning to reproduce the thermospheric changes with multiple parameters, including geomagnetic, interplanetary magnetic field (IMF), and solar activity parameters. They found that the IMF changes can drive some thermospheric features under nontypical geomagnetic disturbances. Therefore, it is necessary to investigate the ionospheric variability during periods with $K_p < 3$, which have usually been considered geomagnetically quiet times.

Middle- and low-latitude ionospheric structures are strongly affected by thermospheric winds. Neutral winds directly drive ionospheric plasma along the magnetic field lines to induce plasma density changes in the middle latitudes (e.g., Zhang SR et al., 2013; Chen YD et al., 2016). They also drive ions into motion across the magnetic field lines and produce the ionospheric dynamo electric field to generate the $E \times B$ plasma drift, which is important in low and equatorial regions (e.g., Immel et al., 2021; Harding et al., 2024; Zhang RL et al., 2024a). Thus, simultaneous observations of the ionosphere and neutral winds are very important for understanding the day-to-day ionospheric variability.

In this study, we showed changes in the ionospheric TEC and thermospheric zonal winds at a 490 km altitude in January 2024. The maximum daily mean K_p was 1.75 (maximum $K_{p3h} = 3.3$) on

January 12–26, 2024. The ionospheric TEC presented huge changes (the disturbance amplitude attained ~ 20 TEC units [TECU]) in the post-midnight sector around 0° – 90° W and 60° – 80° S (mainly in the Weddell Sea Anomaly [WSA] region) related to the weak geomagnetic disturbances. Further, we showed clear evidence that the TEC oscillations were highly coincident with the zonal winds at 490 km altitude as observed by the GRACE-FO (Gravity Recovery and Climate Experiment Follow-On) satellite. The results of this study indicate that even if the geomagnetic activities are extremely weak, the ionosphere and thermosphere still show remarkable changes, which is valuable information for the study of ionospheric day-to-day variability.

2. Data and Analysis

The GRACE-FO satellite flies around 490 km altitude in a near-circular polar orbit. The neutral mass density and crosswind data are derived from along-track and cross-track accelerations, respectively (Siemes et al., 2023). The accelerometer noise level in the along-track acceleration is approximately 0.1 nm s^{-2} , whereas the cross-track measurements are approximately 1 nm s^{-2} (Hładczuk et al., 2024). The satellite flew over the equator in the post-midnight sector in January 2024. It flew approximately along the geographic meridian plane within 80° latitude; thus, the cross-track winds denote the zonal direction in the middle and low latitudes. The eastward wind was defined as positive.

The global positioning system (GPS) TEC data with a 5-minute resolution, provided by the Massachusetts Institute of Technology (MIT) Haystack Observatory Madrigal database (<http://cedar.openmadrigal.org/ftp/>), was utilized to analyze the ionospheric variations. The TEC data are binned with a window of 15° longitude and 5° latitude over 1 hour.

The 3-hour resolution of the geomagnetic K_p index was obtained from the website of the GFZ Helmholtz Centre for Geosciences (<https://kp.gfz.de/en/data#c134>). The 1-hour resolution of solar wind and 1-day resolution of $F_{10.7}$ data (solar flux at 10.7 cm wavelength) were from the OMNI database (<https://cdaweb.gsfc.nasa.gov/pub/data/omni/>).

For the spectrum analysis, we chose a 15-day sliding temporal window with a step of 1 day to extract the multi-day oscillation and its temporal variations. We used the spectrum analysis to illustrate the relationship between the ionosphere and geomagnetic activity by the least squares fitting method:

$$y = A \cdot \sin(2\pi \cdot \frac{t}{T}) + B \cdot \cos(2\pi \cdot \frac{t}{T}) + C,$$

where t is the observational time of day and T presents the oscillation period in the day. During the analysis, the periods varied from 2 to 8 days with steps of 6 hours to determine the spectra of the observation and the amplitudes of the oscillations. The coefficients included A , B , and C , where C represents the background value. The oscillation amplitude was expressed as

$$R_T^2 = A_T^2 + B_T^2.$$

3. Results

Figure 1a shows the $F_{10.7}$ data for January 2024. The $F_{10.7}$ was

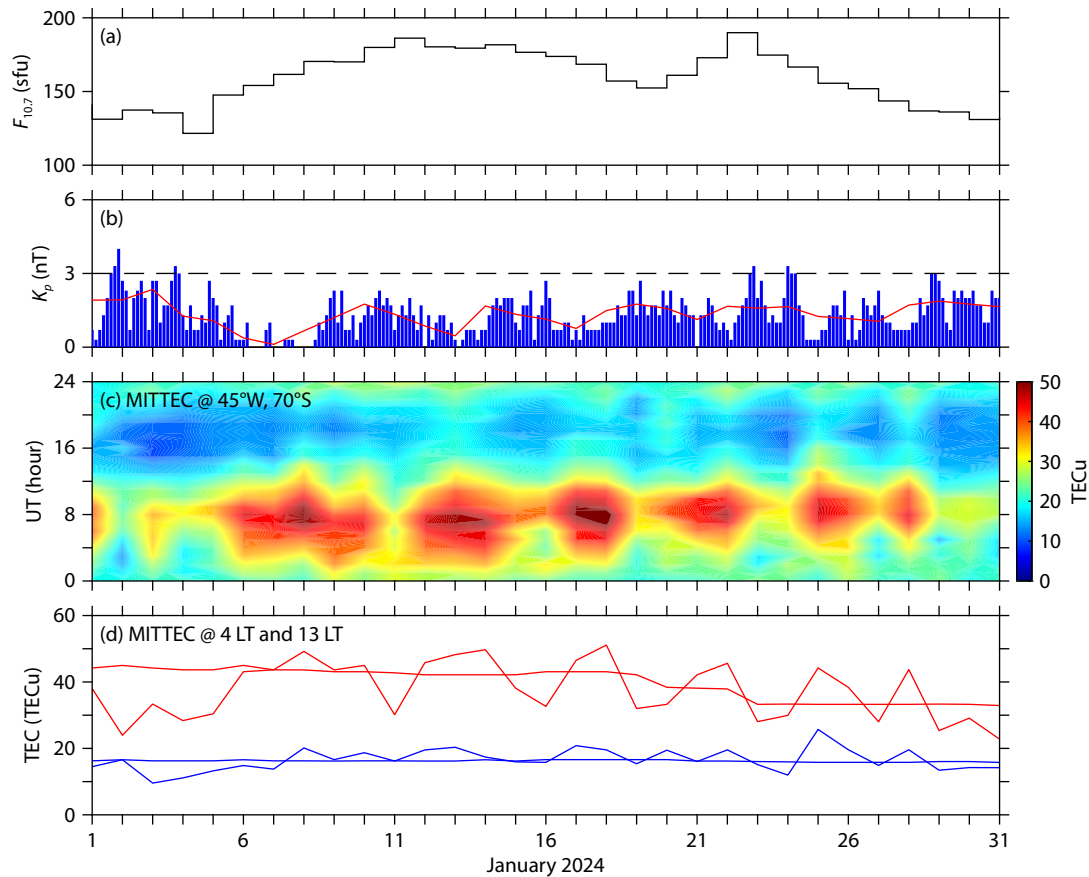


Figure 1. (a) The $F_{10.7}$ in January 2024. (b) The K_p in January 2024. The blue bars denote K_{p3hr} , the red line represents daily K_p , and the black line marks 3, which is traditionally regarded as the boundary between quiet and disturbance times. (c) The MIT TEC at (45°W, 70°S). (d) The TEC changes at 4 LT (red) and 13 LT (blue). The thin lines denote the 27-day moving average.

120–190 sfu (solar flux units), representing a solar moderate condition. As shown in Figure 1b, the daily mean K_p was smaller than 3 throughout the month of January 2024. The maximum K_{p3hr} was larger than 3 for only several short intervals; it reached 4 at 18–21 universal time (UT) on January 1, 3.3 at 18 UT on January 3, 3.3 at 21 UT on January 22, and 3.3 at 0 UT on January 24. The K_{p3hr} was less than 3.3 on January 12–26, and the maximum daily mean K_p was 1.75, demonstrating that the geomagnetic activities were not robust in this period. The period of January 12–26 is often referred to as geomagnetic quiet days, but we could see weak periodic changes in the K_p index.

Figure 1c presents the TEC diurnal changes at 45°W and 70°S. The TEC displayed the diurnal changes and was larger at 0–12 UT (21–9 local time [LT]) than at 12–24 UT, showing the typical nighttime enhancement. This region is located near the Weddell Sea, and the night TEC enhancement would be related to the WSA. The WSA was initially identified in ionosonde data in the 1950s by Bellchambers and Piggott (1958), who noted that the midnight to noon f_oF_2 ratio was greater than unity in summer. Furthermore, the TEC exhibited an obvious multi-day oscillation; that is, the TEC seemed to enhance (decrease) when the K_p index became weak (strong). Figure 1d illustrates the temporal evolution of TEC at 4 LT and 13 LT in January 2024 with the corresponding 27-day average TEC. The 27-day average TEC was determined by using a symmetric

27-day window consisting of 13 days before and 13 days after each central day. The TEC at 4 LT showed obvious multi-day oscillations compared with the 27-day average, and it changed from ~50 to 30 TECu when the daily K_p changed from 0.5 to 1.75 nT. The TEC at 13 LT showed weaker changes compared with those at 4 LT.

Figures 2a–2c display periodograms of the $F_{10.7}$, K_{p3hr} , and TEC. Some previous studies have focused on the recurrent geomagnetic activity and periodic high-speed solar wind streams (Lei JH et al., 2008). We used the spectrum analysis to illustrate the effect of geomagnetic activities on the TEC and did not focus on the period change. The K_p showed quasi-6-day oscillations around January 6–11 and quasi-4-day periods on January 12–26. The K_p oscillation amplitude was very weak and smaller than 0.5 nT. The TEC displayed quasi-6-day oscillations around January 6–11 and presented the obvious periodic signals with quasi-4-day oscillations on January 12–26, similar to the K_p periodogram. During these intervals, the $F_{10.7}$ did not show a similar period, meaning that the TEC changes were not related to solar irradiation.

Figure 3a exhibits the TEC spectrum along the 45°W meridian plane on January 12–26, 2024, which shows the quasi-4-day oscillation at 80°–30°S with maximum amplitude around 70°S. This spectrum indicates that the weak geomagnetic activities modulated the TEC at 80°–30°S along 45°W. Figure 3b indicates the

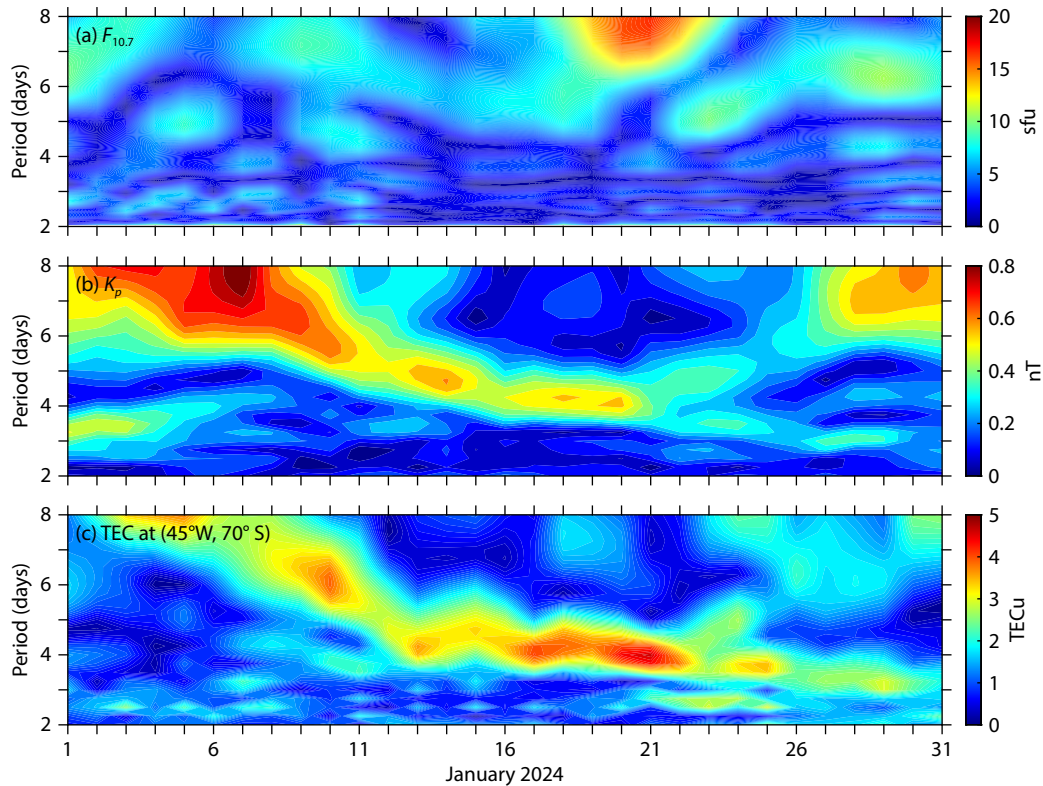


Figure 2. Period spectrum of the $F_{10.7}$, K_p , and TEC at (45°W , 70°S). The period spectrum was made in a 15-day temporal window with a step of 1 day.

universal time changes of the TEC spectrum at (45°W , 70°S) on January 12–26, 2024, which clearly shows that the quasi-4-day oscillation dominates the spectrum at 3–10 UT (0–7 LT), with a maximum amplitude of ~ 10 TECu at 7 UT. Figure 3c shows the latitudinal and universal time variations of the quasi-4-day oscillation in TEC at 45°W and that the maximum amplitude occurred near 70°S during 3–10 UT, reaching ~ 11 TECu. The amplitude gradually seemed to shift to lower latitudes as the universal time became later. Considering that the ionosphere exhibits prominent longitudinal variations, we wanted to examine the longitudinal variations in the ionospheric responses to the 4-day oscillation by using the TEC map. Figure 3d shows the latitude and longitude variations of the 4-day amplitude at 4 LT. The 4-day amplitude peaked around 0° – 120°W and 60° – 80°S . The global spectrum distribution was similar at 0–7 LT.

Figure 4a shows the MIT TEC at 2 LT at 45°W in January 2024. The TEC presents a clear multi-day oscillation at 60° – 80°S . Figure 4b gives the zonal winds observed by the GRACE-FO satellite near 45°W . We selected the orbit closest to 45°W in each day, and zonal winds for each orbit were binned in 1° latitude here. The GRACE-FO flew near 3 LT on January 1 and 0.5 LT on January 31. The zonal winds were dominated by westward winds within 30° – 75°S , where the zonal winds seemed to keep a synchronized oscillation with the ionospheric TEC. The westward winds became stronger when the middle-latitude TEC was depressed. The disturbance amplitude of the westward winds could attain ~ 120 m/s at 60° – 75°S , where the ionospheric TEC showed huge changes to the weak geomagnetic activities.

The neutral winds play a predominant role in variations in the F-region electron density at middle latitudes by lifting up or lowering the F-region ionization (Rishbeth, 1972). The northward winds blowing toward the equator raise $h_m F_2$, whereas poleward winds lower $h_m F_2$ in the southern hemisphere. In this study, the TEC changes were concentrated around the WSA region. Numerous studies have attributed the WSA to variations in the magnetic field declination and inclination acting in conjunction with the neutral winds (e.g., Horvath, 2006, 2007; He MS et al., 2009; Horvath and Lovell, 2009; Lin CH et al., 2009, 2010; Chen YD et al., 2016; Richards et al., 2017). In summer, local sunset occurs later. Further, the equatorward wind prevails at nighttime, which could drive the plasma to higher altitudes, where the recombination is very slow. The $N_m F_2$ could then increase and plasma would be preserved for a longer time. Chen CH et al. (2011) identified the equatorward wind as the major cause of the WSA, together with a downward flux of plasma from the plasmasphere. Klimenko et al. (2015), using topside sounder and ionosonde data together with a simulation, concluded that the WSA is caused by neutral winds and their composition.

The vertical effect winds induced by the horizontal neutral winds, W , depend on the configuration of the magnetic field. Let U and V be the zonal (eastward positive) and meridional (northward positive) wind components, D and I be the magnetic declination (eastward positive) and inclination angles (positive in the northern hemisphere and negative in the southern hemisphere); then W can be expressed as

$$W = -U \cdot \sin D \cdot \sin I \cdot \cos I - V \cdot \cos D \cdot \sin I \cdot \cos I.$$

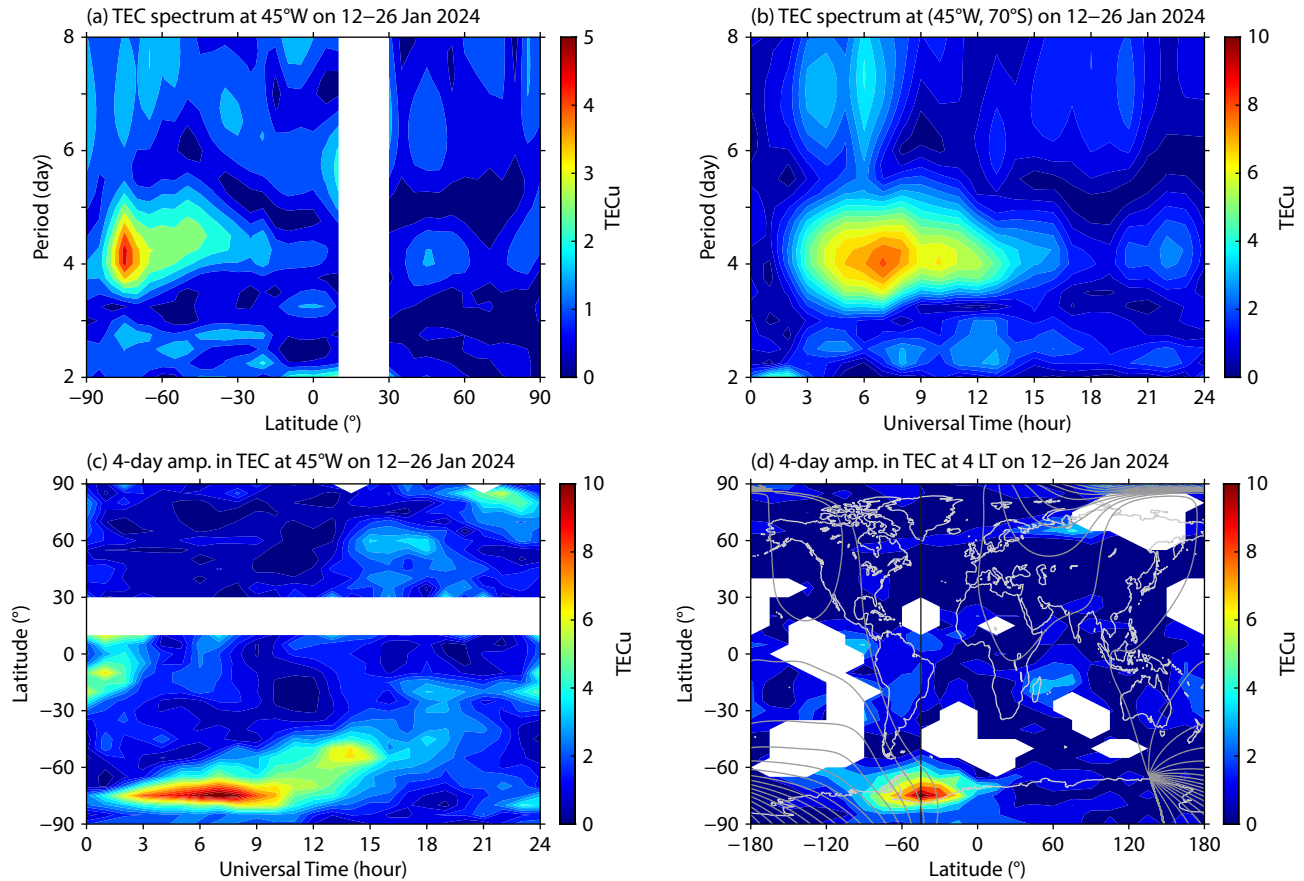


Figure 3. (a) Spectrum of TEC at 45°W on January 12–26, 2024. (b) Spectrum of TEC at (45°W, 70°S). (c) Latitudinal variations in the 4-day amplitude of MIT TEC at 45°W. (d) Global distribution of the 4-day amplitude of MIT TEC at 4 LT. The black line marks 45°W. The coasts and positive magnetic declination are plotted.

We would like to emphasize the effects of the zonal winds on the vertical effect winds in this study. Figure 5 shows the global distribution of the MIT TEC, GRACE-FO zonal winds, and vertical effect winds induced by zonal winds around 2 LT on January 14, 16, and 18, 2024. In the top panels, the typical WSA phenomenon occurred around 0°–120°W and 50°–80°S. The WSA was strong on January 14, became weak on January 16, and was enhanced again on January 18, displaying the typical 4-day period. The gray curves denote the region with a positive magnetic declination, and the negative declination is not shown. The enhanced TEC mainly occurred in regions with a positive magnetic declination, and a slight TEC enhancement occurred around the zero magnetic declination. The post-midnight zonal winds were dominant westward in a wide longitudinal range of the middle latitudes in the southern hemisphere and became more westward on January 16 compared with the other days. The vertical effect winds depend on the geomagnetic declination, and the eastward wind led to the upward effect wind when the geomagnetic declination was positive in the southern hemisphere. The westward winds combined with the positive declination resulted in the downward motion of the plasma around the positive declination region on January 16 compared with those on January 14 and 18. Therefore, the TEC became weaker in the positive declination (around the WSA) on January 16.

4. Discussion

As shown in Section 3, the geomagnetic K_{p3h} index was smaller than 3.3 on January 12–26, 2024, and these weak geomagnetic activities presented the quasi-4-day oscillations with an amplitude smaller than 0.5. As we have shown, even during this weak geomagnetic disturbance, the middle-latitude ionospheric TEC underwent remarkable changes, which can reasonably be explained by disturbances in the zonal winds and declination. The following explanation addresses what caused the middle-latitude zonal winds and TEC changes, as well as the underlying physical mechanisms.

The solar wind is an important driver for changes in geomagnetic activity. As shown in Figure 6, we explored periodograms of the solar wind velocity, dynamic pressure, and IMF B_z and B_y and found that none of these individual parameters exhibited the 4-day period shown in the K_{p3h} index. Figure 6 also shows periodograms of the solar wind dawn–dusk electric field $V \cdot B_z$ and the electric field $V \cdot B_{\perp} = V \cdot (B_z^2 + B_y^2)^{1/2}$ in the plane perpendicular to the Earth–Sun line. The $V \cdot B_{\perp}$ showed a similar period and temporal changes as K_{p3h} , whereas $V \cdot B_z$ did not. The $V \cdot B_z$ represents the contribution of the IMF B_z , whereas $V \cdot B_{\perp}$ essentially reflects the joint roles of the IMF B_z and B_y . The $B_{\perp}$ periodogram also presents a similar periodicity as K_{p3h} . The K_{p3h} oscillations may have resulted from the combined effects of the IMF B_y and B_z . We there-

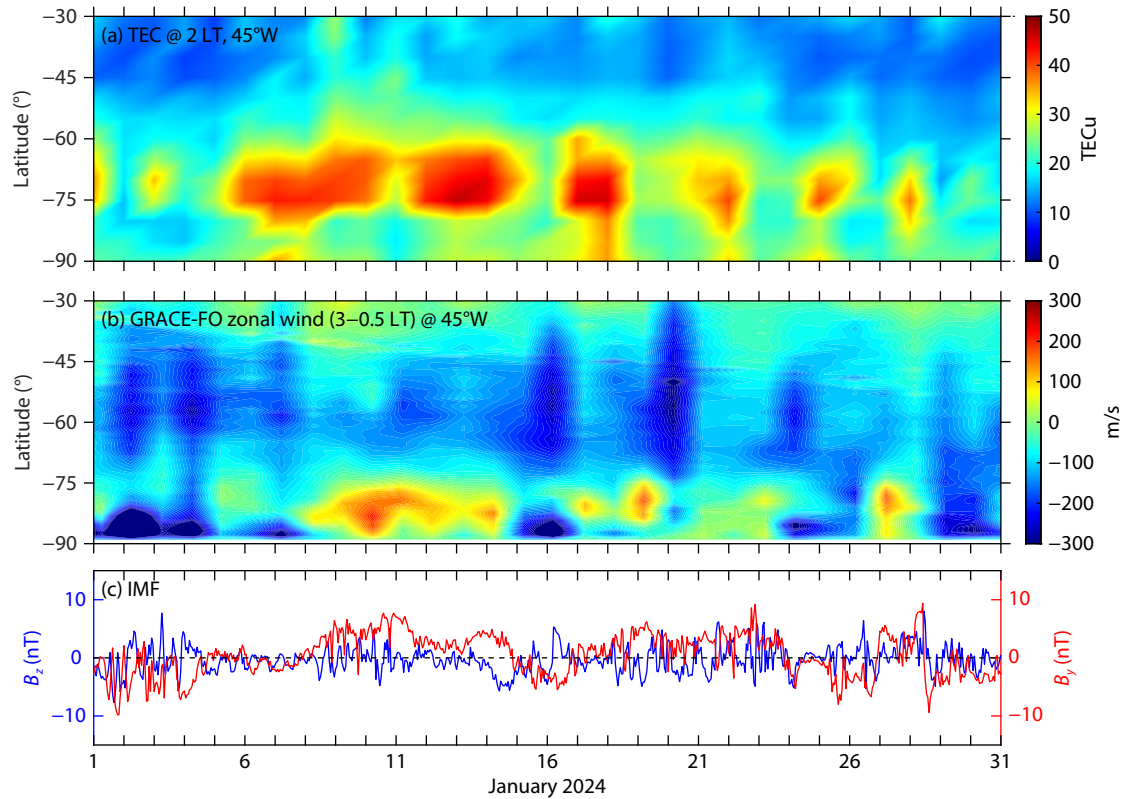


Figure 4. Latitudinal variations in (a) MIT TEC and (b) GRACE-FO zonal winds around 2 LT at 45°W. The IMF B_y (red) and B_z (blue) are shown in (c).

fore show the IMF B_z and B_y in Figure 4c. The IMF B_z and B_y oscillated with magnitudes ranging from -8 to 8 nT during January 12–26, 2024.

In the high latitudes of the post-midnight to dawn side, the positive winds in GRACE-FO data denote the sunward (eastward) wind and the negative winds represent the anti-sunward (westward) wind in Figure 4b. These wind patterns are generally caused by the ion drag of ionospheric plasma convection (Förster et al., 2017; Zhang RL et al., 2026). When the westward winds intensified at the middle latitudes on January 2, 4, 7, 16, 20, 24, and 30, the high-latitude winds also became more negative or decreased above 80°S in Figure 4b, meaning that the middle-latitude winds were possibly related to the polar wind disturbances.

Disturbances in the solar wind electric field alter polar convection, which disturbs the neutral winds via ion drag forces (e.g., Xiong C et al., 2015; Zhang SR et al., 2015; Förster et al., 2017; Oyama et al., 2023). We have shown that the solar wind electric field $V \cdot B_\perp$ exhibited periodic oscillations similar to those of K_p and TEC. The high-latitude ionospheric convection is enhanced during the southward IMF B_z and becomes asymmetric under the influence of the IMF B_y (e.g., Wing et al., 1995; Park et al., 2006; Knipp et al., 2011; Walsh et al., 2014). The ionospheric convection is distorted into “banana-shaped” and “orange-shaped” patterns under strong IMF B_y influences (Tenfjord et al., 2015; Cai XG et al., 2022). When the IMF B_y is positive, a banana-shaped ion convection cell appears on the dusk side, and a more rounded, orange-shaped ion convection cell occurs on the dawn side in the southern hemisphere. Under this condition, the anti-sunward flow tends to tilt

toward the dusk side. An opposite distribution of the southern hemisphere ion convection cells emerges when B_y is negative. The ion–neutral collision is a fundamental mechanism that transfers plasma kinetic energy to the kinetic and thermal energies of neutral particles or vice versa. Ion drag plays a crucial role in the thermospheric wind dynamics at the F-region altitude. Thus, traces of ionospheric plasma convection can be detected in the thermosphere wind at high latitudes (Förster et al., 2017).

We show the B_z and B_y in Figure 4c. When the westward wind intensified above $\sim 75^\circ\text{S}$ near January 2, 4, 7, 16, 24, and 30, the IMF B_z was southward or oscillated between northward and southward, the IMF B_y turned negative, and the high-latitude positive winds became negative or decelerated. When the IMF B_y turned negative, the anti-sunward convection could extend toward the dawn side (Tenfjord et al., 2015). In this case, the GRACE-FO might encounter anti-sunward convection and observe the negative winds. The anti-sunward ion flow could drive the strong equatorward winds via the ion drag force. The equatorward winds were gradually deflected westward as they propagated into the middle latitudes owing to the Coriolis force. Consequently, the westward winds became stronger. Middle-latitude westward winds that originate from high-latitude energy have been verified in previous studies (e.g., Emmert et al., 2004; Xiong C et al., 2015).

The zonal wind was dominantly positive above $\sim 75^\circ\text{S}$ on January 9–14 and 17–23, 2024, as shown in Figure 4. In these intervals, the IMF B_z oscillated near 0, and the IMF B_y was positive. The GRACE-FO satellite detected positive winds above $\sim 75^\circ\text{S}$ latitude in the

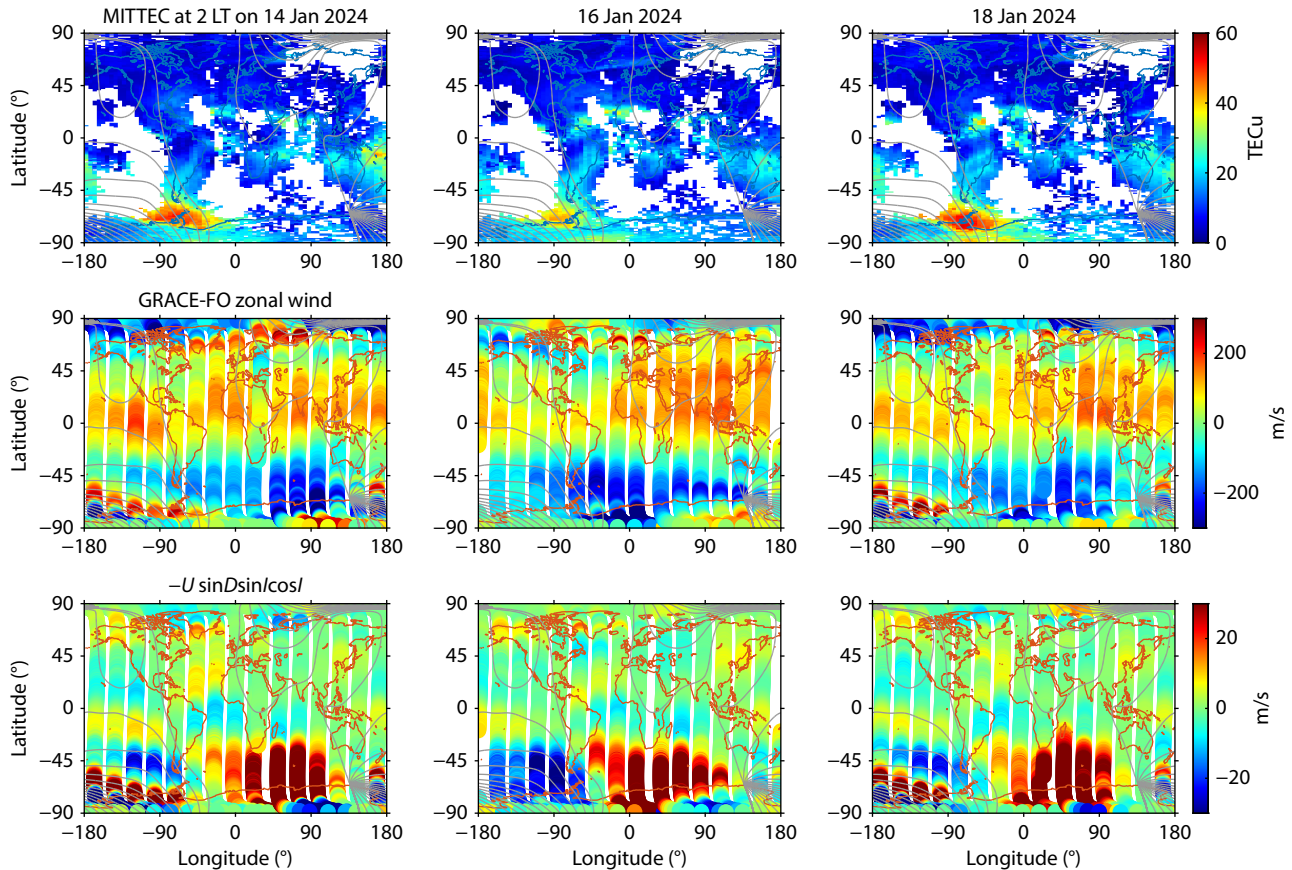


Figure 5. The top panels give the latitude and longitude variations in MIT TEC at 2 LT on January 14, 16, and 18, 2024. The middle panels display the GRACE-FO zonal wind on similar days. The bottom panels show the vertical effect winds induced by the zonal winds associated with the geomagnetic declination and inclination. In all panels, the gray curves mark the regions with a positive magnetic declination.

post-midnight sector, meaning that the satellite encountered the sunward return flow of the rounded, orange-shaped ion convection on the dawn side. Oyama et al. (2023) compared the disturbance winds and plasma convection pattern during magnetic activities over Tromsø, Norway (69.6°N and 19.2°E), during the winter months and identified the sunward winds. Although the neutral winds are dominant eastward on the dawn side under the horizontal components of the Coriolis and centrifugal forces, the neutral winds have preferentially equatorward disturbances (e.g., Förster et al., 2017; Oyama et al., 2023). These equatorward winds will gradually deflect to westward when they propagate into the middle latitudes because of the Coriolis force. But equatorward winds possibly still existed when the westward winds were observed. However, the equatorward winds associated with the geomagnetic inclination could uplift the electron density to a higher altitude and enhance the TEC while the ionospheric TEC is decreased during the period of the westward winds. Thus, the equatorward disturbance winds did not seem to contribute to the ionospheric TEC decrease when the weak geomagnetic activities became strong, or the equatorward disturbance winds could hinder the TEC decrease in this period.

The descriptions above do not seem to explain the changes on January 12 and 20 where the B_y was positive. But we noticed that when the positive B_y decreased on January 12 and 20, the anti-sunward ion flow could gradually shift to the dawn side and thus

weaken the sunward flow. Therefore, the positive winds decelerated above 75°S on January 12 and 20. Because of the shift of the anti-sunward flow, the equatorward winds intensified in the post-midnight–dawn side, and the middle-latitude winds possibly turned more westward around 0–6 LT under the Coriolis force.

When the disturbance winds propagate to lower latitudes, they will shift to later local times (Emmert et al., 2004; Xiong C et al., 2015). In Figure 3c, we can see that the TEC disturbances occurred at later local times in lower latitudes, which might be related to the disturbance wind effects. On the other hand, we mainly state that the ionospheric TEC can be disturbed by weak geomagnetic disturbances via thermospheric wind processes. Further, the weak geomagnetic disturbances can induce O/N₂ changes in the middle latitudes, as proposed by Cai XG et al. (2020, 2022) and Zhai CZ et al. (2023). In this study, when the disturbance winds propagated to the middle and low latitudes, they might have carried the lower O/N₂ and partly contributed to the TEC decrease. No corresponding composition observations are available in this case, so we do not discuss them further in this study.

Additionally, the low atmospheric wave activity is a key driver of the ionosphere and thermosphere changes. The diverse atmospheric waves have been studied extensively, whereas the quasi-4-day wave (Q4DW) remains a relatively understudied feature (Forbes, 1995). Earlier work by Hirota and Hirooka (1984) identified

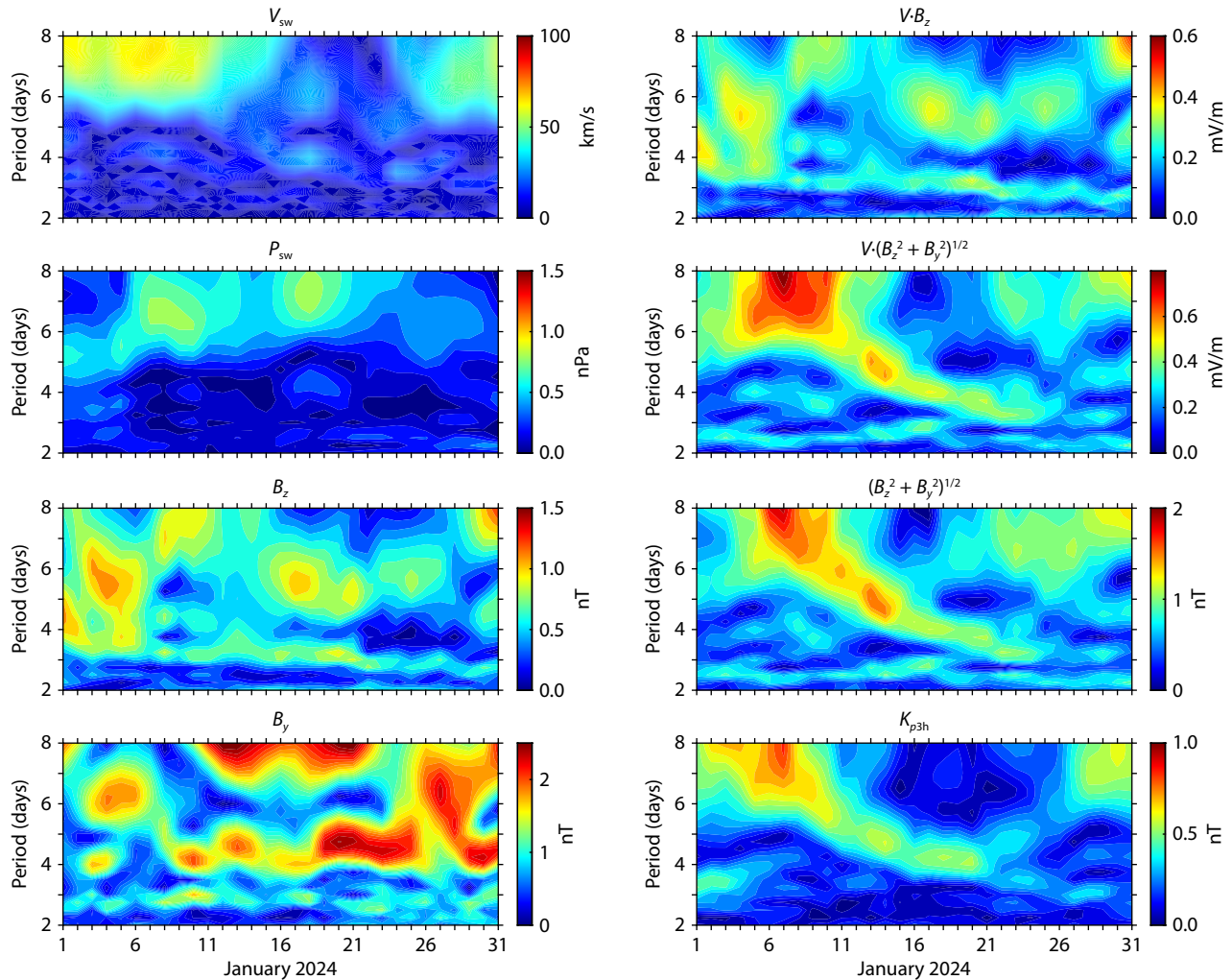


Figure 6. Period spectrum of the solar wind velocity V_{sw} , dynamic pressure P_{sw} , IMF B_z and B_y , solar wind electric field $V \cdot B_z$ and $V \cdot B_{\perp} (= V \cdot (B_z^2 + B_y^2)^{1/2})$, $B_{\perp} = (B_z^2 + B_y^2)^{1/2}$, and K_{p3h} in January 2024.

the westward-propagating quasi-4-day oscillations with zonal wavenumber 2 (Q4DW-W2) in the stratosphere region. Ma Z et al. (2020) observed the Q4DW-W2 in the mesosphere and lower thermosphere region during the northern winter of 2018–2019. Wang WX et al. (2026) showed quasi-4-day oscillations in the ionosphere during this same winter and suggested they are mainly due to the nonlinear interaction of Q4DW and semidiurnal westward-propagating tide with zonal wavenumber 2 (SW2) tides. Yamazaki et al. (2021) performed a climatological analysis using measurements from the Aura Microwave Limb Sounder (Aura/MLS) and showed that the Q4DW-W2 recurs seasonally. The peak amplitudes at the middle latitudes occur in May and August in the northern hemisphere and in February and November in the southern hemisphere.

We analyzed the MLS geopotential height (GPH) data to check whether a Q4DW occurred in the middle atmosphere in January 2024. Figure 7 shows the latitude and date changes of the Q4DW-W1 and Q4DW-W2 at 96 km altitude from December 2023 to January 2024. The precision of the MLS GPH data is ± 160 m at 96 km altitude. A slight enhancement in the Q4DW-W1 occurred at the middle latitudes around January 1, 2024, but it disappeared

after January 10, 2024. No corresponding TEC changes were observed on January 1–10, which suggests that the weak Q4DW-W1 could not modulate the ionosphere. The amplitude of the Q4DW-W2 was very weak throughout January 2024. Thus, we can exclude the low atmospheric forcing and confirm that the TEC oscillations are mainly related to the geomagnetic activities and solar wind forcing.

5. Conclusions

We demonstrate that even when the geomagnetic activity was weak during what have usually been considered geomagnetically quiet times, it could cause significant changes in the ionospheric TEC and thermospheric winds in January 2024. The main conclusions are summarized as follows:

- (1) We analyzed the ionospheric MIT TEC changes in January 2024 and found that the TEC showed obvious changes related to the weak geomagnetic activities. The maximum daily mean K_p was 1.75 [$K_{p3h} < 3.3$] on January 12–26. When the geomagnetic activities became stronger, the TEC was depressed from ~ 50 to 30 TECu from the midnight to dawn sectors around the WSA region.

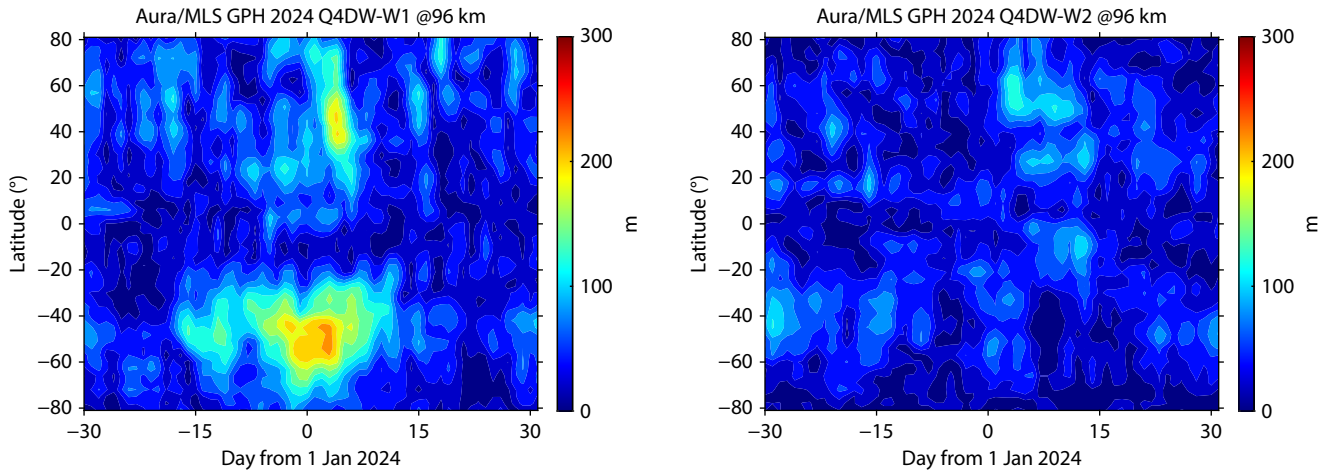


Figure 7. Latitude and date changes of the westward-propagating quasi-4-day waves with zonal wavenumber 1 (left, Q4DW-W1) and 2 (right, Q4DW-W2) at ~96 km obtained from the Aural/MLS GPH data. The date began from January 1, 2024.

(2) The GRACE-FO satellite observed that the middle-latitude zonal winds were dominant westward in the post-midnight sector and became more westward when the geomagnetic activities were enhanced. Around the WSA region with a positive magnetic declination, the westward winds could drive the plasma to low altitudes, where the recombination rate is high, thus weakening the ionospheric TEC.

(3) We showed that the ionospheric TEC oscillations are related to variations in the solar wind electric field $V \cdot B_{\perp} = V(B_z^2 + B_y^2)^{1/2}$. The IMF B_z and B_y might jointly modulate the polar region neutral wind via the ion drag force of polar convection. The disturbance winds propagate into the middle latitudes and are deflected westward because of the Coriolis force, where they further affect the ionosphere via thermospheric dynamics associated with the geomagnetic declination.

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Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Open Research

The GRACE-FO satellite data can be downloaded from https://thermosphere.tudelft.nl/data/data/version_02/GRACE-FO_data/. The MIT TEC data are from <http://cedar.openmadrigal.org>. The solar wind data were obtained from <https://cdaweb.gsfc.nasa.gov/pub/data/omni/>. The geomagnetic K_p index can be obtained from the website <https://kp.gfz.de/en/data#c134>.

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