

A comparative case study of low-latitude ionosphere–thermosphere responses to successive wave-1-dominant and wave-2-dominant sudden stratospheric warming events in 2022 using the ICON and GOLD missions

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Key Points:

- The Ionospheric Connection Explorer (ICON) observed enhancements and reversals in the mesosphere and lower thermosphere mean meridional circulation during two sudden stratospheric warming (SSW) events.
- Enhanced and depleted nighttime F-region electron densities were observed by the Global-scale Observations of the Limb and Disk (GOLD) mission during the two SSW events.
- An enhanced semidiurnal tide was observed during the second SSW event.

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Abstract: Previous studies have demonstrated that sudden stratospheric warming (SSW) events can have a substantial impact on the Earth's ionosphere–thermosphere (IT) system. In this study, we present a case study using observations from that National Aeronautics and Space Administration's (NASA's) Ionospheric Connection Explorer (ICON) and Global-scale Observations of the Limb and Disk (GOLD) missions to examine low-latitude IT responses during two successive SSW events in 2022 with different wavenumbers of the dominant planetary waves (wave-1 and wave-2), and we compare their event-time responses relative to the same pre-SSW reference period. Compared with observations during the pre-SSW periods, the first SSW event is characterized by southeastward wind accelerations below ~99 km and northwestward wind accelerations above ~99 km within the latitude range of 0°–40°N. In contrast, the second SSW event exhibits westward and northward acceleration (below ~99 km) and eastward and southward acceleration at higher altitudes (above ~99 km). Equatorial $E \times B$ vertical ion drifts show upward drift in the morning during the first SSW and downward perturbations in the post midnight hours during the second, which may be attributed to changes in zonal winds. Meanwhile, significant enhancement of $\Sigma O/N_2$ (the column density ratio of atomic oxygen to molecular nitrogen) is observed during the daytime, along with a rise of ~46 K in thermospheric temperature at an altitude of 150 km during the first SSW event. The $\Sigma O/N_2$ and thermospheric temperature also increase during the second. The net effects of electric fields and atmospheric circulation result in an increase in nighttime F-region electron density during the first SSW event and a decrease during the second, as observed by GOLD. During the second SSW event, the semidiurnal migrating tide (SW2) is enhanced in the low-latitude region.

Keywords: sudden stratospheric warming; ionosphere; tides

Plain Language Summary

Previous studies have shown that sudden stratospheric warming (SSW) events can have a substantial impact on the Earth's ionosphere–thermosphere (IT) system, but most have focused on the effects of a single SSW event, with fewer studies comparing the effects of different types of SSW events. This study presents a case study of low-latitude IT responses to two successive SSW events in 2022 with distinct planetary wave characteristics (wave-1-dominant versus wave-2-dominant). The results show that during the two SSW events, the direction of horizontal wind changes is different, which likely led to observed upward and downward perturbations in the IT system.

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bations in the equatorial vertical $E \times B$ drifts between the two SSW events. During the first SSW event, the thermospheric $\Sigma O/N_2$ and neutral temperature at 150 km increase, and during the second SSW event, the $\Sigma O/N_2$ ratio increases and the neutral temperature drops. The combined effects of wind and electric fields resulted in an increase in nighttime F-region electron density during the first SSW event and a decrease during the second SSW event.

1. Introduction

The state of the ionosphere–thermosphere (IT) system is jointly controlled by external driving sources from above (the sun and magnetosphere) and below (lower atmospheric waves). Studying the influences from above, such as geomagnetic storms, high-speed solar wind streams, and solar radiation, can aid in understanding the solar- and magnetospheric-related physical processes governing the state of the IT system. Under geomagnetic quiet conditions, atmospheric waves propagating from the lower atmosphere drive substantial variability across various temporal and spatial scales in the IT system.

Sudden stratospheric warming (SSW) events are phenomena coupling the lower and upper atmosphere. These events are associated with the amplification of planetary waves propagating upward from the troposphere and their interaction with the stratospheric mean flow, leading to an increase in winter polar stratospheric temperatures and a deceleration of the stratospheric zonal mean winds (Matsuno, 1971; Andrews et al., 1987; Butler et al., 2015). Sudden stratospheric warming events are generally categorized into major or minor warming (Butler et al., 2015). Major SSW events are commonly identified by a rapid increase in zonal mean temperatures in the high-latitude stratosphere, together with a reversal of the zonal-mean zonal winds from eastward to westward at 60°N and 10 hPa (Manney et al., 1999; Charlton and Polvani, 2007). Minor SSW events are typically associated with an increase in zonal mean temperatures poleward of 60°N, accompanied by a weakening, but not a reversal, of the zonal mean eastward winds at 60°N and 10 hPa.

As one of the most remarkable large-scale meteorological phenomena in the polar stratosphere during winter, SSWs have an impact not confined to the stratosphere but extending from the troposphere to the upper atmosphere. Numerous models and observational techniques have been utilized to investigate the atmospheric response to an SSW from the troposphere to the IT system (Funke et al., 2010; Kurihara et al., 2010; Chandran et al., 2014; Laskar and Pallamraju, 2014; Gan Q et al., 2020, 2023; Oberheide et al., 2020; Vargin et al., 2022). For instance, perturbations associated with SSW events can extend downward from the stratosphere into the troposphere (Baldwin and Dunkerton, 2001), ultimately influencing weather patterns. Beyond the classification of SSWs into major and minor events, SSWs are also commonly categorized into vortex displacement and vortex splitting events according to the morphology and continuity of the polar vortex (Charlton and Polvani, 2007; Matthewman et al., 2011); in general, displacement events are more often associated with enhanced planetary wavenumber-1 activity, whereas splitting events are more frequently linked to strengthened wavenumber-2 activity.

Because the intensity of stratospheric forcing and the polar vortex configuration can differ substantially among events, SSWs with different strengths and types may induce distinct magnitudes and spatiotemporal structures in the mesosphere and lower thermosphere (MLT) and in the upper IT system. During SSW events, the polar stratosphere undergoes a significant temperature increase. Concurrently, as the stratospheric zonal winds decelerate or reverse, the zonal and meridional winds in the MLT undergo substantial changes (Dowdy et al., 2007; Wang L and Alexander, 2009; Chen X et al., 2012). Such differences in SSW strength and morphology can modulate gravity wave (GW) filtering and the MLT residual circulation to different degrees (Zeng XY and Zhong G, 2024), thereby altering neutral temperature and wind fields and ultimately affecting ionospheric electrodynamics. These dramatic changes in neutral temperature and wind lead to thermodynamic and dynamic adjustments, as well as electrodynamic changes in the ionosphere. Simulations have shown that during SSW events, the mesosphere cools while the thermosphere warms (Liu HL and Roble, 2002; Fuller-Rowell et al., 2011; Liu HX et al., 2013). Meanwhile, the equatorial $E \times B$ drift and ionospheric electron density typically exhibit semidiurnal variations (Chau JL et al., 2009; Goncharenko et al., 2010; Zhang RL et al., 2018). The amplitude, duration, and local time structure of these perturbations may also vary with the strength of the SSW and the polar vortex configuration.

The primary reasons for the IT system changes induced by SSWs are likely related to variations in the tides, planetary waves, and GWs associated with SSWs. Observations (Pancheva et al., 2009; Chen X et al., 2012; Chau JL et al., 2015; Li N et al., 2020; Gasperini et al., 2023) and simulations (Liu HL et al., 2010; Fang TW et al., 2012; Forbes and Zhang XL, 2012; Pedatella and Liu HL, 2013; Zhou X et al., 2025) have shown that tidal components, such as the solar migrating semidiurnal tide (SW2), migrating semidiurnal lunar tide (M2), and nonmigrating westward-propagating semidiurnal tides with wavenumber-1 (SW1), as well as terdiurnal tides, can be enhanced during SSW events. The dissipation of enhanced migrating and nonmigrating tides in the MLT region leads to zonal momentum forcing, which alters the zonal mean winds in the lower thermosphere (Miyahara and Wu DH, 1989; Forbes et al., 1993). The dissipation of enhanced tides alters the meridional circulation as a result of the Coriolis effect (Yamazaki and Richmond, 2013; Pedatella et al., 2016; Oberheide et al., 2020; Gasperini et al., 2023; Ma H et al., 2025). Changes in the mean circulation result in variations in atomic oxygen (O) and molecular nitrogen (N_2) in the lower thermosphere, which propagate to higher altitudes through molecular diffusion, affecting the thermospheric composition (Yamazaki and Richmond, 2013; Jones et al., 2014). Additionally, the enhanced tides modulate the electric fields through the ionospheric E-region dynamo (Chau JL et al., 2009), changing the vertical ion drifts and electron density (Fejer et al., 2010; Chau JL et al., 2012; Fejer and Tracy, 2013).

Previous studies have mainly focused on the impact of isolated SSW events on the IT system, whereas the effects of different types of SSW events have received less attention. During the northern hemisphere winter of 2022, a minor SSW event followed

closely by a sudden stratospheric final warming (SSFW) event provided an ideal opportunity to investigate this phenomenon. Using National Centers for Environmental Prediction reanalysis data, Vargin et al. (2022) examined the dynamical evolution during the two events and found that the residual meridional circulation weakened in the upper stratosphere but strengthened in the middle and lower stratosphere. However, the concurrent responses of the low-latitude IT system to these two successive SSW events remain unclear. Therefore, this study utilizes combined observations from the National Aeronautics and Space Administration's (NASA's) ICON and GOLD missions, including ICON horizontal winds and ion drifts, as well as GOLD disk $\Sigma\text{O}/\text{N}_2$, neutral temperature, and nighttime OI 135.6-nm radiance, to analyze critical physical processes such as tides, winds, composition, and electric fields, to investigate the response of the low-latitude IT system to the two successive SSW events of distinct types that occurred in 2022.

2. Data and Methodology

2.1 ICON

The Ionospheric Connection Explorer was launched on October 10, 2019, into a near-circular orbit at an altitude of 590 km and an inclination of 27°. It measured the processes that directly modify the ionosphere through the dynamics of the neutral atmosphere (Immel et al., 2018). The Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI) instrument onboard ICON measured wind profiles in the upper atmosphere by observing the Doppler shift of the red (~630.0 nm) and green (~557.7 nm) emission lines of atomic oxygen (Englert et al., 2017). The red channel measured zonal and meridional winds over a range of 90 to 300 km during the day and covered only 90 to 110 km at night because of the substantial difference in emission intensity of the green line between day and night. The red line wind data covered 160–300 km during the day and 200–300 km at night. We use versions 05 and 04 of the MIGHTI neutral wind. To ensure the reliability of the results, we use only data with a wind quality factor of 1, labeled as “good,” which largely eliminates measurements contaminated by radiation near the South Atlantic Anomaly. The ion velocity meter (IVM) onboard measured the *in situ* three-dimensional ion velocity at the spacecraft's altitude. Positive values indicate northward field-aligned drift and upward vertical $E \times B$ drift (Heelis et al., 2017). This study uses version 06 of the IVM Level 2 plasma drift data product, with data quality ensured by flag-based (quality flags equal to 0) selection.

The least squares fitting method (Wu et al., 1995) is utilized to perform spectral analysis of tides and extract their amplitudes:

$$y = A \cos \left[2 \left(\frac{t}{T} - s\lambda \right) \right] + B \sin \left[2\pi \left(\frac{t}{T} - s\lambda \right) \right] + C. \quad (1)$$

In Equation (1), T represents the tidal period, t denotes the universal time (UT), s is the zonal wavenumber (positive eastward), and λ is the normalized longitude. The fitting results include the parameters A , B , and C , where C represents the zonal mean. In our calculations, a 41-day sliding window, which has been demonstrated in previous studies to be effective for extracting solar tides (Cullens

et al., 2020; Forbes et al., 2022), with a 1-day step is utilized to capture the temporal variations in tidal amplitudes. For ICON horizontal wind data, the fitting is conducted at specific altitudes and latitudes, with data within a $\pm 3^\circ$ latitudinal window considered representative of the given latitude.

2.2 GOLD

The GOLD far-ultraviolet imager is onboard a geostationary communication satellite at 47.5°W, launched on January 25, 2018. The GOLD instrumentation includes two independent, identical imaging spectrographs that observe the far-ultraviolet (132–162 nm) spectrum of the Earth's atmosphere over the same region (maximum 60°S–60°N, 120°W–20°E) daily from 06:10 to 00:40 UT of the next day, with a spectral resolution of 0.2 nm during daytime (Eastes et al., 2020) and 0.35 nm during nighttime. In this study, we use the daytime disk data, including the disk-neutral temperature (T_{DISK}) and $\Sigma\text{O}/\text{N}_2$, as well as the peak electron density (N_{MAX}) at night. The daytime observations cover the airglow emissions in the OI 135.6-nm and N_2 Lyman–Birge–Hopfield (LBH) bands between 140.0 and 150.0 nm, which are used to derive $\Sigma\text{O}/\text{N}_2$ (Correia et al., 2021) and the effective T_{DISK} (Evans et al., 2024). The $\Sigma\text{O}/\text{N}_2$ and T_{DISK} data products have a spatial (horizontal) resolution of 250×250 km at the spacecraft nadir. The NI1 data provide a time series of 135.6-nm nightglow two-dimensional images representing the peak electron density of the F_2 layer ($N_m F_2$).

3. Results

3.1 SSW Effects on the Thermosphere

Figure 1 summarizes the temporal evolution from January 30 to April 20, 2022, of (a) the polar stratospheric temperature, (b) the zonal-mean zonal wind, (c) the geopotential height amplitudes of planetary wave-1 (solid) and wave-2 (dashed), (d) the planetary wave momentum flux, as well as (e) the solar $F_{10.7}$ radio flux index and (f–g) the geomagnetic activity indices K_p and Dst . The gray curves in panels (a), (c), and (d) show the 1979–2021 climatological means, which provide a multiyear background for comparison. Overall, two consecutive SSW events occurred in February–March 2022. The first warming began on March 1 (DOY 60), when the polar stratospheric temperature increased rapidly from ~214 K to ~238 K around March 6 (DOY 65). Meanwhile, the eastward zonal mean wind at 60°N within ~20–70 km decelerated markedly, and a reversal from eastward to westward flow occurred above ~45 km. At 60°N and 10 hPa, however, the zonal mean wind decreased from ~50 m/s before the SSW to ~8 m/s near the peak (Figure 1b) without reversal, indicating that this event was a minor SSW (Charlton and Polvani, 2007). Thereafter, the wind field gradually returned to the pre-SSW eastward state.

The second warming began to intensify around March 16 (DOY 75), during which the polar stratospheric temperature increased again, reaching its maximum on March 20 (DOY 79), rising from ~223 K to ~244 K. In this event, the eastward wind at 60°N within ~25–70 km clearly reversed, and the zonal mean wind at 10 hPa reached a minimum of approximately –7 m/s on DOY 79, characterizing a major SSW event (Charlton and Polvani, 2007) and, more

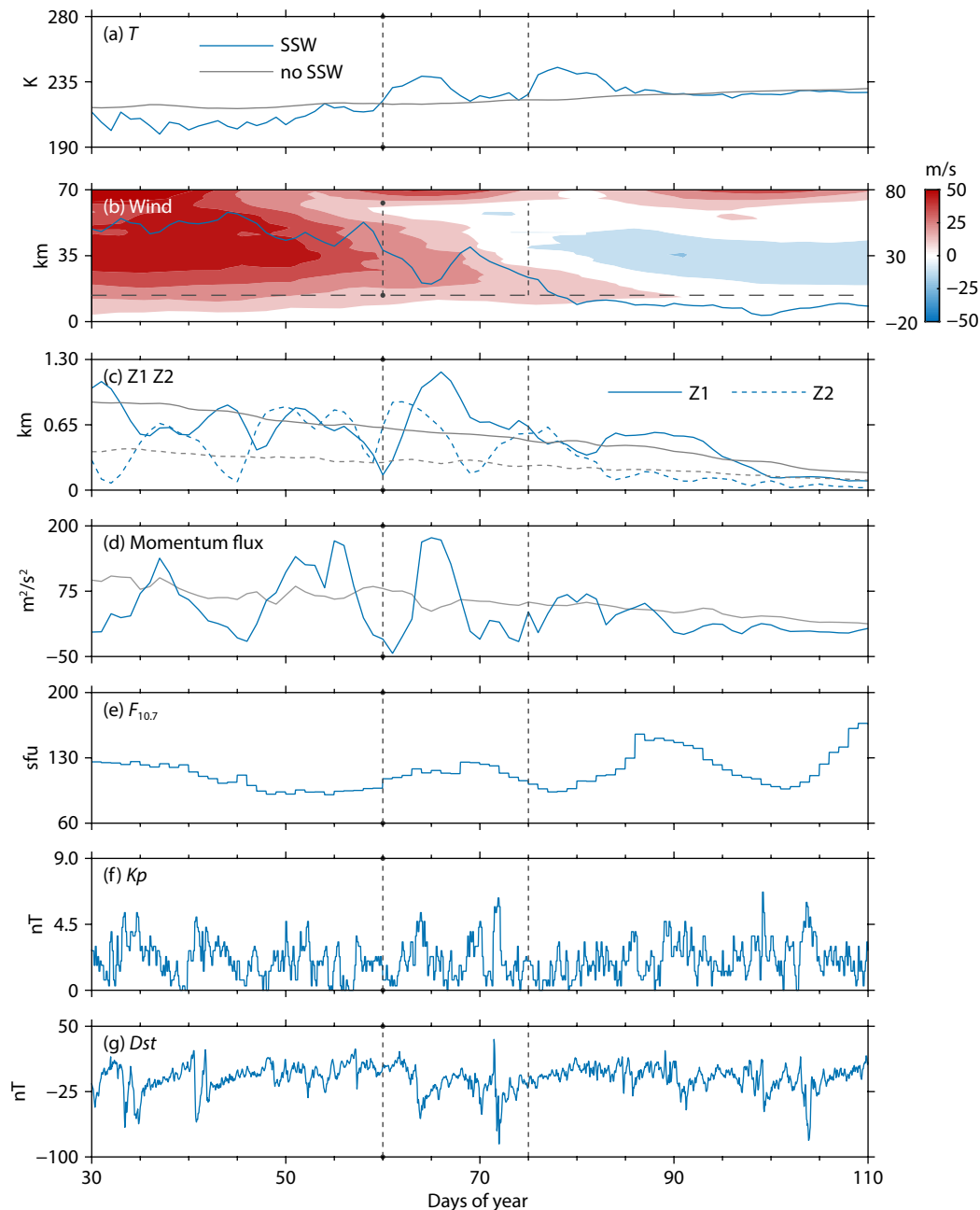


Figure 1. (a) Temporal evolution of the stratospheric temperature at 90°N and 10 hPa from January 30 to April 20, 2022, derived from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2); the gray curve denotes the climatological mean temperature evolution for 1979–2021. (b) Temporal and altitudinal variations in the 2022 MERRA-2 zonal-mean zonal wind at 60°N. The blue line represents the zonal-mean zonal wind at 60°N and 10 hPa. The dashed gray line represents the zero wind line. (c) The solid (dashed) blue curve shows the geopotential height variation associated with planetary wave-1 (wave-2), whereas the solid (dashed) gray curve denotes the corresponding climatological mean. (d) Same as (c), but for the momentum flux of planetary waves. (e–g) Time series of the $F_{10.7}$, Kp , and Dst indices, respectively. The two dashed black vertical lines mark the onset dates of the two SSW events (days of year [DOY] = 60 and 75).

specifically, a sudden stratospheric final warming (SSFW) event that affected only the stratosphere because it marked the end of the winter westerlies.

In terms of planetary wave activity (Figure 1c), wave-1 exhibits relatively larger amplitudes during the first SSW, whereas wave-2 becomes more prominent during the second SSW, suggesting

distinct dynamical forcing regimes with wave-1 dominance and wave-2 dominance, respectively (Ma Z et al., 2020). In addition, the planetary wave momentum flux (Figure 1d) shows a pronounced enhancement following the first SSW relative to the climatological mean, whereas it subsequently weakens and returns close to the climatological level after the second SSW. This contrast indicates differences in the strength of planetary wave

forcing (and associated wave-mean-flow interaction) between the two events. For the solar and geomagnetic background conditions, $F_{10.7}$ remains generally stable prior to early March (DOY ~ 60) but then increases substantially and displays multiple peaks during DOY 60–90. In the subsequent analysis, we extract SSW-related signals by defining the 30-day mean prior to the SSW (DOY 30–59) as the reference background and computing anomalies for each SSW phase using 5-day means (e.g., DOY 60–65 and DOY 75–80) relative to this reference, which helps suppress day-to-day variability and enables a consistent intercomparison between the two successive events. The K_p and Dst indices (Figures 1f and 1g) indicate that geomagnetic activity is not extremely quiet during the two events, with intermittent moderate disturbances and a recovery phase overlapping the second event. Accordingly, we minimize geomagnetic contamination by selecting analysis windows away from the strongest disturbances and by averaging over 5-day intervals; nevertheless, we cannot fully rule out storm-time contributions. Even so, the coherent low-latitude IT variations reported here are most consistent with SSW-related forcing acting under low to moderate geomagnetic conditions.

To analyze the variations in the thermospheric winds caused by the SSW, we compare the winds during the SSW period with a pre-SSW background. Here, the mean over DOY 30–59 is taken as the pre-SSW reference, and wind anomalies are computed for the two SSW phases (DOY 60–65 and DOY 75–80) relative to this reference. Figures 2a and 2d show the latitude–altitude distributions of the pre-SSW mean zonal wind (U) and meridional wind (V), respectively, whereas Figures 2b and 2c present (ΔU) and Figures 2e and 2f show the corresponding (ΔV) during the two SSW phases. Positive (negative) differences indicate enhanced eastward–northward

(westward–southward) winds. Prior to the SSWs (Figures 2a and 2d), the thermospheric winds exhibit pronounced latitude–altitude structures. The zonal wind is predominantly westward, with generally negative values across the low to midlatitudes ($\sim -10^\circ$ to 40°) between 94 and 109 km. The meridional wind is relatively weak near the equator but shows a distinct northward wind over the northern hemisphere low to midlatitudes.

During the first SSW phase (ΔU ; Figure 2b), the wind perturbations display clear vertical stratification at the low and midlatitudes: an eastward enhancement dominates at lower altitudes (below ~ 99 km), whereas a westward enhancement emerges at higher altitudes (above ~ 99 km), indicating an intensified vertical shear in the zonal wind perturbations. The westward enhancement is most pronounced near 30° – 40° N at higher altitudes (~ 104 – 109 km), reaching local amplitudes of ~ 60 m/s. In contrast, the lower altitude eastward enhancement is primarily confined to the equator– 20° N sector, yielding an overall “eastward at lower altitudes and westward at higher altitudes” pattern. The meridional wind also changes substantially during the first SSW (ΔV ; Figure 2e): below ~ 99 km, a southward acceleration (negative anomaly) dominates, with stronger responses over the northern hemisphere low to midlatitudes. At higher altitudes, the meridional wind anomalies exhibit a more complex latitudinal structure, featuring enhanced northward flow at higher altitudes in the equatorward southern hemisphere, as well as a similar enhancement over 10° – 30° N above ~ 105 km.

During the second SSW phase (ΔU ; Figure 2c), the zonal wind anomalies show a latitudinal distribution distinct from that during the first warming. At low altitudes, an eastward acceleration appears over $\sim 15^\circ$ – 40° and can reach ~ 60 m/s, whereas a westward-enhancement region is evident at higher altitudes, indi-

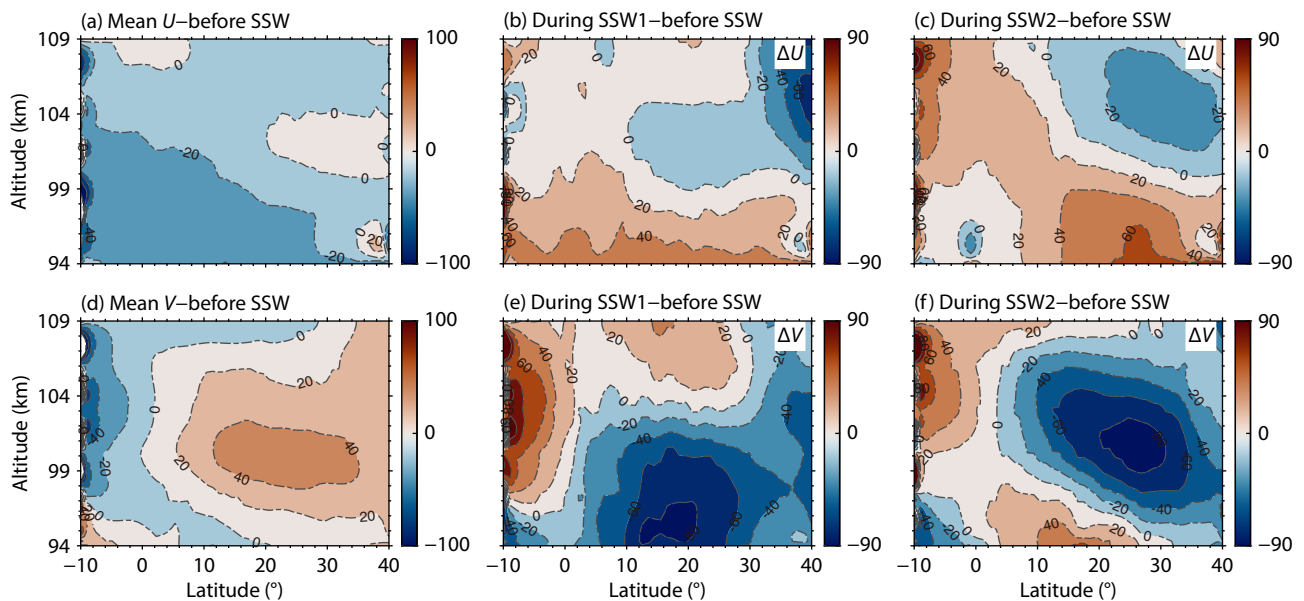


Figure 2. (a) Mean zonal wind (U) prior to the SSW (DOY 30–59). (b–c) Zonal wind differences (ΔU) during the two SSW periods (SSW1: DOY 60–65; SSW2: DOY 75–80) relative to the pre-SSW mean. (d) Mean meridional wind (V) prior to the SSW. (e–f) Meridional wind differences (ΔV) during the two SSWs relative to the pre-SSW mean. Positive (negative) values indicate an enhancement of eastward–northward (westward–southward) winds.

cating that the perturbations remain vertically stratified. However, both the latitude band of the primary response and the direction of the lower altitude enhancement differ from those in the first SSW. For the meridional wind (ΔV ; Figure 2f), southward acceleration dominates over 10° – 40° N, whereas a northward acceleration signal emerges south of the equator ($\sim -10^{\circ}$ to 0°), indicating a tendency toward enhanced cross-equatorial flow.

To investigate the thermospheric compositional response to the SSWs at low and midlatitudes, we follow the same analysis strategy as that applied to the ICON observations in Figure 2. Because the thermospheric composition is highly sensitive to solar radiation and local time variability, the observations are restricted to a fixed local time (LT = 10:30) to minimize contamination from diurnal variations and changes in solar irradiance. The mean over DOY 30–59 is adopted as the pre-SSW reference, and differences between each SSW period and the reference period are then computed to highlight SSW-related perturbations. Figure 3 presents the spatial distribution of the GOLD $\Sigma O/N_2$ product, where Figure 3a shows the pre-SSW background mean (DOY 30–59) and Figures 3b and 3c show the anomalies during the two SSW phases relative to the pre-SSW period.

Relative to the pre-SSW state, $\Delta \Sigma O/N_2$ is dominated by positive anomalies during both SSW phases, indicating an enhanced rela-

tive abundance of atomic oxygen (O), a reduced contribution from molecular nitrogen (N_2), or both at low and midlatitudes. The enhancement is mainly observed at low to midlatitudes in the southern hemisphere. In contrast, changes near the equator and at low to midlatitudes in the northern hemisphere remain close to zero or exhibit only weak positive anomalies, indicating a southern hemisphere-biased compositional response. A further comparison of the two events shows that the $\Delta \Sigma O/N_2$ enhancement is stronger during the second SSW period, with the maximum increase reaching ~ 0.29 during the first SSW and ~ 0.37 during the second, implying a more pronounced low-latitude thermospheric compositional perturbation associated with the second event.

Similar to Figure 3, Figure 4 illustrates the spatial distribution of the neutral temperature at ~ 150 km observed by GOLD. Relative to the pre-SSW period, during the first SSW period, the neutral temperature predominantly increases, with a maximum enhancement of up to 105 K. In contrast, during the second SSW period, the neutral temperature decreases over the latitude range of $\sim 45^{\circ}$ – 15° S. The thermospheric temperature features observed during the second warming are consistent with previous observations (Yigit et al., 2023, 2024).

3.2 SSW Effects on the Ionosphere

The thermosphere and ionosphere are coupled systems through

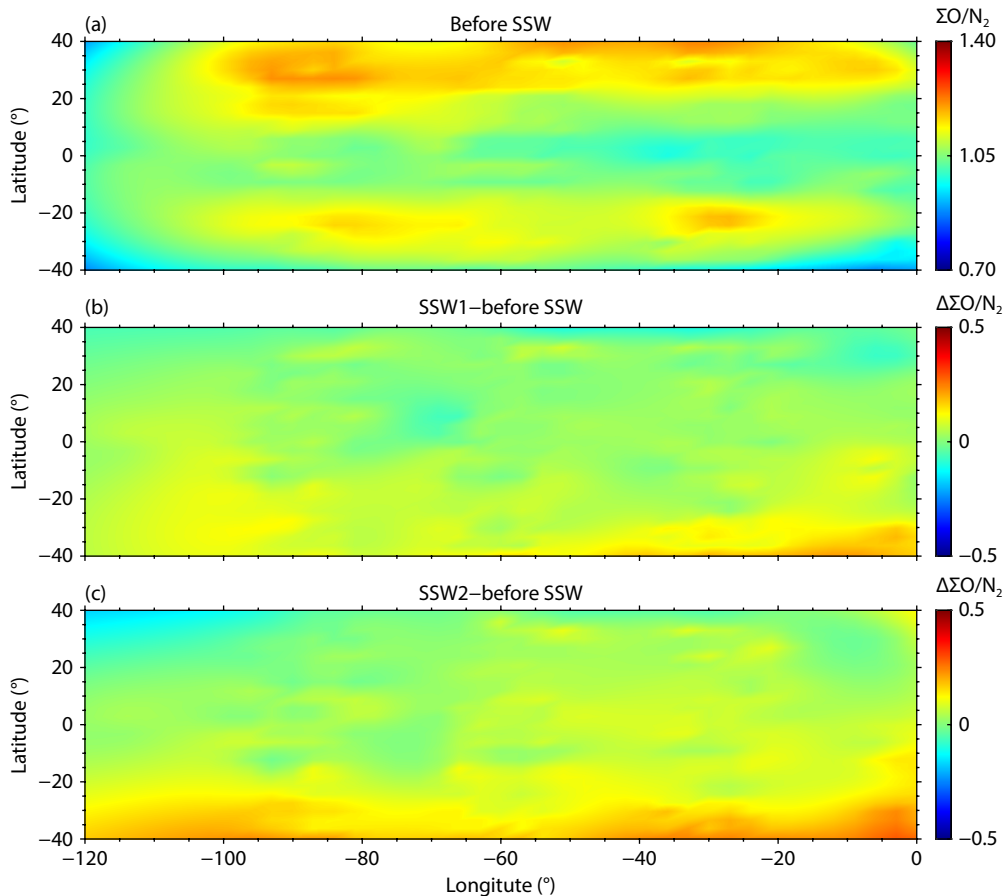


Figure 3. (a) Mean GOLD $\Sigma O/N_2$ at a fixed local time (LT = 10:30) prior to the SSW (DOY 30–59). (b–c) Differences in $\Sigma O/N_2$ ($\Delta \Sigma O/N_2$) during the two SSW periods (SSW1: DOY 60–65; SSW2: DOY 75–80) relative to the pre-SSW mean.

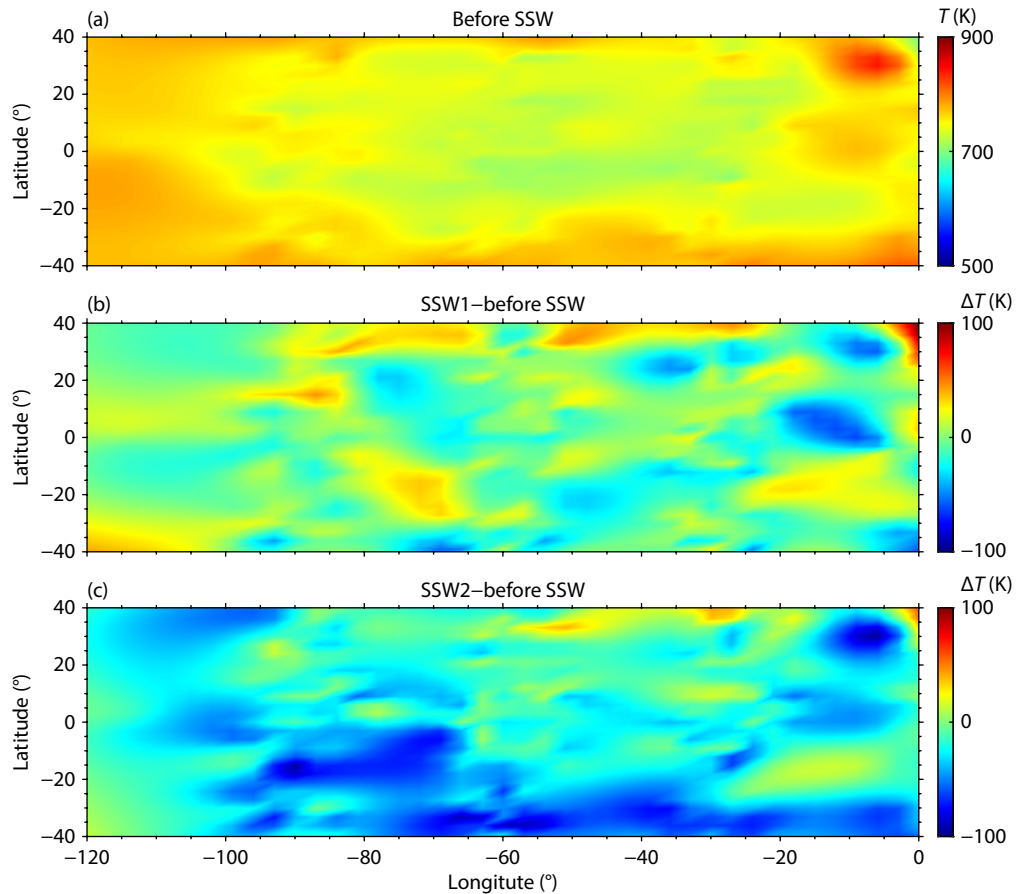


Figure 4. Same as Figure 3, but for the GOLD neutral temperature observed at an altitude of ~ 150 km, with the time fixed at 10:30 LT.

chemical, thermal, and dynamic processes. The ICON satellite completes 14–15 orbits per day, and in the following analysis, we use the equatorial (averaged within $\pm 1^\circ$ magnetic latitude) plasma drifts during the ascending orbits. With ICON's local time precession rate of ~ 48 days, we select the 48 days following the two SSW events (April 13–May 8, 2022) for the same analysis as a reference period. The local time, latitude, and longitude sampling patterns are identical in these two periods. Figure 5 shows the longitudinal and temporal structure of the equatorial vertical ion drifts (Figures 5a and 5b) and field-aligned drifts (Figures 5c and 5d) observed by the ICON IVM, with the bottom panels (Figures 5e and 5f) indicating the local time of the equatorial crossings. The dashed black lines mark the onset times of the two SSW events.

As the local time shifts from noon to predawn, the vertical $E \times B$ drift gradually moves downward in both periods (Fejer, 2011a). From February 24 to March 6, 2022 (DOY = 55–65), an upward disturbance is observed in the $E \times B$ drift. During the first SSW, the upward $E \times B$ drift is mainly observed in the longitude range of 70°W – 200°E , reaching a maximum of 29 m/s on February 26. In the reference period (April 13–May 8, 2022, DOY = 103–128), upward plasma drift also occurs, with amplitudes generally ~ 7 m/s from April 13 to 20 (DOY = 103–110), which is smaller than the amplitudes observed during the SSW, suggesting that the first SSW period induces an upward $E \times B$ drift in the equatorial region in the morning, likely because of the strengthening of the eastward

equatorial electric field, in agreement with previous electric field observations based on Jicamarca incoherent scatter radar measurements during SSWs (Fejer et al., 2010, 2011b). This enhancement in the electric field could have driven upward plasma motion, raising the ionosphere and potentially explaining the observed increase in electron density during the first SSW event in Figure 6. In contrast to the reference period, the second SSW primarily shows downward plasma drift, reaching a maximum of -30 m/s from February 24 to 26 (DOY = 55–57), indicating that the second SSW induced downward plasma drift in the equatorial region during the post midnight hours. The field-aligned ion drifts predominantly exhibit a northward direction during both periods. Compared with the reference period, the field-aligned ion drifts during both SSW events extend over a broader range and persist for longer, indicating that the SSWs induced a northward perturbation in the field-aligned ion drifts.

Similar to Figures 3a to 3c, Figures 6a to 6c show the spatial distributions of the OI 135.6-nm radiance observed by GOLD and the corresponding differences relative to the pre-SSW reference period over latitudes 40°S – 40°N and longitudes -60°W – 0°E at a fixed time of 20:00 LT. Figure 6a presents the mean radiance background during the pre-SSW period (DOY 30–59), whereas Figures 6b and 6c show the radiance differences during the first and second SSW phases relative to the reference, respectively. The difference maps indicate that, during the first SSW, the OI 135.6-

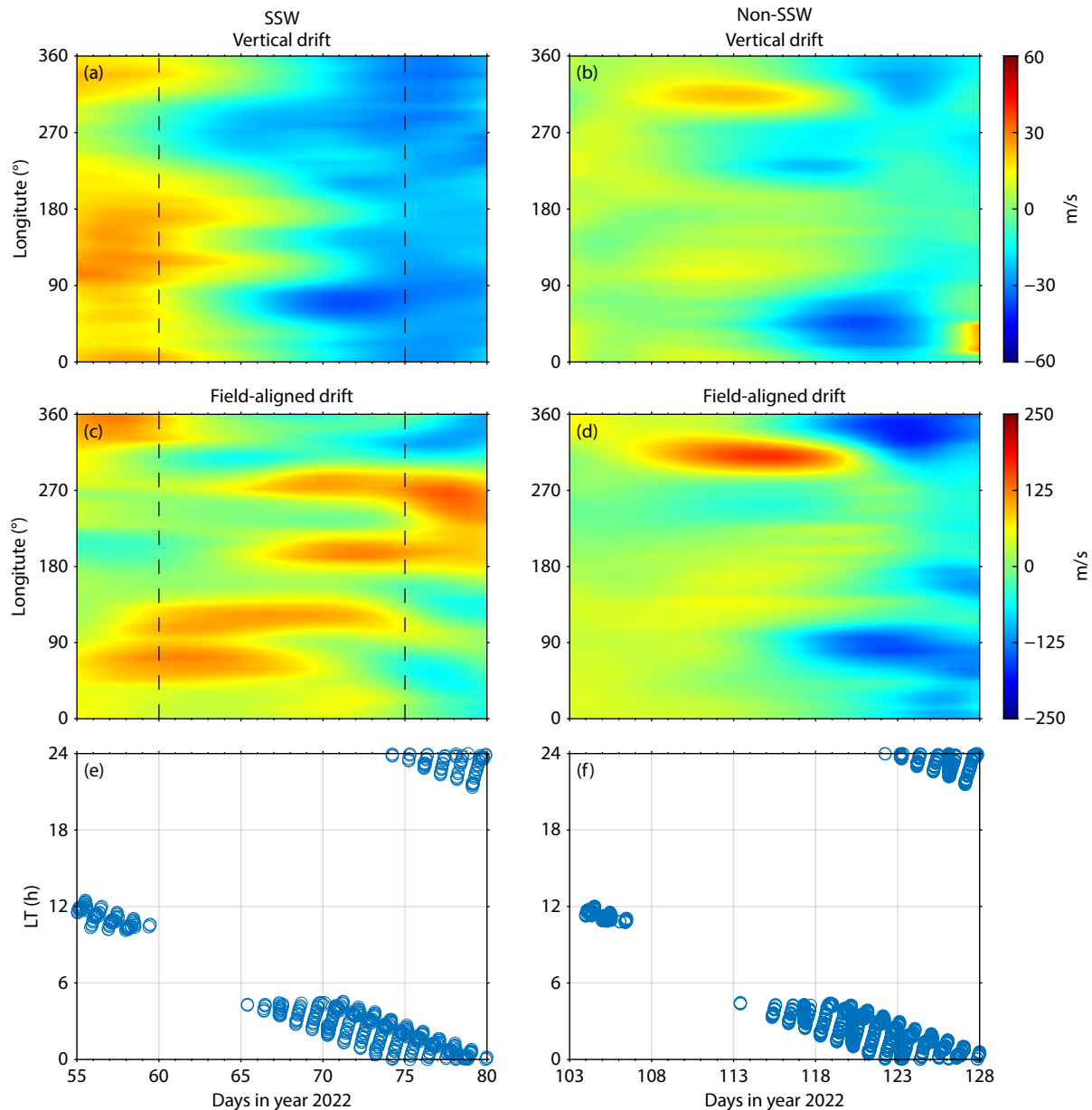


Figure 5. The longitudinal patterns of equatorial (averaged within $\pm 1^\circ$ magnetic latitude) vertical $E \times B$ drift (top panels) and field-aligned drifts (middle panels) observed by the ICON ion velocity meter (IVM) during two specific periods: February 24–March 21 (DOY = 55–80), 2022, and April 13–May 8 (DOY = 103–128), 2022. The dashed black lines indicate the onset of the two SSW events, and the bottom panel shows the local time of the satellite's equatorial crossing. Data gaps occur during DOY 60–65 and DOY 108–113 because of the unavailability of across-equator IVM observations.

nm radiance is substantially enhanced in the equatorial ionization anomaly (EIA) crest regions, with local increases reaching up to ~ 83 Ra (Rayleigh). In contrast, only a weak enhancement (~ 18 R) is observed near the geomagnetic equator. This crest-dominated enhancement pattern is consistent with GPS observations of an intensified EIA over the African sector (Idolor et al., 2022). During the second SSW, the enhancement is shifted closer to the geomagnetic equator with an amplitude of ~ 51 R, whereas the radiance at the original EIA crest locations decreases markedly, yielding a contrasting structure characterized by enhancement near the equator and depletion at the crests. This change indicates

that the EIA structure contracts toward the magnetic equator during the second warming.

These observations demonstrate the response of the low- and midlatitude IT system to the two SSW events in 2022. The deceleration or reversal of stratospheric and mesospheric winds associated with the SSW alters the propagation conditions for atmospheric waves (tides and GWs), which can propagate upward to thermospheric altitudes, affecting the electrodynamics and thermal effects at low and midlatitudes. The response of zonal wind wave amplitudes in the MLT region to the two SSWs is examined by

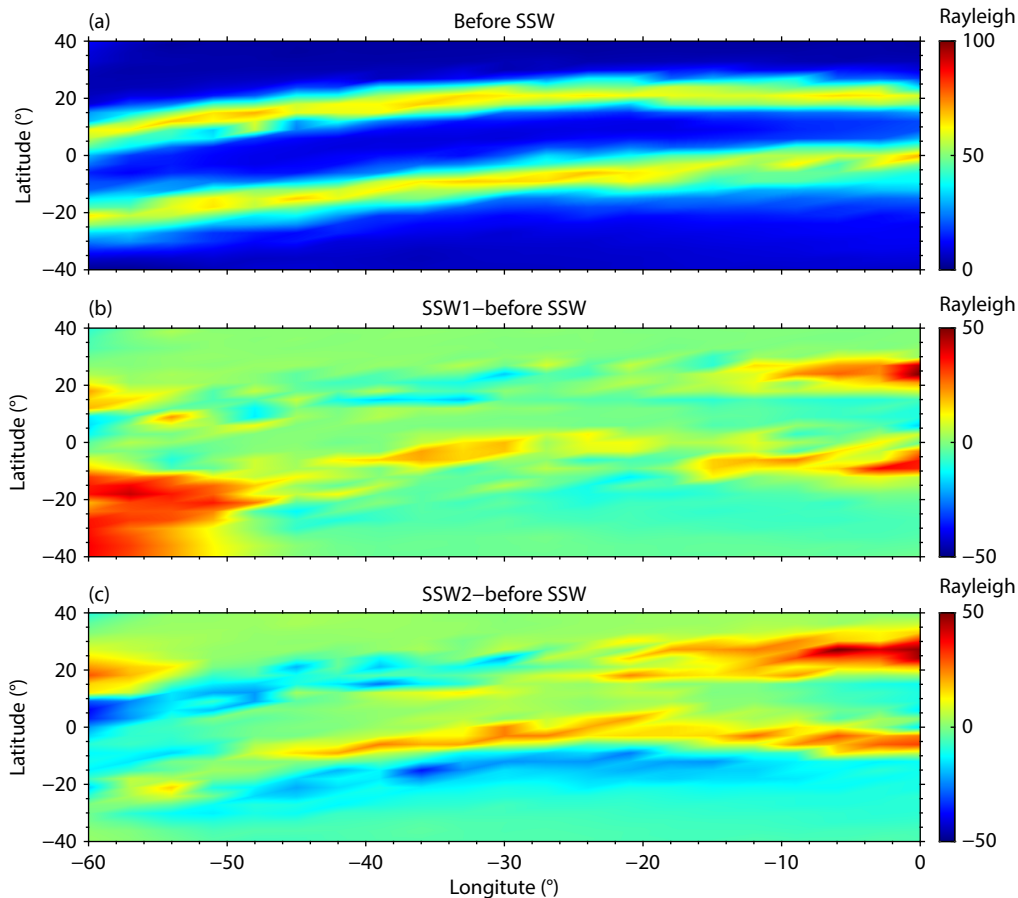


Figure 6. Similar to Figure 3, but depicting the GOLD two-dimensional 135.6-nm radiance at 20:00 LT.

using the 41-day running averages of MIGHTI observations to analyze the variations in lower atmospheric tidal waves. Figure 7 illustrates the latitudinal and temporal variations of the MIGHTI zonal mean winds near 93 km (Figure 7a) and 106 km (Figure 7a') and the zonal mean wind wave amplitudes of SW2, SW1, and SW3 near 93 km (Figures 7b–7d) and 106 km (Figures 7b'–7d'), where the blank areas in Figures 7a and 7a' indicate regions where MIGHTI data of poor quality were removed.

After the onset of the first SSW, increased eastward winds are observed at 93 km across almost all latitudes covered by ICON, with a maximum change of 105.6 m/s. Nonetheless, no significant changes occur in the amplitudes of SW1, SW2, and SW3 tides at both altitudes, indicating that the changes in the IT system during the first SSW are not driven by tidal variations. During the second SSW, the eastward winds around 93 km show a weakening, especially between 20° and 40°N, whereas the eastward wind enhancement around 106 km from –10° to 5°N increases from 18.5 to 44 m/s, and that from 15° to 35°N shows a weaker westward enhancement from –37.3 to –59.6 m/s, a change of 22.3 m/s, which is consistent with the wind variations shown in Figure 2. Around March 13–19 (DOY = 72–78), a moderate increase occurs in the amplitude of the SW2 at approximately 93 km near 5°–15°N, rising from ~2 m/s before the onset of the second SSW to ~11 m/s during the event. This increase begins shortly before the onset of the second SSW. Previous studies have shown an

enhancement in SW2 tidal amplitudes following major SSW events (Fang TW et al., 2012; Gasperini et al., 2023; Yiğit et al., 2024). Our results are consistent with the previously observed enhancement of semidiurnal tides in the thermosphere at low- and midlatitudes during SSWs. The enhanced SW2 during the SSW can interact with stationary planetary waves to generate the SW1 and SW3 (Coll and Forbes, 2002; Liu HL et al., 2010; He et al., 2017), and the latitudinal and temporal structure in Figure 7 is consistent with this mechanism.

4. Discussion

In this study, we investigate the responses of the low-latitude IT system to two different types of SSW events in 2022, based on multi-instrument observations from the ICON and GOLD missions. To illustrate the differences in IT responses during the two SSWs, Table 1 summarizes the variations in key parameters, including winds, tides, composition, and ion drifts. As shown in Table 1, the IT system exhibits opposite responses during the two events, which can be attributed to their distinct physical mechanisms. The SSW events modify the propagation conditions for atmospheric waves by altering the zonal wind fields in the stratosphere, thereby affecting the upward coupling into the IT system. During the first SSW, no significant changes in the tides (SW1, SW2, SW3) are observed. In contrast, during the second SSW, a notable enhancement of the SW2 tide is observed at 93 km altitude, with

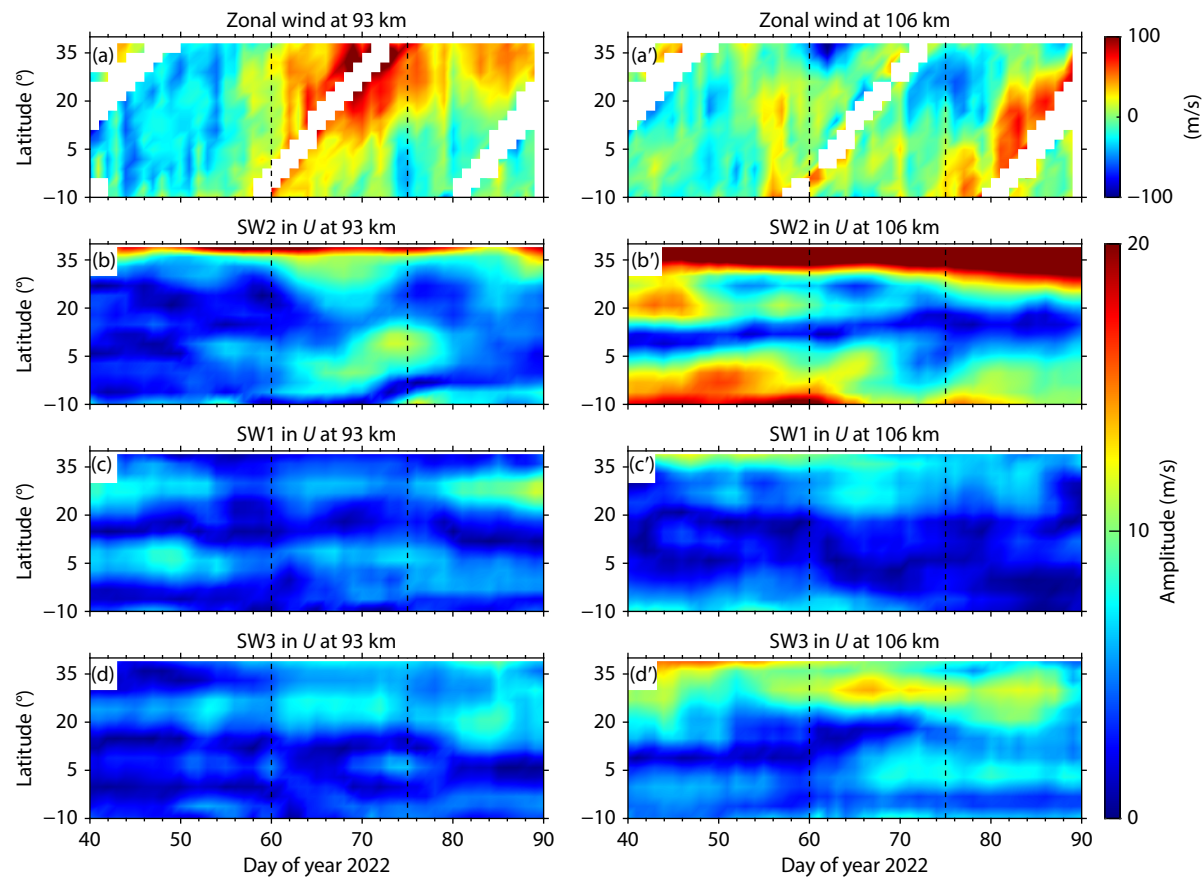


Figure 7. (a) Daytime zonal-mean zonal winds near 93 km observed by the Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI) from February 9 to March 31, 2022. (b–d) SW2, SW1, and SW3 amplitudes in the zonal mean wind averaged over 41 days. (a'–d') Same as (a) to (d), but near 106 km. The two dotted black lines signify the onset of the two warmings, respectively, when the stratospheric temperature at 90°N and 10 hPa increases.

Table 1. Summary of key characteristics of the two 2022 SSW events.^a

Characteristic	First warming	Second warming
Minimum zonal wind (m/s)	8	−7
Temperature increase (K)	24	21
SSW type	Minor SSW	SSFW
Zonal wind	<99 km: westward-to-eastward reversal >99 km: westward acceleration	<99 km: westward acceleration >99 km: eastward acceleration
Meridional wind	<99 km: southward acceleration >99 km: northward acceleration	<99 km: northward acceleration >99 km: southward acceleration
O/N ₂	Increase	Increase
Vertical drift	Upward perturbation	Downward perturbation
OI 135.6-nm radiance	Enhanced EIA	Equatorward-shifted EIA
Tidal activity	No significant change	Enhanced SW2

^aSSW, sudden stratospheric warming; SSFW, sudden stratospheric final warming; EIA, equatorial ionization anomaly; SW2, semidiurnal migrating tide.

its amplitude increasing from ~2 to 11 m/s, suggesting that intensified tidal activity is the primary driver of IT variations during the second event. In contrast, different processes may dominate during the first event. The dissipation of enhanced SW2 tides during the second SSW results in westward momentum deposition

in the thermosphere, leading to an acceleration of westward zonal winds above 99 km. During the daytime, the electrodynamics at low- and midlatitudes are primarily controlled by the electric fields generated by the E-region dynamo (Heelis, 2004). At these altitudes, enhanced semidiurnal tides can produce semidiurnal

variations in the electric fields, which are mapped to the F-region, redistributing vertical $E \times B$ drifts. As shown in Figure 7, the downward perturbations of equatorial vertical $E \times B$ drifts observed during the second SSW event are consistent with those reported by Zhang et al. (2022) during the 2021 major SSW event from ICON observations.

In addition to modulating the electric fields, the dissipation of upward-propagating tides can influence the meridional circulation in the MLT region. Our wind observations show that during the second SSW, the meridional wind over geographic latitudes 10° – 40° N exhibits a clear height-dependent change: a northward acceleration at lower altitudes (below 99 km) and a stronger southward enhancement at higher altitudes (above 99 km). This pattern suggests a more pronounced disturbance and adjustment of meridional transport in the low to midlatitude region. Previous studies (Oberheide et al., 2020; Martinez et al., 2024; Zhang JR et al., 2025) have shown that thermospheric composition anomalies during SSW events—including substantial variations in O/N_2 —are generally associated with disturbances in the residual mean meridional circulation and related vertical motions. In some cases, enhanced low-latitude upwelling has been reported to reduce O/N_2 (Oberheide et al., 2020; Martinez et al., 2024; Zhang JR et al., 2025). In contrast to those cases where O/N_2 decreases dominate, the O/N_2 increase observed in this study is more consistent with the composition redistribution associated with changes in meridional transport and the implied vertical redistribution (e.g., reduced upwelling or enhanced downwelling), which would increase the relative abundance of O-rich air and thus raise O/N_2 . It should be noted that because the spatial coverage of our wind and O/N_2 observations does not fully overlap, the mechanism proposed here is intended as a qualitative interpretation; further confirmation will require more complete global wind fields, dedicated model diagnostics, or both. Our results suggest that the wind anomalies in this SSW may be more closely related to tidal activity. The ionospheric responses can be understood as a combined effect of electrodynamic forcing and thermospheric composition-neutral changes, with the relative importance of these processes differing between SSW1 and SSW2. Consistent with this picture, previous studies have demonstrated that upward-propagating tides can substantially modify thermospheric winds and temperature, alter atomic oxygen, and consequently affect the F-region electron density (e.g., Jones et al., 2014, 2016). These previously reported results are qualitatively consistent with the variations observed during the second SSW event in this study, supporting the view that enhanced semidiurnal tidal activity (SW2 and SW3) likely played an important role during SSW2.

In addition to tidal effects, GW activity may influence the low and midlatitude IT system. During the first SSW, the westward acceleration of stratospheric zonal winds can modify GW filtering, potentially allowing more eastward-propagating GWs to reach higher altitudes (Yigit and Medvedev, 2012; Miyoshi et al., 2015). The enhanced GW activity dissipates in the MLT region, potentially leading to eastward momentum deposition (opposite the tides). This, in turn, can affect the IT system through mechanisms similar to tidal dissipation. Miyoshi et al. (2015) used the GW whole-atmosphere model, which indicated that enhanced GW activity during SSW events can induce downward winds at ~ 100 km, potentially

leading to an increase in the O mixing ratio. This report is qualitatively consistent with the observed rise in O/N_2 during the first SSW event. Additionally, no significant tidal (SW2, SW1, and SW3) changes are observed during the first SSW, which may indicate that different forcing pathways (tides or GWs) may be involved across the two events, rather than implying a unique driver. However, we emphasize that the present study does not include direct GW diagnostics; therefore, the GW contribution cannot be quantified and the observed IT variations cannot be uniquely attributed to GWs. The coupled variations in GWs and tides are possible causes of thermosphere–ionosphere changes during SSW events.

5. Summary

Combining observations from the ICON and GOLD satellites, we investigated the IT system response to the two successive SSW events in 2022 with distinct planetary wave characteristics (wave-1-dominant versus wave-2-dominant). Wind, temperature, and $\Sigma O/N_2$ parameters during the SSW events were compared with those before and during the pre-SSW periods, yielding the following results:

- (1) After the first SSW, an enhancement of eastward and southward mean winds is observed at lower altitudes (below ~ 99 km), whereas westward and northward mean winds are enhanced at higher altitudes (above ~ 99 km). This may explain the upward perturbations in the equatorial vertical $E \times B$ drift observed by ICON during the SSW events. The thermospheric $\Sigma O/N_2$ increases, with a maximum change of 0.3125. The neutral temperature at 150 km rises by approximately 46 K. The combined effects of electric fields and atmospheric circulation results in the more pronounced EIA.
- (2) The second SSW event is characterized by an acceleration of northward and westward winds below 99 km and an enhancement of eastward and southward winds above this altitude. This pattern may induce the downward perturbations in the equatorial vertical $E \times B$ drift observed by ICON. The thermospheric $\Sigma O/N_2$ increases, accompanied by thermospheric cooling. The equatorward shift of the EIA observed by GOLD during the two SSW events can be attributed to the combined influence of electric fields and atmospheric circulation.
- (3) During the second SSW, the SW2 is enhanced in the low-latitude region.

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Data Availability Statement

The ICON data are available at the website <https://cdaweb.gsfc.nasa.gov/pub/data/icon/>. The GOLD data are

from <http://gold.cs.ucf.edu/>. The K_p , $F_{10.7}$, and Dst indices are from https://cdaweb.gsfc.nasa.gov/cdaweb/sp_phys/, and the MERRA-2 temperature and zonal wind were obtained from the NASA Goddard Space Flight Center's Global Modeling and Assimilation Office at https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/data_access/.

References

- Andrews, D. G., Leovy, C. B., and Holton, J. R. (1987). *Middle Atmosphere Dynamics* (Vol. 40). Academic Press.
- Baldwin, M. P., and Dunkerton, T. J. (2001). Stratospheric harbingers of anomalous weather regimes. *Science*, 294(5542), 581–584. <https://doi.org/10.1126/science.1063315>
- Butler, A. H., Seidel, D. J., Hardiman, S. C., Butchart, N., Birner, T., and Match, A. (2015). Defining sudden stratospheric warmings. *Bull. Am. Meteor. Soc.*, 96(11), 1913–1928. <https://doi.org/10.1175/BAMS-D-13-00173.1>
- Chandran, A., Collins, R. L., and Harvey, V. L. (2014). Stratosphere-mesosphere coupling during stratospheric sudden warming events. *Adv. Space Res.*, 53(9), 1265–1289. <https://doi.org/10.1016/j.asr.2014.02.005>
- Charlton, A. J., and Polvani, L. M. (2007). A new look at stratospheric sudden warmings. Part I: Climatology and modeling benchmarks. *J. Climate*, 20(3), 449–469. <https://doi.org/10.1175/JCLI3996.1>
- Chau, J. L., Fejer, B. G., and Goncharenko, L. P. (2009). Quiet variability of equatorial $E \times B$ drifts during a sudden stratospheric warming event. *Geophys. Res. Lett.*, 36(5), L05101. <https://doi.org/10.1029/2008GL036785>
- Chau, J. L., Goncharenko, L. P., Fejer, B. G., and Liu, H. L. (2012). Equatorial and low latitude ionospheric effects during sudden stratospheric warming events. *Space Sci. Rev.*, 168(1–4), 385–417. <https://doi.org/10.1007/s11214-011-9797-5>
- Chau, J. L., Hoffmann, P., Pedatella, N. M., Matthias, V., and Stober, G. (2015). Upper mesospheric lunar tides over middle and high latitudes during sudden stratospheric warming events. *J. Geophys. Res.: Space Phys.*, 120(4), 3084–3096. <https://doi.org/10.1002/2015JA020998>
- Chen, X., Hu, X., and Xiao, C. (2012). Variability of MLT winds and waves over mid-latitude during the 2000/2001 and 2009/2010 winter stratospheric sudden warming. *Ann. Geophys.*, 30(6), 991–1001. <https://doi.org/10.5194/angeo-30-991-2012>
- Coll, M. A. I., and Forbes, J. M. (2002). Nonlinear interactions in the upper atmosphere: The $s = 1$ and $s = 3$ nonmigrating semidiurnal tides. *J. Geophys. Res.: Space Phys.*, 107(A8), SIA 3-1–SIA 3-15. <https://doi.org/10.1029/2001JA900179>
- Correia, J., Evans, J. S., Lumpe, J. D., Krywonos, A., Daniell, R., Veibell, V., McClintock, W. E., and Eastes, R. W. (2021). Thermospheric composition and solar EUV flux from the Global-Scale Observations of the Limb and Disk (GOLD) mission. *J. Geophys. Res.: Space Phys.*, 126(12), e2021JA029517. <https://doi.org/10.1029/2021JA029517>
- Cullens, C. Y., Immel, T. J., Triplett, C. C., Wu, Y. J., England, S. L., Forbes, J. M., and Liu, G. P. (2020). Sensitivity study for ICON tidal analysis. *Prog. Earth Planet. Sci.*, 7(1), 18. <https://doi.org/10.1186/s40645-020-00330-6>
- Dowdy, A. J., Vincent, R. A., Tsutsumi, M., Igarashi, K., Murayama, Y., Singer, W., Murphy, D. J., and Riggins, D. M. (2007). Polar mesosphere and lower thermosphere dynamics: 2. Response to sudden stratospheric warmings. *J. Geophys. Res.: Atmos.*, 112(D17), D17105. <https://doi.org/10.1029/2006JD008127>
- Eastes, R. W., McClintock, W. E., Burns, A. G., Anderson, D. N., Andersson, L., Aryal, S., Budzien, S. A., Cai, X., Codrescu, M. V., ... Woods, T. N. (2020). Initial observations by the GOLD mission. *J. Geophys. Res.: Space Phys.*, 125(7), e2020JA027823. <https://doi.org/10.1029/2020JA027823>
- Englert, C. R., Harlander, J. M., Brown, C. M., Marr, K. D., Miller, I. J., Stump, J. E., Hancock, J., Peterson, J. Q., Kumler, J., ... Immel, T. J. (2017). Michelson Interferometer for Global High-Resolution Thermospheric Imaging (MIGHTI): Instrument design and calibration. *Space Sci. Rev.*, 212(1–2), 553–584. <https://doi.org/10.1007/s11214-017-0358-4>
- Evans, J. S., Lumpe, J. D., Eastes, R. W., Correia, J., Aryal, S., Laskar, F., Veibell, V., Krywonos, A., Plummer, T., and McClintock, W. E. (2024). Disk images of neutral temperature from the Global-Scale Observations of the Limb and Disk (GOLD) mission. *J. Geophys. Res.: Space Phys.*, 129(6), e2024JA032424. <https://doi.org/10.1029/2024JA032424>
- Fang, T. W., Fuller-Rowell, T., Akmaev, R., Wu, F., Wang, H. J., and Anderson, D. (2012). Longitudinal variation of ionospheric vertical drifts during the 2009 sudden stratospheric warming. *J. Geophys. Res.: Space Phys.*, 117(A3), A03324. <https://doi.org/10.1029/2011JA017348>
- Fejer, B. G., Olson, M. E., Chau, J. L., Stolle, C., Lühr, H., Goncharenko, L. P., Yumoto, K., and Nagatsuma, T. (2010). Lunar-dependent equatorial ionospheric electrodynamic effects during sudden stratospheric warmings. *J. Geophys. Res.: Space Phys.*, 115(A8), A00G03. <https://doi.org/10.1029/2010JA015273>
- Fejer, B. G. (2011a). Low latitude ionospheric electrodynamics. *Space Sci. Rev.*, 158(1), 145–166. <https://doi.org/10.1007/s11214-010-9690-7>
- Fejer, B. G., Tracy, B. D., Olson, M. E., and Chau, J. L. (2011b). Enhanced lunar semidiurnal equatorial vertical plasma drifts during sudden stratospheric warmings. *Geophys. Res. Lett.*, 38(21), L21104. <https://doi.org/10.1029/2011GL049788>
- Fejer, B. G., and Tracy, B. D. (2013). Lunar tidal effects in the electrodynamics of the low latitude ionosphere. *J. Atmos. Solar-Terr. Phys.*, 103, 76–82. <https://doi.org/10.1016/j.jastp.2013.01.008>
- Forbes, J. M., Roble, R. G., and Fesen, C. G. (1993). Acceleration, heating, and compositional mixing of the thermosphere due to upward propagating tides. *J. Geophys. Res.: Space Phys.*, 98(A1), 311–321. <https://doi.org/10.1029/92JA00442>
- Forbes, J. M., and Zhang, X. L. (2012). Lunar tide amplification during the January 2009 stratosphere warming event: Observations and theory. *J. Geophys. Res.: Space Phys.*, 117(A12), A12312. <https://doi.org/10.1029/2012JA017963>
- Forbes, J. M., Oberheide, J., Zhang, X. L., Cullens, C., Englert, C. R., Harding, B. J., Harlander, J. M., Marr, K. D., Makela, J. J., and Immel, T. J. (2022). Vertical coupling by solar semidiurnal tides in the thermosphere from ICON/MIGHTI measurements. *J. Geophys. Res.: Space Phys.*, 127(5), e2022JA030288. <https://doi.org/10.1029/2022JA030288>
- Fuller-Rowell, T., Akmaev, R., Wu, F., Fedrizzi, M., Viereck, R. A., and Wang, H. J. (2011). Did the January 2009 sudden stratospheric warming cool or warm the thermosphere?. *Geophys. Res. Lett.*, 38(18), L18104. <https://doi.org/10.1029/2011GL048985>
- Funke, B., López-Puertas, M., Bermejo-Pantaleón, D., García-Comas, M., Stiller, G. P., Von Clarmann, T., Kiefer, M., and Linden, A. (2010). Evidence for dynamical coupling from the lower atmosphere to the thermosphere during a major stratospheric warming. *Geophys. Res. Lett.*, 37(13), L13803. <https://doi.org/10.1029/2010GL043619>
- Gan, Q., Eastes, R. W., Burns, A. G., Wang, W. B., Qian, L. Y., Solomon, S. C., Codrescu, M. V., and McClintock, W. E. (2020). New observations of large-scale waves coupling with the ionosphere made by the GOLD mission: Quasi-16-day wave signatures in the F-region OI 135.6-nm nightglow during sudden stratospheric warmings. *J. Geophys. Res.: Space Phys.*, 125(4), e2020JA027880. <https://doi.org/10.1029/2020JA027880>
- Gan, Q., Oberheide, J., Goncharenko, L., Qian, L., Yue, J., Wang, W., McClintock, W. E., and Eastes, R. W. (2023). GOLD synoptic observations of quasi-6-day wave modulations of post-sunset equatorial ionization anomaly during the September 2019 Antarctic sudden stratospheric warming. *Geophys. Res. Lett.*, 50(12), e2023GL103386. <https://doi.org/10.1029/2023GL103386>
- Gasperini, F., Jones, M., Jr., Harding, B. J., and Immel, T. J. (2023). Direct observational evidence of altered mesosphere lower thermosphere mean circulation from a major sudden stratospheric warming. *Geophys. Res. Lett.*, 50(7), e2022GL102579. <https://doi.org/10.1029/2022GL102579>
- Goncharenko, L. P., Chau, J. L., Liu, H. L., and Coster, A. J. (2010). Unexpected connections between the stratosphere and ionosphere. *Geophys. Res. Lett.*, 37(10), L10101. <https://doi.org/10.1029/2010GL043125>
- He, M., Chau, J. L., Stober, G., Hall, C. M., Tsutsumi, M., and Hoffmann, P. (2017).

- Application of Manley-Rowe relation in analyzing nonlinear interactions between planetary waves and the solar semidiurnal tide during 2009 sudden stratospheric warming event. *J. Geophys. Res.: Space Phys.*, 122(10), 10–783. <https://doi.org/10.1002/2017JA024630>
- Heelis, R. A. (2004). Electrodynamics in the low and middle latitude ionosphere: A tutorial. *J. Atmos. Solar-Terr. Phys.*, 66(10), 825–838. <https://doi.org/10.1016/j.jastp.2004.01.034>
- Heelis, R. A., Stoneback, R. A., Perdue, M. D., Depew, M. D., Morgan, W. A., Mankey, M. W., Lippincott, C. R., Harmon, L. L., and Holt, B. J. (2017). Ion velocity measurements for the Ionospheric Connections Explorer. *Space Sci. Rev.*, 212(1–2), 615–629. <https://doi.org/10.1007/s11214-017-0383-3>
- Idolor, O. R., Akala, A. O., and Bolaji, O. S. (2022). African and American Equatorial Ionization Anomaly (EIA) responses to 2013 SSW event. *J. Geophys. Res.: Space Phys.*, 127(3), e2021JA029848. <https://doi.org/10.1029/2021JA029848>
- Immel, T. J., England, S. L., Mende, S. B., Heelis, R. A., Englert, C. R., Edelstein, J., Frey, H. U., Korpela, E. J., Taylor, E. R., ... Sirk, M. M. (2018). The Ionospheric Connection Explorer mission: Mission goals and design. *Space Sci. Rev.*, 214(1), 13. <https://doi.org/10.1007/s11214-017-0449-2>
- Jones Jr, M., Forbes, J. M., Hagan, M. E., and Maute, A. (2014). Impacts of vertically propagating tides on the mean state of the ionosphere-thermosphere system. *J. Geophys. Res.: Space Phys.*, 119(3), 2197–2213. <https://doi.org/10.1002/2013JA019744>
- Jones Jr, M., Forbes, J. M., and Hagan, M. E. (2016). Solar cycle variability in mean thermospheric composition and temperature induced by atmospheric tides. *J. Geophys. Res.: Space Phys.*, 121(6), 5837–5855. <https://doi.org/10.1002/2016JA022701>
- Kurihara, J., Ogawa, Y., Oyama, S., Nozawa, S., Tsutsumi, M., Hall, C. M., Tomikawa, Y., and Fujii, R. (2010). Links between a stratospheric sudden warming and thermal structures and dynamics in the high-latitude mesosphere, lower thermosphere, and ionosphere. *Geophys. Res. Lett.*, 37(13), L13806. <https://doi.org/10.1029/2010GL043643>
- Laskar, F. I., and Pallamraju, D. (2014). Does sudden stratospheric warming induce meridional circulation in the mesosphere thermosphere system?. *J. Geophys. Res.: Space Phys.*, 119(12), 10133–10143. <https://doi.org/10.1002/2014JA020086>
- Li, N., Luan, X. L., Lei, J. H., Bolaji, O. S., Owolabi, C., Chen, J. S., Xu, Z. W., Li, G. Z., and Ning, B. Q. (2020). Variations of mesospheric neutral winds and tides observed by a meteor radar chain over China during the 2013 sudden stratospheric warming. *J. Geophys. Res.: Space Phys.*, 125(5), e2019JA027443. <https://doi.org/10.1029/2019JA027443>
- Liu, H. L., and Roble, R. G. (2002). A study of a self-generated stratospheric sudden warming and its mesospheric–lower thermospheric impacts using the coupled TIME-GCM/CCM3. *J. Geophys. Res.: Atmos.*, 107(D23), ACL 15–1–ACL 15–18. <https://doi.org/10.1029/2001JD001533>
- Liu, H. L., Wang, W., Richmond, A. D., and Roble, R. G. (2010). Ionospheric variability due to planetary waves and tides for solar minimum conditions. *J. Geophys. Res.: Space Phys.*, 115(A6), A00G01. <https://doi.org/10.1029/2009JA015188>
- Liu, H. X., Jin, H., Miyoshi, Y., Fujiwara, H., and Shinagawa, H. (2013). Upper atmosphere response to stratosphere sudden warming: Local time and height dependence simulated by GAIA model. *Geophys. Res. Lett.*, 40(3), 635–640. <https://doi.org/10.1002/grl.50146>
- Ma, H., Liu, L. B., Liu, H. X., Zhang, R. L., Yu, T. T., Qi, Y. F., Han, T. W., Qiu, L. H., Du, R. J., ... Chen, Y. D. (2025). The ionospheric responses during the 2020–2021 SSW from multiple simultaneous observations. *J. Geophys. Res.: Space Phys.*, 130(8), e2024JA033164. <https://doi.org/10.1029/2024JA033164>
- Ma, Z., Gong, Y., Zhang, S. D., Luo, J. H., Zhou, Q. H., Huang, C. M., and Huang, K. M. (2020). Comparison of stratospheric evolution during the major sudden stratospheric warming events in 2018 and 2019. *Earth Planet. Phys.*, 4(5), 493–503. <https://doi.org/10.26464/epp2020044>
- Manney, G. L., Lahoz, W. A., Swinbank, R., O'Neill, A., Connew, P. M., and Zurek, R. W. (1999). Simulation of the December 1998 stratospheric major warming. *Geophys. Res. Lett.*, 26(17), 2733–2736. <https://doi.org/10.1029/1999GL900516>
- Martinez, B. C., Lu, X., Pedatella, N. M., Wu, H., and Oberheide, J. (2024). Impact of the polar vortex on sub-seasonal O/N₂ variability in the lower thermosphere using GOLD and WACCM-X. *J. Geophys. Res.: Space Phys.*, 129(6), e2024JA032724. <https://doi.org/10.1029/2024JA032724>
- Matthewman, N. J., and Esler, J. G. (2011). Stratospheric sudden warmings as self-tuning resonances. Part I: Vortex splitting events. *J. Atmos. Sci.*, 68(11), 2481–2504. <https://doi.org/10.1175/JAS-D-11-07.1>
- Matsuno, T. (1971). A dynamical model of the stratospheric sudden warming. *J. Atmos. Sci.*, 28(8), 1479–1494. [https://doi.org/10.1175/1520-0469\(1971\)028<1479:ADMOTS>2.0.CO;2](https://doi.org/10.1175/1520-0469(1971)028<1479:ADMOTS>2.0.CO;2)
- Miyahara, S., and Wu, D. H. (1989). Effects of solar tides on the zonal mean circulation in the lower thermosphere: Solstice condition. *J. Atmos. Terr. Phys.*, 51(7–8), 635–647. [https://doi.org/10.1016/0021-9169\(89\)90062-7](https://doi.org/10.1016/0021-9169(89)90062-7)
- Miyoshi, Y., Fujiwara, H., Jin, H., and Shinagawa, H. (2015). Impacts of sudden stratospheric warming on general circulation of the thermosphere. *J. Geophys. Res.: Space Phys.*, 120(12), 10897–10912. <https://doi.org/10.1002/2015JA021894>
- Oberheide, J., Pedatella, N. M., Gan, Q., Kumari, K., Burns, A. G., and Eastes, R. W. (2020). Thermospheric composition O/N₂ response to an altered meridional mean circulation during sudden stratospheric warmings observed by GOLD. *Geophys. Res. Lett.*, 47(1), e2019GL086313. <https://doi.org/10.1029/2019GL086313>
- Pancheva, D., Mukhtarov, P., and Andonov, B. (2009). Nonmigrating tidal activity related to the sudden stratospheric warming in the Arctic winter of 2003/2004. *Ann. Geophys.*, 27(3), 975–987. <https://doi.org/10.5194/angeo-27-975-2009>
- Pedatella, N. M., and Liu, H. L. (2013). The influence of atmospheric tide and planetary wave variability during sudden stratosphere warmings on the low latitude ionosphere. *J. Geophys. Res.: Space Phys.*, 118(8), 5333–5347. <https://doi.org/10.1002/jgra.50492>
- Pedatella, N. M., Richmond, A. D., Maute, A., and Liu, H. L. (2016). Impact of semidiurnal tidal variability during SSWs on the mean state of the ionosphere and thermosphere. *J. Geophys. Res.: Space Phys.*, 121(8), 8077–8088. <https://doi.org/10.1002/2016JA022910>
- Vargin, P. N., Koval, A. V., and Guryanov, V. V. (2022). Arctic stratosphere dynamical processes in the winter 2021–2022. *Atmosphere*, 13(10), 1550. <https://doi.org/10.3390/atmos13101550>
- Wang, L., and Alexander, M. J. (2009). Gravity wave activity during stratospheric sudden warmings in the 2007–2008 Northern Hemisphere winter. *J. Geophys. Res.: Atmos.*, 114(D18), D18108. <https://doi.org/10.1029/2009JD011867>
- Wu, D. L., Hays, P. B., and Skinner, W. R. (1995). A least squares method for spectral analysis of space-time series. *J. Atmos. Sci.*, 52(20), 3501–3511. [https://doi.org/10.1175/1520-0469\(1995\)052<3501:ALSMFS>2.0.CO;2](https://doi.org/10.1175/1520-0469(1995)052<3501:ALSMFS>2.0.CO;2)
- Yamazaki, Y., and Richmond, A. D. (2013). A theory of ionospheric response to upward-propagating tides: Electrodynamical effects and tidal mixing effects. *J. Geophys. Res.: Space Phys.*, 118(9), 5891–5905. <https://doi.org/10.1002/jgra.50487>
- Yigit, E., and Medvedev, A. S. (2012). Gravity waves in the thermosphere during a sudden stratospheric warming. *Geophys. Res. Lett.*, 39(21), L21101. <https://doi.org/10.1029/2012GL053812>
- Yigit, E., Gann, A. L., Medvedev, A. S., Gasperini, F., Sakib, M. N., and Wu, Q. (2023). Variations of low-latitude thermospheric winds and temperature during the 2020/2021 major sudden stratospheric warming as observed by ICON and GOLD Satellites. *Authorea Preprints*.
- Yigit, E., Gann, A. L., Medvedev, A. S., Gasperini, F., Wu, Q., and Sakib, N. (2024). Observation of vertical coupling during a major sudden stratospheric warming by ICON and GOLD: A case study of the 2020/2021 warming event. *Front. Astron. Space Sci.*, 11, 1384196. <https://doi.org/10.3389/fspas.2024.1384196>
- Zeng, X. Y., and Zhong, G. (2024). Analysis of gravity wave activity during stratospheric sudden warmings in the northern hemisphere. *Earth Planet. Phys.*, 8(2), 415–422. <https://doi.org/10.26464/epp2024007>

- Zhang, J. R., Oberheide, J., Pedatella, N. M., and Liu, G. P. (2025). Impact of Arctic and Antarctic sudden stratospheric warmings on thermospheric composition. *J. Geophys. Res.: Space Phys.*, 130(1), e2024JA032562. <https://doi.org/10.1029/2024JA032562>
- Zhang, R., Liu, L., Ma, H., Chen, Y., and Le, H. (2022). ICON observations of equatorial ionospheric vertical $E \times B$ and field-aligned plasma drifts during the 2020–2021 SSW. *Geophys. Res. Lett.*, 49(16), e2022GL099238. <https://doi.org/10.1029/2022GL099238>
- Zhang, R. L., Liu, L. B., Balan, N., Le, H. J., Chen, Y. D., and Zhao, B. Q. (2018). Equatorial ionospheric disturbance field-aligned plasma drifts observed by C/NOFS. *J. Geophys. Res.: Space Phys.*, 123(5), 4192–4201. <https://doi.org/10.1029/2018JA025273>
- Zhou, X., Zhang, N., Wang, Z. Q., Ruan, H. B., Cai, Y. H., Yu, Y., He, M. S., Wang, J. Y., Li, M. Y., ... Yue, X. N. (2025). Ionospheric day-to-day variability driven by nonlinear interactions between the terdiurnal tide and planetary waves under magnetospheric modulation. *Geophys. Res. Lett.*, 52(23), e2025GL119445. <https://doi.org/10.1029/2025GL119445>