Direct Observational Evidence of Altered Mesosphere Lower Thermosphere Mean Circulation from a Major Sudden Stratospheric Warming

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December 21, 2022

Abstract

Sudden stratospheric warmings (SSWs) are large-scale phenomena characterized by dramatic dynamic disruptions in the stratospheric winter polar regions. Previous studies, especially those employing whole atmosphere models, indicate that SSWs have strong impacts on the circulation of the mesosphere lower thermosphere (MLT) and drive a reversal in the mean meridional circulation (MMC) near 90-125 km altitude. However, the robustness of these effects and the roles of SSW-induced changes in global-scale wave activity to drive the reversal have been difficult to observe simultaneously. This work employs horizontal lower thermospheric (~93-106 km altitude) winds near 10S-40N latitude from the Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI) instrument onboard the Ionospheric Connection Explorer (ICON) to present observational evidence of a prominent MLT MMC reversal associated with the January 2021 major SSW event and to demonstrate connections to semidiurnal tidal activity and possible associations with a ~3-day ultra-fast Kevin wave (UFW).
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Key Points:

• A prominent (∼30 m/s) reversal in the MLT mean meridional circulation during the January 2021 major SSW is observed in MIGHTI winds
• Strong (∼35 m/s) MLT westward flow enhancements are observed following the onset of the SSW
• Amplification in MLT SW2 zonal wind amplitudes are consistent with the observed westward flow enhancements

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Abstract

Sudden stratospheric warmings (SSWs) are large-scale phenomena characterized by dramatic dynamic disruptions in the stratospheric winter polar regions. Previous studies, especially those employing whole atmosphere models, indicate that SSWs have strong impacts on the circulation of the mesosphere lower thermosphere (MLT) and drive a reversal in the mean meridional circulation (MMC) near 90-125 km altitude. However, the robustness of these effects and the roles of SSW-induced changes in global-scale wave activity to drive the reversal have been difficult to observe simultaneously. This work employs horizontal lower thermospheric (∼93-106 km altitude) winds near 10°S-40°N latitude from the Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI) instrument onboard the Ionospheric Connection Explorer (ICON) to present observational evidence of a prominent MLT MMC reversal associated with the January 2021 major SSW event and to demonstrate connections to semidiurnal tidal activity and possible associations with a ∼3-day ultra-fast Kevin wave (UFW).

Plain Language Summary

The winds in the mesosphere lower thermosphere (MLT) are strongly impacted by dramatic changes in the stratospheric winter polar regions associated with Sudden Stratospheric Warmings (SSWs). Models have shown that the climatological direction of the MLT north-south and vertical circulation, characterized by equatorward flow near ∼100-120 km and poleward flow near ∼80-100 km, reverses following the onset of SSWs. Yet, the impacts and causes of these dynamical effects are not well established observationally due to the lack of comprehensive global measurements of the MLT region. This study evaluates the evolution of MLT winds and associated tidal and ultra-fast Kevin wave (UFW) variations during the January 2021 SSW using horizontal wind observations from the Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI) instrument onboard the Ionospheric Connection Explorer (ICON) to present observational evidence of a large MLT north-south wind reversal due to the SSW and associated global-scale wave influences.

1 Introduction

Stratospheric Sudden Warmings (SSWs) are global-scale meteorological events driven by the dissipation of vertically-propagating planetary waves originating in the troposphere
SSW events are characterized based on the changes that occur in the stratosphere, including a rapid increase in polar temperatures and deceleration of the zonal mean zonal winds. A SSW is classified as a major SSW if the zonal mean zonal winds at 60°N and 10 hPa reverse from eastward to westward (e.g., Charlton and Polvani, 2007). SSWs lead to significant disturbances in the whole atmosphere (Stening, 1977), producing remarkable changes in composition, dynamics, and electrodynamics of the whole ionosphere-thermosphere system, pole-to-pole, as demonstrated by a number of modeling and observational studies (e.g., Goncharenko and Zhang, 2008; Chau et al., 2009; Goncharenko et al., 2010; Chau et al., 2012, 2015; Butler et al., 2015; Zulicke et al., 2018; Laskar et al., 2019; Pedatella et al., 2014, 2016, 2018, 2022; Jones et al., 2020; Oberheide et al., 2020; Oberheide 2022; Siddiqui et al., 2022; Liu et al., 2022). Modeling and observational evidence also suggest that SSW impacts can extend into the summer mesosphere and mesopause region through inter-hemispheric coupling (e.g., Becker and Fritts, 2006; Tan et al., 2012; Liu et al., 2013, 2014; Miyoshi et al., 2015; Lieberman et al., 2021; Goncharenko et al., 2022). Thus, SSWs provide an exemplary case to study the coupling between the lower atmosphere and the overlying atmospheric regions.

It is now well established that the deceleration and reversal of winter stratospheric wind associated with SSWs produce significant changes in the propagation conditions of global-scale waves that lead to strong changes in upper atmospheric circulation (e.g., Liu and Roble, 2002; Tan et al., 2012; Yiğit and Medvedev, 2012, 2016; Yuan et al., 2012; Yiğit et al., 2014, 2016; Miyoshi et al., 2015; Liu, 2017; Jones et al., 2020). These SSW-induced wind and temperature disturbances in the stratosphere and mesosphere lead to enhancements in the solar semidiurnal migrating tide (SW2, 12-hour period and westward zonal wave number s = 2) and other non-migrating tidal components (e.g., Chang et al., 2009; Liu et al., 2010; Pancheva et al., 2009; Pedatella et al., 2012; Pedatella and Liu, 2013) due to nonlinear interactions with stationary planetary waves (e.g., Liu et al., 2010; Sathishkumar and Sridharan, 2013), changes in the tidal propagation conditions (e.g., Jin et al., 2012) and stratospheric ozone distribution (e.g., Goncharenko et al., 2012; Siddiqui et al., 2019). SSWs can also lead to resonant amplification of the lunar semidiurnal migrating tide (M2, 12.42-hour period) because of the atmospheric Pekeris mode (Forbes and Zhang, 2012; Liu et al., 2022). Modeling evidence (e.g., Yamazaki et al., 2020) also suggests that ultra-fast Kevin waves (UFKWs) may be amplified during SSWs, how-
ever, the relationship between SSWs and UFKWs remains unclear (e.g., England et al., 2012; Liu et al., 2012; Phanikumar et al., 2014; Sassi et al., 2013, Yamazaki et al., 2020).

Previous modeling studies (e.g., Miyoshi et al., 2015; Zhang J. et al., 2021, 2022; Orsolini et al., 2022; Wang et al., 2022) suggest that the climatological direction of the mesosphere-lower thermosphere (MLT) mean meridional circulation (MMC), characterized by upwelling in the middle winter latitudes, equatorward flow near ∼100-120 km, and poleward flow near ∼80-100 km, reverses following the onset of SSWs. Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy (GAIA) model simulations from Miyoshi et al. (2015) revealed that MMC reversed in the lower thermosphere. More recently, Orsolini et al. (2022) used the Whole Atmosphere Community Climate Model with thermosphere and ionosphere eXtension (WACCM-X) in the specified dynamics configuration to show that the lower thermospheric mean meridional circulation reverses for about 10 days following the onset of elevated stratopause events in the northern hemisphere largely driven by westward-propagating planetary waves. Important impacts on MLT mean circulation have also been reported observationally (e.g., Oberheide, 2022) including enhancements of both eastward and westward directed flow associated with wave dissipation. Zhang R. et al. (2022) used Ionospheric Connection Explorer (ICON) Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI) and Ion Velocity Meter (IVM) data to investigate ionosphere-thermosphere coupling during the January 2021 SSW, suggesting the importance of the F-region northward wind changes in driving anomalous ionospheric field-aligned flows. However, no studies have investigated the lower-altitude wind patterns which are thought to dominate the ionospheric SSW response.

This study examines zonal and meridional MLT (∼93-106 km) wind observations from the MIGHTI instrument onboard ICON to present observational evidence of a prominent MLT MMC reversal associated with the January 2021 major SSW event and to demonstrate connections to semidiurnal tidal activity and possible impacts on a ∼3-day UFKW with s = -1 (hereafter, UFKW1). After a brief description of the data and methods (Section 2), we show impacts on MLT dynamics and connections to wave drivers (Section 3), and provide the conclusions (Section 4).
2 ICON MIGHTI Neutral Wind Profiles and Wave Diagnostics

ICON is a NASA Heliophysics System Observatory (HSO) mission launched on 10 October 2019 into a nearly circular ~590 km altitude and ~27° inclination orbit to study the connections between the dynamics of the neutral atmosphere near 90-300 km and the electrodynamics of the low-latitude ionosphere (Immel et al., 2018; Immel and Eastes, 2019; Immel et al., 2021). ICON retrieves neutral wind profiles in the upper atmosphere using the Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI) instrument from remote observations of green ~557.7 nm and red ~630.0 nm airglow emissions (Harlander et al. 2017). This work employs zonal and meridional neutral winds (ICON data product L2.2 V04) from ~93 km to ~106 km altitude, where continuous day and night observations are available in the 10°S to 40°N latitude range. More information on MIGHTI wind, error analyses, and validation can be found in Englert et al. (2017), Harding et al. (2017, 2021), and Makela et al. (2021). Recently, Yiğit et al (2022) examined the climatology of MIGHTI mean zonal and meridional winds and associated mean circulation finding the prevalence of eastward zonal winds and northward meridional winds and general agreement with middle thermospheric wind climatologies, validating the use of MIGHTI to study mean winds.

Based on the occurrence of occasional gaps, data quality issues, and instrument calibrations, MIGHTI allows for stable extraction of solar tides within 41-day moving windows (Cullens et al., 2020; Forbes et al., 2022). In this work, semidiurnal tidal fits are performed using 41-day moving windows on winds averaged in 6° latitude, 60° longitude, and 2-hour UT bins extending from 10°S to 40°N using the native ~2.5 km altitude sampling. This binning effectively removes the effects of small-scale variations and improves the statistics while also leading to smoother visual depictions. Wind data flagged as bad (quality flag = 0) are not included. Many of the 0-flagged data are connected with South Atlantic Anomaly contamination. Their removal leaves gaps near 270°-330°longitude in the Southern Hemisphere that are not significantly affecting the latitude regions of primary interest for this study. Forbes et al. (2022) provide more details on the tidal diagnostics of the composite data, which closely follows the procedure adopted by Gasperini et al. (2021) in the analyses of ICON IVM data and by Gasperini et al. (2015, 2017, 2018, 2020) in the analysis of Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) observations. After the exact UFKW1 period is determined using spectral analysis, simultaneous least-squares fits are performed on these 41-day windows to de-
Figure 1. (a) MERRA-2 zonal and diurnal average zonal wind near 60°N latitude during 1 December 2020 - 31 January 2021. (b) Same as (a), but for MERRA-2 temperature averaged 60°N-90°N latitude. (c) Time series of (a) at 10 hPa. (d) Time series of F10.7 (black line) and Kp (blue line, left y-axis) for the same period as (a)-(c). The orange vertical lines indicate 3 January 2021 when the zonal mean zonal winds at 60°N and 10 hPa first reversed from eastward to westward.

Figure 1 shows the height-time structure of the longitude and diurnal mean zonal wind at 60°N (panel a) and 60°-90°N polar cap temperature (panel b), the time series of the zonal mean zonal wind at 10 hPa (panel c) and the time series of the solar and geomagnetic indices (panel d) for 1 December 2020 - 31 January 2021. A major SSW event, indicated by a reversal of the 60°N stratospheric zonal mean zonal winds, started on 3 January 2021, with westward winds that persisted through 21 January (with a 2-day eastward interruption). The relatively long persistence of westward wind during this SSW was explained as a reflection of persistent strong dynamical forcing overtaking non-adiabatic cooling effects (e.g., Lu et al., 2021). More information on the lower and middle atmospheric response to this SSW can be found in the recent work by Rao et al. (2021). The geomagnetic Kp index (blue line in Figure 1d) exhibits periods of moderate activ-
Figure 2. MIGHTI longitude-mean day/night averaged meridional winds near 106 km (a) and 93 km (b) during 1 December 2020 - 31 January 2021. (a')-(b') Same as (a)-(b), but for zonal winds. MIGHTI meridional mean winds as a function of altitude (∼94-106 km) and latitude (∼0-40°N) during 7 December - 2 January (c) and 3-29 January (c'). (c'') Difference between (c') and (c). (d)-(d'') Same as (c)-(c''), but for zonal winds. The orange vertical lines in (a)-(a') and (b)-(b') indicate 3 January 2021 when the zonal mean zonal winds at 60°N and 10 hPa first reversed from eastward to westward.

It is important to note that the recurrent moderate geomagnetic activity present during this 62-day period is unlikely to generate variability at MLT heights that would significantly alias into the dynamic response to the SSW, especially considering that its day-to-day variability is very different than the timescale of the SSW (see the discussion in Oberheide (2022)).

Next, the dynamic response of the MLT to the SSW is examined by employing longitude- and day/night-averaged (hereafter, ‘zonal mean’) MIGHTI wind observations between ∼93 km and ∼106 km. Figure 2 shows the temporal evolution of zonal mean MIGHTI meridional (panels a and b) and zonal (panels a' and b') winds as a function of latitude (10°S-35°N) during 1 December 2020 - 31 January 2021 near 106 km and 93 km, respectively. After removing seasonal and longer-term effects by generating residuals from 27-day running means, the winds are then averaged between Dec 7 - Jan 2 (‘Before SSW’) and Jan 3 - Jan 29 (‘During SSW’), and their altitude (∼94-106 km) and latitude (∼0-40°N) structure is illustrated in Figures 2c-2c' (Figures 2d-2d') for the meridional (zonal) components. To best highlight changes associated with the SSW, Figure 2c'' (Figure 2d'') shows the differences between the ‘During SSW’ and the ‘Before SSW’ case for the meridional (zonal) wind component. As visible by close inspection of Figures 2a-2b and best
Figure 3. ICON/MIGHTI mean zonal winds near 93 km (a), MIGHTI 41-day mean zonal wind SW2 (b), SW1 (c), SW3 (d), and UFKW1 (e) amplitudes near 93 km during 1 Dec 2020 - 31 Jan 2021. (a’)-(e’) Same as (a)-(d), but near 106 km. The orange vertical lines indicate 3 January 2021 when the zonal mean zonal winds at 60°N and 10 hPa first reversed from eastward to westward.

Illustrated by Figure 2c”, the meridional mean winds are found to experience a marked change in direction from primarily southward before the SSW to primarily northward during the SSW at the upper heights (i.e., above ~98 km) and from mainly northward before the SSW to mainly southward during the SSW at the lower MLT heights (i.e., ~95-98 km). These effects are particularly prominent near 20°N-40°N with meridional wind variations around 10-40 m/s (depending on latitude and altitude). The direction and magnitude of these wind variations provide observational confirmation of previous modeling results (e.g., Miyoshi et al., 2015) and are consistent with the understanding that the typical summer-to-winter MLT flow can be broken down during SSWs, resulting in a two-cell pattern with equatorward motion at lower heights (i.e., <90-95 km) and poleward motion aloft (i.e., >105-110 km).

Prominent enhancements in the westward mean winds following the onset of the SSW are found, with variations up to ~35 m/s compared to the ‘Before SSW’ case as demonstrated by Figure 2d”. These effects exhibit a strong dependency in latitude and some in altitude, with the westward enhancements strongest at the northernmost latitudes sampled by MIGHTI (i.e., ~30°N-40°N). Further, previous modeling work by Miyoshi et al. (2015), Oberheide et al. (2020), and Jones et al. (2020) indicate that these enhanced westward winds observed by MIGHTI are likely driven by periodic westward forcing via the Eliassen-Palm flux divergence, which then contributes to the observed residual MMC in Figure 2.

Finally, the response of MLT zonal wind wave amplitudes to the SSW is examined using 41-day running averages of MIGHTI observations. While a 35-day averaging may
be sufficient to extract the complete tidal spectrum from MIGHTI data (e.g., Cullens et al., 2020), we find that a 41-day averaging provides improved fits for latitudes above \( \sim 25^\circ \text{N} \) (see also discussion in Section 2). Figure 3 shows MIGHTI mean zonal winds near 93 km (panel \( a \)) and 106 km (panel \( a' \)) and SW2, SW1, and SW3 zonal wind tidal amplitudes near 93 km (panels \( b-d \)) and near 106 km (panels \( b'-d' \)). Large enhancements in SW2 zonal wind amplitudes near 93 km and \( 10^\circ \text{N}-35^\circ \text{N} \) occur around 10-20 January concurrent with the significant strengthening in westward mean winds that follows the onset of the SSW. A weaker increase in SW2 amplitudes (and enhanced westward mean winds) also appears near the equator during 1-7 January. Similar to the SW2 MIGHTI wind diagnostics in Oberheide (2022), SW2 displays strong enhancements associated with the SSW near 106 km. SW1, SW2, and SW3 typically attain their largest amplitudes at mid-to-high latitudes, outside of the latitudes observed by ICON. However, recent work by Pedatella (2022) shows that simulated SD-WACCM-X SW2 amplitudes near 110 km are also strongly enhanced between 1-8 January near \( 50^\circ \text{N-60}^\circ \text{N} \) and \( 50^\circ \text{S-60}^\circ \text{S} \), with SD-WACCM-X SW1 and SW3 zonal wind amplitudes also slightly enhanced but exhibiting more day-to-day variability. Also, note that while SSW-induced effects on SW1 and SW3 seem less prominent than those observed on SW2, it is important to keep in mind that day-to-day variability in these tidal components is largely removed by the 41-day averaging.

In addition to the semidiurnal tidal impacts previously noted, evidence of a large (\( \sim 15 \text{ m/s near 106 km} \)) \( \sim 3 \)-day UFKW1 is found during this 62-day period extending from 1 December 2020 to 31 January 2021. Figures 2e-2e' show the latitude-temporal structure of its amplitudes during 1 December - 31 January near 93 km and 106 km, respectively. Enhanced UFKW1 amplitudes near 106 km observed during 11-21 January and \( \sim 0-10^\circ \text{N} \) closely resemble the SW2 amplifications found near 93 km. Connections between SSWs and UFKWs are not unexpected, as enhanced westward mean winds in the middle atmosphere would tend to favor the vertical propagation of UFKWs into the MLT given their eastward-propagation characteristics. It is well known both numerically and observationally (e.g., Forbes, 2000, 2020; Gasperini et al., 2015, 2018, 2020) that background zonal-mean zonal winds can Doppler-shift UFKWs modifying their propagation (e.g., Ekanayake et al., 1997), and thus changing their vertical wavelength (e.g., Forbes and Vincent, 1989) and susceptibility to dissipation. While of certain interest, it would
be beyond the scope of this study to investigate SSW-UFKW connections in further detail and this effort is left as an avenue for possible follow on work.

4 Summary and Conclusions

Previous whole atmosphere modeling studies suggest that the climatological direction of the MLT mean meridional circulation, characterized by equatorward flow near \(\sim 100-120 \text{ km}\) and poleward flow near \(\sim 80-100 \text{ km}\), reverses in response to a major SSW event. However, the veracity of these modeling predictions, the robustness of the effects, and the roles of SSW-induced changes in global-scale activity to drive the reversal have yet to be observed concurrently.

This work employed zonal and meridional MLT wind observations from the MIGHTI instrument onboard ICON in the \(\sim 93-106 \text{ km}\) altitude range to present first-time (to the best of the authors’ knowledge) observational evidence of a prominent MLT MMC reversal associated with the January 2021 major SSW event. The meridional mean winds are found to change in direction from southward before the SSW to northward during the SSW at the upper heights (i.e., above \(\sim 98 \text{ km}\)) and from northward before the SSW to southward during the SSW at the lower MLT heights (i.e., \(\sim 95-98 \text{ km}\)). These large changes in the mean meridional winds are of the order of \(\pm 30 \text{ m/s}\) and are most prominent at the northernmost latitudes sampled by MIGHTI (i.e., \(30-40^\circ \text{N}\)). These wind changes provide observational confirmation of previous modeling results (e.g., Miyoshi et al., 2015) suggesting that the typical summer-to-winter MLT flow is broken down during SSWs and a resulting two-cell pattern emerges with equatorward motion at lower heights and poleward motion aloft.

Prominent enhancements (upward of \(\sim 35 \text{ m/s}\)) in westward mean winds are also found in response to the SSW, with effects that are strongest at higher altitudes (i.e., \(>102 \text{ km}\)) and latitudes (i.e., \(30^\circ-40^\circ \text{N}\)). Large enhancements in SW2 zonal wind amplitudes near \(93 \text{ km}\) and \(10^\circ\text{N}-35^\circ\text{N}\) occurring around 10-20 January are concurrent and nearly colocated with significant strengthening in westward mean winds following the onset of the SSW. Effects associated with SW1 and SW3 are found to play a smaller role, in contrast with the discussion by Zhang R. et al (2022). Spectral analyses also reveal the presence of a \(\sim 3\)-day UFKW1 with enhanced amplitudes (\(\sim 15 \text{ m/s}\)) near \(106 \text{ km}\) occurring during 10-20 January and \(0-10^\circ\text{N}\) that closely resemble the SW2 amplifications.
near 93 km. The latter result supports a possible connection between SSWs and UFKWs that warrants further investigation.

5 Open Research

MIGHTI ICON V04 winds were obtained from https://icon.ssl.berkeley.edu/Data/. Note that preliminary analyses of the recently-released MIGHTI V05 wind product support the main conclusions of this study. The 3-hourly Kp index was obtained from GFZ Potsdam at https://kp.gfz-potsdam.de/app/files/Kp_ap_sine_1932.txt, the F10.7 cm radio flux from NASA/GSFC OMNIWeb at https://omniweb.gsfc.nasa.gov/form/dx1.html, and the MERRA-2 zonal wind and temperature from NASA/GSFC Global Modeling and Assimilation Office (GMAO) at https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/data_access/.

Acknowledgments

ICON is supported by NASA’s Explorers Program through contracts NNG12FA45C and NNG12FA42I. FG acknowledges support from NASA Grant No. 80NSSC22K0019 and NSF Award No. 2113411. MJ acknowledges support from the NASA Early Career Investigator (NNH18ZDA001N-ECIP/18-ECIP_2-0018) and GOLD-ICON Guest Investigators (NNH20ZDA001N-GIGI/20-GIGI20_2-0009) programs.

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Figure 1.
MERRA-2 Zonal & Diurnal Mean U, 60N

MERRA-2 Zonal & Diurnal Mean T, 60N-90N

Zonal & Diurnal Mean Zonal Wind at 60N, 10hPa

F10.7 (black), Kp (blue)
Figure 2.
a. ICON/MIGHTI V (m/s) ~ Long. Mean ~ 106 km

b. ICON/MIGHTI V (m/s) ~ Long. Mean ~ 93 km

c. Mean V ~ Before SSW

d. Mean U ~ Before SSW

c'. Mean V ~ During SSW

d'. Mean U ~ After SSW

c''. During SSW - Before SSW

d''. After SSW - Before SSW