Impact of Arctic and Antarctic Sudden Stratospheric Warmings on Thermospheric Composition

Jiarong Zhang¹, Jens Oberheide¹, Nicholas M Pedatella², and Guiping Liu³

¹Department of Physics and Astronomy, Clemson University, Clemson, SC, USA
²High Altitude Observatory, NSF National Center for Atmospheric Research, Boulder, CO, USA
³ITM Physics Laboratory, Heliophysics Science Division, NASA Goddard Space Flight Center, Greenbelt, MD, USA

May 17, 2024

Abstract

Using the Global-scale Observations of the Limb and Disk (GOLD) and the Global Ultraviolet Imager (GUVI), we examine the impact of sudden stratospheric warmings (SSWs) on the changes of thermospheric composition during the 2018-2019 and 2020-2021 Arctic SSWs and the 2019 Antarctic SSW. Contributions of planetary waves, gravity waves, and migrating tides are assessed by performing numerical experiments with the NSF National Center for Atmospheric Research (NCAR) vertically extended version of the Whole Atmosphere Community Climate Model (WACCM-X). The wind evolution simulated in WACCM-X aligns well with the quasi-geostrophic wind derived from Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) geopotential height measurements during Arctic and Antarctic SSWs. The variations in column integrated O and N₂ density ratio ([O]/[N₂]) are generally similar among WACCM-X, GOLD, and GUVI observations. Following the onset of SSWs, [O]/[N₂] is reduced by ~10% over 50°S-50°N and enhanced by ~20% at higher latitudes. The [O]/[N₂] changes are associated with the reversals of the mean meridional circulation in the lower thermosphere, mainly driven by westward-travelling planetary waves. The results highlight that planetary wave activity during SSWs can significantly impact the mean state of the thermosphere.
Impact of Arctic and Antarctic Sudden Stratospheric Warmings on Thermospheric Composition

Jiarong Zhang\(^1\), Jens Oberheide\(^2\), Nicholas M. Pedatella\(^2\), Guiping Liu\(^3\)

\(^1\)Department of Physics and Astronomy, Clemson University, Clemson, SC, USA
\(^2\)High Altitude Observatory, NSF National Center for Atmospheric Research, Boulder, CO, USA
\(^3\)ITM Physics Laboratory, Heliophysics Science Division, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Abstract

Using the Global-scale Observations of the Limb and Disk (GOLD) and the Global Ultraviolet Imager (GUVI), we examine the impact of sudden stratospheric warmings (SSWs) on the changes of thermospheric composition during the 2018-2019 and 2020-2021 Arctic SSWs and the 2019 Antarctic SSW. Contributions of planetary waves, gravity waves, and migrating tides are assessed by performing numerical experiments with the NSF National Center for Atmospheric Research (NCAR) vertically extended version of the Whole Atmosphere Community Climate Model (WACCM-X). The wind evolution simulated in WACCM-X aligns well with the quasi-geostrophic wind derived from Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) geopotential height measurements during Arctic and Antarctic SSWs. The variations in column integrated O and N\(_2\) density ratio (\(\sum O/N_2\)) are generally similar among WACCM-X, GOLD, and GUVI observations. Following the onset of SSWs, \(\sum O/N_2\) is reduced by \(~10\%) over 50°S-50°N and enhanced by \(~20\%) at higher latitudes. The \(\sum O/N_2\) changes are associated with the reversals of the mean meridional circulation in the lower thermosphere, mainly driven by westward-travelling planetary waves. The results highlight that planetary wave activity during SSWs can significantly impact the mean state of the thermosphere.

Key Points

- \(~10\%) \(\sum O/N_2\) depletion over 50°S-50°N is observed by GOLD and GUVI, as well as simulated in WACCM-X during Arctic and Antarctic SSWs
- At higher latitudes, a \(~20\%) increase in \(\sum O/N_2\) is observed by GOLD and GUVI, as well as simulated in WACCM-X
• \( \sum \frac{O}{N_2} \) variations during SSWs are driven by the reversals of MMC in the lower thermosphere, induced by westward-travelling planetary waves

1. Introduction

Sudden stratospheric warmings (SSWs) are a large-scale meteorological phenomenon in the polar winter stratosphere, characterized by rapid increases in temperature over several days (Butler et al., 2015). SSWs are triggered by large amplitude planetary waves (PWs) that propagate upward from the troposphere into the stratosphere, and the induced wave forcing decelerates the westerly stratospheric winds (Matsuno, 1971). It is widely recognized that PWs, gravity waves (GWs) and atmospheric tides are modified during SSWs (e.g., Jin et al., 2012; Chandran et al., 2013; Sassi et al., 2013; Hibbins et al., 2019; Zhang et al., 2021). The average number of major SSWs is \( \sim 0.6 \) per winter in the Northern Hemisphere (NH) (Butler et al., 2015), while the occurrence in the Southern Hemisphere (SH) is less frequent due to weaker PW forcing.

The dynamical signature of SSWs can extend into the upper atmosphere (Baldwin et al., 2021). Mesospheric mean meridional circulation (MMC) with ascent at the summer pole and descent at the winter pole is weakened during SSWs (Holton, 1983), indicated by long-lived trace species from observations (Manney et al., 2009; Orsolini et al., 2010; Lee et al., 2011; Straub et al., 2012; Bailey et al., 2014; Zhang et al., 2023). Above the mesosphere, the thermosphere transitions from a well-mixed fluid controlled by eddy diffusion to one dominated by molecular diffusion between 100 and 120 km (Jones et al., 2022). In the lower thermosphere (LT), the MMC is characterized by ascent in the winter mid-to-high latitudes and descent in the summer high latitudes (Lossow et al., 2009; J. C. Wang et al., 2022; N. Wang et al., 2022), driven by high phase speed GWs (Qian et al., 2017). The LT MMC plays a significant role in the structure and variability of the thermospheric composition and ionospheric density (Qian et al., 2017). Thermospheric composition is commonly represented by the column number density ratio of atomic oxygen to molecular nitrogen \( (\sum \frac{O}{N_2}) \). \( \sum \frac{O}{N_2} \) is crucial for the ionosphere, as the photoionization of O is an important source of plasma, and \( N_2 \) controls the loss of ionosphere plasma (Forbes., 2007). Qian and Yue (2017) found that upwelling in the LT significantly decreases \( \sum \frac{O}{N_2} \) in winter and
the downwelling in summer slightly increases $\sum O/N_2$. Consequently, the LT MMC reduces the summer-to-winter latitudinal gradient of $\sum O/N_2$.

The narrow LT MMC is reversed following the onset of SSWs, as simulated in the specified dynamics configuration of Whole Atmosphere Community Climate Model with thermosphere-ionosphere eXtension (SD-WACCM-X) (Orsolini et al., 2022). This reversal could alter the thermospheric composition. Ionospheric responses to SSWs have been observed from the ground (Goncharenko et al., 2010a, b) and from space (Oberheide, 2022). However, the present understanding of the thermospheric composition response to SSWs primarily relies on numerical model simulations due to limited thermospheric observations. Pedatella et al. (2016) found a $\sim15\%$ reduction in $\sum O/N_2$ during the 2013 Arctic SSW through a series of controlled numerical experiments with the National Science Foundation (NSF) National Center for Atmospheric Research (NCAR) thermosphere-ionosphere-electrodynamics general circulation model (TIE-GCM). Oberheide et al. (2020) provided the first observational evidence of a $\sim10\%$ depletion of $\sum O/N_2$ at the onset of the Arctic SSW in early January 2019 using the NASA Global-scale Observations of the Limb and Disk (GOLD). As SSWs rarely occur in the SH, there has been limited exploration of the $\sum O/N_2$ response to Antarctic SSWs. The only exception is the study by Goncharenko et al. (2021). They reported a $\sim5\%$–$15\%$ $\sum O/N_2$ depletion at all longitudes and low latitudes (20°S to 20°N) during the Antarctic SSW in September 2019 observed by Global Ultraviolet Imager (GUVI) limb measurements. In addition, they found that the $\sum O/N_2$ response at middle latitudes in both hemispheres depends on longitude.

The $\sum O/N_2$ depletion during SSWs is likely to be due to a complex combination of circulation changes introduced by GWs, PWs, and atmospheric tides (Pedatella et al., 2016). The dissipation of migrating diurnal and semidiurnal tides introduces a net westward momentum forcing, leading to a decrease in O and an increase in N$_2$ in the LT (Forbes et al., 1993; Müller-Wodarg and Aylward, 1998; Jones et al., 2014; Pedatella et al., 2016). These changes in lower thermosphere composition propagate through molecular diffusion into the upper thermosphere (Yamazaki and Richmond, 2013). Miyoshi et al. (2015) found that SSW events weaken eastward GW drag in the
thermosphere, which in turn weakens the southward meridional circulation and decreases lower thermospheric O using a GW-resolving whole atmosphere model. Moreover, traveling PWs can also impact the composition of the thermosphere (Sassi et al., 2016; Orsolini et al., 2022). The relative influences of various wave forcings in the LT on $\sum O/N_2$ variability during SSWs are still poorly understood.

As mentioned earlier, the observed response of $\sum O/N_2$ to Arctic and Antarctic SSWs has been largely unexplored, and there is a need for clarification on the dominant wave forcing. The main objective of this study is to present $\sum O/N_2$ variations during the recent Arctic SSW events in the winters of 2018/2019 and 2020/2021, as well as the Antarctic SSW event in September 2019 observed by GOLD. The differences in $\sum O/N_2$ response to Arctic and Antarctic SSWs will be discussed. $\sum O/N_2$ is also observed by GUVI onboard the Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics (TIMED) satellite. As GUVI samples high latitudes and two-thirds of the Earth that GOLD cannot see, $\sum O/N_2$ observed by GUVI will be compared with GOLD. In addition, to clarify the respective roles of GWs, PWs, and migrating tides in changing $\sum O/N_2$, we will conduct modeling simulations using the SD-WACCM-X.

The manuscript is organized as follows. Section 2 describes GOLD version 5.2 $\sum O/N_2$, GUVI version 13 $\sum O/N_2$, the model framework and simulations, and the methodology. Section 3 presents the characteristics of $\sum O/N_2$ during Arctic and Antarctic SSWs, as observed in GOLD, GUVI, and simulated in SD-WACCM-X. This section also discusses the dominant wave forcings involved. Section 4 presents the conclusions.

2. Data and Methodology

2.1 GOLD $\sum O/N_2$

The GOLD instrument has been operated on the SES-14 telecommunication satellite in a geostationary orbit at 47.5°W longitude since 2018 (Eastes et al., 2017, 2020). The GOLD imager consists of two identical and independent channels (Channels A and B) observing the Earth’s far ultraviolet airglow at $\sim$134-162 nm (Eastes et al., 2017, 2020). The NH and SH are scanned
separately from east to west with each scan lasting ~12 minutes (Correira et al., 2021). GOLD has the advantage of separating temporal and spatial changes over the Americas and Atlantic. \( \sum O/N_2 \), referenced to a fixed \( N_2 \) vertical column density of 10\(^{17} \) cm\(^{-2} \), is retrieved from the intensity ratio of the disk O 135.6 nm to \( N_2 \) Lyman-Birge-Hopfield (LBH) emission radiance at a half-hour cadence, but at a one-two hour cadence since September 2021.

Note that \( O^+ \) radiative recombination within the equatorial ionization anomalies can produce O 135.6 nm emission, leading to an error in \( \sum O/N_2 \). The error in the derived GOLD \( \sum O/N_2 \) is \( \sim 1\%-2\% \) during solar and geomagnetic quiet times but can reach 10%-20% as solar and geomagnetic activity increases (Correira et al., 2021). Additionally, the data have been corrected to compensate for detector degradation. However, sometimes the correction may not be sufficient near the equator, causing artifacts (Qian et al., 2022; Liu et al., 2023). As a result, \( \sum O/N_2 \) variations over the equatorial region must be treated with care.

In this study, we use Level 2 \( \sum O/N_2 \) version 5.2, where a linear trend error introduced by the calibration has been eliminated (details in the GOLD instrument documentation, available at https://gold.cs.ucf.edu/data/documentation/). The GOLD \( \sum O/N_2 \) is averaged during daytime over all observed longitudes (120°W to 20°E).

2.2 GUVI \( \sum O/N_2 \)

The GUVI instrument is onboard NASA's TIMED satellite, launched on 7 December 2001 into a 630 km circular polar orbit with an inclination of 74.1° (Christensen et al., 2003). The TIMED spacecraft precesses 360° in 120 days so that each local time is sampled every 60 days. GUVI detects thermospheric far ultraviolet emissions in five wavelength channels: H Lyman a (121.6 nm), O (130.4 nm), O (135.6 nm), \( N_2 \) LBH short filter band (140–150 nm), and \( N_2 \) LBH long filter band (165–180 nm). \( \sum O/N_2 \), referenced to a fixed \( N_2 \) vertical column density of 10\(^{17} \) cm\(^{-2} \), is derived from the ratio of O 135.6 nm emission and \( N_2 \) LBH 140-150 nm emission (Zhang et al., 2004). The data analyzed in this study are from Level 3 version 13. The GUVI \( \sum O/N_2 \) is averaged over all observed longitudes.
2.3 SABER

Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) is a 10-channel broadband limb-scanning infrared radiometer (1.27–17 μm) onboard the NASA's TIMED satellite (Esplin et al., 2023; Russell et al., 1999). The measurements span latitudes from 82°S to 53°N or 53°S to 82°N daily depending on the 60-day spacecraft yaw cycle that prevents direct solar radiance from entering the SABER telescope. As global winds in the upper atmosphere are notoriously difficult to measure, we compute quasi-geostrophic winds using SABER geopotential height fields, following the methodology used in Oberheide et al. (2002), and previously used to study SABER mesospheric water vapor dynamics during SSW (Zhang et al., 2023).

2.4 SD-WACCM-X

WACCM-X is a comprehensive numerical model that includes chemical, physical and dynamical processes to simulate the Earth's atmosphere from the surface to the upper boundary, which is located between 500 km and 700 km depending on solar and geomagnetic activities (Liu et al., 2018). Version 2.1 incorporates neutral wind dynamo, ionospheric transport, calculations of ion/electron energetics, and temperatures to better resolve thermospheric energetics and thermal structure. It is an atmospheric component of the Community Earth System Model (CESM) version 2.1. In particular, excessively high eddy diffusion coefficients above the turbopause have been revised, fixing the low atomic-to-molecular composition ratios in the thermosphere present in version 2.0.

To simulate the recent SSW events during 2018-2021, we use the specified dynamics (SD) configuration in which the model winds and temperature in the troposphere and stratosphere are constrained by NASA Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2) reanalysis (Gelaro et al., 2017). The horizontal resolution is 1.9° latitude by 2.5° longitude, with 145 vertical levels. The simulation was initialized on October 1, 2018, and output hourly.
For comparisons with GOLD and GUVI, O and N$_2$ density profiles from SD-WACCM-X are averaged daily and zonally and integrated down to an altitude corresponding to an N$_2$ column density of $10^{17}$ cm$^{-2}$.

2.5 Occurrence of SSWs

In this study, we focus on the 2018/2019 and 2020/2021 Arctic SSW events, as well as the 2019 Antarctic SSW event. The two Arctic SSW events are accompanied by an elevated stratopause (ES-SSW), identified following the three criteria used by Limpasuvan et al. (2016). ES-SSW events occur when the stratospheric jet, the GW forcing, and the MMC remain reversed longer than in winters where an SSW occurs without an ES, as noted by Chandran et al. (2013). The onset date of Arctic ES-SSW events is defined as the time when the polar cap averaged (70°N-90°N) zonal-mean zonal wind at 1 hPa reverses from eastward to westward.

In early September 2019, an Antarctic SSW occurred (Eswaraiah et al., 2020; Goncharenko et al., 2020; Miyoshi & Yamazaki, 2020; Yamazaki et al., 2020; Lee et al., 2021). As the zonal-mean zonal wind reversal at 60°S did not reach 10hPa, the event is categorized as a minor warming. The onset date of the 2019 Antarctic SSW event is defined as the time when the zonal-mean zonal wind at 1 hPa and 60°S reverses from eastward to westward.

2.6 Relative $\sum O/N_2$ Anomaly

The deep summer-to-winter thermospheric MMC, driven by solar heating, causes the summer-to-winter difference in $\sum O/N_2$. To elucidate the $\sum O/N_2$ changes associated with SSW, we calculate the relative $\sum O/N_2$ anomaly, defined as the ratio of the anomaly to the climatology. The relative anomaly is a good measure of day-to-day variations in $\sum O/N_2$ (Oberheide et al., 2020). In computing the climatology, we fit annual, semiannual, and ter-annual harmonics at each latitude to GOLD and SD-WACCM-X $\sum O/N_2$. For GUVI $\sum O/N_2$, the climatology comprises the sum of annual and semiannual harmonics, along with a 60-day cycle attributed to the yaw cycle during either ascending or descending leg of orbits. For each year, the climatology is calculated based on a time series spanning around 545 days, beginning on October 1st of previous year and
ending on March 31st of the following year. The anomaly is defined as departures from the climatology.

2.7 Wave Analysis

To clarify the respective roles of waves in altering $\sum O/N_2$ during SSWs, we extract westward-travelling PWs (WPWs), eastward-travelling PWs (EPWs), quasi-stationary PWs (QSPWs), and migrating tides from hourly SD-WACCM-X output using a 2D fast Fourier transform (FFT). 2D FFT is performed on a 61-day window for PWs and a 3-day window for tides. The analysis window is then shifted forward by 1 day. Westward and eastward PWs consist of waves with zonal wavenumbers 1–5 and periods between 2 and 20 days. Quasi-stationary waves are defined as signals with periods longer than 20 days. Regarding migrating tides, our primary focus is on diurnal migrating tides (DW1) and semidiurnal migrating tides (SW2).

To investigate wave activity, we compute the residual MMC $(\tilde{\phi}^*, \tilde{\omega}^*)$ based on the Transformed Eulerian Mean (TEM) formulation in log-pressure vertical coordinates (Andrews et al., 1987). $(\tilde{\phi}^*, \tilde{\omega}^*)$ is a good approximate of the Lagrangian mean flow (Andrews & McIntyre, 1976). To better visualize the circulation, the velocity streamfunction ($\Psi$) of the residual MMC is estimated from a latitudinal integration of $\tilde{\omega}^*$, with a boundary condition of $\Psi = 0$ at the North Pole or the South Pole (Orsolini et al., 2022). The unit of $\Psi$ is m s$^{-1}$. Using Equation 3 in Orsolini et al. (2022), we calculate the contributions of the wave forcings by WPWs, EPWs, QSPWs, DW1, and SW2 to the velocity streamfunction.

3. Results and Discussion

3.1 Characteristics of Arctic and Antarctic SSWs

Figure 1 gives an overview of the 2018/2019 Arctic SSW (panels a & d), 2020/2021 Arctic SSW (panels b & e), and 2019 Antarctic SSW (panels c & f) using SD-WACCM-X and SABER. The vertical gray line indicates the onset of SSWs. The gaps in SABER (panels d-f) are missing data caused by the yaw cycle of the spacecraft. The 2018/2019 and 2020/2021 Arctic SSWs exhibit similar evolution patterns. In the polar region (60°N-80°N), the winter stratosphere and mesosphere are
characterized by eastward winds in early December, associated with the meridional temperature gradient. The eastward zonal-mean zonal wind between 40 km-60 km over the polar region weakens and eventually transitions to westward at the onset of Arctic SSWs (panels a, b, d, e), followed by an elevated stratopause. During the subsequent warming period, the wind reversal propagates to lower altitudes. A comparison between the Arctic SSWs in 2018/2019 and 2020/2021 (panels a, b, d, e) shows that the wind reversal is stronger, and the downward propagation is faster in the latter. The difference can be attributed to different types of SSW events: displacement in 2018/2019 and split in 2020/2021 (Bouillon et al., 2023).

Compared to the Arctic SSWs, the wind reversal is weaker and there is no development of an elevated stratopause during the 2019 Antarctic SSW. The eastward zonal-mean zonal wind undergoes a sharp decrease of ~30 m/s on August 30th and September 3rd in the mesosphere. A reversal of the zonal-mean zonal winds from eastward to westward at 1 hPa occurs in mid-September and descends to lower altitudes in the subsequent days. However, the wind reversal did not reach 10 hPa level, which differs from the Arctic SSW events. Overall, the evolution of winds is similar between SD-WACCM-X simulations and SABER observations, especially below ~80 km.

**Figure 1.** Time-altitude cross sections of zonal-mean zonal wind over 60°N-80°N for Arctic SSWs and 60°S-80°S for Antarctic SSW from (a-c) SD-WACCM-X and (d-f) SABER. In SABER, zonal wind is the zonal component of geostrophic wind. The vertical gray line indicates the onset of SSWs: (a, d) December 24th, 2018; (b, e) January 2nd, 2021; and (c, f) September 9th, 2019.
3.2 $\Sigma O/N_2$ response to Arctic and Antarctic SSWs

The intense oscillation of stratospheric wind during the SSWs has a strong impact on thermospheric composition. Figure 2 shows the time evolution of the daily Kp index and the relative $\Sigma O/N_2$ anomaly during the SSWs, simulated by SD-WACCM-X and observed by GUVI and GOLD. The Kp index remains at relatively low geomagnetic activity (Kp<3) for most days, with a slight increase to 3 at the end of December 2019 and 4 in early September 2020 (panels a-c). Following the onset of SSWs, both the simulated (panels d-f) and observed (panels g-l) $\Sigma O/N_2$ exhibit a reduction over 50°S-50°N and an enhancement at higher latitudes. As day-to-day $\Sigma O/N_2$ variations are highly correlated with the Kp index (Martinez and Lu, 2023), the depletion during SSWs is attenuated at the end of December 2019 when geomagnetic activity is relatively large. The variations in $\Sigma O/N_2$ following the SSWs align with findings from Oberheide et al. (2020). Their TIE-GCM simulation with climatological lower boundary but realistic geomagnetic and solar forcing, along with a free-running WACCM-X simulation with constant low geomagnetic and solar forcing, confirmed that any $\Sigma O/N_2$ variations following SSWs are primarily attributed to SSW related changes rather than geomagnetic activity.

The variations of $\Sigma O/N_2$ following the onset of SSWs are generally similar among SD-WACCM-X, GUVI, and GOLD observations. However, differences between model simulations and observations emerge during certain SSW events. For the 2018/2019 Arctic SSW, the variation and magnitude of $\Sigma O/N_2$ simulated in SD-WACCM-X are more comparable to GOLD than to GUVI (panels d, g, j). Following the onset of SSW, $\Sigma O/N_2$ over 50°S-50°N is reduced by ~8% in SD-WACCM-X and GOLD, but ~14% in GUVI. At around 60°S, $\Sigma O/N_2$ is increased by ~12% in GOLD, whereas this is ~30% in GUVI. The enhancement in $\Sigma O/N_2$ around 60°S is not properly represented in the model. We note that there is stronger $\Sigma O/N_2$ depletion in the NH and enhancement in the SH relative to the climatology before the SSWs in GUVI. Following the 2020/2021 Arctic SSW, the $\Sigma O/N_2$ depletion in SD-WACCM-X is consistent with GUVI (panels e, h, k), at ~10%. In contrast, GOLD observes ~10% $\Sigma O/N_2$ increase during the same period (January 8-14, 2021). The source of the discrepancy between GUVI and GOLD is unknown.
Furthermore, the positive anomaly at around 60°S is smaller observed in GOLD compared to GUVI and shifts to higher latitudes in SD-WACCM-X.

Although the 2019 Antarctic SSW is a minor warming, there is $\Sigma O/N_2$ variations following the onset (panels f, i, l). The reduction of $\Sigma O/N_2$ over 50°S-50°N is ~10% in SD-WACCM-X, GUVI, and GOLD. In the equatorial region, the reduction is much stronger (~20%) observed by GOLD. As noted in section 2.1, this could be attributed to insufficient correction to compensate for detector degradation. Moreover, GOLD observes reduced $\Sigma O/N_2$ values over broader latitudes (60°S-60°N), compared to 30°S-30°N in GUVI observations and WACCM-X simulations. Both the simulated and observed $\Sigma O/N_2$ exhibit an enhancement at higher latitudes.

Overall, the results show that the $\Sigma O/N_2$ is reduced by ~10% over 50°S-50°N following the 2018/2019 Arctic SSW, 2019 Antarctic SSW, and 2020/2021 Arctic SSW. These features are generally similar among SD-WACCM-X, GUVI, and GOLD observations. Observations and model simulations also suggest an increase of $\Sigma O/N_2$ by ~20% at higher latitudes, except for the absence of a SH enhancement during the 2018/2019 SSW in the model.
Figure 2. Time series of (a-c) Kp index and (d-l) daily averaged relative $\sum \frac{O}{N_2}$ anomaly as a function of latitude, simulated by (d-f) SD-WACCM-X, observed by (g-i) GUVI, and (j-l) GOLD. The vertical gray line indicates the onset of SSWs. The unit of the relative anomaly (d-l) is percentage.

To further understand the variations in $\sum \frac{O}{N_2}$, we examine the distribution of atomic oxygen ($O$) and the atomic oxygen to molecular nitrogen ratio ($O/N_2$) in the LT (Figure 3). The changes of $O$ and $O/N_2$ during SSWs are mostly identical, indicating that $O$ is the dominant component rather than $N_2$. Similar magnitude changes in $O/N_2$ at 110 km and $\sum \frac{O}{N_2}$ following the onset of SSWs confirm that the changes propagate vertically from the lower to upper thermosphere by molecular diffusion. As $\sum \frac{O}{N_2}$ is sensitive to thermospheric circulation and effective diffusion by atmospheric waves (Liu et al., 2022), in the following section, we analyze the MMC and explore the contributions of different wave forcings to the circulation using SD-WACCM-X.

Figure 3. Time-latitude evolutions at 110 km of (a-c) atomic oxygen and (d-f) atomic oxygen to molecular nitrogen ratio relative anomaly simulated by SD-WACCM-X. The vertical gray line indicates the onset of SSWs. The relative anomaly is computed with mean, annual, semi-annual, and ter-annual cycle removed. The unit is percentage.

3.3 Possible mechanisms

Figure 4 shows altitude-latitude cross-sections of the MMC as represented by the velocity streamfunction from 50 km to 200 km. The climatological structure of the three MMC cells across the mesosphere, LT, and thermosphere during December-January is evident in panel a. The mesospheric MMC is a clockwise circulation (red contours), characterized by high-latitude ascent in the summer hemisphere, poleward motions, and descent in the winter hemisphere. In the LT (100–125 km), the MMC reverses to a narrow counterclockwise circulation (blue contours), with
weak ascent in the winter middle latitudes and descent in the summer high latitudes. The LT MMC in the summer hemisphere is thicker, as noted by Orsolini et al. (2022). Higher in the thermosphere, the LT MMC transitions to the deep summer-to-winter thermospheric MMC.

The LT MMC undergoes significant changes during the SSW period (panels b-c). The circulation reverses to a clockwise direction in the winter hemisphere, while strengthening in the summer hemisphere following the onset of SSWs. The changes in circulation result in strong ascent at the equator, poleward motion at middle latitudes, and descent at high latitudes around 100-125 km. Consequently, the depletion of $\sum O/N_2$ over 50°S-50°N is associated with the upward and poleward transport of atomic oxygen poor air from the equatorial region, while the increase poleward of 50° is attributed to the downward transport of atomic oxygen rich air from higher altitudes.

The MMC differs between the two recent Arctic SSW events (panels b-c), which could be attributed to different types of SSW events. The mesospheric MMC reverses to counterclockwise in the winter hemisphere during the 2018/2019 Arctic SSW. Furthermore, the reversal of the LT MMC in the winter hemisphere is stronger, resulting in $\sim$2% more $\sum O/N_2$ depletion compared to the 2020/2021 Arctic SSW. In contrast, the LT MMC in the summer hemisphere becomes more counterclockwise during the 2020/2021 Arctic SSW, leading to an increase of $\sum O/N_2$ at the summer pole. Overall, the general features of MMC align well with previous model results (e.g., Miyoshi et al., 2015) and observations (e.g., Gasperini et al., 2023).

**Figure 4.** Altitude-latitude cross-sections of velocity streamfunction averaged in (a) December-January 2018-2022, 10 days after the onset of SSW on (b) December 24th, 2018, and (c) January 2nd, 2021, from SD-WACCM-X. Red (blue) contours show clockwise (counterclockwise) circulation. The unit is $10^{-4}$ m/s.
The structure of the three MMC cells across the mesosphere, LT, and thermosphere in August-September is illustrated in Figure 5. The climatological winter (SH)-to-summer (NH) circulation is evident in the LT (100-125 km), stacked between two summer-to-winter circulations in the mesosphere and thermosphere (panel a). During the 2019 Antarctic SSW period, the mesospheric and thermospheric MMC are disrupted (panel b). An anomalous clockwise circulation (red contours) is apparent at southern latitudes between 60-80 km, characterized by high-latitude ascent, equatorward motions, and descent at lower latitudes. In the LT, the circulation reverses to a counterclockwise direction, resulting in strong ascent at summer middle latitudes (30°N-60°N) and descent at winter high latitudes (60°S-90°S) around 100-125 km. As a result, $\sum O/N_2$ depletes over 30°S-30°N and increases at higher latitudes (Figure 2).

Figure 5. Altitude-latitude cross-sections of velocity streamfunction averaged in (a) August-September 2019-2022 and (b) 10 days after the onset of SSW on September 9th, 2019, from SD-WACCM-X. The unit is $10^{-4}$ m/s.

To get insight into the dominant wave forcings driving the MMC, we examine the contributions of different wave forcings to the velocity streamfunction based on the downward-control principle (Figure 6). 110 km is chosen since this altitude centrally locates the LT MMC reversal as shown in Figures 4 and 5. Starting a few days prior to the onset of Arctic SSWs, the narrow LT circulation reverses from counterclockwise (negative) to clockwise (positive), whereas during the Antarctic SSW, it changes from clockwise to counterclockwise (black line in panels a-c), consistent with
Figures 4-5. The changes in the velocity streamfunction are primarily attributed to the resolved waves (dashed magenta line in panels a-c). We further decompose the resolved waves into WPWs, EPWs, QSPWs, DW1, and SW2. Comparisons of the contributions of these different wave forcings to the circulation (panels d-f) suggest that WPWs are the main contributor to the positive (negative) velocity streamfunction following the onset of Arctic (Antarctic) SSWs.

Figure 6. Time series of the velocity streamfunction at 110 km from the 20 days prior to 20 days after the onset from SD-WACCM-X. (a–c) Contributions to the total velocity streamfunction (solid black line) by the resolved waves (dashed magenta line), parametrized gravity wave drag (solid red line), zonal wind tendency (dashed purple line), and the residual contribution from the friction and viscosity term (dashed orange line). (d–f) Contributions to the resolved waves by westward-propagating planetary waves (PWs) (blue solid line), eastward-propagating PWs (blue dashed line), quasi-stationary PWs (blue dotted line), semi-diurnal migrating tide (SW2, green dashed line), and diurnal migrating tide (DW1, green solid line). The vertical gray line indicates the onset of SSWs. A latitude averaging over (a, b, d, e) 30°N-60°N and (c, f) 30°S-60°S was done. The unit is 10^{-4} m/s.

4. Conclusions

As SSWs rarely occur in the SH, there has been limited exploration of their impacts on \( \sum O/N_2 \) and the associated dynamical mechanism. This study compares \( \sum O/N_2 \) variations during the 2018/2019 Arctic SSW, 2019 Antarctic SSW, and 2020/2021 Arctic SSW, as observed by GOLD, GUVI, and simulated by WACCM-X in specified dynamics configuration. To our knowledge, this study represents the first comparison of the differences in the impacts of Arctic and Antarctic SSWs on thermospheric composition using both observations and model simulations. We also determine the respective roles of PWs, GWs, and migrating tides in affecting \( \sum O/N_2 \) during the SSWs. Our main conclusions are as follows.
Arctic and Antarctic SSWs have similar impacts on thermospheric composition as observed by GUVI and GOLD, as well as simulated by WACCM-X. GOLD and GUVI both provide the observational proof that $\sum O/N_2$ is reduced by $\sim 10\%$ over $50^\circ\text{S}-50^\circ\text{N}$ and enhanced by $\sim 20\%$ at higher latitudes following the onset of SSWs. With global coverage, SD-WACCM-X suggests comparable variations in $\sum O/N_2$.

Differences between the observed and simulated $\sum O/N_2$ emerge in magnitude during certain SSW events. For the 2018/2019 Arctic SSW, the variation and magnitude of $\sum O/N_2$ simulated in SD-WACCM-X are more comparable to GOLD than to GUVI. The $\sum O/N_2$ depletion in SD-WACCM-X is consistent with GUVI, but not with GOLD during the 2020/2021 Arctic SSW. For this particular event, the cause of the difference in $\sum O/N_2$ between GOLD and GUVI is unknown. Additionally, GOLD observes reduced $\sum O/N_2$ values over broader latitudes ($60^\circ\text{S}-60^\circ\text{N}$) during the 2019 Antarctic SSW, compared to $30^\circ\text{S}-30^\circ\text{N}$ in GUVI observations and WACCM-X simulations.

The dynamical mechanism linking the LT MMC change and the variations of $\sum O/N_2$ is similar during Arctic and Antarctic SSWs. Following the onset of the SSWs, westward-travelling planetary waves reverse the NH LT MMC and strengthen the SH LT MMC. Consequently, the atomic oxygen over $50^\circ\text{S}-50^\circ\text{N}$ is reduced, while it is increased at higher latitudes. The change in the LT propagates into the upper thermosphere through molecular diffusion. Our results highlight that planetary variability during SSWs can impact the mean state of the thermosphere.

**Acknowledgments**

J.Z., J.O., and N.M.P. acknowledge support by NASA Grant 80NSSC20K1353. We thank Abigail Long for providing the SABER geostrophic wind dataset. This material is based upon work supported by the NSF National Center for Atmospheric Research, which is a major facility sponsored by the U.S. National Science Foundation under Cooperative Agreement 1852977.

**Data Availability Statement**
References


