

## Article

# Role of QBO and MJO in Sudden Stratospheric Warmings: A Case Study

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**Abstract:** The impact of the quasi-biennial oscillation (QBO) and Madden–Julian oscillation (MJO) on the dynamics of major sudden stratospheric warmings (SSWs) observed in the winters of 2018, 2019, and 2021 is investigated. Using data from the MERRA-2 reanalysis, we analyze the daily mean variability of critical atmospheric parameters at the 10 hPa level, including zonal mean polar cap temperature, zonal mean zonal wind, and the amplitudes of planetary waves 1 and 2. The results reveal dramatic increases in polar cap temperature and significant wind reversals during the SSW events, particularly in 2018. The analysis of planetary wave (PW) amplitudes demonstrates intensified wave activity coinciding with the onset of SSWs, underscoring the pivotal role of PWs in these stratospheric disruptions. Further examination of outgoing long-wave radiation (OLR) anomalies highlights the influence of QBO phases on tropical convection patterns. During westerly QBO (w-QBO) phases, enhanced convective activity is observed in the western Pacific, whereas the easterly QBO (e-QBO) phase shifts convection patterns to the maritime continent and central Pacific. This modulation by QBO phases influences the MJO's role during SSWs, affecting tropical and extra-tropical weather patterns. The day-altitude variability of upward heat flux reveals distinct spatiotemporal patterns, with pronounced warming in the polar regions and mixed heat flux patterns in low latitudes. The differences observed between the SSWs of 2017–2018 and 2018–2019 are likely related to the varying QBO phases, emphasizing the complexity of heat flux dynamics during these events. The northern annular mode (NAM) index analysis shows varied responses to SSWs, with stronger negative anomalies observed during the e-QBO phase compared to the w-QBO phases. This variability highlights the significant role of the QBO in shaping the stratospheric and tropospheric responses to SSWs, impacting surface weather patterns and the persistence of stratospheric anomalies. Overall, the study demonstrates the intricate interactions between stratospheric dynamics, QBO, and MJO during major SSW events, providing insights into the broader implications of these atmospheric phenomena on global weather patterns.

**Keywords:** SSW; MJO; QBO; NAM index



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## 1. Introduction

Sudden stratospheric warmings (SSWs) are dramatic meteorological phenomena that profoundly impact the winter circulation of the Northern Hemisphere. These events are

characterized by a rapid increase in stratospheric temperatures and a weakening or reversal of the westerly winds that typically circulate around the pole [1–3]. SSWs play a crucial role in coupling the stratosphere and troposphere, often leading to significant changes in surface weather patterns, including cold air outbreaks in mid-latitudes and alterations in storm tracks [4].

The occurrence and evolution of SSWs are influenced by various atmospheric oscillations, among which the quasi-biennial oscillation (QBO) and the Madden–Julian oscillation (MJO) are of particular interest. The QBO is a periodic reversal of zonal winds in the tropical stratosphere, alternating between easterly and westerly phases with an average period of about 28 months [5]. It has been shown to modulate the strength of the polar vortex and the frequency of SSWs through its impact on the vertical propagation of planetary waves [6,7].

The MJO, on the other hand, is a tropical phenomenon characterized by an eastward-moving pulse of cloud and rainfall near the equator that typically recurs every 30 to 60 days [8–10]. Recent studies have suggested that the MJO can influence stratospheric dynamics by modulating the upward propagation of planetary waves, potentially acting as a precursor to SSW events [9,10].

During the active phase of the MJO, enhanced convective activity generates deep convective clouds, which play a critical role in modulating both tropical and global atmospheric circulation. This process is well-documented, with studies highlighting the eastward propagation of organized convection, leading to widespread cloud formation and increased precipitation in the tropics [10]. The interaction between the MJO and convectively coupled equatorial waves further facilitates the clustering of clouds, influencing atmospheric processes at both lower and upper levels (Kiladis et al., 2009) [11]. Conversely, during the suppressed phase of the MJO, convective activity is significantly reduced, resulting in clearer skies and diminished cloud cover, which underscores the dynamic nature of cloud variability (Hendon & Salby, 1994) [12]. These alternating phases of cloud formation and suppression are crucial for understanding how tropical oscillations influence polar stratospheric dynamics, as the MJO's modulation of large-scale atmospheric patterns has far-reaching impacts beyond the tropics. Extending this research to assess cloud behavior over longer time scales would provide further insight into the MJO's role in global atmospheric variability.

While the individual effects of the QBO and MJO on stratospheric dynamics have been studied extensively, their combined influence during specific SSW events remains an area of active research. The winters of 2018, 2019, and 2021 provided unique opportunities to examine these interactions, as each year featured a major SSW event under different QBO phases and varying MJO conditions.

The northern annular mode (NAM), also known as the arctic oscillation (AO), is a crucial climate index representing fluctuations in atmospheric mass between the Arctic and mid-latitudes in the Northern Hemisphere. It serves as a key indicator of the strength and stability of the polar vortex, with significant implications for both stratospheric and tropospheric dynamics (Thompson & Wallace, 2000) [13]. A positive NAM phase is characterized by a strong, well-confined polar vortex, leading to cold temperatures over the polar regions and milder mid-latitude conditions. In contrast, a negative NAM phase indicates a weakened vortex, allowing more wave activity and increasing the likelihood of SSWs (Baldwin & Dunkerton, 2001) [14]. In the context of this study, the NAM Index is critical in assessing the impact of the quasi-biennial oscillation (QBO) and Madden–Julian oscillation (MJO) on major SSW events. Our findings suggest that during the easterly QBO (e-QBO) phase, stronger negative NAM anomalies are observed, reflecting enhanced wave breaking and more frequent SSW occurrences. This highlights the role of the QBO in modulating polar stratospheric variability and its coupling with the troposphere, influencing surface weather patterns and temperature anomalies. Understanding the NAM's variability in relation to QBO and MJO phases provides valuable insights into the complex interactions governing stratospheric dynamics and their broader climatic impacts.

This study focuses on analyzing the roles of the QBO and MJO during major SSW events that occurred in the winters of 2018, 2019, and 2021. The primary objectives are to (1) investigate how different QBO phases modulate the MJO's influence on tropical convection patterns before and after SSW events, (2) examine the heat flux variability in polar and low-latitude regions during these SSWs and its relationship to the QBO phase, and (3) assess the stratosphere–troposphere coupling through analysis of the northern annular mode (NAM) index during each SSW event and the overall influence of these tropical oscillations on polar stratospheric dynamics. By exploring these interactions, the study aims to enhance the understanding of how tropical and stratospheric dynamics intertwine, thereby improving predictive capabilities and providing insights into the broader impacts of SSWs on global climate and weather systems.

## 2. Data and Methodology

This study examines the impact of the quasi-biennial oscillation (QBO) and Madden–Julian oscillation (MJO) on SSWs during the winters of 2018, 2019, and 2021. The analysis utilizes a combination of observational and reanalysis datasets to assess the variability and interactions of key atmospheric parameters across different QBO phases.

### 2.1. MERRA-2 Reanalysis Data

The modern-era retrospective analysis for research and applications, version 2 (MERRA-2) dataset was used to evaluate atmospheric parameters, including zonal mean polar cap temperature, zonal mean zonal wind at 60° N, and planetary wave amplitudes at 10 hPa. MERRA-2 provides comprehensive reanalysis data with high temporal and spatial resolution, enabling detailed analysis of stratospheric and tropospheric dynamics [15].

### 2.2. Outgoing Longwave Radiation (OLR) Data

OLR data, serving as a proxy for tropical convection and MJO activity, was sourced from NOAA satellite observations [16]. Anomalies were calculated relative to a climatological mean to identify deviations associated with each SSW event, highlighting the modulation of tropical convection by different QBO phases [17].

### 2.3. Northern Annular Mode (NAM) Index

The NAM index, which measures the variability of stratospheric circulation, was derived from geopotential height anomalies across multiple altitudes. This index is crucial for assessing the extent of stratosphere–troposphere coupling during SSWs [18,19].

### 2.4. Methodology

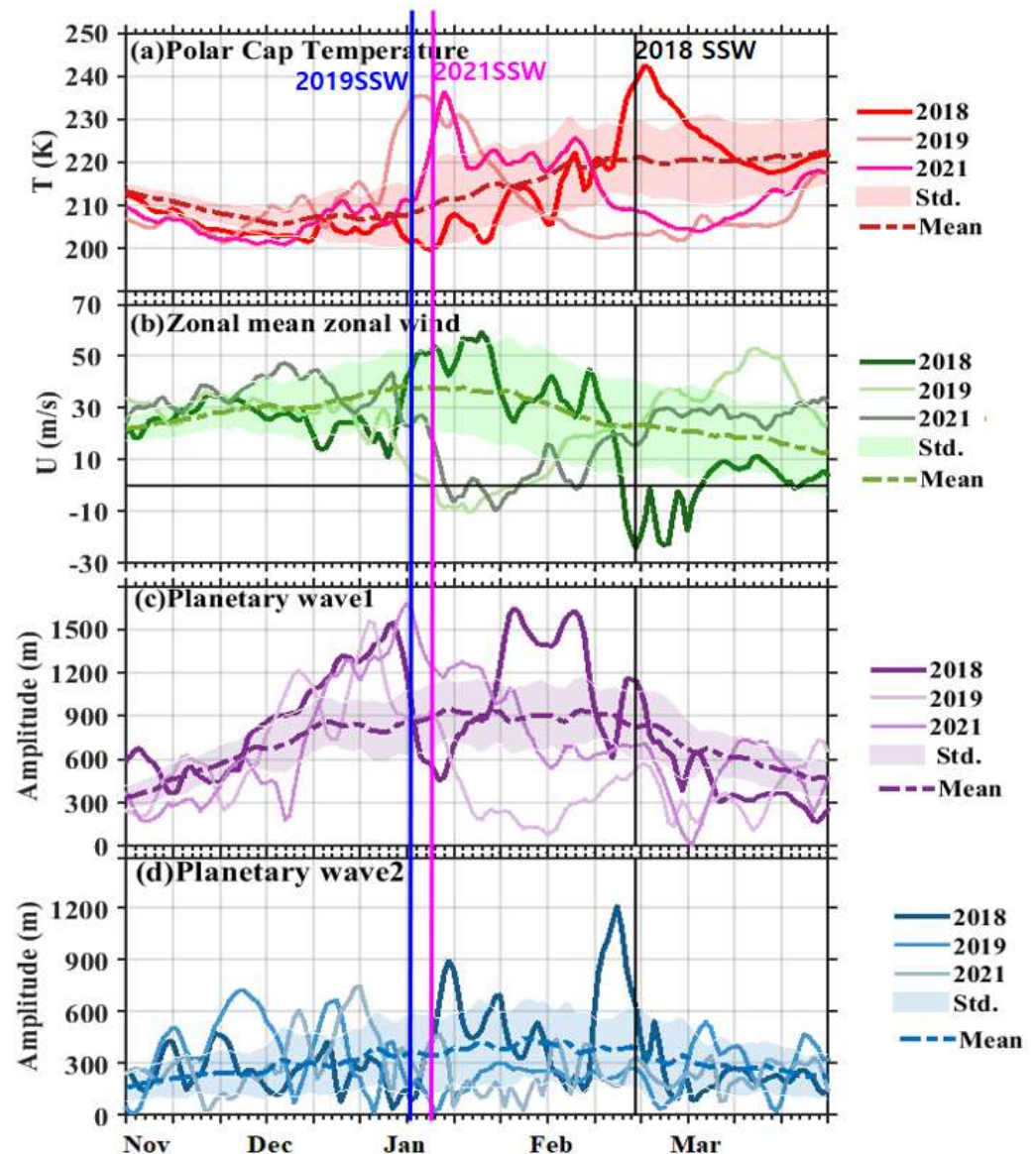
Data was analyzed for each winter from 1 November to 31 March, covering the typical SSW season and capturing the evolution of atmospheric conditions leading up to and following SSW events. However, the analysis period was extended from 1 December to 30 April to capture the full extent of stratosphere–troposphere coupling and the longer-term impacts of SSWs on the NAM index, which can persist well into the spring season. The atmospheric parameters were compared against a 42-year climatological mean (1979–2020) to highlight the deviations during SSW events tested for statistical significance using a Monte Carlo approach, ensuring that the results were robust and not due to random variability.

## 3. Results and Analysis

### 3.1. Meteorological and Dynamical Aspects of SSWs

Figure 1 provides a detailed view of the daily mean variability of several critical atmospheric parameters during the winters of 2018, 2019, and 2021, which were marked by major SSWs. These parameters are analyzed at the 10 hPa level, using data from the MERRA-2 reanalysis. The figure also includes a comparison with the 42-year climatological mean (1979–2020) and its associated standard deviation, shown as shaded regions. Figure 1a shows the temporal evolution of the polar cap temperatures for the specified winters. The

SSWs are characterized by dramatic increases in temperature, particularly evident in 2018, where the temperature spike surpasses both the climatological mean and the standard deviation. The temperature rise is indicative of the weakening or breakdown of the polar vortex, a well-documented phenomenon during SSWs [20]. Figure 1b depicts the zonal mean zonal wind at 60° N, a key metric for assessing the strength and stability of the polar vortex. SSWs generally lead to a marked weakening or even reversal of these winds. During the winter of 2018, the wind reversal was notably stronger, whereas in other events, it tends to be weaker. This reversal is a defining characteristic of major SSW events, in which the polar vortex either significantly weakens or fully disintegrates [19,21]. The dashed horizontal line indicates the zero-wind level.



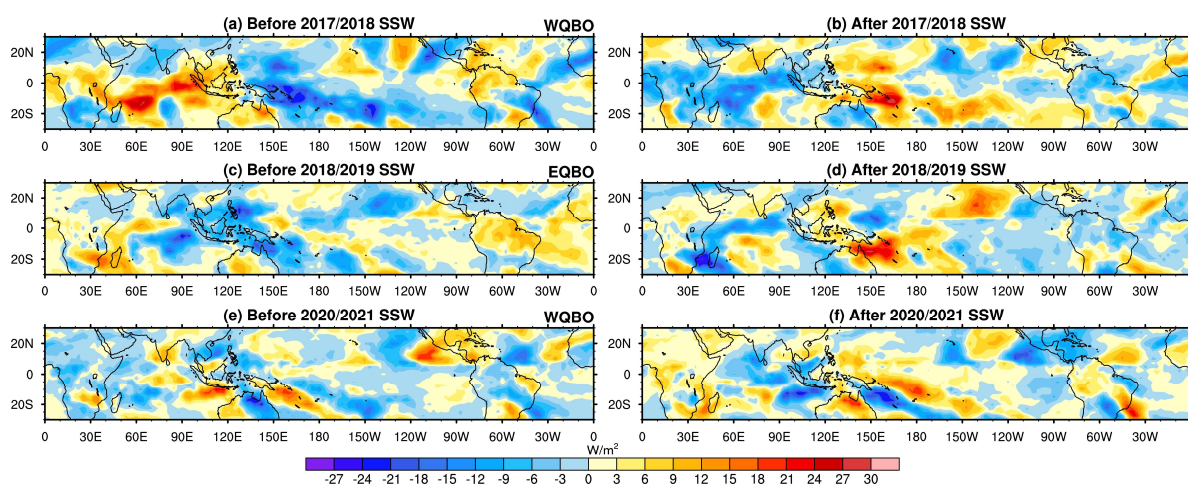
**Figure 1.** The daily mean variability of the (a) zonal mean polar cap temperature (60°–90° N), (b) zonal mean zonal wind at 60° N, (c) amplitude of the planetary wave 1 ( $k = 1$ ), and (d) amplitude of the planetary wave 2 ( $k = 2$ ) at 60° N obtained from MERRA-2. The parameters of other SSW winters also shown for the comparison. The 42 years (1979–2020) mean and the standard deviation are shown with a shaded region. All the parameters are estimated at 10 hPa level. The vertical line indicates the SSW day in each winter. The dashed horizontal line in (b) indicates the zero-wind level.

Figure 1c,d displays the amplitude of planetary wave 1 ( $k = 1$ ) (PW1) and wave 2 ( $k = 2$ ) (PW2) at 60° N, respectively. The variation in wave amplitude for 2018, 2019, and

2021 highlights the intensification of PW activity (both wave 1 and wave 2) before and during SSW events. Peaks in wave amplitude correspond with the timing of the SSWs, demonstrating the critical role these waves play in disrupting the polar vortex. The 2018 event, in particular, shows strong wave activity (wave 1), aligning with the significant temperature and wind anomalies observed [18]. Although wave 2 is generally less intense than wave 1 in all three SSWs, its influence is vital in the complex atmospheric dynamics that result in SSWs [20]. The variations in PW activity underline the importance of multi-wave interactions in the development of these events. The vertical lines in each panel mark the onset of SSWs, and the comparison with the long-term mean underscores the extraordinary nature of these events, particularly in 2018, where all parameters exhibit significant deviations from climatological norms.

### 3.2. Convective Activity During the SSWs

Figure 2 shows the anomalies in outgoing longwave radiation (OLR) before and after the major SSWs in 2018, 2019, and 2021 under different phases of QBO. The figure illustrates how tropical convection patterns, as captured by OLR anomalies, are influenced by the interactions between the MJO and the QBO during SSW events. Figure 2a,b depict the OLR anomalies a month before and after the 2017/2018 SSW during the westerly phase of the QBO (WQBO). An enhancement of convective activity in the Western Pacific, indicated by negative OLR anomalies (shown in blue), is noticed. This pattern aligns with the findings of Baldwin and Dunkerton (2001) [18], who demonstrated that stratospheric changes, including SSWs, can modulate tropical convection and impact tropospheric weather patterns. Figure 2c,d shows that for the 2018/2019 SSW during the easterly QBO phase (EQBO), there is a notable shift in convection, particularly over the Indian Ocean, the maritime continent, and the central Pacific, with increased OLR anomalies after the SSW event (shown in red). This observation is consistent with studies by Garcia and Salby (1984) [22], which highlight how localized tropical heating can have far-reaching impacts on global atmospheric circulation, influencing both the tropics and extratropics. However, the 2020/2021 SSW occurred again under the WQBO phase (Figure 2e,f), with observed OLR anomalies showing patterns similar to those in the 2017/2018 event, indicating a recurring influence of the QBO phase on tropical convection during SSWs. Kidston et al. (2015) [4] discuss the influence of stratospheric variability, such as SSWs, on tropospheric phenomena, including jet stream positioning and storm tracks, which are closely related to convective activity in the tropics as seen in these panels.



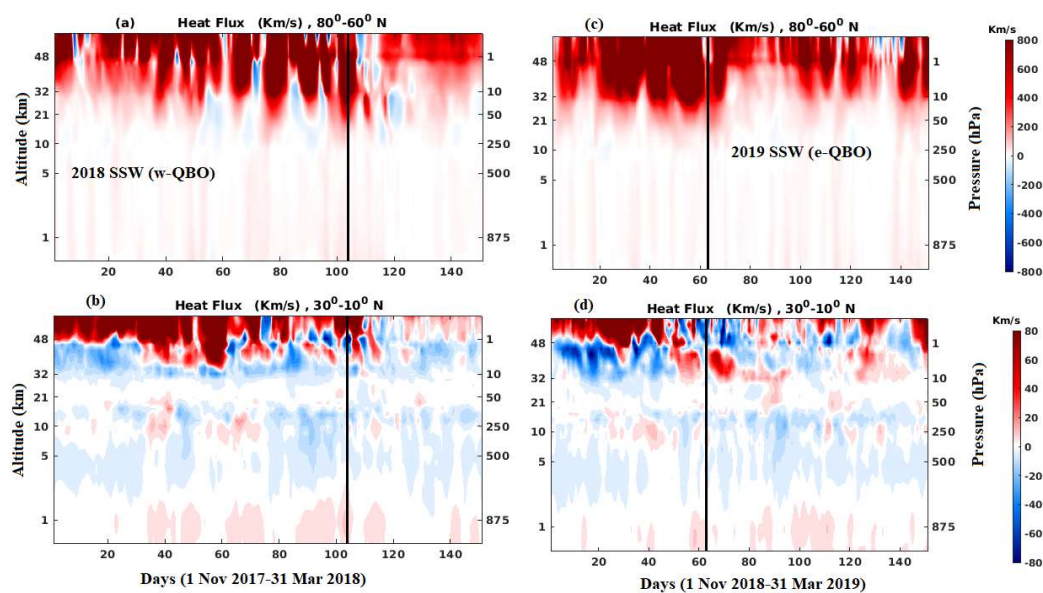
**Figure 2.** OLR ( $\text{W m}^{-2}$ ) anomalies for 2018 SSW (a,b), 2019 SSW (c,d), and 2021 SSW (e,f), with a time average of a month before and after each SSW.

Thus, Figure 2 emphasizes the role of QBO phases in modulating the MJO's response during SSW events, which in turn affects tropical convection patterns. Baldwin et al.

(2001) [5] provide a comprehensive review of the QBO's effects on atmospheric circulation, supporting the observed variations in OLR anomalies in different QBO phases (WQBO vs. EQBO) shown in the figure. Additionally, Garfinkel et al. (2012) [9] elaborate on how tropical factors like the MJO serve as precursors to stratospheric polar vortex anomalies, reinforcing the connections seen between tropical and polar dynamics in this figure.

### 3.3. Heat Flux During the SSWs

Figure 3 illustrates the day-altitude variability of heat flux for different QBO conditions, averaged over polar ( $60^{\circ}$ – $80^{\circ}$  N) and low-latitude ( $10^{\circ}$ – $30^{\circ}$  N) regions during the 2017–2018 and 2018–2019 SSW winters. Figure 3a,b represent the 2017–2018 SSW, which occurred under westerly QBO conditions (w-QBO), while Figure 3c,d show the 2018–2019 SSW under easterly QBO conditions (e-QBO). The heat flux is depicted in units of Km/s, with the vertical black line marking the onset of the SSW event.



**Figure 3.** Day-altitude variability of upward heat flux, averaged (a) over polar ( $60^{\circ}$ – $80^{\circ}$  N) and (b) low-latitudes ( $10^{\circ}$ – $30^{\circ}$  N) during 2017–2018 SSW winter (c), and (d) same as (a), and (b), respectively, but for 2018–2019 SSW winter. The vertical line indicates the SSW day.

During the westerly QBO conditions (2017–2018 SSW, w-QBO) and at the polar region (Figure 3a), the heat flux is positive throughout the stratosphere, particularly between 10 km and 40 km altitude, indicating strong upward propagation of PWs into the stratosphere. The increase in heat flux values prior to the SSW suggests an enhanced interaction between the troposphere and stratosphere, which is a characteristic precursor to SSW events [23]. The peak heat flux occurs around 100 days, aligning closely with the onset of the SSW. Whereas at the low latitudes (Figure 3b), the variability in heat flux is more subdued compared to the polar region, with mixed positive and negative values indicating weaker wave activity. The weaker heat flux in the lower latitudes aligns with the understanding that SSWs are primarily driven by polar and mid-latitude wave forcing [21].

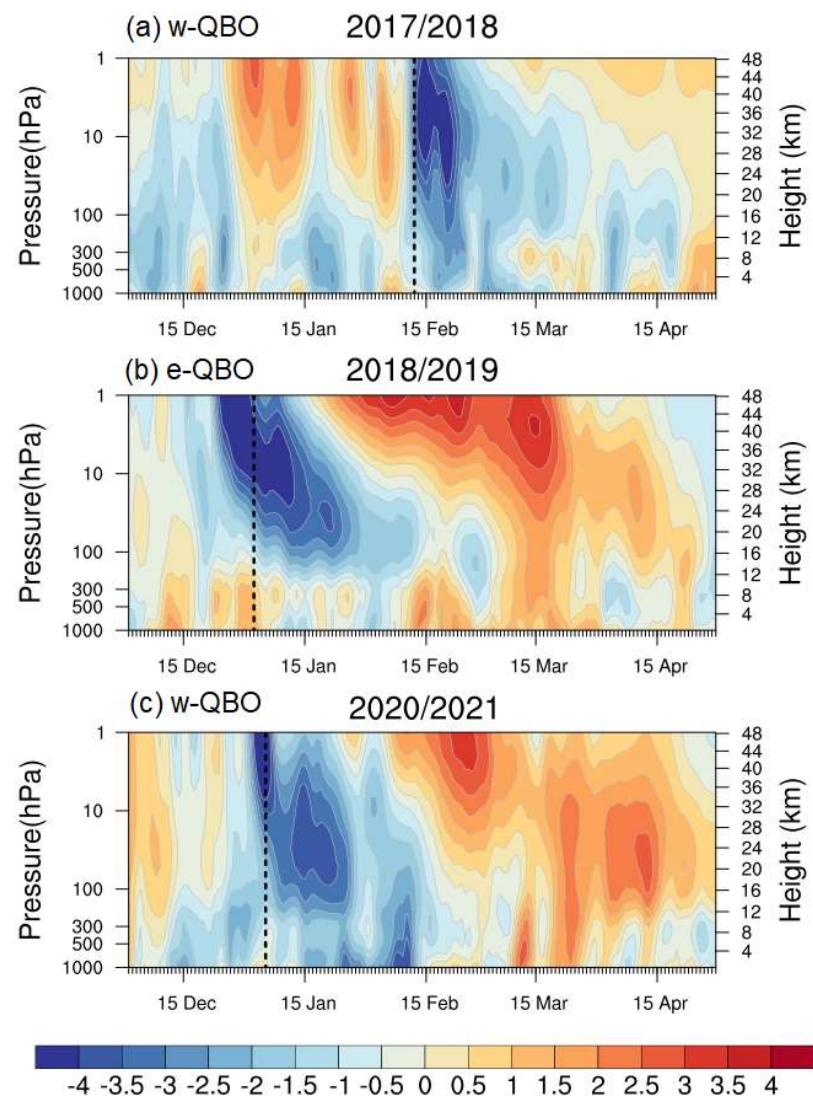
During the easterly QBO conditions (e-QBO) (2018–2019 SSW), similar upward propagation of PWs is evident in the polar region (Figure 3c), but with slightly lower intensity compared to the w-QBO year. This difference reflects the modulation of SSW dynamics by the phase of the QBO, where e-QBO typically leads to a less conducive environment for strong wave propagation [18]. The onset of the 2018–2019 SSW is marked by a moderate increase in heat flux, peaking just before the vertical line marking the event onset. However, at the low latitudes in panel (Figure 3d), the heat flux again shows less variability, with negative values prevailing at higher altitudes. This suggests a suppression of upward wave propagation, consistent with the presence of easterly winds in the lower stratosphere

associated with the e-QBO phase [6]. The overall weaker heat flux supports the idea that e-QBO conditions may lead to weaker SSWs compared to w-QBO conditions.

Thus, the comparison between westerly and easterly QBO phases illustrates that the w-QBO is generally associated with stronger upward PW propagation, leading to more pronounced SSWs, while the e-QBO tends to dampen this process, resulting in weaker SSWs. This phase-dependent interaction between PWs and the stratosphere underlines the critical influence of QBO phases on the dynamics of SSWs, particularly in the polar stratosphere.

### 3.4. Northern Annular Mode (NAM) Index During the SSWs

Figure 4 depicts the day-height variability of the Northern Annular Mode (NAM) index during the three major SSW events in (a) 2017/2018, (b) 2018/2019, and (c) 2020/2021. The panels display the pressure levels from 1000 hPa to 1 hPa, corresponding to heights from the surface up to approximately 48 km in the stratosphere. The color shading represents the NAM index anomalies, with blue colors indicating negative anomalies and red colors indicating positive anomalies.



**Figure 4.** Day-height variability of the Northern Annular Mode (NAM) index during (a) 2018 SSW, (b) 2019 SSW, and (c) 2021 SSW. The vertical dashed line indicates the SSW day in each winter.

NAM Response for different SSWs:

The NAM index is a key indicator of stratospheric circulation variability, with negative values indicating a weakened vortex and positive values representing a stronger vortex. The NAM response for the three different SSW events is discussed below.

(a) 2017/2018 (w-QBO) SSW Event (Figure 4a):

Before the SSW event, the NAM index shows weak positive anomalies in the lower stratosphere, suggesting a stable and strong polar vortex typical of winter conditions. Around the SSW day (indicated by the vertical dashed line on approximately 15 February), there is a rapid transition to negative anomalies in the upper stratosphere, which descends to the lower levels post-SSW. This indicates a weakening and displacement of the polar vortex, consistent with the effects of SSWs. This pattern aligns with previous findings that westerly QBO (w-QBO) conditions can influence the vertical propagation of PWs, enhancing the likelihood of SSW events (Baldwin and Dunkerton, 2001) [18].

(b) 2018/2019 (e-QBO) SSW Event (Figure 4b):

During this SSW, under easterly QBO (e-QBO) conditions, the NAM index anomalies display a similar but more pronounced downward propagation of negative anomalies compared to the w-QBO event (see peak values). This enhanced signal could be attributed to the stronger coupling between the troposphere and stratosphere under e-QBO conditions, facilitating more vigorous wave activity that disrupts the polar vortex [6,22]. Notably, the negative anomalies reach deeper into the troposphere, suggesting a more profound and extended impact on surface weather patterns, such as cold air outbreaks in the mid-latitudes.

(c) 2020/2021 (w-QBO) SSW Event (Figure 4c):

In the 2020/2021 SSW event, which occurred under w-QBO conditions, the NAM index exhibits a robust negative anomaly onset around mid-January. This pattern is similar to that of the 2017/2018 event but appears more intense, indicating a stronger disruption of the polar vortex. The persistence of negative anomalies through to late March suggests that the 2020/2021 SSW had lasting effects on the stratospheric circulation, consistent with observations that SSWs can lead to prolonged impacts on the polar stratosphere [2,21].

Overall, the 2018/2019 e-QBO event (Figure 4b) shows a stronger negative NAM anomaly compared to the w-QBO phases in the other years (Figure 4a,c), indicating a more intense disruption of the polar vortex, which aligns with studies suggesting that e-QBO phases may lead to stronger vortex weakening [6].

In all three SSW events, the weakening of the stratospheric polar vortex (negative NAM) descends over time from higher levels (~1 hPa) down to the lower stratosphere (~100 hPa). This downward propagation of anomalies is a typical feature of SSWs [14]. The w-QBO years (2017/18 and 2020/21) show a more gradual weakening of the NAM, while the e-QBO year (2018/19) shows a sharper and more pronounced NAM weakening.

Thus, Figure 4 shows clear modulation of the stratospheric polar vortex by the QBO during different SSW events. The e-QBO year (2018/2019) displays a stronger weakening of the vortex, consistent with prior studies on the Holton–Tan effect, whereas the w-QBO years exhibit less intense disturbances. These results highlight the role of the QBO phase in modulating stratospheric dynamics, particularly during SSWs.

QBO Influence on NAM index:

The QBO phase modulates the upward propagation of PWs into the stratosphere. In e-QBO years, the stratospheric polar vortex tends to weaken more intensely, as planetary wave activity is enhanced [14]. The 2018/2019 SSW (during e-QBO) shows stronger planetary wave interaction, evident in the more pronounced negative NAM signal, consistent with the Holton-Tan mechanism, which suggests that the stratospheric polar vortex is more disturbed during e-QBO phases [6]. In contrast, the w-QBO phases (2017/18 and 2020/21) show weaker wave-mean flow interaction, which is reflected in less intense NAM variability.

Thus, the three SSW events illustrate the dynamic response of the stratospheric and tropospheric circulations to major SSWs, modulated by the phase of the QBO. The differences in the timing, depth, and persistence of the NAM index anomalies between w-QBO

and e-QBO conditions highlight the importance of the QBO phase in determining the characteristics and impacts of SSW events.

#### 4. Discussions

The QBO is a dominant mode of variability in the equatorial stratosphere, characterized by alternating easterly and westerly zonal winds with an average period of about 28 months. Its origin is primarily driven by the interaction of vertically propagating equatorial waves, including Kelvin waves (which propagate eastward) and Rossby-gravity waves (which propagate westward). These waves are generated in the troposphere by convection and modulate the momentum balance in the stratosphere through wave-mean flow interactions. As they propagate upward, they dissipate, depositing momentum that drives the alternating wind phases.

The QBO significantly influences global atmospheric circulation, including the polar vortex and SSW frequency, by modulating the upward propagation of planetary waves. During the easterly phase (e-QBO), planetary wave activity is enhanced, leading to a greater likelihood of SSWs, while the westerly phase (w-QBO) suppresses this wave activity [5].

The MJO is a dominant mode of intraseasonal variability in the tropics, characterized by large-scale eastward-propagating convective anomalies with periods of 30–60 days. It originates from interactions between tropical convection, large-scale circulation, and ocean–atmosphere coupling. The MJO modulates global weather by influencing the Walker circulation, monsoons, and even extratropical regions through teleconnections [10].

The interaction between the MJO and stratospheric processes occurs primarily through the modulation of convectively generated waves that influence the QBO and planetary wave propagation. These interactions play a critical role in the onset and intensity of SSWs [14].

SSWs are dramatic disruptions of the winter polar vortex, characterized by a rapid warming of the polar stratosphere and a reversal of the westerly zonal winds. They are triggered by the amplification and breaking of upward-propagating planetary waves, which decelerate the polar vortex and lead to its collapse. These events are often associated with increased upward heat flux from the troposphere due to enhanced planetary wave activity, particularly in the presence of favorable QBO and MJO phases.

The QBO influences the occurrence and frequency of SSWs by modulating the wave dynamics that propagate into the stratosphere. During the easterly QBO phase, there is a greater tendency for planetary wave activity to reach the stratosphere, resulting in more frequent and intense SSWs [24].

##### *Physical Mechanisms Influencing QBO, MJO, and SSWs:*

###### *(a) Solar Activity and its Influence on Stratospheric Dynamics.*

Solar activity, primarily driven by the 11-year solar cycle, plays a pivotal role in modulating stratospheric conditions. Variations in solar ultraviolet (UV) and extreme ultraviolet (EUV) radiation directly influence the thermal structure of the upper stratosphere by altering ozone production. Increased solar UV radiation during solar maxima enhances ozone concentrations, warming the upper stratosphere and altering the meridional temperature gradient. This modifies planetary wave propagation, which is a key driver of SSWs.

Furthermore, the coupling between the QBO and solar activity has been well documented. During solar maxima, the westerly phase of the QBO tends to dominate, which is associated with a higher frequency of SSWs. Labitzke and van Loon (1988) [25] demonstrated this solar-QBO interaction, highlighting how solar variability influences the likelihood and intensity of SSWs. This underscores the role of solar radiation in shaping stratospheric dynamics.

###### *(b) Volcanic Aerosols and Their Impact on Wave Propagation.*

Volcanic eruptions significantly alter stratospheric dynamics by injecting sulfur dioxide (SO<sub>2</sub>) into the stratosphere, forming sulfate aerosols that increase the albedo and absorb solar radiation [26]. This cooling of the troposphere and warming of the lower stratosphere disrupts the normal propagation of planetary waves. These perturbations can

either enhance or suppress SSW formation depending on the location and intensity of the aerosol distribution.

For instance, the 1991 Mount Pinatubo eruption provided a clear example of how volcanic aerosols can affect stratospheric circulation. The increased aerosol load weakened the polar vortex, creating conditions favorable for SSW events. Additionally, volcanic aerosols can influence the QBO by altering the radiative heating of the equatorial stratosphere.

#### *(c) Galactic Cosmic Rays (GCRs) and Stratospheric Variability.*

Galactic cosmic rays (GCRs) are high-energy particles that ionize the atmosphere, influencing cloud microphysics and atmospheric conductivity. During solar minima, when the Sun's magnetic field weakens, GCR flux increases, leading to enhanced ionization in the stratosphere. This has implications for atmospheric chemistry, particularly in ozone concentration and water vapor content, which are critical for stratospheric thermal dynamics.

Increased GCR activity has been linked to changes in the polar vortex strength. The ionization effects alter the stratosphere's electric field, which can affect the development of planetary waves and the initiation of SSWs. Svensmark (2007) [27] proposed that GCR-induced changes in cloud cover and stratospheric chemistry could be significant modulators of the stratospheric response to space weather.

#### *4. Ionosphere-Lithosphere Interactions and Atmospheric Coupling*

Ionosphere-lithosphere coupling plays an emerging role in understanding stratospheric dynamics, especially in the context of SSWs. Large-scale lithospheric events such as earthquakes and volcanic eruptions generate gravity waves that propagate upward, influencing the stratospheric and mesospheric circulation. These interactions can modify the distribution of planetary waves critical for the onset of SSWs.

For example, Pulinets and Ouzounov (2011) [28] discussed how lithospheric disturbances, through atmospheric electrical circuits, can influence atmospheric dynamics. The propagation of gravity waves generated by seismic activity has been linked to anomalies in stratospheric temperature and wind patterns, potentially modulating the timing and intensity of SSWs.

#### *5. Stratospheric Ozone Variability and Its Role in Planetary Wave Dynamics*

Ozone variability is a key driver of stratospheric temperature gradients, influencing planetary wave propagation and the development of SSWs. Ozone absorbs UV radiation, and fluctuations in its concentration can alter the thermal structure of the stratosphere. Reduced ozone levels, as seen during the Antarctic ozone hole, have been linked to changes in the strength and persistence of the polar vortex.

Shindell and Schmidt (2004) [29] highlighted how ozone depletion in the Southern Hemisphere contributed to shifts in stratospheric circulation patterns. The QBO's interaction with ozone variability further modulates wave activity, illustrating the critical role ozone plays in the dynamics of SSWs and the broader stratospheric circulation.

By considering solar activity, volcanic aerosols, GCRs, ionosphere–lithosphere interactions, and stratospheric ozone variability, we provide a comprehensive physical interpretation of the mechanisms driving these critical atmospheric phenomena. This discussion enhances the understanding of how these factors contribute to the observed variability, paving the way for future research into the intricate processes shaping global atmospheric dynamics.

## **5. Summary and Conclusions**

This study provides a comprehensive analysis of the interactions between the quasi-biennial oscillation (QBO), the Madden–Julian oscillation (MJO), and major sudden stratospheric warmings (SSWs) during the winters of 2018, 2019, and 2021. By examining critical atmospheric parameters such as polar cap temperature, zonal mean zonal wind, planetary wave amplitudes, outgoing longwave radiation (OLR) anomalies, heat flux variability, and the northern annular mode (NAM) index, this research highlights the complex interplay between tropical oscillations and polar stratospheric dynamics. Key findings are mentioned below:

1. **QBO Phase Influence:** The QBO phase significantly modulates the characteristics of SSWs. The SSW events in 2018 and 2021, which occurred during the westerly QBO (w-QBO) phase, exhibited enhanced convective activity and distinct changes in zonal wind patterns. Conversely, the 2019 SSW under the easterly QBO (e-QBO) phase was associated with a stronger disruption of the polar vortex and more pronounced negative NAM anomalies, reflecting the QBO's critical role in shaping stratospheric responses.
2. **Tropical Convection and MJO:** The analysis of OLR anomalies revealed that the MJO's influence on tropical convection varies with the QBO phase. During w-QBO phases, enhanced convective activity was observed in the western Pacific, whereas during the e-QBO phase, convection patterns shifted towards the Indian Ocean, maritime continent, and central Pacific. This modulation by the QBO impacts the upward propagation of planetary waves, subsequently affecting the development and intensity of SSWs.
3. **Heat Flux Dynamics:** The variability in upward heat flux across polar and low-latitude regions demonstrated distinct responses under different QBO phases. The study found that upward heat flux into the stratosphere was stronger under w-QBO conditions, facilitating more pronounced SSWs, while e-QBO phases showed weaker wave forcing, resulting in less intense stratospheric disturbances. This highlights the importance of heat flux as a mediator between tropical variability and stratospheric dynamics.
4. **Stratosphere–Troposphere Coupling:** The NAM index analysis underscored the significant stratosphere–troposphere coupling during SSW events, with negative anomalies propagating downward from the stratosphere to the troposphere. The 2019 SSW, occurring under e-QBO conditions, showed a more robust downward propagation of NAM anomalies, indicating a stronger impact on surface weather patterns, such as cold air outbreaks in mid-latitudes.

These findings highlight the intricate relationships between QBO, MJO, and SSWs, emphasizing the need for integrated approaches in understanding and predicting SSW events. The study underscores the influence of tropical oscillations on polar stratospheric processes, which have significant implications for weather patterns in the northern hemisphere. By elucidating the role of QBO phases in modulating the MJO and subsequent stratospheric responses, this research provides valuable insights into the broader impacts of tropical–extratropical interactions on global atmospheric circulation. This study is based on the recent SSW events, and future analyses with extended data will aim to capture a more robust signal and detailed physical processes.

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