~~Large Ozone Intrusions during Sudden Stratospheric Warmings Enhance Ozone Radiative Forcing Over South Asia~~

Large Ozone Enhancement over South Asia Triggered by Sudden Stratospheric Warming under Westerly QBO phase: Implications on Ozone Radiative Forcing

Shubhajyoti Roy[1, 2], Satheesh Chandran PR[1], Suvarna Fadnavis[1*], Vijay Sagar[1], Michaela I. Hegglin[3,4,5], Rolf Müller[3], Prashant Chavan[1]

[1]Indian Institute of Tropical Meteorology, Centre for Climate Change Research, India

[2]Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, Pune, India

[3]Institute of Energy and Climate Systems: Stratosphere (ICE-4), Forschungszentrum Jülich, Jülich, Germany

[4]Institute for Atmospheric and Environmental Research, University of Wuppertal, Wuppertal, Germany

[5]Department of Meteorology, University of Reading, Reading, United Kingdom

*Corresponding author email: suvarna@tropmet.res.in

Abstract

Tropospheric ozone pollution in South Asia is mainly blamed on anthropogenic emissions. However, based on ERA5 reanalysis data, this study highlights the contribution of stratospheric ozone intrusions into the Upper Troposphere and Lower Stratosphere (UTLS) associated with Sudden Stratospheric Warming (SSW) events in enhancing upper tropospheric ozone over the South Asian region~~,~~. We report an enhancement in ozone in the UTLS by more than 80% for 2018 and ~30% within ±6 days of the onset during SSW events concurrent with the westerly phase of ~~the QBO~~ Quasi-biennial oscillation (WQBO-SSW) compared to non-SSW years. The equatorward shift (south of 30°N) of the subtropical jet during WQBO-SSW causes ~~deepening~~ lowering of the tropopause and more Rossby-wave ~~penetration~~ breaking in the upper troposphere. This results in higher ~~Rossby-wave breaking and~~ stratospheric ozone intrusions over the South Asian region. The ozone enhancement during WQBO-SSW events produces an instantaneous radiative forcing at the top of the atmosphere of 0.09 ± 0.05 $W.m^{-2}$ due to UTLS ozone changes and 0.17 ± 0.05 $W.m^{-2}$ from total-column ozone changes over South Asia. ~~The elevated tropospheric ozone levels resulting from stratospheric intrusions pose a threat to humans and vegetation.~~

Keywords: Sudden stratospheric warming, stratosphere intrusions, ozone radiative forcing, South Asian region, Rossby wave breaking.

1. Introduction

Tropospheric ozone is a short-lived greenhouse gas that plays a crucial role in atmospheric chemistry and radiative forcing (Wang et al., 2022). It is also a major air pollutant that significantly affects human health (Lim et al., 2012; Fleming et al., 2018), damages

vegetation (~~Fowler et al., 2009;~~ Feng et al., 2021), disrupts ecosystems, and imposes economic costs (Dewan and Lakhani, 2022). In South Asia, a significant amount of tropospheric ozone is a growing concern due to its increased hazardous health effects (~~Silva et al., 2013;~~ Lin et al., 2018).

The contribution from the downward transport of ozone-rich air from the stratosphere is the largest natural source of tropospheric ozone (e.g., Fadnavis et al., 2010; Roy et al., 2020). Studies have reported that stratospheric influence on the tropospheric ozone exceeds 50% in the winter season at the extratropics (Williams et al., 2019). Wang and Fu (2021) estimate that stratosphere-to-troposphere exchange (STE) contributes approximately 347±12 Tg year^{-1} to the global tropospheric ozone budget based on both observations and reanalysis data. CMIP6 model simulations for the period 1997 to 2014 indicate that up to 30% of surface ozone in the Northern Hemisphere during winter (DJF) is due to stratospheric ozone intrusions (Li et al., 2024). In the Northwest Pacific, STE increases mid and upper-tropospheric ozone by about 96% in winter and 40% in summer between 1990 and 2020 (Ma et al., 2024). Roy et al. (2023) reported an ozone enhancement of ~40 ppb in the upper troposphere over the Indian region caused by stratospheric intrusions associated with tropical cyclones.

Sudden stratospheric warming (SSW) events play a key role in atmospheric dynamics and stratospheric ozone intrusions into the troposphere (e.g., Williams et al., 2024). SSWs are one of the most significant large-scale dynamical phenomena in the stratosphere during winter (Butler et al., 2015; ~~de la Cámara et al., 2018;~~ Baldwin et al., 2021). Enhanced planetary wave activity from the troposphere disrupts the stratospheric polar vortex, decelerating or even reversing the stratospheric westerlies, and causing a rapid rise in polar stratospheric temperatures by up to 50 K within few days (Baldwin et al., 2021). SSW events are crucial in modulating

extreme heat, air pollution, wildfires, wind extremes, storm clusters, tropical cyclones, and sea ice melt in the northern high latitudes (Domeisen and Butler, 2020; Domeisen et al., 2020). The temperature and wind anomalies associated with SSWs propagate downward into the troposphere over timescales ranging from weeks to months, impacting tropospheric weather in the Northern Hemisphere for up to 40 days following the onset of the event (Baldwin and Dunkerton, 2001; Hall et al., 2021). Studies also suggest that SSWs are often followed by an equatorward shift of the tropospheric jet stream and storm tracks, as well as surface pressure anomalies that resemble the negative phase of the Northern Annular Mode (Sigmond et al., 2013; Kidston et al., 2015). Projection studies suggest that SSW events will increase by approximately one event per decade by the end of the 21st century (Charlton-Perez et al., 2008). High greenhouse gas emission scenarios indicate a doubling in SSW frequency (Schimanke et al., 2012). Considering the frequent occurrences and the potential role of SSWs in STE, it is important to investigate SSWs influence on tropospheric ozone enhancements and the associated radiative effects.

SSW events have a significant influence on STE and impact the tropospheric ozone budget, particularly in high-latitude regions (Xia et al., 2023; Williams et al., 2024; Lee et al., 2025). Based on 11 polar-night jet oscillation (PJO) type SSW events from 1980 to 2013 and chemistry-climate model simulations, STE led to an average increase of 5–10% in near-surface ozone over the Arctic (Williams et al., 2024). Xia et al. (2023) reported an even more pronounced increase of 76% in Arctic surface ozone due to STE in the 2020/21 SSW event. While most of these studies focus on the polar regions, some have identified SSW-induced ozone variability in the mid-latitudes (Liu et al., 2009; ~~Lu et al., 2022;~~ Williams et al., 2024). ~~For example, Lu et al. (2022) demonstrated that meteorological changes associated with SSWs cause~~

poor air quality in the Beijing-Tianjin-Hebei region. Liu et al. (2009) noted an ozone enhancement of about 186 Tg in the upper troposphere over East Asia during the 2002–2003 SSW, using MOZART-3 simulations. However, tropospheric ozone variations during SSW events over South Asia are among the least studied. Additionally, the broader implications of these events on the ozone radiative forcing over this region remain largely underexplored.

In this study, we investigate the impact of all the SSW events from 1962 to 2018 on ozone variability in the upper troposphere and lower stratosphere (UTLS: 300-50 hPa) over the South Asian region (20-35°N, 65-90°E) using ERA5 reanalysis data. The composite is obtained by averaging data with the onset day as a central date (details in the 'Methods' section). Here, we report a significant ozone enhancement in the UTLS over South Asia, leading to increased ozone radiative forcing. All SSWs were examined during the period from 1962 to 2018. This revealed more equatorward shift of the subtropical jet over South Asia (~23°N) and associated large ozone intrusion in this region during the 2018 SSW relative to other SSW years. This motivated us to report the detailed mechanism of the 2018 SSW as a case study. A recent study by Shi et al. (2023) reported that during reports the influence of the 2018 SSW over East Asia, surface temperatures dropped by up to ~18°C relative to pre-event conditions causing anomalous cooling of 18°C. However, to our knowledge, UTLS ozone responses over South Asia during this event have received limited attention, which motivates our emphasis on the 2018 case. We further extend the analysis to all SSWs and assess their contribution to upper-tropospheric ozone and regional ozone radiative forcing.

The paper is organised as follows. Section 2 describes the ERA5 reanalysis dataset, and the computation of ozone radiative forcing using the radiative-kernel method. Section 3 presents

the (i) UTLS ozone changes during the 2018 SSW event over South Asia, (ii) composite analysis of SSWs, and (iii) ozone radiative forcing. Section 4 summarises the main findings.

2. Methods

2.1 ERA 5 Reanalysis Data

We analysed daily data of ozone, zonal and meridional winds, geopotential height (GPH), and potential vorticity (PV) from the fifth-generation reanalysis dataset (ERA5) provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al., 2020). The ERA5 ozone field is generated through assimilation of multiple satellite- and ground-based observations, including TOMS (1978–2006), SBUV v8.6 (1978–present), CCI MIPAS (2005–2012), SCIAMACHY (2002–2012), Aura MLS v4.2 (2004–present), and OMI-DOAS (2004–present) (Hersbach et al., 2020; S-RIP Final Report, 2022). Comparison of ERA5 ozone with observations shows a slight overestimation in the UTLS. For example, over the North India region, ERA5 shows an overestimation of ~20 ppb ozone (Fadnavis et al., 2023). However, ERA5 ozone showed lesser biases compared to other reanalyses (Fadnavis et al., 2023). The S-RIP (2022) assessment report states an overestimation of zonal mean ozone by ~10–40% between 50°N and 50°S. ~~Overall, ERA5 ozone shows lesser biases than other reanalyses (Fadnavis et al., 2023). We analysed ERA5 ozone, geopotential height, winds, and potential vorticity (PV) data for this study.~~ The ERA5 variables have a horizontal resolution of 0.25° × 0.25° across 37 standard pressure levels (1000 to 1 hPa). Composite analysis is conducted for all variables for ±30 days, centered on the onset of SSW events (30 days before and after the onset), to assess the impact.

Daily anomalies in ozone, geopotential height, winds, and PV during the SSW days were calculated by subtracting the corresponding calendar-day climatology, computed from all the

non-SSW years. The long-term trend is removed from the daily ERA5 data before computing anomalies. This approach ensures that anomalies reflect deviations from typical background conditions. To determine statistical significance, we used the Monte Carlo bootstrap and the Wilcoxon signed-rank test. For the Monte Carlo, we built a calendar-matched ~~null~~non-SSW background ensemble by resampling days from non-SSW years within the same day-of-year window (20,000 resamples). We then use a bias-corrected and accelerated (BCa) bootstrap with 20,000 resamples to form 95% confidence intervals. For 2018, we checked whether the observed value lay outside the BCa interval of the background ensemble. For the composite, we computed the event composite mean and tested it against the distribution of composite means obtained from the same non-SSW background ensemble (20,000 resamples). ~~whether the mean anomaly differed from zero.~~ A grid point was considered significant if the event composite mean lay outside the 95% BCa confidence interval of this background distribution. Next, we applied an exact Wilcoxon signed-rank test to the same data. A grid point is called significant only when both tests agree at 95% significance.

The onset of all the ~~2018~~ SSW events is identified as the day when the zonal mean westerly winds at 10 hPa and 60°N reverse their direction from westerlies to easterlies (Charlton and Polvani 2007). Figure S1 shows the temporal evolution of the zonal-mean zonal wind at 60° N and 10 hPa for the 2018 SSW event. To diagnose stratospheric intrusions, we use potential vorticity (PV) as a dynamical tracer of stratospheric air and adopt the 2-PVU contour as a proxy for the dynamical tropopause (e.g., Kunz et al., 2011; Holton et al., 1995). Intrusions are identified from PV streamers or tropopause folds when high-PV (≥2 PVU) extends equatorward and downward into the upper troposphere (e.g., Sprenger et al., 2007) ~~associated for Rossby-wave breaking (RWB) in the upper troposphere. A PV value greater than 2 PVU in the upper~~

~~troposphere is taken as an indicator of a stratospheric intrusion (e.g., Holton et al., 1995; Stohl et al., 2003)~~. To demarcate the boundary between the troposphere and stratosphere, we used the WMO lapse-rate tropopause (WMO 1997). We used the lapse rate tropopause (LRT) derived from the ERA5 data for the present study (Hoffmann and Spand 2022). This definition is adopted to mark a temporally varying troposphere–stratosphere boundary that is consistent with the dynamical changes. Further, phases of the Quasi-biennial oscillation (QBO) are identified using zonal-mean zonal wind data from radiosonde observations published by the Freie Universität Berlin. The classification of westerly and easterly QBO phases is based on winds at 70 hPa. Periods with positive zonal wind values (>0 $m.s^{-1}$) are identified as the westerly QBO (WQBO), while periods with negative zonal wind values (<0 $m.s^{-1}$) are classified as the easterly QBO (EQBO).

2.2 Computation of ozone radiative forcing

The ozone radiative forcing (RF) is estimated using an ozone radiative kernel method (Skeie et al., 2020). The radiative kernel is constructed using the University of Oslo radiative transfer model (Myhre et al., 2011) by perturbing the ozone layer-by-layer. Temperature, water vapour, and clouds are incorporated into the model from ECMWF's forecast for the year 2003 and applied as monthly averages. The model calculates radiative forcing using a broad-band scheme for longwave radiation (Myhre and Stordal, 1997) and the DIScrete Ordinate Radiative Transfer (DISORT) code for shortwave radiation (Stamnes et al., 1988). Previous studies have shown that the ozone radiative forcing estimates from the radiative kernel technique and a radiative transfer model agree within 0.01 $W.m^{-2}$ globally (Iglesias-Suarez et al., 2018). Before applying the kernel, the ERA5 ozone data are linearly interpolated to the kernel resolution (~5.6° × 5.6° horizontal, with 60 vertical levels). The interpolated ozone fields are first converted into

178 layer-wise partial column amounts in Dobson units (DU) following Ziemke et al. (2001). Ozone
179 anomalies in DU are then computed from the non-SSW climatology at each grid point. These
180 layer wise DU anomalies are multiplied by the long-wave instantaneous clear-sky ozone kernel
181 ($W.m^{-2}.DU^{-1}$), which gives the change in top-of-atmosphere (TOA) long-wave radiative flux
182 (defined as an increase in net downward flux; $\Delta (F_{in} - F_{out}) > 0$) per DU of ozone change in
183 each layer. Following Shell et al. (2008), we calculate the instantaneous ozone RF by vertically
184 summing the layer wise TOA contributions from the UTLS and the total atmosphere.

185 **3. Results**

186 **3.1 Polar vortex evaluation in 2018 SSW event**

187 The time evolution of the vortex structure depicted by PV at 10 hPa for ±30 days around
188 the 2018 SSW onset is shown in Fig. 1. As the SSW event approaches, the vortex begins to
189 elongate and become asymmetrical (Fig. 1a-g) due to the influence of planetary wave activity
190 propagating upward from the troposphere; such deformation of the vortex was reported in the
191 past (e.g., Baldwin et al., 2021). On the onset day (12 February), the vortex splits into two high-
192 PV lobes, one positioned over North America and another over Eurasia (Fig. 1h). Following the
193 onset, smaller vortices exhibit swirling and filamentation, with the Eurasian lobe drifting
194 westward (Fig. 1i-j). Polar vortex splitting or deformations cause equatorward meandering of
195 upper tropospheric jet that affect the Rossby wave breaking (RWB) and ozone intrusions in the
196 mid-latitudes (Baldwin et al., 2021; Albers et al., 2015; ~~Gomez-Escolar et al., 2014~~). The
197 equatorial meandering of the jet may influence the tropical region; however such analysis is
198 sparse. In the following sections we show the influence of the 2018 SSW on the South Asian
199 region. First we show ozone variation in the UTLS over South Asia and then explain the
200 associated dynamical changes in RWB and the upper tropospheric jet.

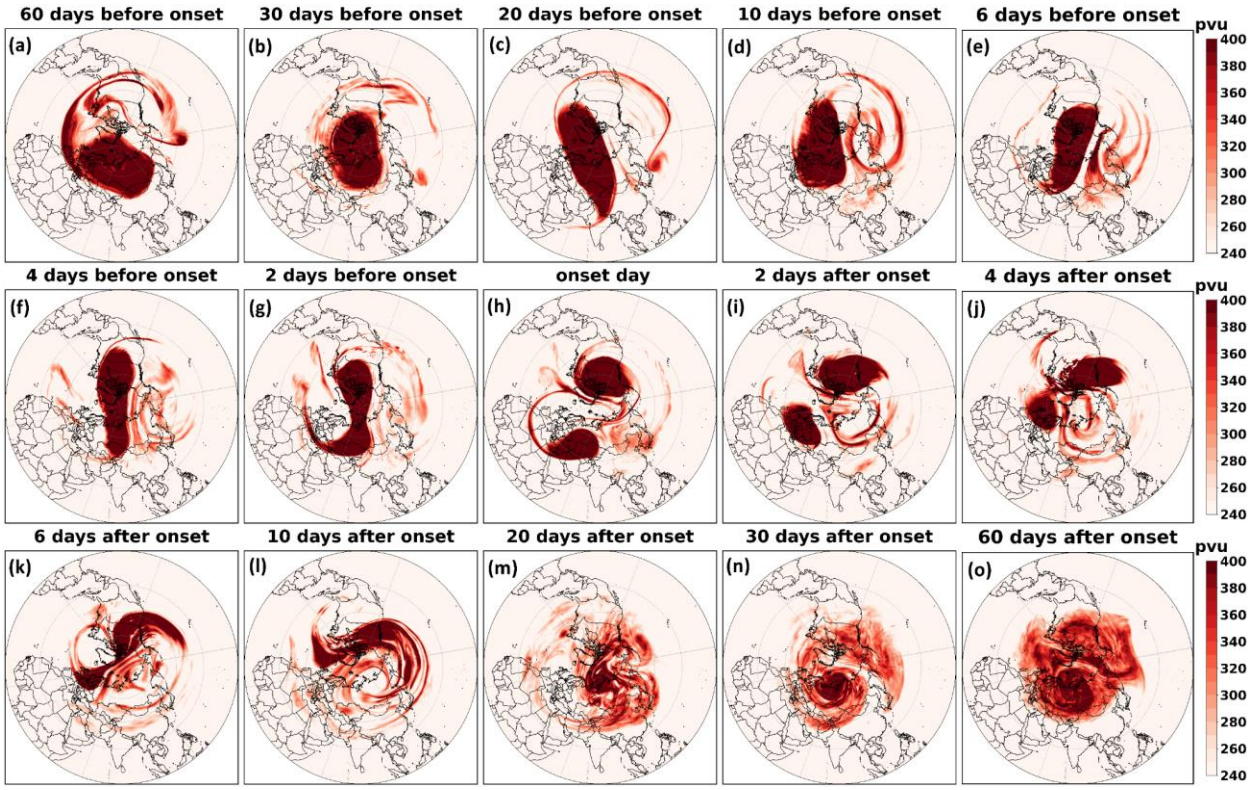

Figure 1. Time slice of the spatial distribution of potential vorticity (PV) at 10 hPa from 30 days before to 30 days after the onset of the 2018 SSW event.

3.2 February 2018 SSW case: UTLS ozone variation

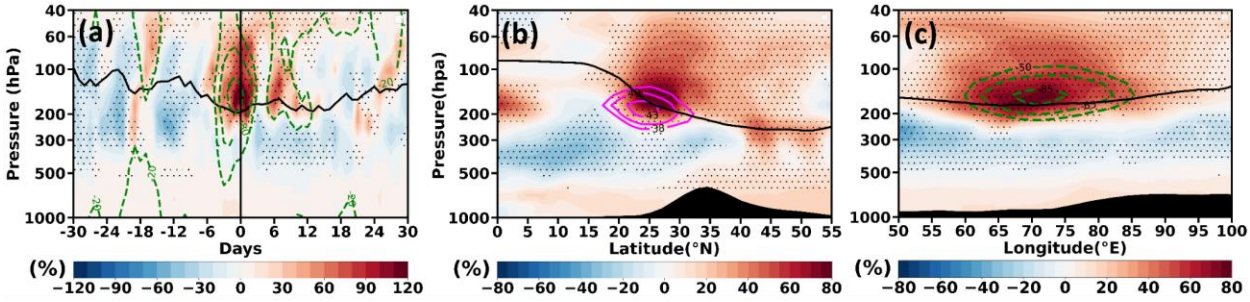

Figure 2. (a) Temporal evolution of vertical ozone anomalies averaged over the South Asian region (65-90°E, 20-35°N) from 30 days before to 30 days after the onset for the 2018 event. (b) Latitude-pressure section of ozone anomalies averaged over South Asia (65 - 90°E) for ±6 days around the onset for 2018 SSW event. (c) is the same as that of (b) but represents longitude variations of vertical ozone anomalies averaged over South Asia (20-35°N). The ~~horizontal and the~~ vertical solid black line in (a) represent ~~380 K potential temperature isoline and~~ the onset day~~, respectively~~. Magenta solid contour lines in (b) represent the mean zonal wind and green dashed contour lines in (a) and (c) represent the GPH anomaly. Solid black lines in panels ~~(b-c)~~ (a-c) represent the lapse rate tropopause. Black dots indicate a region of 95% confidence level. ~~(Figure created using Python software).~~

~~In this section, we discuss the ozone enhancement in the UTLS over South Asia associated with the 2018 SSW event and the possible mechanism responsible.~~ Figures 2a show vertical distribution of the temporal evolution of ozone anomalies averaged over South Asia for the 2018 SSW event. There is a large ozone enhancement in the UTLS, with values >80% (>150 ppb) in 2018 within ±6 days around the SSW-onset. Figure 2a indicates that the ozone enhancements in the UTLS region coincide with negative geopotential height (GPH) anomalies. Since the most pronounced ozone enhancement in the UTLS is observed within ±6 days around the SSW onset, all subsequent analyses in this study are performed for this time period. The latitude–pressure (Fig. 2b) and longitude-pressure (Fig. 2c) cross-sections of ozone anomalies show large ozone enhancement for ±6 days around the onset in the UTLS over South Asia, exceeding 60% (>80 ppb). Interestingly, a peak in ozone enhancement is seen at the subtropical jet core (Fig.2b). This suggests the role of the subtropical jet causing ozone enhancement in the upper troposphere over South Asia ~~(discussed in section 3.1.1)~~. The strong negative GPH anomaly (indicating a low-pressure area) coincident with large ozone enhancements, provides evidence of stratospheric intrusions occurring during the 2018 SSW event (Fig. 2c). In addition, the reduced tropopause height near the onset in Fig.2a suggests the occurrence of tropopause folds. Earlier studies have shown that Rossby wave breaking (RWB) produces tropopause folds; provide an efficient pathway for quasi-isentropic descent of ozone-rich stratospheric air into the UTLS (Sprenger et al., 2003; Holtan et al., 1995). Past literature reports ozone enhancements in the polar region associated with SSW (e.g., Baldwin et al., 2021); however, high ozone enhancement in the UTLS over the South Asian region underscores the unique regional impacts of SSWs.

~~3.1.1 Causative Mechanisms for Changes in UTLS Ozone~~

~~In this section~~ Further, we discuss the possible mechanism responsible for the ozone enhancement in the UTLS over South Asia associated with the 2018 SSW event. Several studies have shown that SSW-related planetary wave disturbances occur across a deep layer of the stratosphere (e.g., ~~McIntyre, 1982; McIntyre and Palmer, 1983;~~ Albers et al., 2016). These disturbances extend downward and disrupt horizontal flows in the upper troposphere (200 hPa) (Albers et al., 2016). To explore the influence of these disturbances over the South Asian region, we analysed GPH anomalies at 200 hPa. The evolution of GPH anomalies at 200 hPa for ±2 days around the SSW onset (Feb. 12, 2018) is shown over the South Asian region in Fig. 3a-e and for the Northern Hemisphere in (Fig. S2a-e). In the Northern Hemisphere, patterns of high and low GPH anomalies at 200 hPa in the subtropical region (15-40°N) indicate the presence of synoptic-scale Rossby waves in the upper troposphere (Fig. S2a-e). The low GPH anomaly over South Asia (also see Fig. 3a-e) indicates a low-pressure area causing deepening of trough. It is associated with the eastward propagation of Rossby waves which can facilitate enhanced stratospheric intrusions.

RWB is characterised by large filaments of high-potential vorticity (PV) air extending towards the equator. The 2 PVU contour lines along with ozone anomaly maps at 200 hPa depicted in Fig. 3f-j shows clear indications of RWB causing ozone intrusions over South Asia. Such quasi-isentropic equatorward excursions cause irreversible ozone intrusion from the lower stratosphere into the upper troposphere (e.g., Holton et al., 1995; Waugh and Polvani, 2000~~; Albers et al., 2016~~).

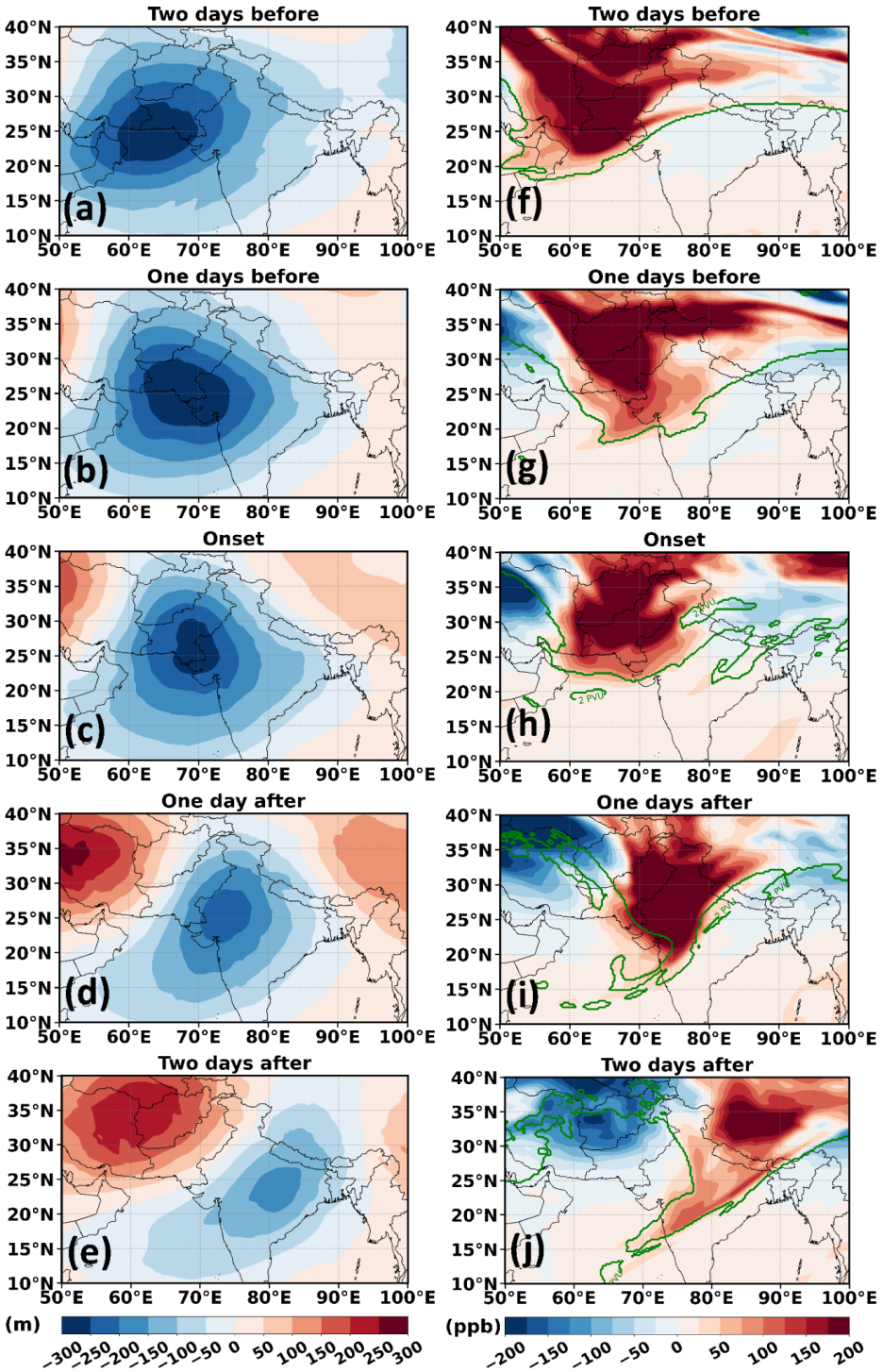

Figure 3. Spatial map of (a-e) GPH anomaly at 200 hPa, (f-j) ozone anomaly at 200 hPa from 6 days before to 6 days after the onset of the 2018 SSW event, along with 2 PVU contour (green solid line), shown at 3-day intervals. ~~The inside red square box represents the South Asian region considered for the present study. (Figure created using Python software).~~

Figures 3f-j clearly show that intrusions near SSW onset days cause large ozone enhancements >150 ppb (>80%) over South Asia. Since the location and strength of the subtropical jet set the refractive waveguide and the location of wave breaking (Hoskins & Ambrizzi 1993; Hitchman & Huesmann 2007), we next diagnose the jet's evolution during this period. Figure 4 displays the latitude-time Hovmöller diagrams of zonal wind at 200 hPa and the time-altitude section around the onset over the South Asian region. Figure 4 clearly shows the equatorward shift of the subtropical jet around onset, creating the background flow conducive to the RWB and ozone intrusions seen in Fig. 3. The time evolution of zonal winds depicted in Figure 4a shows that thirty days before the onset, the subtropical jet core is positioned over the northern part of the Indian subcontinent, and migrates equatorward (south of 23°N) more prominently for ±6 days around the onset. The vertical variation of zonal wind (Fig. 4b) also indicates an equatorward displacement of the subtropical jet, with enhanced westerlies near 200 hPa extending into 10–20°N over 65–90°E around the onset day. ~~clearly depicts the intensification of westerly wind over the Indian region around 200 hPa close to the onset day, facilitating Rossby wave breaking (Fig. 3b)~~. ~~The strength of zonal wind is strong within ±6 days around the onset, causing higher ozone intrusions during this period (see Figs. 1b and 3b).~~ Such changes in jet structure are consistent with a stronger upper-tropospheric Rossby-wave waveguide and background conditions under which RWB is more likely to occur near the tropopause (Hoskins and Ambrizzi 1993; Homeyer and Bowman 2013).

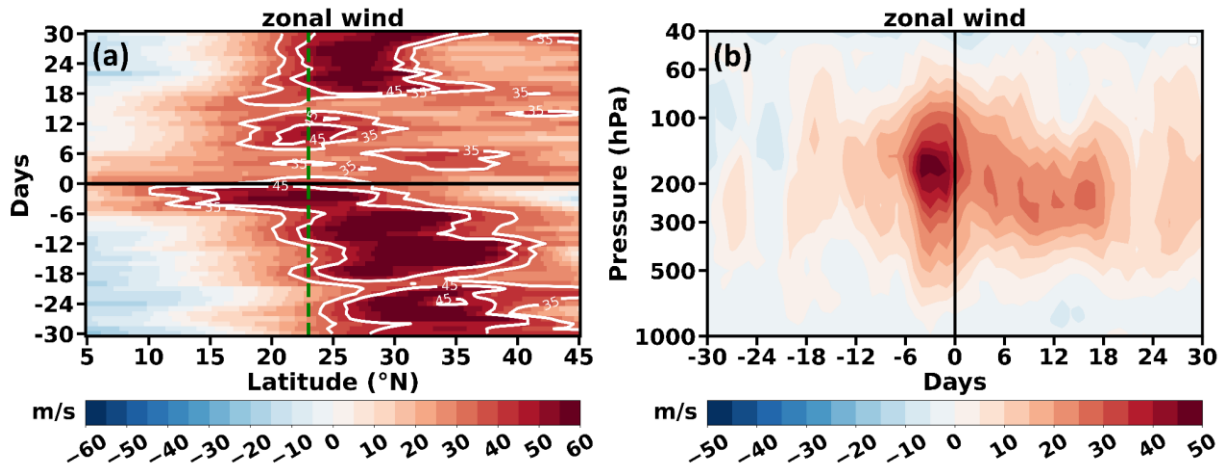

Figure 4. (a) Latitude-time plot of zonal wind averaged over South Asia (65° - 90° E) at 200 hPa. (b) Temporal evolution of vertical zonal wind averaged over the South Asian region (65 - 90° E, 10 - 20° N) for ±30 days around the onset of the 2018 SSW event. The horizontal ~~dashed~~ solid line in (a) and the vertical solid line in (b) represent the onset day. The vertical dashed line in (a) represents 23°N. ~~(Figure created using Python software).~~

The observed equatorward shift of the subtropical jet during the 2018 SSW may also be influenced by the concurrent phase of the Quasi-Biennial Oscillation (QBO) (e.g., White et al., 2016; ~~Lachmy et al., 2014;~~ Li et al., 2023). Notably, the February 2018 SSW took place during the westerly phase of the QBO (Butler et al., 2020). Earlier studies have reported an equatorward shift of the subtropical jet over the East Asia–North Pacific region during the westerly phase of QBO (Park et al., 2021). Our analysis reveals a similar equatorward displacement of the subtropical jet over South Asia during SSWs (Fig. 4a), coinciding with the westerly QBO phase. During the westerly QBO, the associated secondary circulation warms the equatorial lower stratosphere and cools the subtropics, sharpening and shifting the UTLS meridional temperature gradient equatorward (e.g., Hitchman et al., 2021). By thermal-wind balance, this strengthens upper-tropospheric westerlies on the equatorward flank and displaces the subtropical jet equatorward over South Asian longitudes, favouring subtropical wave guidance, RWB, and PV-streamer intrusions (Homeyer & Bowman, 2013; Albers et al., 2016). Additionally, previous studies have shown that the westerly phase of QBO (WQBO) is associated with a lowering of the

tropopause (Collimore et al., 2003; Kumar et al., 2014). This lowering perturbs the subtropical waveguide structure and enhances tropopause fold activity (Kumar et al., 2020), thereby increasing the frequency of Rossby wave breaking and strengthening stratosphere–troposphere exchange, causing enhanced ozone intrusions.

3.3 Composite UTLS Ozone Response during all SSW Events

Further, we investigate the twenty-seven major SSW events from 1962 to 2017, to examine their influence on ozone variability in the upper troposphere over the South Asian region. ~~A detailed examination of individual SSW events revealed that ozone intrusions during some SSW events extend deeper and farther equatorward compared to others. Our analysis shows that, as in the 2018 case, SSW coinciding with the westerly phase of QBO (fifteen out of twenty-seven major SSW, WQBO-SSW) are associated with deeper and equatorward intrusion of ozone compared to those SSW coinciding with the Easterly phase of QBO (twelve out of twenty-seven, EQBO-SSW).~~ Motivated by the 2018 case study, we examined whether the QBO-phase dependence is evident across events. Table 1 lists all the major SSW events considered in this study along with their QBO phases. Of the 27 major SSWs, 15 occur during the westerly phase (WQBO-SSW) and 12 during the easterly phase (EQBO-SSW).

Table 1. List of all major SSW events from 1962 to 2018 considered for the present analysis alongside their onset dates and QBO phases at 70 hPa.

Year	Onset day	QBO Phase
1963	28 January	Westerly
1966	23 February	Easterly
1968	7 January	Westerly
1969	13 March	Easterly
1970	2 January	Westerly
1971	18 January	Easterly
1973	31 January	Easterly
1977	9 January	Westerly
1979	22 February	Westerly
1980	29 February	Easterly
1981	4 March	Westerly
1984	24 February	Westerly
1985	1 January	Easterly
1987	23 January	Westerly
1988	14 March	Westerly
1989	21 February	Westerly
1999	26 February	Easterly
2000	20 March	Westerly
2001	11 February	Westerly
2003	18 January	Westerly
2004	5 January	Easterly
2006	21 January	Easterly
2007	24 February	Westerly
2008	22 February	Easterly
2009	24 January	Easterly
2010	9 February	Westerly
2013	6 January	Easterly
2018	12 February	Westerly

Previous studies have shown that the QBO phase can modulate the dynamical coupling between the stratosphere and troposphere during SSWs (Remya et al, 2023), influencing the extent of ozone transport into the upper troposphere (Zhang et al., 2021). Our analysis shows that, during the composite WQBO-SSW events, ozone intrudes down to 400 hPa, with anomalies exceeding ~30% (over 80 ppb) within ±6 days of the onset (Fig. 5a). On the other hand, during the composite EQBO-SSW events, no significant ozone intrusion is evident within the same period (Fig. 5b). The latitude–pressure (Fig. 5c) and longitude–pressure (Fig. 5d) sections for WQBO-SSW further reveal enhanced ozone in the UTLS within ±6 days over South Asia, with

anomalies exceeding 20% (>60 ppb). As seen earlier (Fig. 2b-c), the maximum ozone enhancement in the WQBO–SSW composite is located near the subtropical jet core (Fig. 5c) along with a strong negative GPH anomaly (Fig. 5d), indicating that jet dynamics and troughing play a key role in modulating UTLS ozone responses during WQBO-SSW. ~~However, the amplitde of ozone enhancement in the UTLS is smaller in the composite of all WQBO-SSW than in 2018. This subdued effect is due to averaging across multiple episodic events occurring at different times within ±6 days around the SSW onset.~~ The enhancement in mean ozone of all WQBO-SSW composite is smaller than in 2018, since there is variation in space and time of ozone intrusions during individual SSW. The averaging across multiple events may subdue the effect but it remains statistically significant over South Asia.

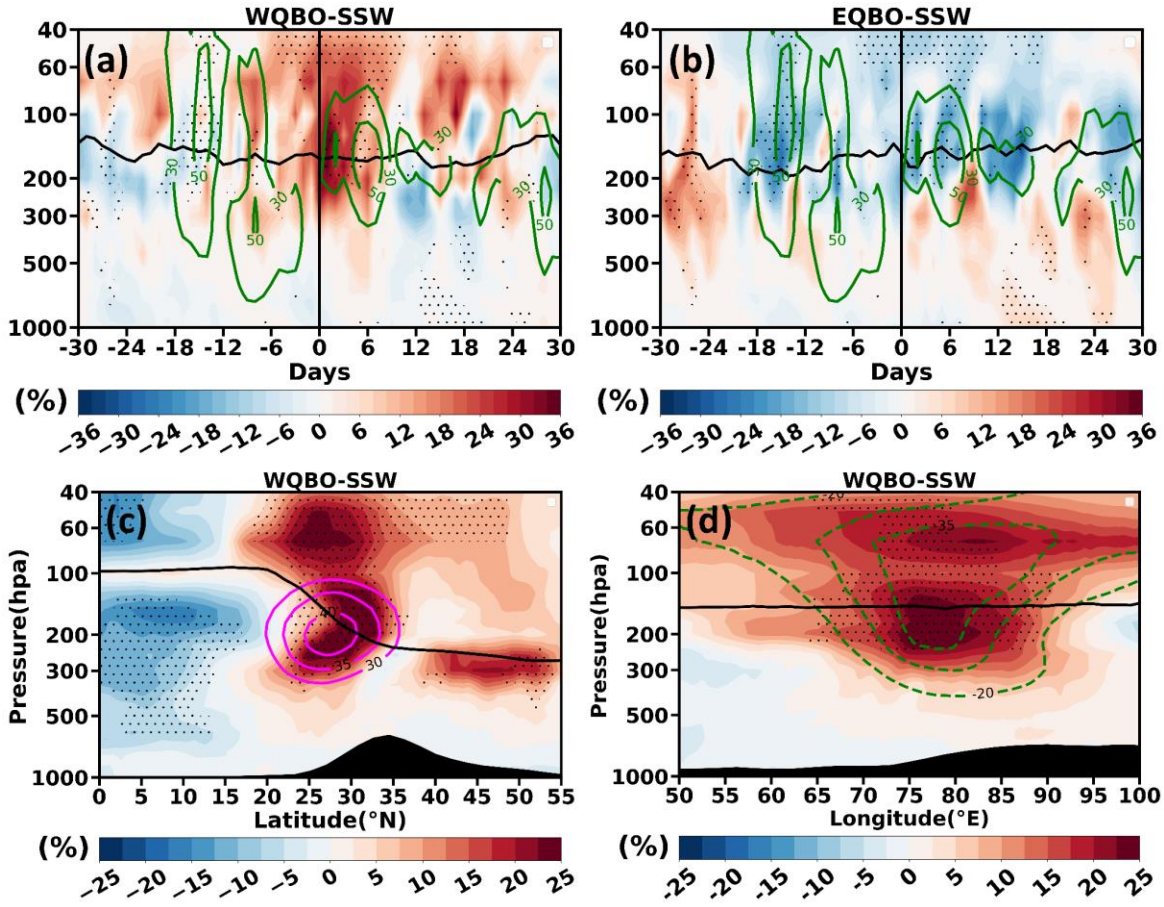

Figure 5: Temporal evolution of vertical ozone anomalies averaged over the South Asian region (65-90°E, 20-35°N) from 30 days before to 30 days after the onset for (a) WQBO-SSW and (b) EQBO-SSW. (c) Latitude-pressure cross-section of ozone anomalies averaged over South Asia (65 - 90°E) for ±6 days around all the WQBO-SSW onsets. (d) is the same as that of (c) but represents the longitude variation of vertical ozone anomalies averaged over South Asia (20 - 35°N). The ~~horizontal solid line in (a-b) represents a 380 K potential temperature isoline, and the~~ vertical solid line in (a-b) represents the onset day. Magenta contour lines in (c) represent the mean zonal wind, and dashed green contour lines in (a,d) represent the negative GPH anomaly and solid green contour lines in (b) represent the positive GPH anomaly. Solid black lines in ~~(c-d)~~ (a-d) represent the lapse rate tropopause. Black dots indicate a region of 95% confidence level. ~~(Figure created using Python software).~~

Further, we analysed the synoptic wave structure prevailing in the upper troposphere for WQBO-SSW and EQBO-SSW composites within ±6 days around the onset, using the 200 hPa GPH anomaly as a proxy (Figs. 6a–b). The alternating trough–ridge patterns in GPH over the subtropics indicate synoptic-scale Rossby waves in the upper troposphere. During the WQBO-SSW a pronounced low GPH anomaly is observed over the South Asian region (Fig. 6a), whereas high GPH dominates during the EQBO-SSW (Fig. 6b). The anomalous low over South Asia during WQBO-SSW events indicates a deepening of the upper-tropospheric trough, which favours the tropopause folding and associated stratospheric intrusions into the upper troposphere (e.g., Knowland et al., 2017; Sprenger et al., 2007).

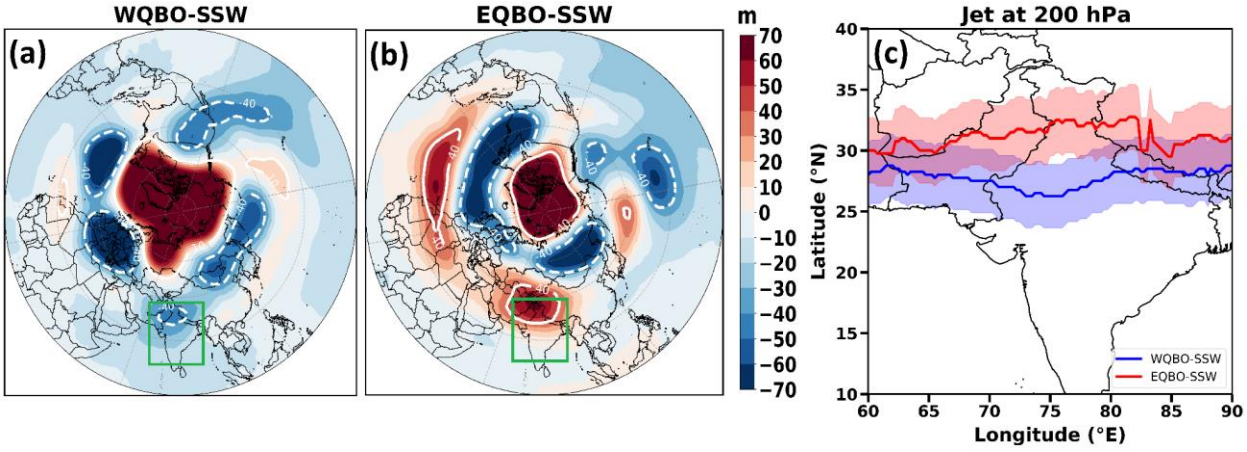

Figure 6. Spatial map of GPH anomaly for (a) WQBO-SSW and (b) EQBO-SSW and (c) jet core at 200 hPa averaged for ±6 days around the onset. White solid and dashed contour line in (a-b) indicates positive and negative GPH anomaly. The square box in (a-b) represents the South

Asian region considered for the present study. Blue line and red line in (c) represents the jet core for westerly phase and easterly phase of QBO respectively. The shading in (c) represents standard error. ~~(Figure created using Python software).~~

Further, we show the position of the subtropical jet core within ±6 days around the SSW onset for WQBO-SSW and EQBO-SSW. Figure 6c shows that during WQBO-SSW, the subtropical jet shifts equatorward, with the jet core (blue lines) located south of 30°N over the South Asian region. Whereas, during the EQBO-SSW, the jet core (red line) remains north of 30°N. (Detailed mechanism discussed in the section 3.2).

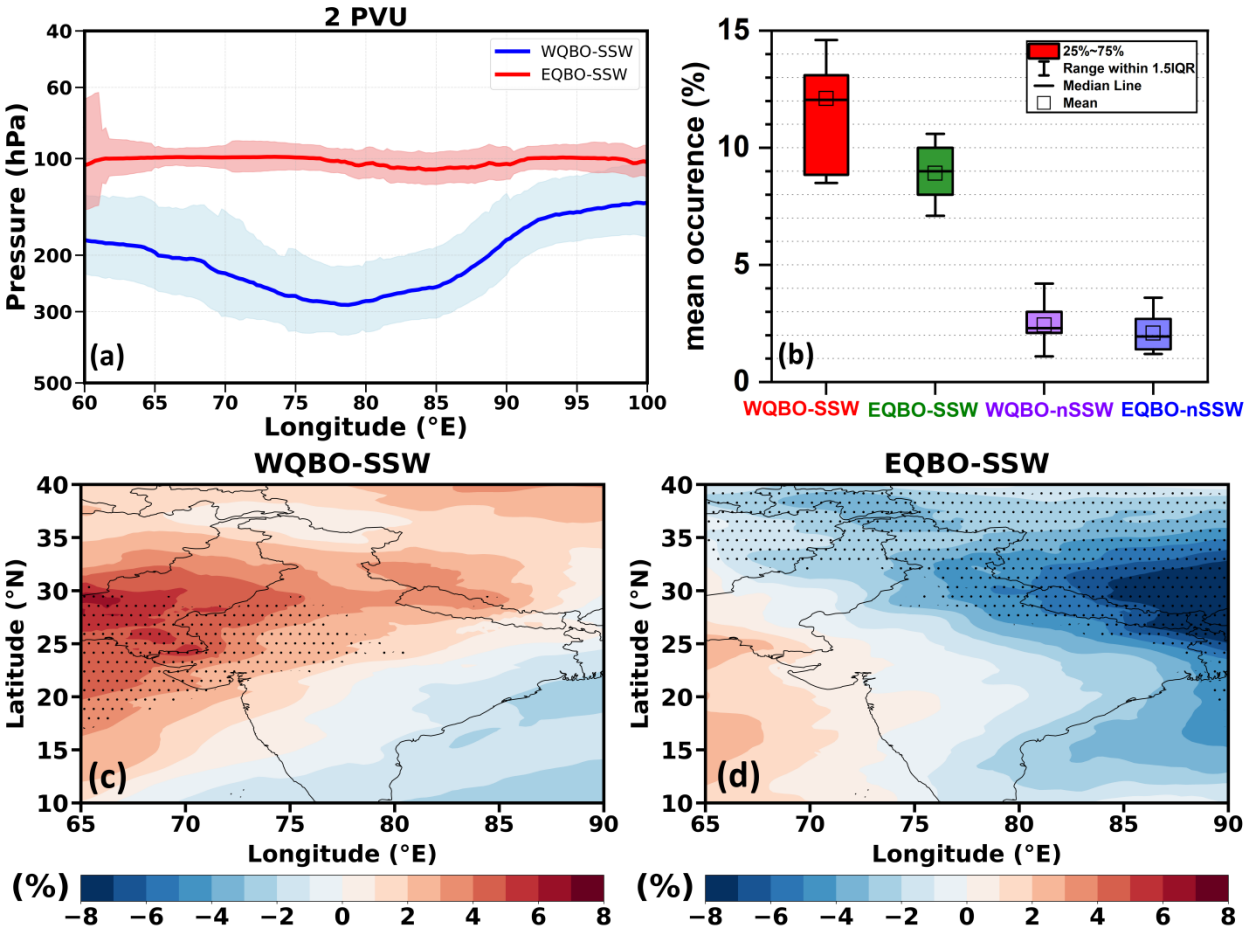

Figure 7. (a) Longitude-pressure cross section of 2PVU line averaged over South Asia (20-35°N) for WQBO-SSW and EQBO-SSW composites, shown for the days of maximum intrusion selected within ±6 days around the onset. The shading represents standard error. (b) Area-averaged occurrence frequency (%) of Rossby wave breaking events during January-March over South Asia identified from PV > 2 and Ozone >80 ppbv at 300 hPa for WQBO-SSW, EQBO-SSW, WQBO-nonSSW, and EQBO-nonSSW. (c) UTLS ozone anomaly composites (in %) for

±30 days around onset for WQBO-SSW relative to WQBO-nonSSW. (d) same as that of (c) but for EQBO-SSW relative to EQBO-nonSSW. Stippling indicates a region of 95% confidence level. ~~(Figure created using Python software).~~

The PV–based RWB diagnostics for composite of WQBO–SSW and EQBO–SSW is shown in Figure 7a. For each event, the day of maximum intrusion within ±6 days around the onset was chosen to capture the most representative feature, as averaging over the period tends to smooth out the signal. The longitude–pressure cross section (Fig. 7a) shows that during the WQBO–SSW, the 2 PVU contour extends farther downward into the upper troposphere, consistent with more pronounced tropopause folding and PV intrusion signatures~~indicating stronger PV intrusions~~. On the other hand, during EQBO–SSW events, the 2 PVU contour remains ~~confined to~~ at higher altitudes, suggesting weaker intrusions.

Further, we computed the occurrence frequency of RWB over South Asia during January–March for WQBO-SSW, EQBO-SSW, WQBO-nonSSW, and EQBO-nonSSW. Fig 7b shows the highest occurrence of ~12 % for WQBO-SSW, while RWB frequency is less for EQBO-SSW, WQBO-nonSSW, and EQBO-nonSSW. UTLS ozone also shows the highest enhancement for WQBO-SSW. Thus, equatorial shift of sub-tropical jet during WQBO-SSW causes RWB over south Asia leading to large ozone intrusions (Fig. 7d).

3.4 Radiative Forcing of ozone associated with WQBO-SSWs over the South Asian region

Further, we assessed instantaneous radiative forcing at the top of the atmosphere (TOA) due to ozone enhancements in (1) the UTLS and (2) total-column over the South Asian region associated with WQBO-SSW events. The instantaneous RF is computed for ±6 days around the onset. RF at TOA due to the ozone enhancements in the UTLS is 0.25 ± 0.18 $W.m^{-2}$ for the 2018 SSW, while the WQBO-SSW composite produces a forcing of 0.09 ± 0.05 $W.m^{-2}$.

Further, the estimated RF at the TOA due to the total-column ozone changes is 0.28 ± 0.19 $W.m^{-2}$ for the 2018 event and 0.17 ± 0.05 $W.m^{-2}$ for the composite. These results highlight the significant role of WQBO-SSW events in modulating the radiative balance ~~in the troposphere, particularly in~~ at the ~~UTLS~~ TOA over South Asia. These changes in RF will affect UTLS temperature, stability, high clouds, and STE (e.g., Xia et al., 2018; Nowack et al., 2014).

4. Conclusions

Using the ERA5 reanalysis (1962–2018), we investigated the impact of sudden stratospheric warmings (SSWs) on ozone variations in the UTLS (300–50 hPa) over South Asia. Unlike prior global analyses, we demonstrate that SSWs coinciding with the westerly phase of QBO (WQBO-SSW) lead to a substantial enhancement in UTLS ozone and radiative forcing over the South Asian region, whereas SSWs associated with the easterly phase of QBO (EQBO-SSW) do not. Our analysis shows that, unlike high latitudes, the South Asian response is not a direct downward influence. These low-latitude impacts are mediated by Rossby-wave dynamics. In particular, Rossby-wave breaking (RWB) and PV-streamer intrusions develop with the equatorward meandering of the subtropical jet.

We find that SSWs coinciding with the westerly phase of the QBO (WQBO-SSW) are associated with an equatorward shift (south of 30°N over South Asia) of the subtropical jet and lowering of tropopause which intensifies RWB and the largest UTLS ozone anomalies over South Asia. An enhancement in ozone anomalies (ranging from 30 to 80% or 80 to 150 ppb for composite and 2018) in the UTLS is noted during the WQBO-SSW years relative to the non-SSW calendar-day climatology within ±6 days of onset. This ozone enhancement in the UTLS during WQBO-SSW events contributes an instantaneous radiative forcing at the top of the atmosphere of 0.25 ± 0.18 $W.m^{-2}$ for the 2018 and 0.09 ± 0.05 $W.m^{-2}$ during the composite. Due

to total-column ozone changes, instantaneous RF at the top of the atmosphere increases by 0.28 ± 0.19 $W.m^{-2}$ for 2018 and 0.17 ± 0.05 $W.m^{-2}$ for the WQBO-SSW composite. This positive TOA radiative forcing does not necessarily imply surface warming, as ozone perturbations can also induce negative surface radiative forcing. For example, Williams et al. (2024) reported a surface forcing of −0.36 $W.m^{-2}$ associated with ozone changes in the UTLS. Our radiative kernel method does not estimate a surface forcing associated with ozone changes in the UTLS. The enhancement in ozone and associated RF can affect the stability and temperature of the UTLS, high clouds, and STE. However, such analysis is beyond the scope of the present study.

~~This large increase in radiative forcing produces positive feedback on the warming climate of this region. Ozone intrusions are warranted to elevate pollution effects and climate warming, impacting people's health, the ecosystem, and the economy~~. ~~In addition, the frequency of SSW is projected to increase in a warming climate (Kim et al., 2017), which will further increase stratospheric ozone intrusions and potentially amplify the consequences of positive feedback mechanisms~~. Since the evolution of the polar vortex modulates subtropical Rossby-wave guides that affect South Asia, these stratospheric influences must be represented in regional prediction systems. ~~We emphasise that climate models should be extended to the stratosphere, including polar vortex dynamics, for accurate prediction of climate over South Asia.~~ Earlier studies have shown that using high-top, stratosphere-resolving models improve subseasonal-to-seasonal predictability (Hardiman et al., 2012; Charlton-Perez et al., 2013; Scaife et al., 2022). We emphasise that models should be extended to the stratosphere, including polar vortex dynamics, for accurate sub seasonal-to-seasonal prediction over South Asia.

Code and data availability

The ERA5 data that support the findings of this study are openly available from https://cds.climate.copernicus.eu/ (10.24381/cds.bd0915c6). All the Figures are created using the Python software. The python code used to plot figures in this paper are available from https://doi.org/10.5281/zenodo.17639489

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Author contributions

Conceptualisation: S.F. Supervision: SF, MH, RF Investigation and methodology: SC, SR, VS, and PC. Writing: all authors.

Competing interests

At least one of the (co-)authors is a member of the editorial board of Atmospheric Chemistry and Physics.

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