https://doi.org/10.5194/egusphere-2025-1098
Preprint. Discussion started: 7 April 2025

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

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https://doi.org/10.5194/egusphere-2025-1098
Preprint. Discussion started: 7 April 2025

Abstract

Tropospheric ozone pollution in South Asia is mainly blamed on anthropogenic emissions. However, this study highlights the contribution of stratospheric ozone intrusions into the troposphere associated with sudden stratospheric warming (SSW) events in enhancing tropospheric ozone over the South Asian region using ERA-5 reanalysis data. We report that specifically split-downward propagating SSWs (dSSWs) cause enormous ozone enhancement in the upper troposphere and lower stratosphere (UTLS) over South Asia around the dSSW-onset, with a maximum of ~290% within ±30 days. The ozone intrusions propagate deep into the troposphere, causing near-surface maximum ozone increase by 43% within ±30 days around the SSW-onset. The ozone enhancement increases ozone radiative forcing in the troposphere by 0.04±0.03 W.m^{-2} and UTLS by 0.08±0.06 W.m^{-2} over South Asia. Frequent SSW events in a warming climate will thus likely increase stratospheric ozone intrusions and ozone radiative forcing over South Asia, potentially exacerbating regional climate warming. The elevated tropospheric ozone amounts due to stratospheric intrusions are posing 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 large amount of tropospheric ozone is a growing concern because of its ill effects, resulting in rising mortality rates (Silva et al., 2013; Lin et al., 2018).

The increase in tropospheric ozone levels in South Asia is primarily attributed to enhanced anthropogenic emissions (Rathore et al., 2023). However, the contribution from the downward transport of ozone-rich air from the stratosphere is the largest natural source of tropospheric ozone. Studies have reported that stratospheric influence on the tropospheric ozone exceeds 50% in the winter season at the extra tropics (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 models suggest that up to 30% of surface ozone in the Northern Hemisphere during winter (DJF) is being attributed 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 (Ma et al., 2024). Numerous observational and reanalysis studies confirm that stratospheric intrusions enhance surface ozone levels over East Asia and the Tibetan Plateau by ~15 ppb (e.g., Ou-Yang et al., 2022; Yin et al., 2023). Roy et al. (2023) reported an ozone enhancement of ~40 ppb in the upper troposphere over the Indian region due to stratospheric intrusions associated with tropical cyclones.

Sudden stratospheric warming (SSW) events are significant drivers of STE, playing 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 occurring 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

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westerlies, and causing a rapid rise in polar stratospheric temperatures by up to 50 K within just a few days (Baldwin et al., 2021). SSW events play a crucial role in modulating tropospheric weather phenomena, such as 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 surface weather in the Northern Hemisphere for up to 40 days following the event onset (Baldwin and Dunkerton, 2001; Hall et al., 2021). 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), and high greenhouse gas emission scenarios show a doubling in SSW frequency (Schimanke et al., 2012). Considering the frequent occurrences and the potential role of SSWs in STE, it is crucial to investigate SSW's influence on tropospheric ozone enhancements and the associated radiative effects.

SSW events are classified into two categories, namely displaced or split events, based on the geometry of the polar vortex (Charlton and Polvani, 2007). In the displaced case, the vortex is displaced off the pole, while it is split into two baby vortices in the split case. Further, SSWs are classified as downward propagating and non-downward propagating. Downward propagating SSWs (dSSWs) show a downward progression of polar cap height anomalies across vertical levels that reach the surface and exhibit strong surface impacts, while this is not the case for non-downward propagating SSWs (nSSWs) (Hall et al., 2021). dSSWs lead to long-lasting tropospheric circulation changes in contrast to nSSWs (; Karpechko et al., 2017). The dSSWs 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). Among dSSWs, studies indicate that the surface effects of split events typically appear

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nearly a week earlier than those of displaced SSWs (Mitchell et al., 2013; Hall et al., 2021). Furthermore, CMIP5 models suggest that split events tend to propagate downward to the surface more quickly than displacement events (Hall et al., 2021).

SSW events significantly influence STE and impact the tropospheric ozone budget, particularly in high-latitude regions (Xia et al., 2023; Lu et al., 2023; Williams et al., 2024). Based on SSW events from 1980–2013 and chemistry-climate model simulations, STE led to an average 5–10% increase 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 as well (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 downward-propagating SSW events from 1962 to 2018 on tropospheric ozone variability over South Asia [20-35°N, 65-90°E] using ERA5 data. The composite is obtained by averaging data with the onset day as a central date (details in the 'Methods' section). Here, we report enormous ozone enhancement in the troposphere over South Asia, leading to an increase in ozone radiative forcing, which further elevates warming in South Asia. We present a detailed mechanism for the latest 2018 split-dSSW event and a composite analysis of all split-dSSW events from 1962 to 2018. The net radiative forcing estimation using the radiative kernel approach is described in the 'Methods' section.

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2. Methods

2.1 ERA 5 Data

We analysed daily data of ozone, zonal and meridional winds, geopotential height, 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 data, with a horizontal resolution of 0.25°×0.25° and 37 pressure levels ranging from 1000 hPa to 1 hPa, were utilized for this study. Composite analysis was conducted for all variables for a 121-day period centred on the onset of SSW events (60 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 daily mean of all the non-SSW days for ±61 days near the onset of the SSW. The anomalies obtained from climatology (1962-2018) also show features similar to those when one use the mean of all the non-SSW days (see Fig. S1. and Fig. 1a-b). We prefer to use the mean of all the non-SSW days instead of climatology since climatology includes SSW events.

The onset of each SSW event 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 S2. shows the temporal evolutions of the zonal-mean zonal wind at 60° N and 10 hPa for all the split-dSSWs considered for the present study.

2.2 Computation of ozone radiative forcing

The radiative forcing (RF) due to ozone 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

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forecast for the year 2003 and applied as monthly averages. The model calculates radiative forcing using a broad-band scheme for longwave (Myhre and Stordal, 1997) and DIScrete Ordinate Radiative Transfer code for shortwave (Stamnes et al., 1988). Previous studies show that the ozone radiative forcing estimates from the radiative-kernel technique and radiative transfer model agree within 0.01 W.m^{-2} globally (Iglesias-Suarez et al., 2018). Before the application of kernel, the ERA5 ozone data is linearly interpolated to the kernel resolution (~5.6° × 5.6° horizontal with 60 vertical levels). This interpolated ozone field is converted into Dobson units following Ziemke et al. (2001) and is multiplied with the kernel to estimate the RF. The tropospheric ozone RF is determined by summing the RF contributions from all atmospheric layers between the surface and the tropopause (Shell et al., 2008). A similar approach is applied to estimate radiative forcing for the UTLS region and the total atmosphere. The tropopause pressure is identified based on the WMO lapse rate tropopause definition.

2.3 Dynamical changes in PV, GPH and ozone in the stratosphere during the 2018 event

The time evolution of the vortex structure depicted by PV at 10 hPa for ±60 days around the 2018 SSW onset is shown in Fig. S3. Since SSW effects are seen for ±60 days around the onset (Limpasuvan et al., 2004; Scheffler et al., 2022), we analysed the evolution of SSW during these days. As the SSW event approaches, the vortex begins to elongate and become asymmetrical due to the influence of planetary waves propagating upward from the troposphere, such deformation of vortex is reported in the past (e.g., Baldwin et al., 2021). Sixty days before onset, a strong, stable polar vortex is evident, but as the event approaches, planetary wave activity causes elongation and asymmetry (Fig. S3). On the onset day (12 February), the vortex splits into two high-PV lobes over Eurasia and North America (Fig. S3h). Following the onset, baby vortices exhibit swirling and filamentation, with the Eurasian

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lobe drifting westward. Earlier, de la Camara et al. (2018) demonstrated that planetary-scale wave breaking intensifies mixing and facilitates the diffusion of PV from the vortex by elongating and stirring the PV fields. These PV variations align with changes in GPH and ozone fields (e.g., Baldwin et al., 2021), emphasizing stratospheric circulation changes (Fig. S3).

Since major changes in the vortex occur ±6 days around the onset, we show the variations in ozone and GPH during this period (Fig. S4). The GPH anomalies at 10 hPa highlight stratospheric circulation changes, showing a transition from a wave-1 to a wave-2 pattern just before onset. On onset day, strong positive GPH anomalies appear over the Arctic, while negative anomalies correspond to the baby vortices (Fig. S4a-h). This pattern persists for six days and weakens as positive anomalies extend into the United States. Ozone anomalies follow a similar pattern (Fig. S4i-p), with negative values inside the vortex during the pre-onset period due to chemical loss (Manney et al., 2015; Baldwin et al., 2021). After onset, the transport of ozone-rich air leads to positive anomalies at the North Pole. A similar sudden increase in the transport of ozone-rich and high GPH air to the polar region on the onset days is reported by many other studies (Bouillon et al., 2023; Veenus et al., 2023; Shi et al., 2024). Following the onset, positive ozone anomalies spread southward along two branches, one along the northern parts of Africa, Eurasia and the Indian subcontinent and the other over the Atlantic and southern US. This indicates the transport of ozone-rich air towards lower latitudes. Several studies have reported earlier that SSWs cause stratosphere-troposphere coupling in the mid and low latitudes (e.g., Gomez-Escolar et al., 2014; Albers et al., 2016; Williams et al., 2024). The disruption of the polar vortex and the resulting stratospheric conditions redirect planetary waves toward lower latitudes, leading to significant tropospheric circulation changes (Gomez-Escolar et al., 2014).

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3. Results

3.1 Vertical variation of Ozone over the South Asian region during SSW events

We investigated all SSW events from 1962 to 2018 to assess their impact on ozone variability in the upper troposphere over the South Asian region. The categorization of split/displaced and downward (dSSW)/non-downward (nSSW) propagating SSW is as per Hall et al., (2021). Table 1 lists the split-dSSW, displaced-dSSW, and nSSW events considered in this study.

Table 1. List of downward propagating split SSW events from 1962 to 2018 considered for the present analysis alongside their onset dates.

Split dSSW	Onset day	Displaced dSSW	Onset day	non-downward SSW	Onset day
1963	28 January	1965	16 December	1966	23 February
1968	7 January	1968	28 November	1969	13 March
1971	20 March	1980	29 February	1970	2 January
1977	9 January	1981	4 March	1971	18 January
1979	22 February	1981	4 December	1973	31 January
1985	1 January	1984	24 February	1987	23 January
1988	14 March	1998	15 December	1987	8 December
1999	26 February	2000	20 March	1989	21 February
2009	24 January	2001	11 February	2001	30 December
2010	9 February	2004	5 January	2003	18 January
2013	6 January	2006	21 January	2007	24 February
2018	12 February	2008	22 February		
		2010	24 March		

We analyzed ozone variations in the UTLS during split-dSSW, displaced-dSSW, and nSSW events. During the SSW event, the disrupted vortex couple with the troposphere, causing shifts in the tropospheric westerly jet and distinctive patterns of anomalous surface temperature and sea-level pressure over a period up to 60 days after SSW onset (e.g., Mitchell et al., 2013; Butler et al., 2017). Figure 1a-d illustrates spatial maps of ozone

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anomalies in the UTLS over the South Asian region, averaged over 30 days prior to and after SSW onset (±30 days) for the aforementioned cases. There is a distinct enhancement in ozone levels in the UTLS, in the 20°–35°N belt, by 8–16% (40 – 45 ppbv) in the 2018 split-dSSW event and by 4–10% (35 – 40 ppbv) in the composite of all split-dSSWs compared to the non-SSW climatology (Fig. 1a-1b). Ozone enhancement in the UTLS is not seen for ±30 days in the case of displaced-dSSW and nSSW events (see Fig. 1c-d). This highlights the importance of considering split-dSSW events when assessing the impact of SSWs on ozone variability in the South Asian region. Ozone enhancement is associated with Rossby wave breaking (RWB) in the vicinity of the South Asian region which is seen only in the case of split-dSSW (discussed in section 2.2).

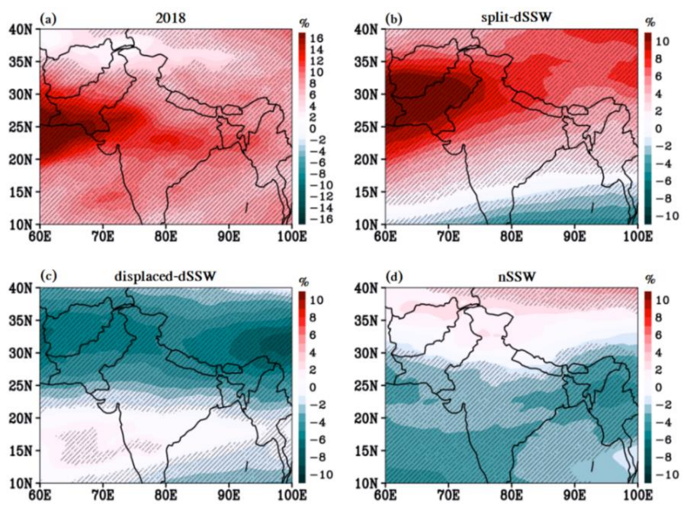

Figure 1. Composite map of ERA5 ozone anomalies in the UTLS (250–50 hPa) over the South Asian region, averaged from ± 30 days around the onset for (a) the 2018 split-dSSW event, (b) all split-dSSWs (12 events), (c) all displaced-dSSWs (12 events), and (d) all nSSWs (9 events) as listed in Table-1. Hatched lines in Figs. a-d indicates a region of 95% confidence level based on the student's t-test. (Figure created using the COLA/GrADS software).

Figures 2a-b show the temporal evolution of vertical ozone anomalies averaged over South Asia for the 2018 split-dSSW event and the composite of all split-dSSWs. There is a

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large ozone enhancement in the UTLS, with values >80% (>150 ppb) in 2018 and >30% (>80 ppb) for the composite of split-dSSWs within ±6 days around the SSW-onset. Figure 2a-b indicates that the ozone enhancements in the UTLS region are episodic and coincide with downward propagating negative geopotential height (GPH) anomalies. The negative GPH anomaly and lowering of the 380 K potential temperature isoline along with a positive ozone enhancement in Fig. 2a-b indicate stratospheric intrusions associated with SSW events. The ozone intrusions over the Indian region are stronger from 5 days before the onset and last for ~15 days, causing an ozone enhancement of ~36% in 2018 and 16 % in split-DSSW composite in the UTLS during this period (see Fig. S5a-b).

Figure 2 a-b shows that ozone enhancement in the UTLS is smaller in composite split-dSSW than in 2018 (in the UTLS, and surface). This subdued effect is due to averaging across multiple episodic events occurring at different times within ±30 days around the SSW onset. Hence, to show the ozone enhancement during the SSW event, we picked up the maximum ozone increase within ±30 days in the upper troposphere and near the surface over South Asia for each of the split dSSWs (Fig. 2c-d). Figure 2c-d shows clear evidence of a substantial ozone increase (50 to 250 %) in the UTLS (150 hPa) and (15 to 45%) near the surface (850 hPa) during the split-dSSWs. Further, the lead-lag correlation between the ozone variation in the upper troposphere and at surface levels shows that downward propagation of ozone from 200 hPa to the near-surface occurs with 10- and 25-days lag in 2018 and 5- days lead to 10- days lag in the case of composite (Fig. S6).

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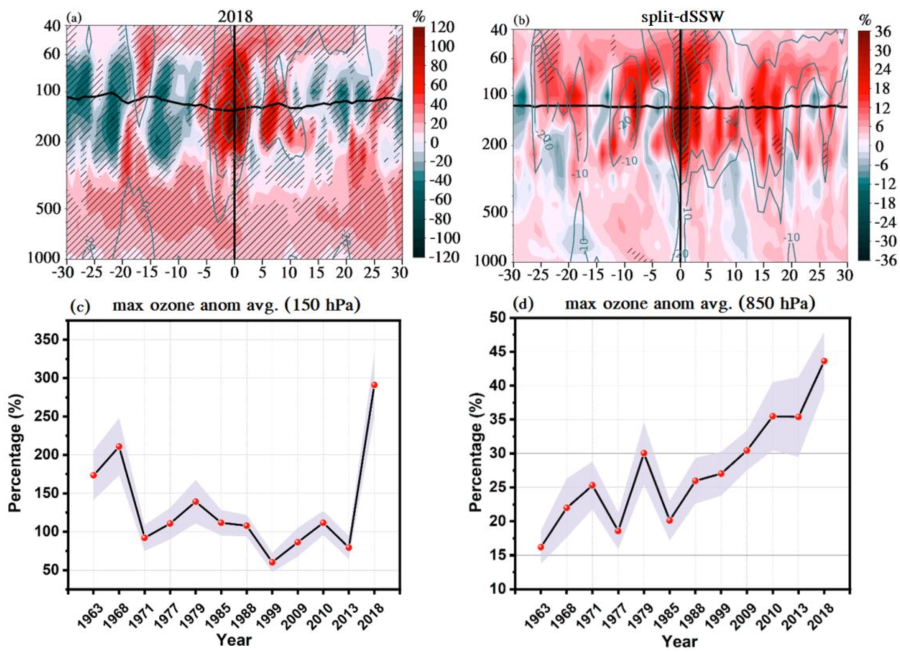

Figure 2. Temporal evolution of vertical ozone anomalies averaged over the South Asian region (65-90°E, 20-35°N) from 30 days before to 30 days after the onset for (a) the 2018 split dSSW event and (b) all the split dSSWs. Hatched lines in Figs. a-b indicates a region of 95% confidence level based on the student's t-test. The sky blue contour line represents the GPH anomaly during the respective period. The horizontal solid line represents 380 K potential temperature isoline, and the vertical solid line represents the onset day. Average of the daily maximum ozone increase within ±30 days over South Asia for each of the split dSSWs in the (c) upper troposphere (150 hPa) and (d) near-surface (850 hPa). The shading in (c) and (d) represents standard error. (Figure created using the COLA/GrADS software).

The latitude-pressure (Fig. 3a-b) and longitude-pressure (Fig. 3c-d) cross-sections of ozone anomalies show large ozone enhancement for ±6 days around the onset in the UTLS over South Asia exceeding >60% in 2018 and >20% in the composite of split-dSSW events. Interestingly, a peak in ozone enhancement is seen at the subtropical jet core (Fig. 3a-b). This suggests the role of the subtropical jet causing ozone enhancement in the upper troposphere over South Asia (discussed later in this section). The anomalous lowering of the tropopause levels along with a strong negative GPH anomaly (indicating a low-pressure area) coincident with large ozone enhancements, provides evidence of stratospheric intrusions occurring during these split-dSSWs (Fig. 3c-d). Past literature reports ozone enhancements in

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the polar region associated with dSSWs (e.g., Baldwin et al., 2021); however, high ozone enhancement in the UTLS over the South Asian region underscores the unique regional impacts of split-dSSWs.

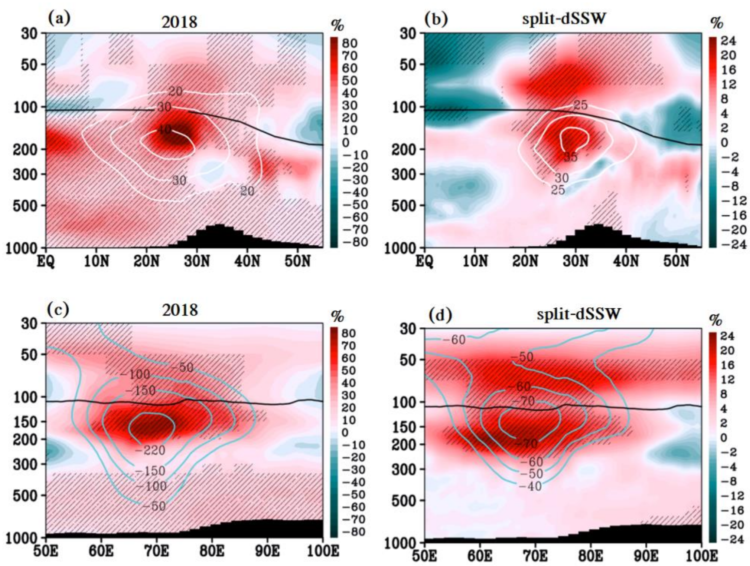

Figure 3. Latitude-pressure section of ozone anomalies averaged over South Asia (65 - 90°E) for ±6 days around the split-dSSW onset for (a) the 2018 event, and (b) the composite of all the split-dSSWs. Figures (c) and (d) are the same as those of (a) and (b) but represent longitude variations of vertical ozone anomalies averaged over South Asia (20-35°N). White contour lines in (a) and (b) represent the mean zonal wind, and sky blue contour lines in (c) and (d) represent the GPH anomaly. Solid black lines in panels a-d represent the tropopause. Hatched lines in panels a-d indicate a region of 95% confidence level based on the student's t-test (Figure created using the COLA/GrADS software).

3.2 Changes in upper tropospheric dynamics and Rossby wave activities associated with the 2018 dSSW event

In this section, we discuss the possible mechanism responsible for the ozone enhancement in the UTLS over South Asia associated with the 2018 dSSW event. The dynamic changes happening in the vortex for 2018 are discussed in the section 2. For the 2018 SSW, the vortex starts deforming 6 days before the SSW-onset and splits on 12 February 2018. After the vortex split, two baby vortices are seen centred over Eurasia and

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North America for 6 days after the onset. Although the vortex over North America remains anchored in that location, the vortex centred over Eurasia gradually drifts westward toward the North Atlantic during this period (see section 2).

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, which are strong in the mid-to-upper stratosphere, extend downward and disrupt horizontal flows in the upper troposphere (200 hPa) (Albers et al., 2016). We analyzed GPH anomalies at 10 hPa and 200 hPa to understand the coupling between the stratosphere and the upper troposphere. Figure 4 illustrates the evolution of GPH anomalies at 10 hPa and 200 hPa, and ozone anomalies at 200 hPa for ±6 days around the SSW onset (Feb 12, 2018). Our analysis shows strong vertical coherence between 10 and 200 hPa levels (see Fig. 4a–e and Fig. 4f–j). Interestingly, the GPH anomalies at 10 hPa and 200 hPa north of 40°N show patterns of wave-1 and wave-2 with lows over America and Eurasia for ±6 days around the onset. The SSW event thus affects the upper tropospheric subtropical jet, which peaks at 200 hPa (Albers et al., 2016).

When the polar vortex splits and the baby vortices move towards the mid-latitudes, they push the mid-latitude synoptic-scale waveguide structure farther equatorward. This displacement channels the eastward propagating synoptic-scale Rossby waves toward the Indian Ocean region, where they eventually break (Albers et al., 2016). The pattern of high and low GPH anomalies in the subtropical region (15-40°N) seen in Fig. 4f-j shows synoptic-scale Rossby waves occurring in the upper troposphere. Rossby wave breaking (RWB) is seen as large filaments of high-PV air extending towards the equator. Such intrusions extend downward from the lower stratosphere into the upper troposphere, causing an enhancement in ozone (e.g. Holton et al., 1995; Waugh and Polvani, 2000; Albers et al., 2016). The 2 PVU

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contour lines and ozone anomaly maps at 200 hPa depicted in Fig. 4k-o show clear indications of ozone intrusions penetrating deep into the tropics, particularly over South Asia. The persistent low and high GPH anomaly over South Asia indicates a deepening trough associated with the eastward propagation of Rossby waves, facilitating enhanced stratospheric intrusions (Figs. 4f-j).

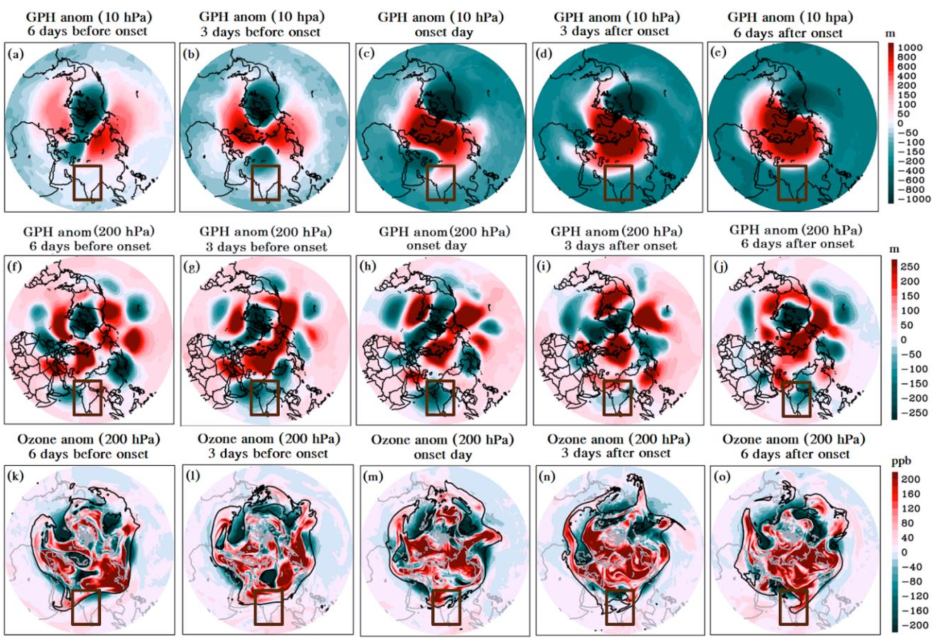

Figure 4. Spatial map of (a-e) GPH anomaly at 10 hPa, (f-j) GPH anomaly at 200 hPa, and (k-o) ozone anomaly at 200 hPa from 6 days before to 6 days after the onset of the 2018 split-dSSW event, shown at 3-day intervals. The black solid line in panels (k-o) represents the 2 PVU isoline. The square box represents the South Asian region considered for the present study (Figure created using the COLA/GrADS software).

RWB facilitates the stripping of stratospheric air (indicated by the 2 PVU contour) along the eastern flank of an anticyclonic centre (positive GPH anomaly, Fig. 4f–j) over the South Asian region, causing large ozone enhancements (Fig. 4k–o). Figures 4k-o clearly show that these episodic intrusions cause large ozone enhancements >150 ppb (>80%) over South Asia. The time evolution of zonal winds depicted in Figure 5a-b also shows that thirty

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days before the onset, the subtropical jet core is positioned over the northern part of the Indian subcontinent but migrates equatorward near the onset day (Fig. 5a). The vertical variation of zonal wind clearly depicts the intensification of westerly wind over the Indian region around 200 hPa close to the onset day, facilitating Rossby wave intrusions (Fig. 5b). The strength of zonal wind is strong within ±6 days around the onset, causing higher ozone intrusions during this period (see Figs. 2a-b and Fig. 5b). Earlier, Albers et al. (2016) have shown that the PV intrusion associated with split SSWs has a significant contribution over the Indian Ocean. Further, we analysed the synoptic wave structure prevailing in the upper troposphere for different SSW cases viz. split-dSSW, split-nSSW, displaced-dSSW, and displaced-nSSW (Figures 5c-f). Figure 5c clearly shows that the persistence of synoptic wave structures is prominent only in the split-dSSW cases. It is not evident in other SSW types (Fig. 5d-f). This persistence of synoptic wave structures enhances RWBs, causing large ozone intrusions during the split-dSSW events.

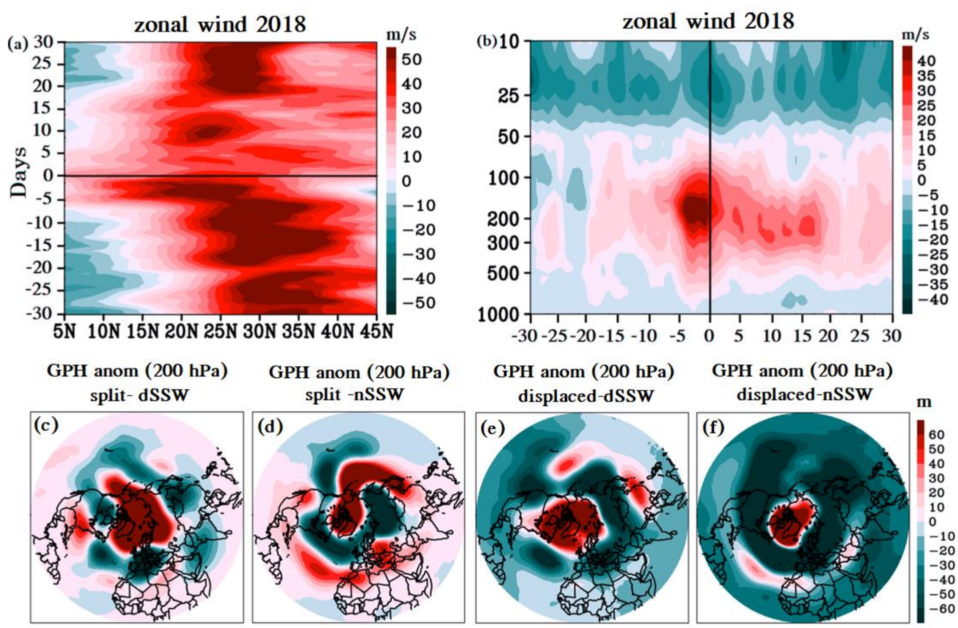

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Figure 5. (a) Latitude-time plot of zonal wind averaged over South Asia (65° to 90° E). (b) Temporal evolution of vertical zonal wind averaged over the South Asian region (65 - 90° E, 10 - 20° N) for ±30 days around the onset of the 2018 dSSW event. The horizontal (in Fig. a) and vertical (in Fig. b) solid lines in the figure represent the onset day. Composite map of GPH anomaly at 200 hPa averaged for ±6 days around the onset during (c) split-dSSW, (d) split-nSSW, (e) displaced-dSSW, and (f) displaced-nSSW cases. (Figure created using the COLA/GrADS software).

3.3 Radiative impact of ozone associated with split-dSSW over the South Asian region

Further, we assessed the radiative impact of ozone enhancements in the UTLS and troposphere over the South Asian region associated with split-dSSW events. Figure 6 presents the computed radiative forcing of ozone averaged over the South Asian region for the 2018 split-dSSW event and the composite of all downward propagating split-dSSWs for ±6 days around the onset. In the troposphere, a positive radiative forcing of 0.3 ± 0.1 $W.m^{-2}$ is observed in the 2018 split-dSSW event, while the composite exhibits a forcing of 0.04 ± 0.03 $W.m^{-2}$ (Fig. 6). In contrast, the UTLS, where the largest percentage increases in ozone are observed, shows a radiative forcing of 0.4 ± 0.2 $W.m^{-2}$ for the 2018 event and 0.08 ± 0.06 $W.m^{-2}$ for the composite. For the total atmosphere, the ozone radiative forcing is 0.5 ± 0.2 $W.m^{-2}$ for the 2018 event and 0.1 ± 0.06 $W.m^{-2}$ for the composite. These results highlight the significant role of split-dSSW events in modulating the radiative balance in the troposphere, particularly in the UTLS over South Asia.

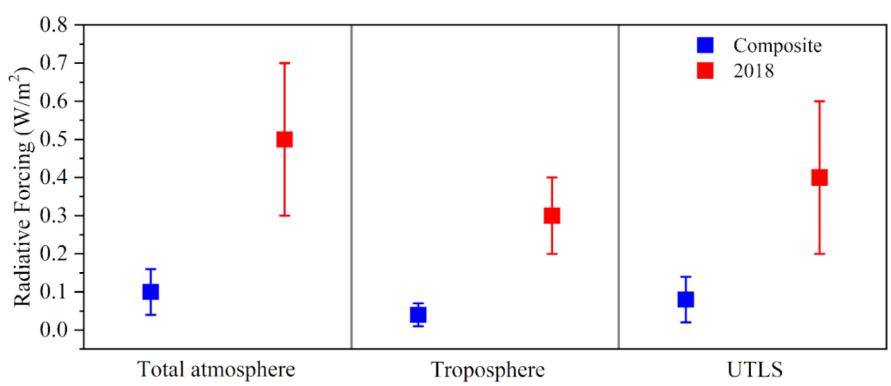

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Figure 6. Average ozone radiative forcing ($W.m^{-2}$) in the total atmosphere, troposphere, and UTLS over the South Asian region calculated for the ±6 days around the onset of the 2018 SSW event and all split dSSW composites (Figure created using Origin, OriginLab, Northampton, MA).

4. Conclusions

The ERA5 reanalysis data shows Rossby wave intensification during split-dSSWs observed for the 1962-2018 time period, which lead to upper tropospheric intrusions over the South Asian region. This leads to substantial ozone enhancements over South Asia, with maximum increases of ~290% and an average of 130% in the UTLS region, and surface-level enhancements reaching up to 43%, with an average increase of 27% (see Fig. 2c-d). The ozone enhancement due to split-dSSWs events is episodic, however, impacts are observed for ~2 months around the SSW onset date.

Near surface ozone enhancements over South Asia also result from factors other than SSW events, including (1) anthropogenic emissions, which increase surface ozone by 20–30 ppb over this region (Gao et al., 2020), and (2) biomass burning that is prominent in the winter and pre-monsoon period causing a surface ozone increase by ~5–10 ppb(Gao et al., 2020). However, ozone enhancements during split-dSSW are substantial over South Asia, leading to an increase in tropospheric ozone radiative forcing of 0.04 ± 0.03 $W.m^{-2}$ and in the UTLS by 0.08 ± 0.06 $W.m^{-2}$ for the composite of all the split-dSSWs, in comparison, changes in anthropogenic emissions over South Asia contribute to a tropospheric ozone radiative impact by 0.02-0.04 $W.m^{-2}$ for 2013–2017 relative to 1995–1999(Wang et al., 2022). These findings underscore the critical role of split-dSSWs in modulating radiative forcing, highlighting their importance as natural drivers of climate variability in addition to anthropogenic influences.

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This large increase in radiative forcing produces positive feedback on the warming climate of this region. The ozone intrusions are warranted to elevate pollution effects and climate warming, impacting people's health, the ecosystem, and the economy. It is projected that the frequency of SSWs will increase in a warming climate, which will further increase stratospheric ozone intrusions and potentially amplify the consequences of positive feedback mechanisms. Hence, we emphasise that climate model should be extended to the stratosphere including polar vortex dynamics for accurate prediction of climate over South Asia. The increase in ozone levels due to biomass burning and anthropogenic activities in South Asia during the winter and pre-monsoon seasons, combined with ozone enhancement from SSW events, will exacerbate ozone pollution across the region. Since SSWs cause large increase in tropospheric ozone over South Asia it should be considered as one of the predictors while prediction of pollution.

Code and data availability

The code and data used in this paper are available from https://zenodo.org/uploads/14604205

Author contributions

Conceptualisation: S.F. Supervision: SF, MH, PH, RF Investigation and methodology: SC, SR and VS. 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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