Influence of Sudden Stratospheric Warming With Elevated Stratopause on the Hydroxyl in the Polar Middle Atmosphere

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Abstract: Based on the specified dynamics simulation of Whole Atmosphere Community Climate Model with ionosphere/thermosphere extension (SD-WACCM-X), the composite response of polar Hydroxyl (OH) layer in the mesosphere and lower thermosphere (MLT) to the Arctic sudden stratospheric warming (SSW) events with elevated stratopause (ES) during 2004-2023 is investigated. A total of ten ES-SSW events are systematically analyzed. Before the onset of ES-SSW events, the OH concentration climatologically peaks at ~7.4 ppbv near 82.4 km. During the stratospheric warming phase, relative to the climatology, the peak height of OH layer undergoes a distinct upward displacement reaching ~85.9 km accompanied by a reduction in the OH concentration to ~2.9 ppbv. This shift is closely linked to an ~11% and ~90.8% reduction in mesospheric temperature and atomic oxygen, respectively, due to enhanced upward residual circulation. During the elevated stratopause phase, the peak height of OH layer experiences a pronounced downward shift to ~80.6 km with a maximum in OH concentration to ~6.8 ppbv. This phase is characterized by ~3.7% and ~137.3% enhancements in mesospheric temperature and atomic oxygen concentrations, respectively, which is driven by intensified downward residual circulation. Further analysis suggests that OH concentration variations are positively correlated to mesospheric temperature anomalies and atomic oxygen redistribution induced by vertical transport, which is attributed to the significant influence of ES-SSW on gravity wave drag (GWs) in the mesosphere.

Key Points

1. The peak height of Arctic OH layer rises during the stratospheric warming phase and descends during the elevated stratopause phase.

2. The change in OH concentration during ES-SSW shows a significant positive correlation with the change in mesospheric atomic oxygen concentration and temperature.

3. The vertical circulation anomalies due to the variations in gravity wave drag during ES-SSW alter the mesospheric atomic oxygen concentration and temperature.

1. Introduction

The middle atmosphere, spanning from ~20 to ~100 km in altitude, plays a vital role in coupling different atmospheric layers and modulating space weather phenomena. Hydroxyl (OH) is a key component in the MLT region, exerting an essential function in atmospheric chemistry and serving as an important indicator for assessing the atmospheric thermal budget. In the mesopause region, OH is primarily produced through the reaction between ozone and atomic hydrogen, forming excited OH* near 87 km. This excited state is deactivated either via photon emission in the Meinel bands (observed as nightglow) or by collisional quenching. The latter process prevails at lower altitudes, where higher atmospheric density facilitates the formation of a ground-state OH layer near 82 km (Damiani et al., 2010).

Despite the relatively well-understood chemical formation of OH, comprehensive observational characterization of its variability remains limited. Nevertheless, measurements from ground-based instruments and satellites, such as Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED)/Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) and Aura Microwave Limb Sounder (MLS), have provided a valuable opportunity to examine OH variability (Damiani et al., 2010; Medvedeva et al., 2019). Shapiro et al. (2012) identified a positive correlation between mesospheric OH variability and 27-day solar irradiance cycles, with stronger responses observed during periods of heightened solar activity. Minschwaner et al. (2011) further demonstrated that ultraviolet actinic flux serves as the primary driver of OH diurnal variability. Li et al. (2005) observed that OH

concentrations peak near local noon, followed by a pronounced decline during nighttime. Additionally, statistical analyses by Gao et al. (2016; 2011; 2010) on the temporal and spatial distributions of OH and O_2 nightglow emissions highlighted significant local time variations, seasonal dependencies, hemispheric asymmetries, and a strong dependence on solar activity. Grygalashvyly et al. (2021) examined the semi-annual variation of the excited OH emission layer at mid-latitudes, attributing the results to the semi-annual oscillation of atomic oxygen and temperature.

Among the most prominent dynamical phenomena in the middle atmosphere are stratospheric sudden warmings (SSW), a large-scale wintertime phenomenon characterized by a rapid stratospheric temperature increase, zonal wind reversal, and substantial disruptions in atmospheric circulation (Manney et al., 2008; Chen et al., 2016; Bolaji et al., 2016; Gu et al., 2021). Studies have shown that SSW events are able to greatly modulate variations of atmospheric chemistry parameters (e.g., Kumar et al., 2024), particularly OH concentration (e.g., Winick et al., 2009). For example, Winick et al. (2009) attributed variations in OH layer to concurrent changes in temperature and atomic oxygen concentration in the upper mesosphere during the winters of 2004 and 2006. Similarly, Gao et al. (2011) documented reductions in OH and O_2 emissions associated with the January 2009 SSW, whereas Medvedeva et al. (2019) identified longitudinal disparities in OH emissions during the January 2013 SSW, which were likely modulated by variations in vertical wind patterns.

Elevated stratopause (ES) events refer to episodes during which the winter polar stratopause initially descends, subsequently becomes indistinct, and eventually reforms at a significantly higher altitude (Manney et al., 2008). Such events arise from strong forcing of the zonal wind and meridional circulation by planetary waves (Torre et al., 2012). In certain cases, ES events occur in connection with SSW events. According to Chandran et al. (2013), ES-SSW events are distinguished by a prolonged reversal of the stratospheric jet, enhanced gravity wave forcing, and intensified mean meridional circulation, relative to winters when SSWs occur without an accompanying ES. Compared with typical SSWs, ES-SSW events are particularly noteworthy because their enhanced downward transport significantly modifies the concentration of minor species in the MLT region (Chandran et al. 2013), such as OH. Given these persistent

anomalies, focusing on ES-SSW events provides a physically meaningful basis for composite analysis. Nevertheless, the investigations into the impacts of ES-SSWs on polar mesospheric chemistry remain limited, owing to the sparse sampling of satellite observations, as exemplified by the TIMED/SABER satellite, which follows a precession orbit and requires several days to achieve full local time coverage. As a result, the influences of ES-SSWs on polar mesospheric OH concentration remain insufficiently understood.

Numerical simulations offer an alternative approach for investigating variations in the OH layer under dynamically complex conditions. The Specified Dynamics Whole Atmosphere Community Climate Model with ionosphere/thermosphere eXtension (SD-WACCM-X) offers a physically consistent representation of mesospheric chemistry and dynamics, allowing for a more continuous and spatially resolved analysis of OH layer responses to ES-SSW events. Previous studies have successfully employed SD-WACCM-X to investigate atmospheric dynamics procession (e.g., Zhang et al., 2025; Orsolini et al., 2022), which demonstrates that the SD-WACCM-X simulations provide a valuable opportunity for capturing OH variations during ES-SSWs in the absence of comprehensive observational coverage.

This study aims to explore the responses of OH concentrations to ES-SSW events using the SD-WACCM-X simulations for the period 2004–2023. Section 2 provides a brief introduction to the datasets, the definition of ES-SSW, and the analysis methods used in this study. Section 3 presents the results, focusing on the peak values and peak height of OH concentrations, along with their temporal evolution in response to ES-SSW events. Section 4 discusses the roles of mesospheric temperature and atomic oxygen in changes of OH layer and the underlying mechanisms of OH concentration variations during ES-SSW events. Finally, Section 5 summarizes the key findings and their implications for mesospheric dynamics during ES-SSWs.

2. Data and Method

2.1 SD-WACCM-X

In this study, the Whole Atmosphere Community Climate Model with ionosphere/thermosphere eXtension (WACCM-X; Liu et al., 2018), an extended version of WACCM embedded within the Community Earth System Model version

2.2.0 (CESM2.2.0) framework developed by the National Center for Atmospheric Research (NCAR) (Gettelman et al., 2019; Danabasoglu et al., 2020), is employed to consider the characteristics of OH layer in the polar mesosphere. WACCM-X is an atmospheric model that simulates atmospheric processes from the surface (~0 km) up to the ionosphere/thermosphere, extending to ~700 km depending on solar activity, which provides a detailed representation of dynamic, chemical, and radiative processes in the stratosphere, mesosphere, and thermosphere. The WACCM-X used in this study is based on the Community Atmosphere Model-6 (CAM-6) physics and the three-dimensional chemical transport Model for Ozone and Related chemical Tracers (MOZART) chemistry (Gettelman et al., 2019). Specifically, WACCM-X incorporates nonorographic gravity wave drag parameterization, solar and geomagnetic forcing, and comprehensive gas and aerosol chemistry (Lee et al., 2021). The middle atmosphere scheme with the D-region chemistry (MAD) is used.

The specified dynamics (SD) configuration of WACCM-X is nudged by Modern-Era Retrospective Analysis for Research and Applications Version 2 (MERRA-2) data (e.g., Molod et al., 2015; Teng et al., 2021) to ensure consistency with observed meteorological conditions. Both chemical and dynamical parameters in SD-WACCM-X are relaxed toward linearly time-interpolated 3-hourly MERRA-2 reanalysis data. The relaxation coefficient is uniform below 50 km, decreases progressively above this altitude, and becomes zero above 60 km (Brakebusch et al., 2013). Consequently, the model is unconstrained by reanalysis above 60 km. The vertical resolution of the model ranges from ~1.1 km to ~3.5 km, with a vertical density of two points per scale height below ~50 km and increasing to four points per scale height above ~50 km (Salinas et al., 2023). Enhanced vertical resolution in the troposphere and stratosphere enables improved representation of key physical processes (Sassi and Liu, 2014). The horizontal resolution is typically set to 1.9° × 2.5° (latitude×longitude). It should be noted that CESM currently provides emission input files for the SD-WACCM-X only up to the year 2015 (https://svn-ccsm-inputdata.cgd.ucar.edu/trunk/inputdata/atm/cam/chem/emis/CMIP6_emissions_1750_2015_2deg). Accordingly, prescribed emissions from CESM input were used prior to 2015, while for subsequent years, the emission fields were set to missing values.

Sensitivity tests conducted for representative pre-2015 years (2009, 2010, and 2013) demonstrate that this treatment has a negligible impact on the simulated mesospheric OH response to SSW (Figure S1), thereby ensuring the robustness of our results.

SD-WACCM-X simulations have been demonstrated to effectively reproduce observed atmospheric responses to ES-SSW events (e.g., Limpasuvan et al., 2016; Lee et al., 2021; Zhang et al., 2021; Zhang et al., 2025; Orsolini et al., 2022). These successes highlight the model's robustness in capturing the dynamical and chemical processes, particularly within the MLT. In this study, model outputs spanning the period from 2004 to 2023 are utilized, with data from December through March extracted for each year, corresponding to the climatological window during which ES-SSW events predominantly occur. To comprehensively elucidate the response of the OH layer on ES-SSW, key variables such as OH, atomic oxygen, temperature, zonal wind, and so on are output. From these outputs, daily means of relevant dynamical and chemical parameters are derived to facilitate temporal-spatial evaluation of ES-SSW responses.

OH emission measurements from the SABER instrument onboard the TIMED satellite (https://saber.gats-inc.com/data.php) are employed to validate, in a qualitative and time-evolution sense, the SD-WACCM-X OH response to ES-SSWs. TIMED satellite was launched on 7 December 2001 and began SABER observations in early 2002. SABER provides global limb observations of OH airglow in the mesosphere and lower thermosphere, with latitude coverage alternating every 60 days between 53° and 83° in the opposite hemisphere (Gao et al., 2011, 2016).

2.2 Definition of SSW and ES Events

According to the criteria established by McInturff (1978), a major SSW is identified when, at 10 hPa or below, the latitudinal mean temperature must increase poleward of 60° latitude, accompanied by a reversal in the zonal-mean zonal winds (i.e., a transition from mean westerly to mean easterly winds poleward of 60° latitude). However, the definition of major SSWs has evolved over the decades and varies across studies, ranging from Northern Annular Mode index values (Baldwin and Dunkerton, 2001) to classifications emphasizing vortex morphology (Charlton and Polvani, 2007), or disturbances centered near the stratopause (~50 km) rather than the canonical 10 hPa level (Tweedy et al., 2013; Stray et al., 2015; Limpasuvan et al., 2016). Given these

188   inconsistencies, we define the SSW onset as the day when the temperature difference

189   between 60°N and 90°N at 10 hPa becomes positive, a diagnostic also adopted in Ma

190   et al. (2020).

191   An elevated stratopause (ES) event is commonly described as a disruption in

192   which the winter polar stratopause initially descends, then becomes indistinct, and

193   eventually reforms at a much higher altitude than usual (Chandran et al., 2013). Despite

194   broad recognition of the phenomenon, a community-wide, internally consistent

195   definition has not yet been established. Consequently, the diagnostic criteria for

196   identifying ES events remain ambiguous, with different studies applying different

197   thresholds. For example, Torre et al. (2012) required the newly reformed stratopause to

198   be displaced by more than 15 km relative to its original altitude, whereas Tweedy et al.

199   (2013) and Harvey et al. (2025) used a threshold of a polar-cap stratopause elevation

200   exceeding 10 km. Yamazaki et al. (2025) defined an elevated stratopause (ES) event as

201   a stratopause detected above 80 km during December–February. In this study, any

202   upward displacement of the stratopause relative to its pre-warming altitude is regarded

203   as an ES event. Applying this criterion, ten ES-SSW events are identified over 2004-

204   2023. Notably, the 2010 and 2018 SSWs with weak stratopause elevations has been

205   treated as ES-SSWs in several studies (e.g., Harvey et al., 2025; Schneider et al., 2025;

206   Harada et al., 2019). Guided by stratopause morphology similarity, the 2021 and 2023

207   warmings are also classified as ES-SSW in our composite analysis, and both display

208   weak stratopause elevations. The stratopause height is defined as the altitude of

209   maximum temperature within the 20-100 km vertical domain (Chandran et al., 2013;

210   Torre et al., 2012). Nearly all identified ES events in our study are associated with major

211   SSWs, with the only exception being the 2012 case, which followed a minor warming

212   but still exhibited a pronounced elevated stratopause.

213   To develop a statistically robust understanding of the OH layer characteristics

214   during ES-SSW, a composite analysis is conducted by temporally aligning each event

215   such that Day 0 corresponds to the SSW onset. This alignment allows for a systematic

216   examination of the temporal evolution and spatial structure of OH layer during ES-

217   SSW events, providing insights into their common features and variability. In this study,

218   the response of OH layer to ES-SSW events is categorized into three distinct stages

219 based on the temporal evolution of temperature: Day -15 to Day 0 is considered the
220 normal stage; Day 0 to Day 5 correspond to the stratosphere warming stage; Day 6 to
221 Day 60 correspond to the elevated stratopause stage. Previous studies (e.g., Pickett et
222 al., 2006) demonstrated that the OH layer is markedly more stable in pressure
223 coordinates than in geometric altitude. Meanwhile, as noted by Grygalashvyly et al.
224 (2014), pressure coordinates are more natural for discussing chemical, physical, and
225 radiative processes, as these processes are largely free from the shrinking of middle
226 atmospheric (SMA) effects on pressure isosurfaces. Guided by these findings, we use
227 log-pressure height ($Z = -H \times \ln(P/P_s)$) (Andrews et al., 1987) as the vertical
228 coordinate for diagnosing the OH responses in SD-WACCM-X, while also providing
229 an approximate geometric-height scale for reference.

230 **3. Results**

231   The SSW event that commenced in January 2009 started as the strongest, most
232 prolonged on record, and isolated, which has been made a focal point for numerous
233 studies (e.g., Manney et al., 2009; Yue et al., 2010; Limpasuvan et al., 2011). These
234 unique characteristics render it particularly suitable for employing the response of
235 mesospheric chemical composition to SSW events. The response of OH concentrations
236 to ES-SSW events is exemplified by the 2009 SSW case, as illustrated in Figure 1. From
237 top to bottom, Figure 1 represents (a) zonal-mean temperature at 10 hPa (~32 km) and
238 80° N, (b) zonal-mean zonal wind at 60° N, (c) temporal variations in OH
239 concentrations at latitudes 75~90° N from SD-WACCM-X, and (d) in OH emission at
240 75-77° N from SABER during January 6, 2009, to March 22, 2009. In Figure 1a, the
241 meridional temperature difference between 60°N and 90°N ($T[80^\circ - 90^\circ] - T[60^\circ - 70^\circ]$
242 K) is denoted by the pink solid line, and the stratopause height is indicated by the green
243 dashed line.

244   Prior to January 10, 2009, the temperature peak is located at ~61 km, with a
245 maximum ~272 K. Subsequently, the peak height drops sharply, reaching ~37.7 km by
246 January 21, 2009. Between January 21 and January 26, 2009, the minimum temperature
247 of ~183.5 K occurs at altitudes above 75 km, while the meridional temperature
248 difference between 60°N and 90°N at 10 hPa transitions to positive values. After
249 January 26, 2009, a new stratopause forms at ~86 km, with an upward displacement of

250 ~25 km compared to the stratopause altitude before January 10, 2009, and subsequently

251 descends to its climatological altitude in conjunction with the recovery of the polar

252 vortex (Limpasuvan et al., 2012). This elevated stratopause event is accompanied by a

253 pronounced downwelling over the winter pole, extending from 45 to 95 km. The

254 enhanced subsidence facilitates the downward transport of MLT air into the stratosphere,

255 thereby modulating the thermal structure and influencing polar chemical processes.

256 Figure 1b depicts the zonal mean zonal wind changes at 60° N. Before the SSW

257 onset, the zonal-mean zonal wind is eastward with a speed of ~85 m/s. During the

258 stratosphere warming phase, the zonal mean flow reverses to westward winds (below 0

259 m/s) in the polar winter stratosphere, confirming the occurrence of a major SSW event.

260 Subsequently, the zonal-mean zonal wind structure during the elevated stratopause

261 exhibits a pattern similar to that of the zonal-mean temperature, with eastward winds

262 prevailing in the mesosphere region at ~91.8 m/s. As the polar vortex recovers, the

263 eastward wind gradually descends to its climatological distribution, mirroring the

264 temperature evolution in the stratosphere and mesosphere.

265 Figure 1c illustrates the temporal variation of OH concentration during the 2009

266 events. Prior to the onset, the OH concentrations remain ~7.2 ppbv with a peak height

267 ~82.4 km, consistent with previous studies (e.g., Pickett et al., 2006). However, between

268 January 21 and January 26, 2009, a pronounced depletion in OH concentrations is

269 observed reaching a minimum of ~2.4 ppbv, while the peak altitude shifts upward to

270 ~86 km. Following January 26, 2009, the peak altitude of OH layer descends to ~78.8

271 km, whereas in geometric coordinates the descent is even larger, reaching ~74 km (not

272 shown). Meanwhile, the peak OH concentrations exhibits a gradual increase, eventually

273 surpassing the pre-SSW levels and reaching values of ~10.6 ppbv. The anomaly

274 persisted and did not return to its climatological level until March 9, 2009.

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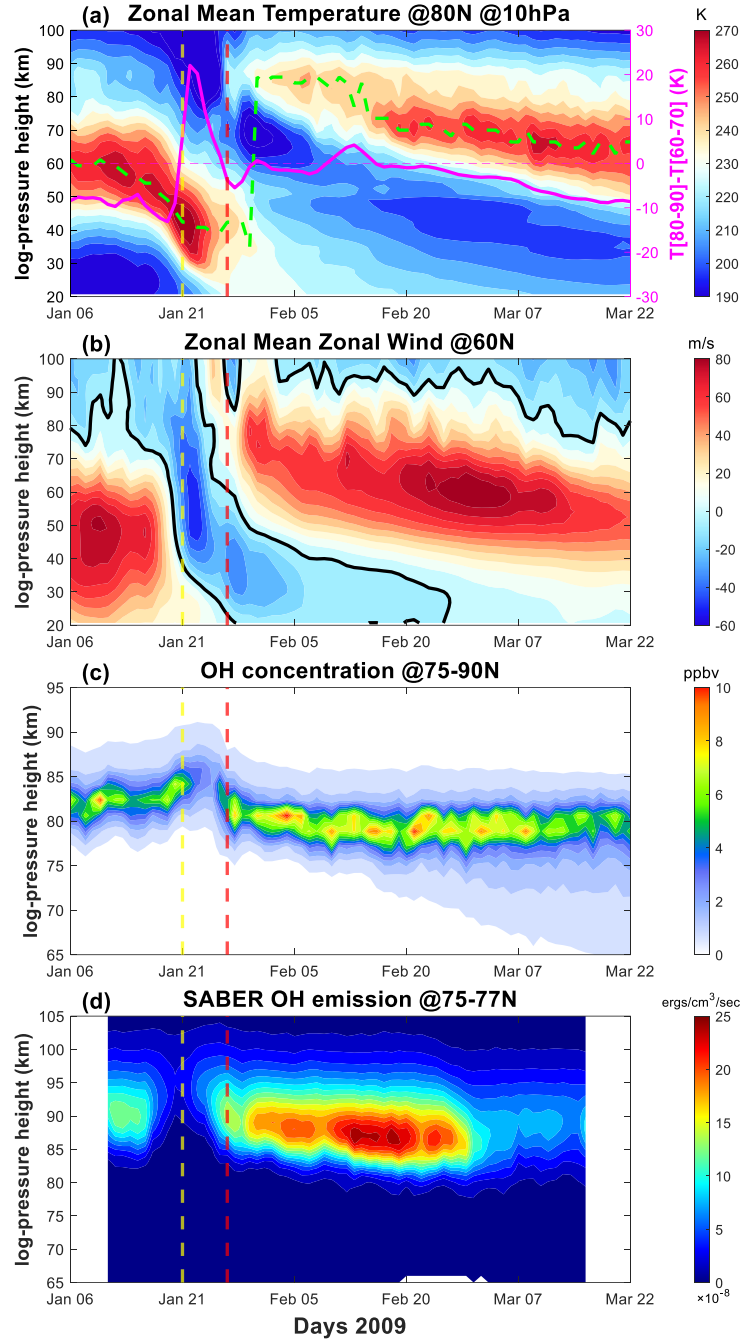
Figure 1. Time versus log-pressure height cross-section of SD-WACCM-X zonal-mean (a) temperature at 80°N, (b) zonal wind at 60°N, (c) OH concentration, and SABER (d) OH emission, during January 06-March 22, 2009. The solid pink line represents the meridional temperature difference between 60°N and 90°N $(T[80°-90°]-T[60°-70°])$, and the dashed green line is the stratopause height. The black solid contour in (b) denotes the zero-wind line. Vertical dashed yellow and red lines are the onset of the stratosphere warming stage and elevated stratopause stage, respectively.

The OH emission retrieved by SABER (Figure 1d) exhibits a temporal evolution broadly consistent with the SD-WACCM-X OH concentration. This correspondence is expected because their shared production mechanism via the $O_3 + H \xrightarrow{k_1} OH^* + O_2$, which forms vibrationally excited OH ~90 km (e.g., Grygalashvyly et al., 2014) and collisional quenching at lower altitudes produces ground-state OH near 82 km (e.g., Damiani et al., 2010). Although the two quantities are not physically identical, they are dynamically linked through the same mesospheric circulation and chemistry. For example, Gao et al., (2011) and Winick et al., (2009) demonstrated that variation in OH emission during the 2009 SSW was modulated by changes in atomic oxygen and mesospheric temperature, and Damiani et al., (2010) showed that the displacement of OH layer was coupled to variations in odd-oxygen (Ox) and mesospheric temperature. Accordingly, we restrict the comparison to qualitative temporal evolution rather than absolute magnitudes to evaluate general consistency between model simulations and satellite observations during ES-SSW events.

Notably, to ensure consistency with the SD-WACCM-X simulations, the SABER OH emissions are also mapped onto log-pressure height, which yields a peak altitude that is slightly higher (~90 km) than those reported in earlier studies (~87km) based on geometric height. This offset is consistent with Grygalashvyly et al. (2014), who compared the OH layer in geometric and log-pressure coordinates and showed that the apparent differences arise because geometric altitudes are affected by SMA, whereas pressure coordinates follow approximately fixed mass surfaces and are largely free from this effect. As a result, the OH peak expressed in log-pressure height tends to appear somewhat higher than when it is expressed in geometric height.

To further validate the observed response of OH concentrations to ES-SSW events, SSW occurrences from 2004 to 2023 are analyzed, aiming to identify common characteristics across multiple events. Based on the criteria outlined in the methodology section, a total of ten ES-SSW events are identified (Manney et al., 2008; Maute et al., 2014; Kodera et al., 2008; Manney et al., 2009; Harada et al., 2010; Jones et al., 2018; Chandran et al., 2013; Goncharenko et al., 2013; De Wit et al., 2014; Karpechko et al., 2018; Rao et al., 2019; Okui et al., 2021; Lu et al., 2021; Qin et al., 2024; Zhang et al., 2025), with their occurrence years and onset dates listed in Table 1. The left column of

the table indicates the years in which ES-SSW events occurred, while the right column

specifies the first day of each event.

Table 1 Onset Day (Day 1 corresponds to January 1 of the Year) of the ES-SSW Events During Boreal Winter of 2004~2023

Years	Onset day	Years	Onset day
2003/2004	Jan 2	2012/2013	Jan 5
2005/2006	Jan 9	2017/2018	Feb 14
2008/2009	Jan 21	2018/2019	Dec 25
2009/2010	Jan 20	2020/2021	Jan 2
2011/2012	Jan 11	2022/2023	Feb 13

Note. ES-SSW, sudden stratosphere warming with elevated stratopause.

Figure 2 presents the temporal variations in OH concentrations for each selected year, centered on the onset day of the ES-SSW event and spanning from 15 days prior to 60 days after the onset. As shown, during the stratosphere warming phase, the peak height of OH concentration undergoes an evident upward displacement to ~86 km, whereas the OH concentrations peak experiences a sharp decline with the minimum of ~1-2 ppbv. Conversely, during the elevated stratopause phase, as the peak height of the OH layer significantly decreases, the peak OH concentration increases rapidly to ~7~9 ppbv at ~78 km, and its maximum is larger than that in the normal stage. The results reveal a consistent pattern similar to that shown in Figure 1c, demonstrating that the influence of ES-SSW events on OH concentration is a common feature across all identified occurrences. In certain years, i.e., 2010, 2018, and 2023, the influence of ES-SSW events on the structure of OH concentration appears weaker, potentially due to variations in event intensity or background atmospheric conditions. Furthermore, although SSW events vary in their duration and intensity, they tend to occur on an annual basis. Some events occur in close succession, as observed in 2008, whereas others appear as isolated episodes, such as the one in 2009. During ES-SSW events, preceding or subsequent SSW-related mesospheric warming and elevated stratopause phases remain active, introducing additional modulation to the observed OH variations.
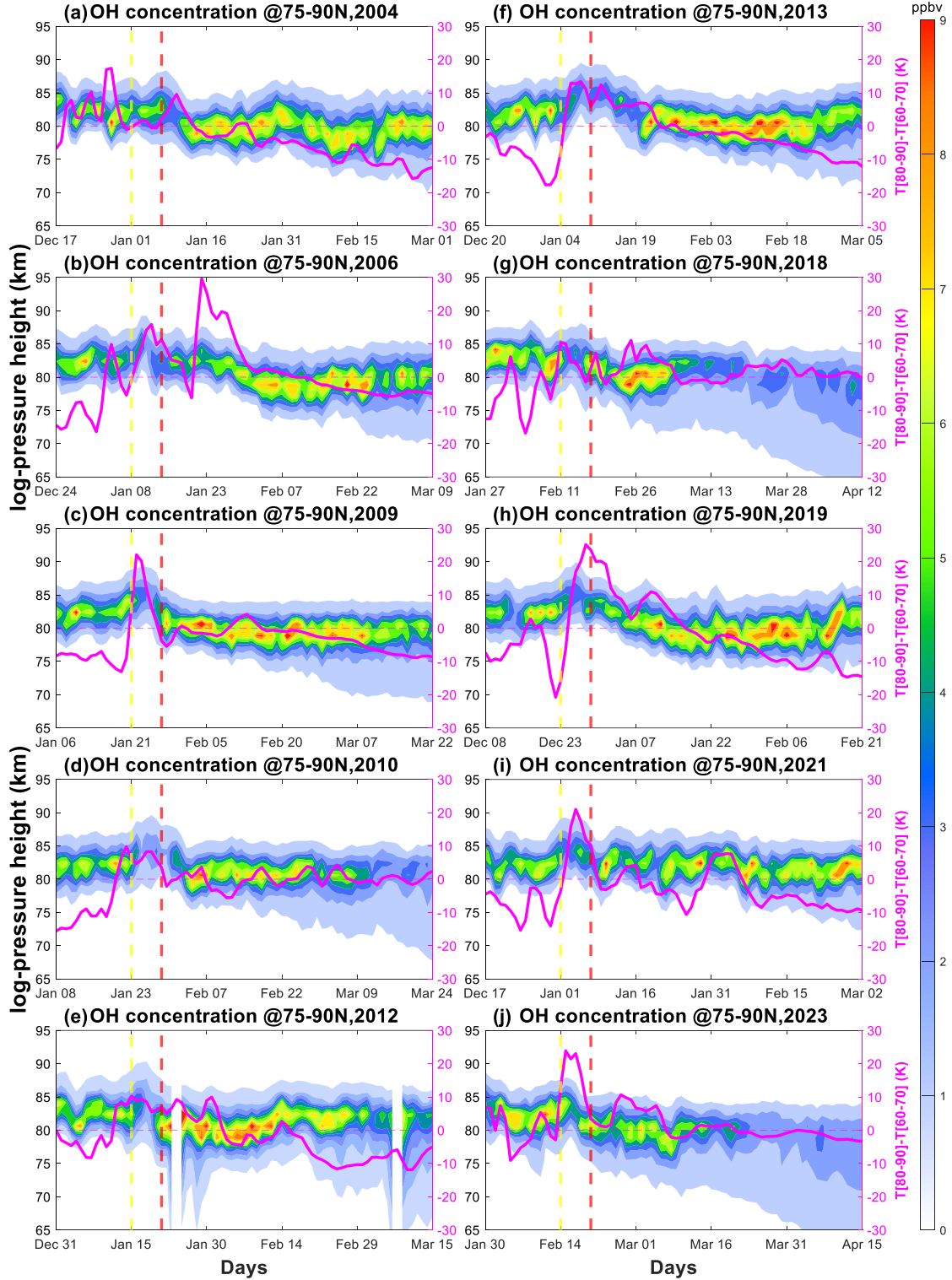
Figure 2. Time versus log-pressure height cross-sections of OH concentrations in ES-SSW events during 2004-2023 are captured in panels a-j. The solid pink line represents the meridional temperature difference between 60°N and 90°N $(T[80° - 90°] - T[60° - 70°])$. Vertical dashed yellow and red lines are the onset of the stratosphere warming stage and elevated stratopause stage, respectively.

Notably, OH concentrations in some SSW events such as February 2010 and 2023, also show a significant downward extension in altitude after March, suggesting that seasonal variability may play a noticeable role in the temporal evolution of OH concentrations. As illustrated in Figure 3, OH concentrations display a clear seasonal pattern, with higher values in the summer hemisphere (May to August in the Northern Hemisphere; November to February in the Southern Hemisphere) and lower values in the winter hemisphere. The peak of OH concentration in the summer hemisphere reaches ~12.5 ppbv, whereas the minimum OH concentration in the winter hemisphere is ~5 ppbv. Additionally, the seasonal cycle also modulates the vertical structure of the OH layer: in summer, OH extends broadly from ~75 km to ~87 km, whereas in winter it is confined near 82.5 km. This summer broadening helps explain the downward extension of OH observed during late-winter sudden stratospheric warming events, such as those in 2010 and 2023.
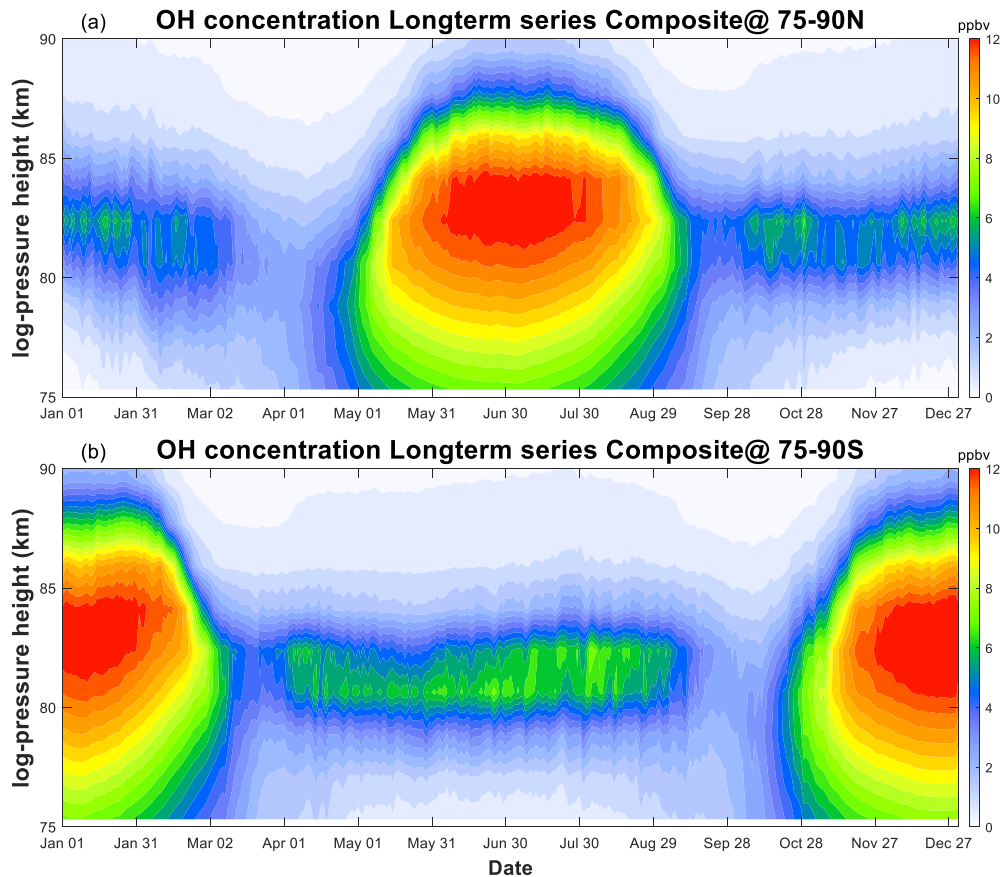
Figure 3. Temporal evolution of OH concentration in the polar region, with the Northern Hemisphere in the top panel and the Southern Hemisphere in the bottom panel.

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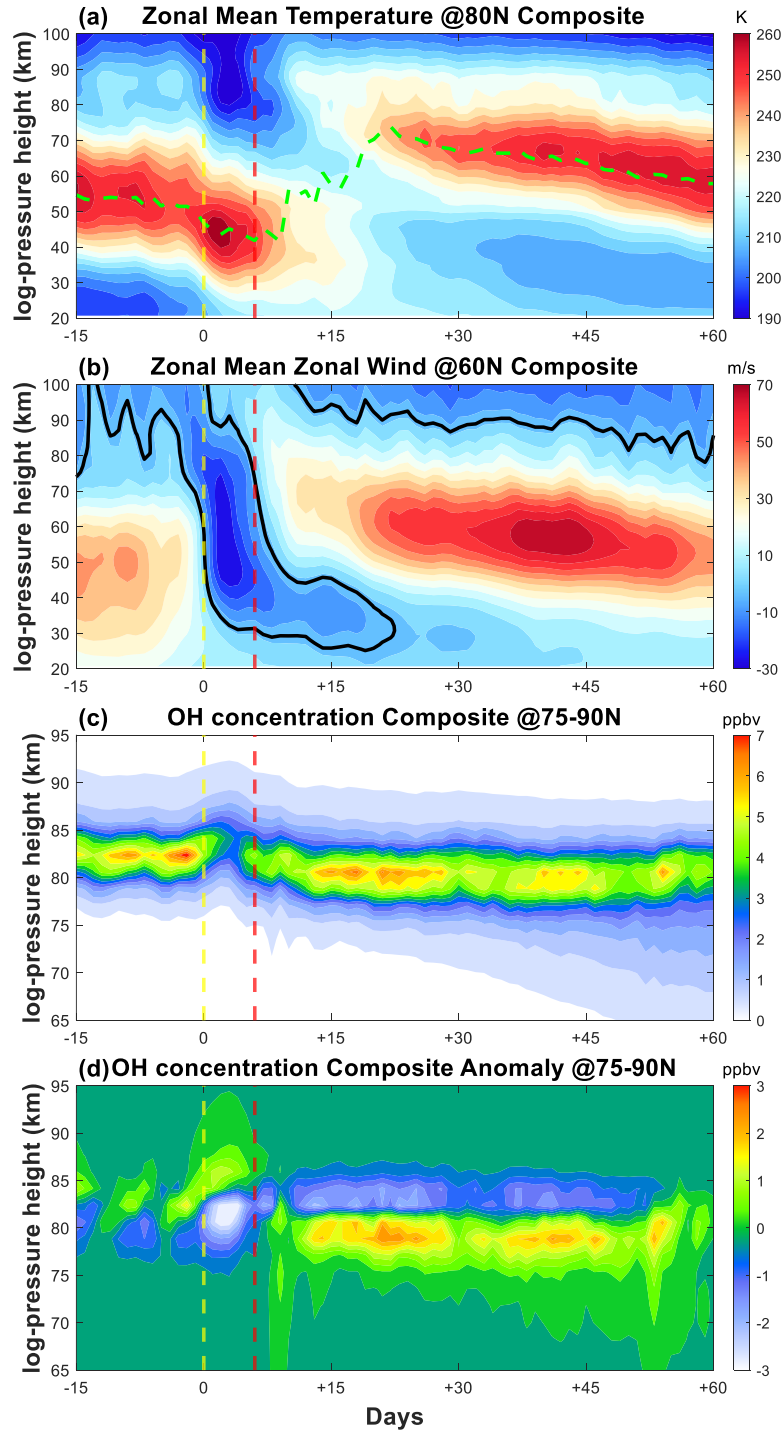


Figure 4. Time versus log-pressure height cross-section of composite zonal mean (a) temperature, (b) zonal wind, (c) OH concentration, and (d) OH concentration anomaly. On the abscissa, time is relative to the ES-SSW onset (Day 0). Vertical dashed yellow and red lines are the onset of the stratosphere warming stage and elevated stratopause stage, respectively. The dashed green line is the stratopause height, while the black solid contour in (b) denotes the zero-wind line.

369   Figure 4 illustrates the composite evolution of zonal mean temperature, zonal

370   mean zonal wind, OH concentration, and OH concentration anomaly (Anomaly derived

371   from original OH concentration minus background average) as functions of altitude and

372   time. The background average of OH concentration is derived from the 20-year average

373   from 2004 to 2023. As depicted in Figures 4a and 4b, significant variations extend

374   across nearly the entire altitude range. In the mesosphere, the zonal mean zonal wind

375   exhibits a rapid weakening of the eastward component around Day -8, then switches to

376   westward after Day 0 with a minimum wind speed of around -27 m/s. Around Day 6,

377   the eastward wind begins to intensify again, reaching a peak velocity exceeding 70 m/s

378   near Day 40. Corresponding thermal changes accompany zonal wind reversal. At the

379   onset of the ES-SSW event, the stratosphere undergoes rapid warming, leading to a

380   sharp descent of the stratopause altitudes. As shown, until Day 3, the stratopause

381   altitude reaches its lowest altitude of ~43.5 km, coinciding with the peak westward wind.

382   The maximum temperature and wind speed are over 260 K and -27 m/s, respectively.

383   After Day 6, as the eastward wind begins to strengthen, a newly formed stratopause

384   emerges near 80 km.

385   The composite variabilities of OH concentrations and OH concentrations anomaly

386   associated with ES-SSW events are examined, as shown in Figures 4c and 4d. Here, the

387   composite results represent the mean structure aligning the temporal series of individual

388   ES-SSW events. Figure 4c illustrates the temporal evolution of OH concentration. Prior

389   to the onset of SSW, the peak of OH concentration exhibits a value of ~7.4 ppbv, with

390   a peak height near 82.4 km. During the stratosphere warming phase, the peak of OH

391   concentration decreases to 2.9 ppbv, while in the elevated stratopause phase, it increases

392   to ~6.8 ppbv. In addition, the peak height of OH concentration rises by ~3.5 km reaching

393   ~85.9 km during the warming phase, before descending by ~2 km to ~80.6 km during

394   the elevated stratopause phase. This temporal evolution is consistent with that in 2009

395   shown in Figure 1. Winick et al. (2009) proposed that the anomalous characteristics of

396   the OH layer may be associated with changes in the atomic oxygen concentration and

397   temperature in the mesosphere, which is driven by the modification of polar circulation

398   induced by SSW events.

399   Similarly, the temporal evolutions are depicted in Figure 4d, which represents the

variability of OH concentration anomaly. As shown, during the stratosphere warming phase, the peak height of OH concentration anomaly occurs at ~85.9 km with a maximum of ~1.3 ppbv. These situations in the elevated stratopause phase are significantly different. Compared to the stratosphere warming phase, the peak of OH concentration anomaly doubles, reaching a maximum of ~2.6 ppbv, while its peak height significantly decreases to ~78 km. These phenomena again demonstrate the consistency between OH concentration enhancements/depletions and peak height descent/ascent, a relationship previously documented in Winick et al. (2009).

4. Discussion

4.1 Temporal variation

During the ES-SSW period, changes in atmospheric circulation lead to a strong descent/ascent motion of air at high latitudes. This dynamic change leads to subsequent increased/decreased atomic oxygen penetrating the mesopause. Within the mesospheric region, OH* is primarily produced through the reaction between ozone (O_3) and atomic hydrogen (H) (Marsh et al., 2006), as described by this equation:

$$O_3 + H \xrightarrow{k_1} OH^* + O_2 \tag{1}$$

According to Equation 1, the reaction rate coefficient k_1 increases with temperature, thereby enhancing the efficiency of OH* production. Ozone is formed through the reaction of atomic oxygen and molecular oxygen, as expressed in the equation:

$$O + O_2 + M \rightarrow O_3 + M \tag{2}$$

Notably, this process, $O + O_3 \rightarrow O_2 + O_2$, also contributes to ozone destruction alongside OH* production. However, below ~95 km, ozone loss due to its reaction with atomic hydrogen significantly exceeds that caused by atomic oxygen by several orders of magnitude (Xu et al., 2010). In addition, ozone may be treated as being in a steady state under nighttime conditions (i.e., polar winter), implying that the production of OH is proportional to atomic oxygen (Gao et al., 2011). This relationship indicates that the temporal evolution of OH concentration is strongly coupled with variations in atomic oxygen abundance and temperature in the mesopause.

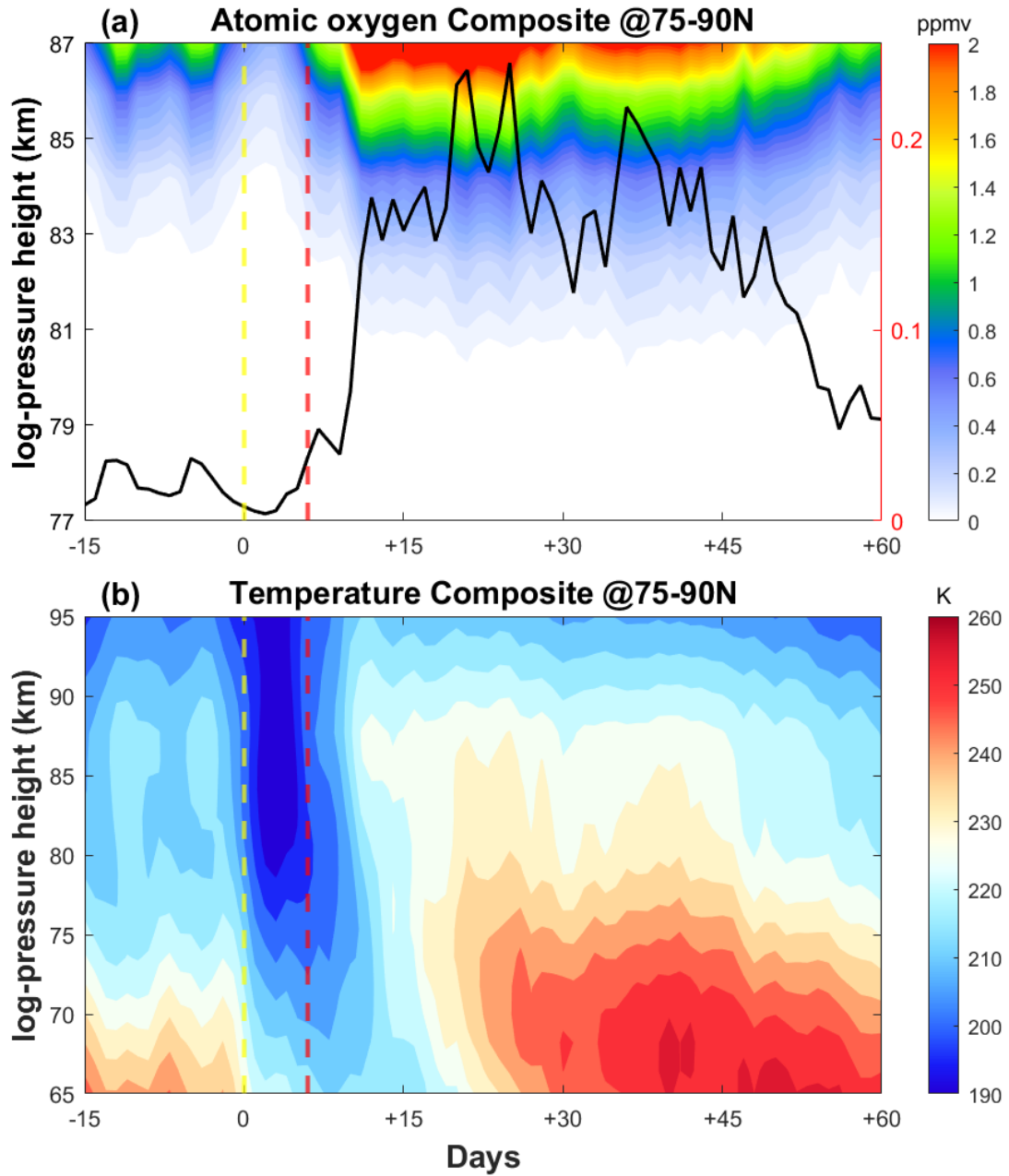



Figure 5. Same as Figure 4, but for (a) atomic oxygen (in units of 10^3) and (b) temperature. The solid black line in (a) represents the temporal evolution of atomic oxygen at 82 km.

Figure 5 presents the composite variations in atomic oxygen (Figure 5a) and temperature (Figure 5b) over high latitudes (75°-90°N). In Figure 5a, the solid black line illustrates the temporal evolution of atomic oxygen concentration at 82 km. The atomic oxygen concentration increases with altitude in the mesopause. Since the atomic oxygen concentration is relatively low at this level, the line plot is included to clearly

highlight its variation throughout the event. The temporal variations of OH (Figure 4c), atomic oxygen (Figure 5a), and temperature (Figure 5b) in the mesopause region exhibit a nearly synchronous evolution. During the stratosphere warming phase, the atomic oxygen concentration experiences a significant decline, with a minimum value of ~5 ppmv at ~82 km, as indicated by the solid black line. Then, the atomic oxygen peak concentration remarkably increases, reaching a peak value of ~240 ppmv, which is substantially higher than the normal stage. Figure 5b displays the composite temperature variation, which closely corresponds to the evolution of atomic oxygen. The temperature minimum reaches its minimum (~190 K) during the stratosphere warming stage and peaks at ~260 K in the elevated stratopause stage.

Figure 6 shows the temporal evolution of the residual circulation

$$(v* = \bar{v} - \rho^{-1}(\rho \frac{\overline{v'\theta'}}{\bar{\theta}_z})_z ; \quad w* = \bar{w} + (a\cos\varphi)^{-1}(\cos\varphi \frac{\overline{v'\theta'}}{\bar{\theta}_z})_\varphi)$$ (Andrews et al., 1987), where

$w*$ and $v*$ denote the vertical and meridional components of the residual circulation, respectively. During the stratosphere warming phase, a strong downwelling (negative $w*$) develops in the stratosphere with a value of ~-1 cm/s, denoting enhanced adiabatic heating. Meanwhile, an anomalous upwelling (positive $w*$) emerges above ~70 km in the mesosphere, peaking at ~1.4 cm/s at ~77 km, suggesting a weakening or even reversal of the climatological downward branch of the residual circulation over the winter polar cap (e.g., Gao et al., 2011; Limpasuvan et al., 2016). These vertical circulation anomalies directly modulate the mesospheric thermal structure: the upwelling leads to adiabatic cooling, consistent with the temperature decrease observed in Figure 4a, while the subsequent recovery of strong downwelling in the elevated stratopause phase (up to -2.5 cm/s) contributes to mesospheric warming. Additionally, the upwelling during the stratosphere warming phase lifts air with lower atomic oxygen concentrations into the mesopause, resulting in a significant depletion of atomic oxygen (Figure 5a). In contrast, enhanced downwelling during the elevated stratosphere phase brings oxygen-rich air downward, increasing atomic oxygen concentration and thereby promoting OH production. During the stratosphere warming

stage, an anomalous equatorward flow also emerges near the mesopause (Figure 6b), indicating a temporal reversal of the climatological poleward residual circulation. As the stratopause elevates, this meridional circulation returns to a poleward pattern. The reversal and recovery of meridional circulation could promote inter-latitudinal transport, potentially contributing to OH variations at lower latitudes, such as the equatorial region.

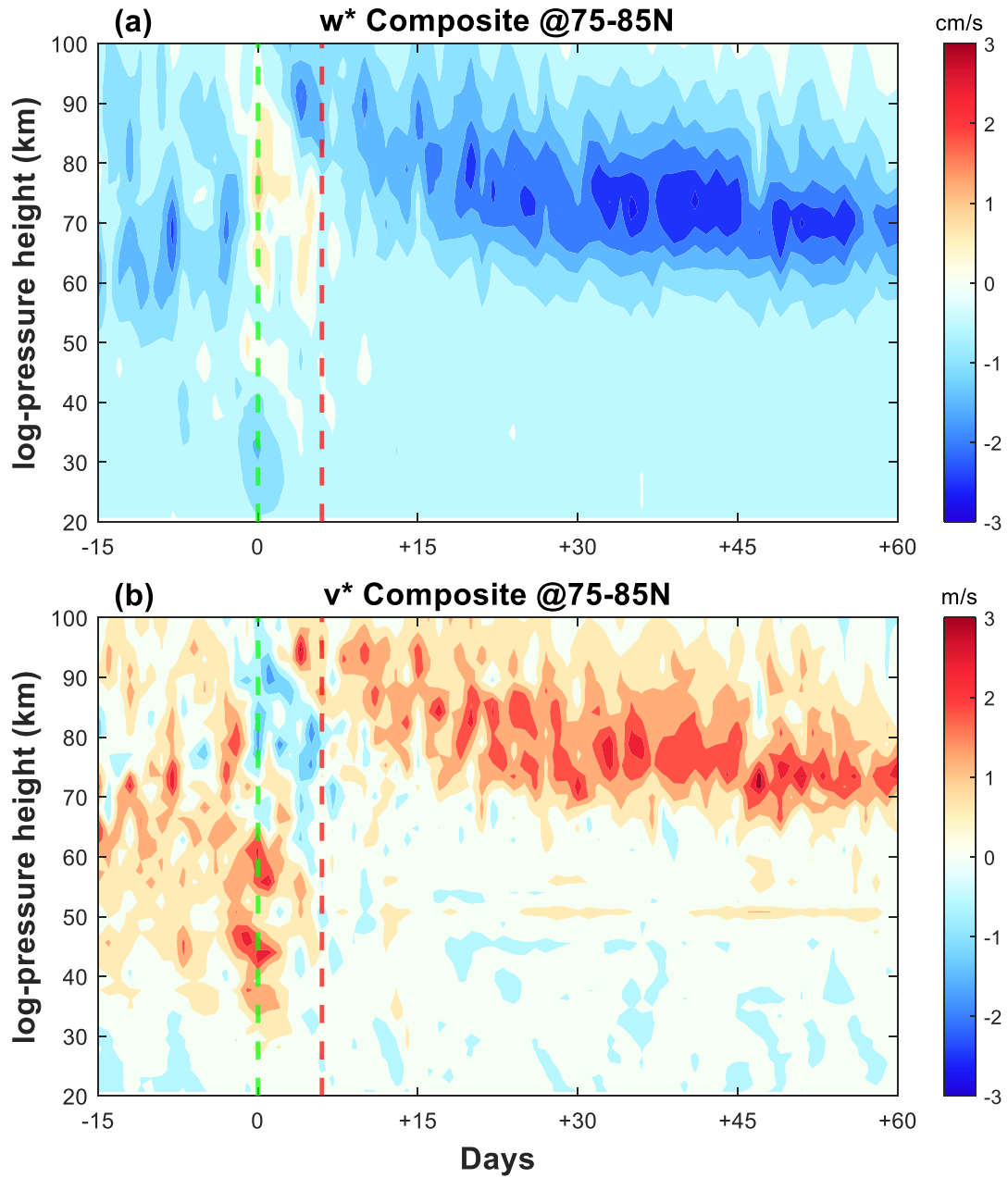



Figure 6. Same as Figure 4, but for (a) $w*$ **and (b)** $v*$ **.**

4.2 Spatial distribution

475   As shown in the preceding figures, the most prominent variations in OH

476 concentration associated with ES-SSW event occur primarily within the first 30 days

477 following the SSW onset, during which OH, atomic oxygen, temperature, and $w*$

478 exhibit substantial perturbations. To further investigate the meridional structure of these

479 responses, the relative variations of these parameters are analyzed across three distinct

480 stages: Stage 1 (Day -10 to Day 0), Stage 2 (Day 0 to Day 5), and Stage 3 (Day 6 to

481 Day 26). Figures 7-9 present the corresponding spatial distributions of each parameter

482 during these stages. The relative variation is derived as follows:

483
$$\text{Reletive variation} = \frac{X_{(i)} - \overline{X}}{\overline{X}} \times 100\% \tag{3}$$

484 in which $X_{(i)}$ represents the variable (OH, atomic oxygen, and temperature) for each

485 ES-SSW event, and $\overline{X}$ stands for the background average obtained by averaging the

486 same calendar dates over 2004–2023.

487   Figure 7 illustrates the ES-SSW-related parameters as functions of latitude and

488 altitude in Stage 1. The spatial structure of OH concentration in the polar mesosphere

489 is depicted in Figure 7a. A local maximum appears near 83 km with an enhancement of

490 10% relative to the background average, whereas below 80 km, OH concentration

491 exhibits a marked decrease, reaching a minimum of -35.7%. Figure 7b presents the

492 situation of the atomic oxygen, which displays notable differences from OH. For

493 instance, the enhancement shifts downward, with a peak of 25.4% located at ~75 km,

494 while the minimum atomic oxygen concentration reaches -46.3% at ~81 km in the polar

495 region. The corresponding temperature distribution (Figure 7c) reveals a warming in

496 the polar stratosphere and cooling in the polar mesosphere with the magnitudes of

497 approximately 3% and -3%, respectively. Figure 7d shows the $w*$ anomaly, which

498 increases slightly to ~0.4 cm/s between ~65 and 83 km at high latitude. Simultaneously,

499 the polar $v*$ anomaly, as indicated by the white arrows, shifts equatorward in the

500 mesosphere. In climatology, the circulation pattern is characterized by a pole-to-pole

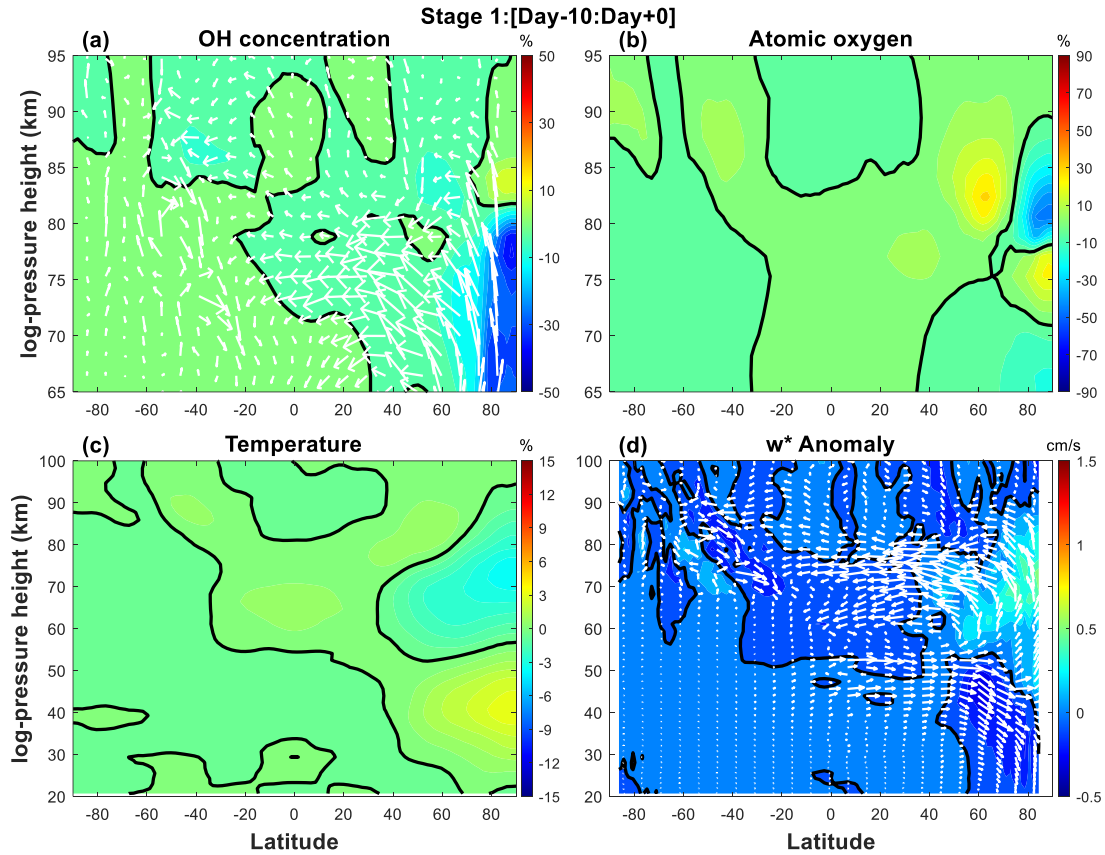
501 circulation from the summer hemisphere toward the winter hemisphere. Notably, slight

502 variations in these parameters can be detected even prior to the onset of the ES-SSW

503 event. This early-stage response may be attributed to the fact that ES-SSW perturbances

504 tend to emerge in the mesosphere several days before becoming evident in the

505 stratosphere (Gao et al., 2011), as also reflected by the temperature variations in Figure

506 4a.

508 **Figure 7. Latitude versus log-pressure height cross-sections of composite relative**

509 **variation in (a) OH, (b) atomic oxygen, and (c) temperature, and composite**

510 **anomaly in (d)** $w*$ **during Day -10 to Day 0 (Stage 1). The zero contour is denoted**

511 **by a bold solid black line, and white arrows in (a) and (d) represent the residual**

512 **circulation anomaly.**

513   Figure 8 illustrates the latitude-altitude structure of various elements in Stage 2,

514 which exhibit significant responses to ES-SSW events. Compared to Stage 1, the OH

515 concentration (Figure 8a) in the polar region displays a marked enhancement with a

516 maximum increase of ~75.9% relative to the background average occurring at ~85.9

517 km. Conversely, the minimum OH concentration reaches a pronounced decrease with

518 an amplitude of -63.5% at ~78.8 km. The variations in atomic oxygen (in Figure 8b)

519 are even more pronounced concerning Stage 2 over the latitudinal range of 75°-90°N,

520 with a minimum reduction to -90.8% and a maximum increase to ~48.3% with respect

521 to the background average. The temperature distribution in Figure 8c also reveals a

noticeable response to the ES-SSW events, with a positive anomaly of 13.9% centered near 32 km and a negative anomaly of -11% around 84 km in the polar region. Figure 8d shows the spatial structure of $w*$ anomaly in Stage 2. Compared to Stage 1, the magnitude of $w*$ anomaly in the polar mesosphere increases significantly, exceeding 1.78 cm/s between ~64.6 km and ~78.8 km. These vertical structures are consistent with the findings of Dyrland et al. (2010) that associated OH airglow temperature perturbations with neutral atmospheric dynamics during the anomalous 2003-2004 winter. Their study also noted altitude-dependent evolution of the polar vortex.

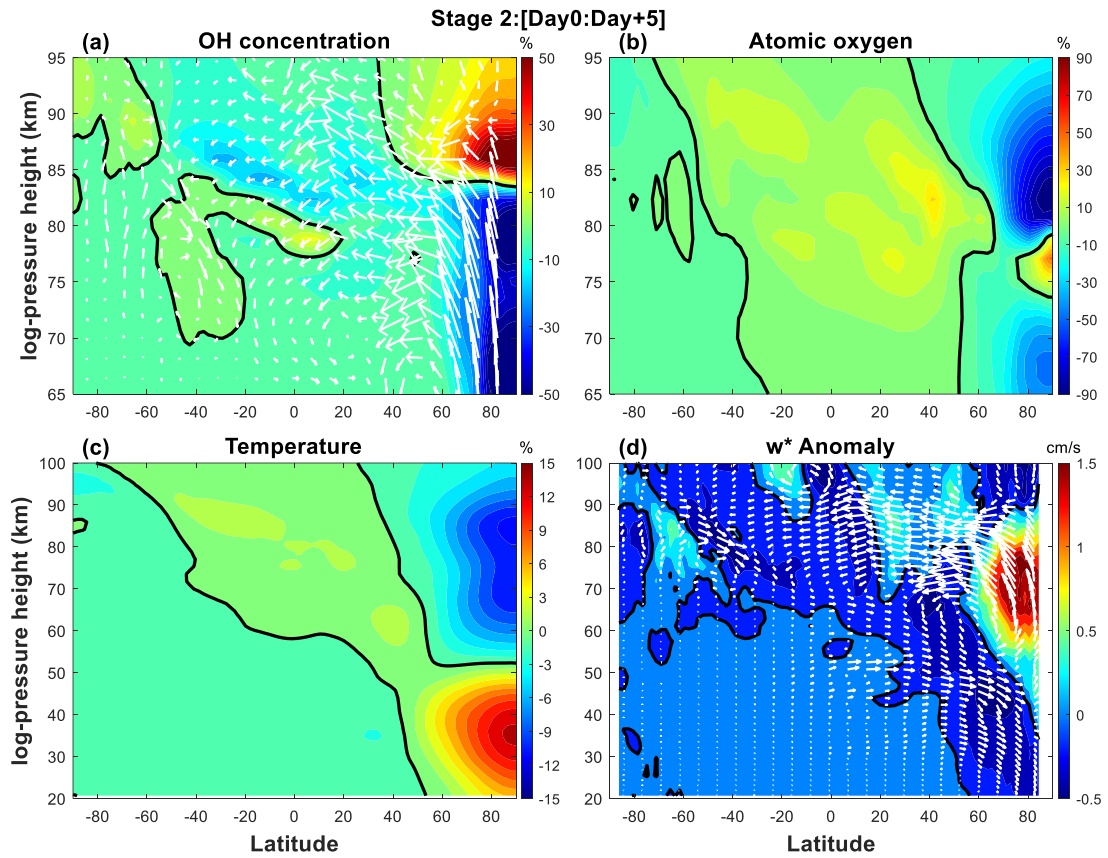



Figure 8. Same as Figure 7, but for Day 0 to Day 5 (Stage 2).

In the present work, the positive $w*$ anomaly at high northern latitudes is clearly observed, as indicated by the white arrows in Figure 8d. This upward motion turns equatorward in the upper mesosphere, forming a distinct pole-to-equator branch of the mesospheric circulation. Simultaneously, below ~50 km, the poleward circulation exhibits a downward motion at the middle and high latitudes. The high-latitude downward circulation below ~50 km and upward circulation above ~50 km result in corresponding stratospheric warming and mesospheric cooling during the SSW period

539 (as also shown in Figure 4a), respectively. Moreover, the upward transport of oxygen-
540 poor air to higher latitudes, facilitated by positive $w*$ anomaly, results in a significant
541 reduction in atomic oxygen concentrations. As a consequence, the peak height of OH
542 layer shifts upward, accompanied by a notable decrease in its peak concentration.

543 In addition, notable variations in OH concentration are also evident in the
544 equatorial mesosphere region during Stage 2. Relative to the background average, a
545 secondary OH peak appears at ~78.8 km with an amplitude of ~13.6%, while a local
546 minimum of approximately -16.9% occurs at a higher altitude of ~82.4 km.
547 Concurrently, both atomic oxygen and temperature exhibit modest enhancements in the
548 equatorial mesosphere, with amplitudes of ~16% and ~1.5%, respectively. The
549 observed temperature response in the equatorial region is consistent with that reported
550 by Gu et al. (2021) in their analysis of the 2009 major SSW event (see their Figure 2e),
551 which documented the middle atmospheric circulation response to SSW. However, the
552 underlying dynamical and chemical mechanisms responsible for these compositional
553 changes in the equatorial region remain unclear and warrant further investigation.

554 Figure 9 depicts the spatial distribution of multiple parameters during Stage 3,
555 corresponding to Day 6 through Day 26 following the onset of the SSW. Compared to
556 the preceding stages, the polar OH concentration structure undergoes a distinct reversal
557 in vertical pattern. Specifically, the OH peak descends to ~78.8 km and intensifies to
558 ~59.5%, while the minimum shifts to a higher altitude (~84.2 km) and weakens to
559 negative 37.7%. As shown in Figure 9b, the atomic oxygen concentration exhibits a
560 pronounced enhancement, with its peak occurring at ~82.4 km and exceeding 137.3%
561 compared to the climatological average at high latitudes. The temperature field (Figure
562 9c) displays a bifurcated structure, with a dominant warming centered around ~28 km
563 with an amplitude of ~7.9% and a secondary weaker warming near the MLT region
564 with a lower amplitude of ~3.7%. The vertical structure of the residual circulation
565 anomaly (Figure 9d) also changes noticeably. The peak of $w*$ anomaly shifts
566 downward to ~57 km with a reduced amplitude (~0.51 cm/s) in the polar region
567 compared to earlier stages. As the mesospheric wind begins to eastward, the residual
568 circulation anomaly transitions to a pole-to-pole pattern from the summer to winter
569 hemisphere, and then descends vertically above ~70 km in the polar region. The

570 negative $w*$ facilitates the downward transport of oxygen-rich air into the polar

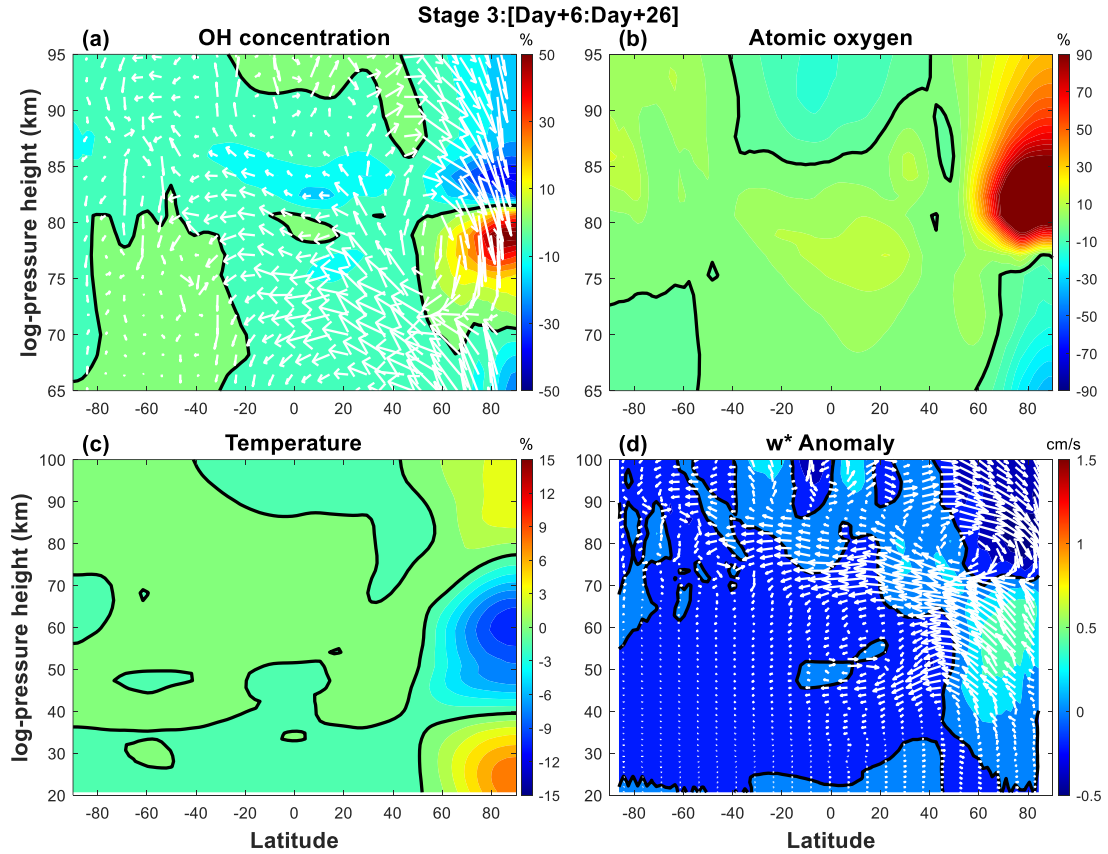
571 mesopause region and warming around 80 km. Consequently, the OH concentration

572 peak increases in magnitude while its altitude decreases. In the equatorial region, the

573 OH distribution in Stage 3 resembles that in Stage 2 but with reduced amplitude. The

574 sustained presence of these anomalies may be attributed to continued enhancements in

575 both atomic oxygen abundance and temperature in the equatorial region.

576

577 **Figure 9. Same as Figure 7, but for Day 6 to Day 26 (Stage 3).**

578 **4.3 Potential mechanism**

579   During ES-SSW events, the reversal/deceleration of the stratospheric winter

580 eastward wind due to planetary wave breaking allows more eastward-propagating GWs

581 to penetrate into higher altitudes, enhancing upward and equatorward motion in the

582 mesosphere. This altered circulation results in mesospheric cooling (Limpasuvan et al.,

583 2012; Lukianova et al., 2015; Gu et al., 2021). The mesospheric OH layer variability

584 may be dominantly controlled by changes in GWs during the ES-SSW events.

585   Figure 10 presents the temporal evolution of zonal wind tendency due to total

586 gravity wave drag (GWD) and zonal wind tendency due to orographic gravity wave

587 drag over the latitudes of 40°-80°N. Under the quiet conditions, westward GWs drag in

the mesosphere sustain the polar circulation downwelling. As planetary wave activity intensifies, the weakening/reversal of the eastward jet starts in the mesosphere and progresses to the stratosphere (Yang et al., 2024; Liu and Roble, 2005), with mesospheric changes preceding the stratospheric response by several days in Figure 4b (Coy et al., 2011; Kurihara et al., 2010; Azeem et al., 2005). Alteration of the wave transmission conditions enables eastward-propagating GWs to penetrate the mesosphere resulting in enhanced eastward GWD that modulates the mesospheric circulation (Figure 6) and induces a slight response in the polar OH layer (Figure 7a).

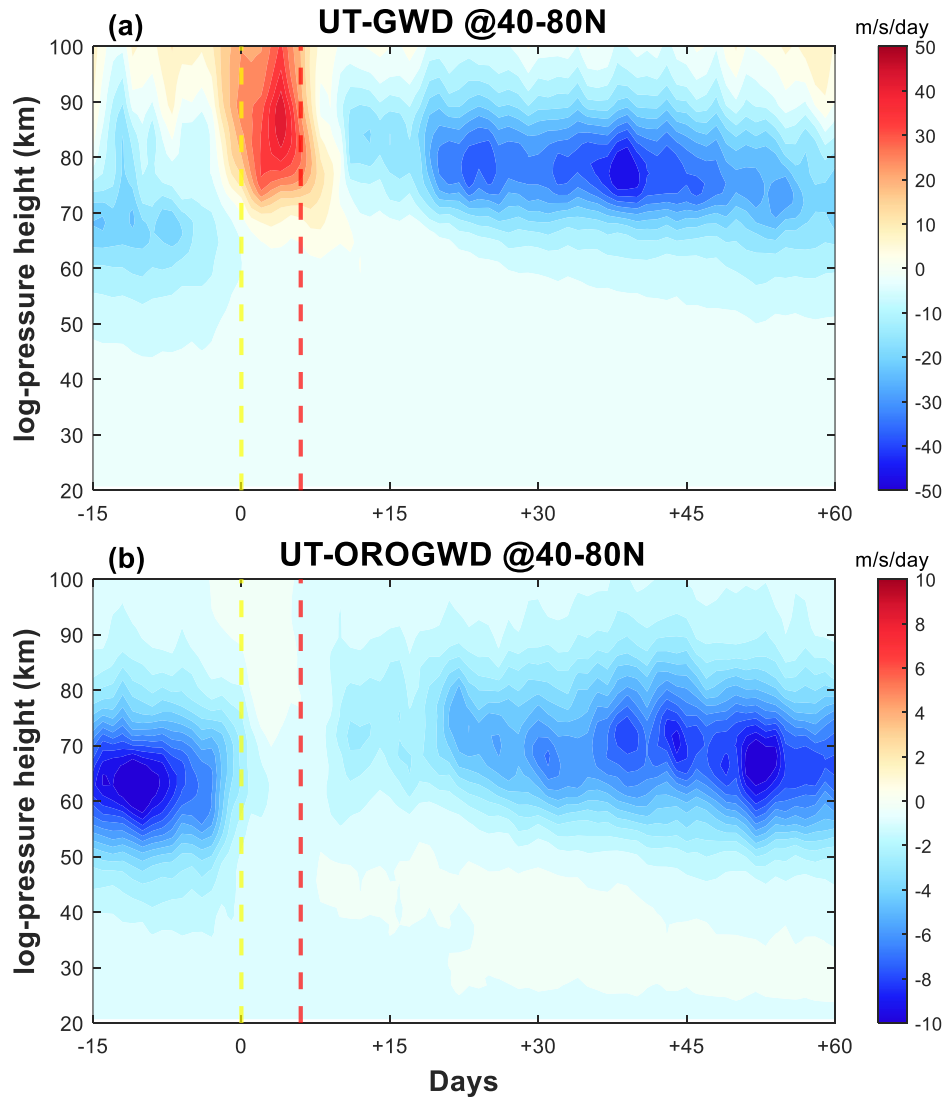



Figure 10. Time versus log-pressure height cross-section of SD-WACCM-X composite zonal mean (a) zonal wind tendency due to total gravity wave drag (UT-GWD) and (b) zonal wind tendency due to orographic gravity wave drag (UT-OROGWD).

Following the stratosphere warming phase, a reversal of the zonal-mean wind from eastward to westward in the polar stratosphere and mesosphere is evident in Figure 4b. The stratospheric westward wind filters out westward phase speed components of GWs and facilitates the upward propagation of eastward-propagating GWs into the mesosphere, which results in anomalously eastward GWs exerting strong positive zonal wind tendency as shown in Figure 10a, peaking in the mesosphere around Day 4 with its maximum of 46.2 m/s/day. Enhanced eastward GWs forcing induces equatorward flow in the mesopause region and enhances the upward residual circulation extending from the stratosphere to the mesosphere at northern high latitudes, which can be seen vertical component and meridional component of residual circulation in Figures 6 and 8d. This upward residual circulation transports oxygen-poor air upward, given that atomic oxygen concentration increases with altitude (seen in Figure 5a), leading to a reduction in atomic oxygen abundance in the upper atmosphere. As a result, the peak OH concentration exhibits a substantial decrease, while its corresponding peak altitude undergoes a pronounced upward shift.

During the elevated stratopause phase, the thermal relaxation rate in the upper mesosphere and lower stratosphere is approximately two to three times that of the lower stratosphere (Wehrbein and Leovy, 1982; Chandran et al., 2014), promoting the rapid recovery of the polar eastward zonal wind (Hitchman et al., 1989). Consistent with the initial response to the disturbance, the recovery of eastward zonal winds first appears in the mesosphere and then progressively propagates downward into the stratosphere. The GWs with westward phase speeds are again able to propagate into the mesosphere and subsequently dissipate, inducing a pronounced negative zonal wind tendency with a peak value reaching ~-45 m/s/day exceeding the climatological average. Enhanced GW breaking at higher latitudes within the MLT region drives an intensified poleward and downward branch of the residual circulation, leading to the reformation of elevated stratopause at high latitudes, as shown in Figure 4a (Chandran et al., 2014). Compared to quiet conditions, where such circulation is largely confined below 50 km, the poleward and downward flow extends above 70 km in the elevated stratopause phase. This pronounced downward motion promotes the descent of dry mesospheric air (Orsolini et al., 2010), which causes an exceptionally strong vertical transport of atomic

oxygen into the mesopause region. Consequently, the OH concentration returns toward the climatological level, with the peak of OH layer occurring at a lower altitude.

Generally, GWs can be categorized into orographic and non-orographic components (Gilli et al., 2020; Richter et al., 2010). As shown in Figure 10b, the momentum deposition induced by orographic GWs is primarily confined to the altitude range of 40~80 km with values ranging from -10.5 to 0.5 m/s/day. During the stratosphere warming phase, orographic GWs are largely filtered and inhibited from upward propagation, leading to a notable reduction of their drag contribution (Liu et al., 2019). In the elevated stratopause phase, the zonal wind tendency associated with orographic GWD shows a different vertical structure compared to that associated with total GWD (see Figure 10a), particularly exhibiting a less significant enhancement at higher altitudes. It is demonstrated that orographically generated GWs play a secondary role in the overall momentum budget relative to non-orographic GWs. Non-orographic GWs, which are parameterized mainly from frontogenesis and convection sources (Holt et al., 2017), dominate the momentum deposition in the mesospheric polar region during ES-SSW events. The contribution from convective GWs is comparatively negligible, while frontogenetical generated GWs emerge as the primary source of GWs drag (Limpasuvan et al., 2012; Limpasuvan et al., 2016). Given the dominant role of frontogenesis GWs in driving mesospheric dynamics during ES-SSW events, it is suggested that the variability observed in the OH layer is predominantly modulated by gravity wave activity associated with frontogenesis.

5   Conclusions

In this paper, the responses of the peak concentration and peak height changes in the polar OH layer to ES-SSW events in the mesosphere are investigated based on SD-WACCM-X simulations. By compositing ten ES-SSW events from 2004 to 2023, distinct variations in OH layer structure associated with different phases of these events are revealed. The results demonstrate that the anomalous behaviors of the OH concentrations are closely synchronous with changes in mesospheric temperature, atomic oxygen concentrations, and the vertical component of the residual circulation in the MLT region. GWs play a pivotal role by altering the vertical motion of circulation

in the MLT region, which modulates the zonal wind and temperature fields. The enhanced downward/upward motion driven by GWs leads to mesospheric warming/cooling and an increase/decrease in atomic oxygen, which facilitates an increase/decrease in OH concentration.

The impact of ES-SSW extends well from the polar to the equator, strongly altering the zonal-mean zonal wind, temperature, and atomic oxygen distribution. However, the response of the mesopause OH layer in the equatorial region to ES-SSW is unclear. Our study enhances the understanding of OH layer responses to stratospheric perturbations and provides new insights into vertical coupling processes in the middle and upper atmosphere. Future research should focus on quantifying the relative contributions of these factors and assessing their implications for long-term atmospheric dynamics and chemistry.

Data availability.
WACCM-X is an open-source software with source code publicly available at https://escomp.github.io/CESM/release-cesm2/downloading_cesm.html#downloading-the-code-and-scripts. The atmospheric forcing data, which are regridded from the MERRA-2 data set and used to run WACCM-X, can be downloaded at https://rda.ucar.edu/datasets/ds313.3/?hash=access. The SABER data employed in this study are available at https://saber.gats-inc.com/data.php. For access to the SD-WACCM-X simulation data, please contact the corresponding authors: Sheng-Yang Gu (gushengyang@whu.edu.cn) or Yusong Qin (qinyusong@whu.edu.cn).

Author contribution. Conceptualization and investigation were conducted by JH. Formal analysis and visualization were performed by JH with guidance and supervision from SYG, YSQ, and YFW. Data curation for SD-WACCM-X was carried out by YXL. All authors contributed to the discussion of results and the revision of the manuscript.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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