

Dear Editor,

We would like to say many thanks the Referee for taking the time to review our manuscript and valuable recommendations. We have tried to follow the referee remarks and have utilized all of them.

In the following, we address the comments point by point and show how the manuscript has been changed accordingly to the comments. Below comments by Referees are in red, our responses are in black, the changes in the manuscript are in blue and brackets.

### **Response to the comments on the paper by Referee 1**

1. I fail to see why the authors felt it necessary to use data from two models, plus satellite measurements, plus reanalysis data, for this study. Can any compelling arguments be put forward for drawing on such a large number of sources of varying types?

2. If the authors nevertheless wish to include all these sources in the paper, they should compare them where possible and discuss the differences in the results based on the different data sources.

The datasets used differ in structure, temporal resolution, altitude ranges, and other characteristics, and each serves a distinct purpose in addressing the objectives of this study. In the revised manuscript, Section 2 has been reorganized (see lines 159–179) to clarify the role of each dataset:

«To investigate the relationship between the NOCE boundary and the transition zone of  $O_x$ - $HO_x$  diurnal oscillations at polar latitudes, model data with sub-daily temporal resolution are required. The specific year is not critical, as our focus is on these short time scales. To this end, we analyzed a one-year simulation of the NCAR Whole Atmosphere Community Climate Model with thermosphere and ionosphere extension (WACCM-X) (Liu et al., 2018) for the year 2000 as a representative example, using hourly output. We performed the simulation using WACCM-X (version 2.1) nudged to Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2, e.g., Molod et al., 2015) data.

To determine the NOCE boundary height, we used version 2.0 of the SABER data product (Level2A) for the simultaneously measured profiles of pressure (p), temperature (T),  $O_3$  (at  $9.6\ \mu m$ ), and the total volume emission rate of  $OH^*$  transitions ( $9 \rightarrow 7$  and  $8 \rightarrow 6$ ) at  $2.0\ \mu m$  at geometrical altitudes. Following Kulikov et al. (2023b), we considered only nighttime data corresponding to solar zenith angles  $\chi > 95^\circ$ .

As noted above, winter processes at mesopause altitudes must be considered within the context of the concurrent dynamics of the upper stratosphere and, in some cases, the lower mesosphere. Here, we examine the evolution of the NOCE boundary height alongside the zonal-mean wind at  $60^\circ N$  and 10 hPa ( $U_{60^\circ N, 10 hPa}$ ) and the 10-hPa temperature difference between the

polar cap and 60°N ( $\Delta T_{90-60^\circ N, 10hPa}$ ). The latter is defined as the difference between the zonal-mean temperature averaged over 80°–90°N and that averaged over 60°–70°N. Both variables were derived from MERRA-2 reanalysis data for the corresponding years. It is worth noting that the use of MERRA-2 data to identify SSWs is a well-established practice.»

In Discussion, we have added the text clarifying the role of CMAM dataset (lines 510-525):

«The 2009 event (Figure 6) demonstrates the most pronounced variations in  $z_{eq}^d$ , particularly during the major SSW that triggered the  $z_{eq}^d$  pulse. A number of studies (e.g., Gao et al., 2012; Medvedeva et al., 2019; Hu et al., 2025) indicate strong perturbations in chemical constituents (specifically, atomic oxygen) and airglow emissions in the mesopause region during both this specific SSW and other major SSWs accompanied by an elevated stratopause. To identify common patterns in the evolution of the NOCE boundary and these characteristics, we examined multiple datasets from various 3D models for 2009 to find one that reproduced the same pulse-like variation in the NOCE boundary during this event. First, we found that the WACCM-X data were unsuitable for this purpose. A likely reason is that the WACCM-X temperature data show a remarkably weaker cooling of the upper mesosphere during this SSW compared to the SABER data, as can be seen by comparing Figure 1(a) in Hu et al. (2025) with Figure S3 for 2009 in the Supplement. Second, the temperatures from the 2009 annual run of the Canadian Middle Atmosphere Model (CMAM; Scinocca et al., 2008), with 6-hourly output provided by the Canadian Centre for Climate Modelling and Analysis, correspond much better to the SABER data (e.g., Shepherd et al., 2014). We used this run to calculate the daily zonal mean evolution of the NOCE boundary at ~80°N (Figure 12), alongside the daily zonal mean vertical profiles of O and the volume emission rates of OH(6-2), O(<sup>1</sup>S) at 557.7 nm, and O<sub>2</sub>(b<sup>1</sup>Σ<sub>g</sub><sup>+</sup>) at 762 nm (Atmospheric Band). »

3. Figures 1-3 show time-height section, nevertheless, the x-axes are labelled as latitude.

Corrected, see Figure 1-3.

4. Figure 1. Figure legend “WACC-X”

Corrected, see the legend of Figure 1.

5. When the authors refer to ‘height’ in the article, or show various heights in the figures—including ‘ $z_{eq}$ ’—it is unclear whether these are geometric altitudes or pseudo-altitudes (so-called ‘log-pressure altitudess’). One can only try to guess, based on the data source. This point needs to be made explicitly clear.

In the revised manuscript, we have addressed the reviewer's comment by adding the necessary explanations to the figure captions, see Figure 1-12:

« Figure 1. Time-height variations of O and H (in  $\text{cm}^{-3}$ ) over various polar locations in September–October 2000, calculated using the 3D chemical transport model WACCM-X. Log-pressure altitude is used as the vertical coordinate. Black lines indicate the NOCE boundary altitude based on criterion (5) ( $\text{Cr} = 0.1$ ).

Figure 4. Latitude-time evolution of the daily mean NOCE boundary  $z_{eq}^d$  (geometrical altitude, km) at northern polar latitudes in 2002–2013 obtained from SABER data. White areas indicate missing data due to satellite geometry.

Figure 6. Time evolution of  $z_{eq}^d$  (geometrical altitude) at  $80^\circ\text{N}$  during 2002–2013, derived from SABER data (black lines with dots, left y-axis). Blue lines represent the zonal mean wind at  $60^\circ\text{N}$  and 10 hPa (right y-axis), while red lines indicate the pole-to- $60^\circ\text{N}$  temperature difference at 10 hPa (right y-axis); both variables are from the MERRA-2 reanalysis. The "↓ES" symbol marks the onset of the ES event in the corresponding years, as identified, for example, by Yamazaki et al. (2025)......»

6. Line 225. Authors write “(geometrical altitude level  $z_{eq}$ )”. Then, at figures 4–5 we can see  $z_{eq}$  from SABER observations. But SABER shows the data on pressure levels, and corresponding altitude just approximate. How authors solve this problem and calculate geometric altitude from pressure?

SABER database provides measured and retrieved profiles in both pressure and geometrical altitudes.

7. Figures 6–9 are based on MERRA-2 reanalysis. Is it geometric altitude or log-pressure altitude?

We apologize for the confusion, which likely stemmed from insufficient detail in the original figure captions. In the revised manuscript, we have addressed this comment by adding the necessary explanations to the captions for all figures.

« Figure 6. Time evolution of  $z_{eq}^d$  (geometrical altitude) at  $80^\circ\text{N}$  during 2002–2013, derived from SABER data (black lines with dots, left y-axis). Blue lines represent the zonal mean wind at  $60^\circ\text{N}$  and 10 hPa (right y-axis), while red lines indicate the pole-to- $60^\circ\text{N}$  temperature difference at 10 hPa (right y-axis); both variables are from the MERRA-2 reanalysis.

Figure 10. Time evolution of  $z_{eq}^d$  (geometrical altitude) at  $80^\circ\text{S}$  (black lines with dots, left y-axis), derived from SABER data for the selected years. Blue lines represent the zonal mean temperature at  $60^\circ\text{S}$  and 0.1 hPa (right y-axis) from the MERRA-2 reanalysis.»

8. During SSW events, significant pressure variations occur in the mesopause, and results expressed in isobaric coordinates may differ considerably from those expressed in geometric coordinates. I therefore advise the authors to stick to one of the two throughout the manuscript.

In the revised manuscript, we have addressed this comment.

9. Figures 8-12. Is it MERRA-2. If - yes, it should be noted explicitly in the text, if –no, too, as well in figures legend.

In the revised manuscript, we have addressed this comment by adding the necessary explanations to the text and the captions for these figures.

10. Lines 436-437. It is well known that southern SSWs are much rarer than northern ones.

Could authors please let to know for readers, for example in Introduction, a little bit more about SSW events in Southern hemisphere? Who first identified it? Are they have identical to the Northern ones mechanism of formation? Why they are much rare? Which role plays GWs for SSWs in Southern hemisphere? If GWs play any role are they captured by MERRA-2 reanalysis?

In the revised manuscript, we have addressed this comment by adding the necessary information in Introduction, see lines 131-146:

« This article focuses on the local evolution of the NOCE boundary at polar latitudes, primarily during Northern Hemisphere winters characterized by major SSWs. It is well established that SSWs are driven by the upward propagation and amplification of planetary waves from the lower atmosphere and their subsequent interaction with the stratospheric zonal flow. A major SSW is commonly identified when the winter polar 10-hPa zonal-mean winds poleward of 60°N reverse from westerly to easterly, accompanied by a reversal of the 10-hPa zonal-mean temperature gradient poleward of 60°N (e.g., Butler et al., 2015). In contrast, during a minor SSW, the temperature gradient reverses without a reversal of the background zonal circulation. Consequently, winter processes at mesopause altitudes must be considered within the context of the concurrent dynamics of the upper stratosphere and, in some cases, the lower mesosphere. In the Southern Hemisphere, SSWs are much rarer and weaker than their Northern Hemisphere counterparts (e.g., Vincent et al., 2022). However, a major SSW occurred in September 2002, profoundly affecting the Antarctic ozone hole that year. More recently, a minor SSW in September 2019 exhibited the largest temperature variations ever recorded in the Southern Hemisphere winter polar stratosphere (Roy et al., 2022). Furthermore, the winter of 2024 was characterized by two successive minor SSWs in mid-July and early August (Zi et al., 2025). For broader context, Vincent et al. (2022) identified all minor SSWs in the Southern Hemisphere between 1994 and 2019 using MERRA-2 reanalysis data.»

11. Lines 443-445. “In addition, we included the temperature at the 0.1 hPa, calculated using MERRA-2 reanalysis data, as an indicator of lower mesosphere dynamics...” – could the temperature be an indicator of the dynamics?

Corrected, see lines 439-441 in the revised manuscript:

«A comparison with MERRA-2 temperature data at 60°S and 0.1 hPa ( $T_{60^{\circ}S,0.1hPa}$ ), shown in Figure 10, indicates that many features of the  $z_{eq}^d$  evolution can be explained by intrinsic mesospheric dynamics.»

12. Figures 13 ( as well 1, 2, 3, 4, 5, 8, 9). Dimensions should be indicated directly on the colour bars or in the figure captions.

In the revised manuscript, we have addressed this comment by adding the necessary explanations to the captions for all figures, see Figure 1-12, for example:

« Figure 13. Time evolution of the daily zonal mean profiles (in geometrical altitude) of O (in  $\text{cm}^{-3}$ ) and the volume emission rate (in  $\text{photon}/(\text{cm}^3 \cdot \text{s})$ ) of OH(6-2), O( $^1S$ ) at 557.7 nm, and O<sub>2</sub>(b $^1\Sigma_g^+$ ) at 762 nm (Atmospheric Band) at ~80°N during January–February 2009, simulated using the Canadian Middle Atmosphere Model (CMAM). The black dotted lines indicate the medians of the respective vertical distributions, while the magenta line marks the daily zonal mean NOCE boundary.»

13. Figure 13 and related text. Is the CMAM correctly reproduce SSW events? Could authors please give a reference, as well references that CMAM generally correctly reproduce dynamics at 80° N?

In the revised manuscript, we have addressed this comment by adding the necessary reference (see line 522).

Shepherd, M. G., Beagley, S. R., and Fomichev, V. I.: Stratospheric warming influence on the mesosphere/lower thermosphere as seen by the extended CMAM, *Ann. Geophys.*, 32, 589–608, <https://doi.org/10.5194/angeo-32-589-2014>, 2014.

14. Why authors do not use WACCM-X or MERRA-2 and jump to CMAM for the only one last figure?

In the revised manuscript, we have addressed this comment by adding the necessary explanations in Discussion, see lines 510-522.

« The 2009 event (Figure 6) demonstrates the most pronounced variations in  $z_{eq}^d$ , particularly during the major SSW that triggered the  $z_{eq}^d$  pulse. A number of studies (e.g., Gao et al., 2012; Medvedeva et al., 2019; Hu et al., 2025) indicate strong perturbations in chemical constituents

(specifically, atomic oxygen) and airglow emissions in the mesopause region during both this specific SSW and other major SSWs accompanied by an elevated stratopause. To identify common patterns in the evolution of the NOCE boundary and these characteristics, we examined multiple datasets from various 3D models for 2009 to find one that reproduced the same pulse-like variation in the NOCE boundary during this event. First, we found that the WACCM-X data were unsuitable for this purpose. A likely reason is that the WACCM-X temperature data show a remarkably weaker cooling of the upper mesosphere during this SSW compared to the SABER data, as can be seen by comparing Figure 1(a) in Hu et al. (2025) with Figure S3 for 2009 in the Supplement. Second, the temperatures from the 2009 annual run of the Canadian Middle Atmosphere Model (CMAM; Scinocca et al., 2008), with 6-hourly output provided by the Canadian Centre for Climate Modelling and Analysis, correspond much better to the SABER data (e.g., Shepherd et al., 2014).»

15. Lines 542-543. “Thus, we can assume that the boundary can be used to monitor significant disturbances in both the  $O_x$ – $HO_x$  components and the airglows generated by physicochemical processes involving them.” –may be vice versa? Because volume emissions observable parameters, and chemical constituents and consequently ozone photochemical equilibrium lower boundaries can be only calculated from these observations?

In the revised manuscript, we have addressed this comment by rephrasing this sentence, see lines 533-555:

« Thus, we can propose that the NOCE boundary can serve as an indicator of disturbances in  $O_x$ – $HO_x$  chemistry and the associated airglow variations arising during such powerful SSWs in the mesopause region.»

16. Could authors please explain in more details how they calculate  $O_2(b1)$  and  $O(1S)$ .

It seem to me they use approximations of McDade et al. (1986). But this paper is not cited.

If my assumption is true, then, it is necessary to note explicitly in the text, which of McDade parameters they use, because McDade give several sets of fitting coefficients for  $O_2(b1)$  and  $O(1S)$  calculations.

17. It is necessary let to know in more details how was calculated  $OH^*$ . Which assumptions and set of coefficients were utilized?

In the revised manuscript, we have addressed these comments by adding the necessary explanations in Discussion, see lines 522-532:

« We used this run to calculate the daily zonal mean evolution of the NOCE boundary at  $\sim 80^\circ N$  (Figure 12), alongside the daily zonal mean vertical profiles of O and the volume emission rates of  $OH(6-2)$ ,  $O(^1S)$  at 557.7 nm, and  $O_2(b^1\Sigma_g^+)$  at 762 nm (Atmospheric Band). To achieve this, the

distributions of OH( $v=1-9$ ), O( $^1S$ ), and O<sub>2</sub>(b $^1\Sigma_g^+$ ) were calculated using established airglow models driven by CMAM profiles of pressure, temperature, and relevant chemical species (O, H, O<sub>2</sub>, and O<sub>3</sub>). Specifically, the OH( $v=1-9$ ) distributions were derived using the model by Panka et al. (2021; see their Table 1 for details), assuming vibrational level equilibrium. The O( $^1S$ ) distributions were calculated using the McDade et al. (1986) approximation, with rate constants updated by Gao et al. (2012). Finally, the O<sub>2</sub>(b $^1\Sigma_g^+$ ) distributions were modeled following Grygalashvyly et al. (2021), utilizing the aforementioned OH( $v=1-9$ ) profiles alongside the standard CMAM atmospheric profiles...»

18. Lines 551-556. “As at mid- and low latitudes, the NOCE criterion clearly indicates the local position and thickness of the transition zone separating deep and weak photochemical oscillations of O and H caused by the diurnal variations in solar radiation.”

- I didn't see anything in this article about low latitudes;
- Where exactly is the point made in this sentence demonstrated?
- How do deep photochemical oscillations differ from weak ones?
- “caused by the diurnal variations in solar radiation” – but in this work authors are in polar night area at nighttime conditions!

In the revised manuscript, we have addressed this comment by rephrasing this sentence, see lines 544-546:

« At polar latitudes, the NOCE criterion clearly indicates the local position and thickness of the transition zone separating pronounced and weak photochemical oscillations of O and H caused by the diurnal variations in solar radiation. »

19. Lines 532-533. “the NOCE boundary rapidly drops down up to 72-74 km”;

Lines 560-561. “Immediately after such SSWs, the NOCE boundary rapidly descends to 72–74 km and can remain there for a long time”

– but at Figure 13 we can see 76-77 km.

In the revised manuscript, we have addressed this comment by rephrasing the text, see lines 550-556:

«Based on SABER observations (Figures 4-7), the most pronounced variability of the NOCE boundary at northern polar latitudes is observed during and after strong SSWs followed by stratopause elevation events. Just prior to or directly during such warmings, the daily mean altitude of the boundary near the North Pole can jump to 87 km, while local values can be even higher, up to 90–92 km. Immediately after such SSWs, the NOCE boundary rapidly descends to 72–74 km and can remain there for an extended period. Thus, the altitude range where the ozone equilibrium

condition is valid for determining O and other mesopause characteristics changes significantly during such events.»

20. Figure 12 partly duplicates Figures 10–11. I believe that, without detracting for the paper, Figures 8–12 could be reorganized.

In the revised manuscript, the multi-panel Figures 10 and 11 have been removed.

21. Figure 13 shows the temporal variation of the vertical profiles of O and the volume emissions during SSW 2009. It can be seen that, jointly with rising of altitude the concentration of atomic oxygen and emission rates are declining. In this context, it is worth noting the results of a recent study [Hu et al., ‘Influence of sudden stratospheric warming with elevated stratopause on the hydroxyl in the polar middle atmosphere’, Atmos. Chem. Phys., <https://doi.org/10.5194/acp-25-18431-2025>, 2025], in which a similar effect was detected.

Please, check other published works which show similar effect.

In the revised manuscript, we have addressed this comment by rephrasing this paragraph, see lines 510-514:

«The 2009 event (Figure 6) demonstrates the most pronounced variations in  $z_{eq}^d$ , particularly during the major SSW that triggered the  $z_{eq}^d$  pulse. A number of studies (e.g., Gao et al., 2012; Medvedeva et al., 2019; Hu et al., 2025) indicate strong perturbations in chemical constituents (specifically, atomic oxygen) and airglow emissions in the mesopause region during both this specific SSW and other major SSWs accompanied by an elevated stratopause.....»

22. Line 149. « $4.1 \cdot 10^{-10}$  hPa» -> « $4.1 \cdot 10^{-10}$  hPa».

Deleted.

23. Seems to me that the English of the paper should be corrected with native English speaker or professional English editor.

The final revised manuscript has been verified and corrected by a professional editor.

Other changes are related to the recommendations and demands of other referee.

Thank you for taking your time to review our manuscript.

With respect,

Mikhail Kulikov, Mikhail Belikovich, Alexey Chubarov, Svetlana Dementyeva, and Alexander Feigin