The present study explores the spatial and temporal distributions of (neutral) air density in the 2021 sudden stratospheric warming event using observational data (AURA/MLS, GNSS-RO and lidar) and global modeling whose dynamics is constrained using the reanalysis (SD-WACCM).

We thank you for your review and comments.

This study emphasizes the importance of density distributions in association with the evolution of anticyclonic and cyclonic vortices during the SSW event. However, flow evolution during the SSW event has been extensively studied using the concept of potential vorticity (e.g,, Harvey et al. 2002; Greer et al. 2013; Lu et al. 2021). Potential vorticity is the dynamic variable that combines the thermodynamic process, and it has good property that it is conserved following fluid elements in the absence of heat and dissipation. That is, there is already good and well-known material invariant quantity that can be used for studies of polar vortex evolutions and mass transport around vortices. Hence, reviewer is not convinced about why we need air density as another key physical quantity for better understanding of vortex evolution.

The reviewer is right that potential vorticity is one of key variables and has been extensively studied. Nevertheless, air density is most key atmosphere quantity for the atmosphere drag force calculation in the design of aircraft (Weaver et al., 2011; Hale et al., 2002). One consequence of the density shears and resulting drag excursions is to cause frequent fluctuations in the angle of attack profile. These large fluctuations could aggravate the heating and also contribute to the saturation of the angle of attack at its corridor limits during maneuvers, which could deteriorate the drag control and the ranging accuracy. This may be the barrier between industry and the atmosphere community. Hale et al. (2002) also reported the model predicts significantly larger atmosphere dispersions at higher latitudes in the winter. SSW events, as the most spectacular global atmospheric phenomenon, were investigated that effects on temperature, wind, vortices and so on. However, as far as we know, there have been no reports of atmospheric density during SSW. The purpose of our work is to present the changes in density at altitude levels during SSW and to find the reasons. These results demonstrate a rapid enhanced density by 50% during the 2021 major SSW and is primarily attributed to the altered planetary waves and residual circulation during the SSW event. Our work is considered to promote the collaborations between industry and the atmosphere community.

As authors discussed, mass transport is important in mean-flow evolution associated with planetary waves, and the mass circulation can be approximately described by the residual circulation. Importance of mass circulation in polar vortex dynamics is not new, and the importance of "mass" transport would not require the use of air density as an additional diagnostic quantity. Reviewer agrees that the importance of neutral air density in the altitudes (z = 200-1000 km) of (Very) Low-Earth Orbit satellites in terms of air drag, but the topic of this study is the middle atmospheric phenomena in which substantial amount of mass transport would be due to radiative heating/cooling, planetary waves and gravity waves. In this sense, referring low-thermospheric studies like Oberhide et al. (2020) is not appropriate. Tidal waves rather than planetary waves would contribute more to mass circulation in the lower thermosphere.

As mentioned above, our study in density is requirement for the atmosphere drag force calculation in the design of aircraft. The atmosphere drag is a direct function of the neutral atmospheric density at a given altitude. The density evolution during SSW events is rarely reported. Dynamic diagnostics and mass transports in this paper can effectively explain the rapid increase in observed atmospheric density during SSW. This isobaric-level form result is commonly used at present, such as Figure 1 in Manney et al.

(2009), Figure 1 in Chandran and Collins (2014), Figure 4 in Kodera et al. (2016) and Figure1 in Lu et al. (2021). The accurate density information at a given altitude is hardly speculated from previous studies. In this mean, our results are new and very meaningful. We have added above discussion in the revised manuscript.

The near space vehicles flight at the airspace 20–100 km and the space shuttle re-enter from an altitude of 122 km to the ground (Hale et al., 2002; Chen et al., 2023). Hale et al. (2002) has reported the density variations will highly influence engine performance, specific fuel consumption, drag, and flight control. So, atmospheric density is not only important for Low-Earth Orbit satellites at the altitudes (z = 160-1600 km), but also for the vehicles in the middle atmosphere at the altitudes (z = 20-100 km). The latter is the topic of our study. We have introduced the importance in the first paragraph. Maybe it wasn't expressed clearly enough. So, we have revised the first paragraph.

"For the near space vehicles flighting at the airspace 20–100 km and the space shuttle, entry phase of which begins at an altitude of 122 km and ends at the ground, the atmosphere variations will highly influence specific fuel consumption, engine performance, drag, communication and flight control (Weaver et al., 2011; Chen et al., 2023). The density variations are manifested as density shear, differences from the standard atmosphere model, and density perturbations dependence on longitude, latitude, and season (Hale et al., 2002). The significant difference between the actual atmosphere density and widely used standard upper air models, such as the 1976 US reference atmosphere, has often been found and contributed to attack angle bias from the reference angle of attack profile, causing adverse thermal consequences (Champion, 1990; Hale et al., 2002). On several flight experiments, the atmospheric drag, a direct function of the neutral atmospheric density at a given altitude, has varied by up to 19% over a few seconds. It is indicated that middle atmospheric density variations require additional attention from aircraft designers and the aircraft industry (Hale et al., 2002; Weaver et al., 2011). Furthermore, 38 Starlink satellites were destroyed by a unexpected geomagnetic storm that led to a density enhancement of over 20% at ~210 km and a larger atmospheric drag on February 4, 2022 (Dang et al., 2022). Atmospheric density is not only important for Low-Earth Orbit satellites at the altitudes (160-1600 km), but also for the vehicles in the middle atmosphere at the altitudes (20-100 km)."

We agree that tidal waves rather than planetary waves would contribute more to mass circulation in the lower thermosphere. However, Oberhide et al. (2020) only the mentioned global-scale wave and did not distinguish the tidal waves and planetary waves. We cite their results here to illustrate the similarity in the material transport by SSW event, not the same waves. We have added a clarification based on your advice in the revised manuscript.

"However, it is should be noted that planetary waves are more dominant in the middle atmosphere, while tidal waves rather than planetary waves would contribute more in the lower thermosphere (Liu et al., 2010)"

Reviewer thinks this manuscript need to be rewritten such that this study either focus more on the middle atmospheric dynamics during the 2021 SSW in more meteorological context or focus more on the lower thermospheric impacts of the 2021 SSW using upper atmospheric observations and SD-WACCM-X. For this reason, reviewer would not recommend this manuscript for publication to ACP, although authors made significant efforts for comprehensive and quantitative analysis.

Thanks to the reviewer's comments. Our focus is the middle atmosphere during the 2021 SSW and the whole paper is centred on this purpose. Maybe, the two lower thermosphere papers cited here have confused the reviewers. We have presented a clear description of the need for middle atmosphere density studies and their value to the industry in the revised manuscript based on the above replies.

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