Response to Referee 3

We thank Referee 3 for the thoughtful and detailed feedback. We appreciate all comments which clearly helped to improving the manuscript, and we addressed all points in the revised version. Reviewer comments are in black, answers in green. The main changes in the revised version are:

- A thorough rewriting of large parts of the text, including the Abstract, to discuss results and relations to atmospheric processes in a much clearer way.
- A clearer discussion of the dry bias in the reconstruction, supported by the inclusion of tropopause height information.
- A new analysis on the relation between the bias in the reconstruction and convection. This, along with the original discussion regarding the convection, has been reorganized and is now presented in Section 3.3.

General comments

Comment 1: This paper addresses a topic that has received considerable attention over the past 20 years or so. And a positive feature of the approach that the authors have undertaken in this work is the direct comparison of their water vapor reconstructions with SAGE-III ISS and MLS water vapor observations. One aspect of the study that deserves more explanation are the significant low biases of the reconstructed water vapor mixing ratios relative to both the SAGE-III and MLS observations that are evident in both Figs. 1 & 2. Following Liu et al. (2010), they attribute the dry bias to "missing cloud microphysics," but that is not the end of the story. Indeed, using the domain-filling approach, the reconstructed water vapor fields at 100 and 82 hPa obtained by Schoeberl, Dessler, and Tao (2013) display very little bias with respect to MLS—without including any microphysics other than allowing for a limited degree of supersaturation at the LCPs. In any case, I would recommend the authors include some commentary on this topic relative to the very interesting study of the dehydration occurring in StratoClim by Konopka et al. (2023), as this addresses the impact of microphysics on dehydration along CLaMS parcel trajectories.

Yes, we agree that microphysical processes as proposed in Liu et al. (2010) are not the only ones that may explain the dry bias of the LDP water vapor reconstructions. As correctly pointed out by the reviewer, Schoeberl et al. (2013) demonstrated that including only a limited degree of supersaturation at LCPs significantly reduces the bias, without requiring more complex microphysical processes. This approach has also been applied in previous studies (Schiller et al., 2009; Ploeger et al., 2011), and we acknowledge that it provides a simplified yet effective representation of cloud processes. However, this simplification does not fully capture the complex cloud microphysics and mixing processes that influence stratospheric water vapor (Poshyvailo et al., 2018). Moreover, according to our results for the NAM, the reconstruction works not as it does for the ASM, showing dry bias beyond this systematic error. Additionally, the difference in dry bias between our study and Schoeberl et al. (2013) may also be influenced by trajectory sampling methods. Their study employed domain-filling forward trajectories based on ERA-Interim and MERRA meteorology, whereas our approach relies on backward trajectories. Since forward an backward trajectory approaches are known to sample cold temperature regions differently it is likely that such differences also cause related differences in reconstructed water vapor mixing ratios. Regarding the Konopka et al. (2023) study, the use of microphysics in box model calculations was included, but it was applied to a much smaller ensemble of data based on a single Geophysical flight during the StratoClim campaign. In their study, they compared forward calculations, initiated in air masses where both water vapor and ice were observed, with the nearest MLS and CALIPSO observations along such forward trajectories. Their results showed a negligible importance of ice, with the best results obtained when simple LDPs along the backward trajectories, starting from the observation point, were calculated. Full microphysical studies using CLaMS-Ice are numerically expensive and require additional assumptions related to ice (noting that observations of ice were available for the StratoClim campaign). We have now incorporated a new discussion of these aspects into the first paragraph in Section 4, explicitly addressing the role of supersaturation, trajectory sampling effects, and missing mixing processes in influencing the reconstruction bias.

Comment 2: One very interesting result is presented in Fig. 5. It shows that while the vast majority of the Lagrangian cold points upstream of the observations in the ASM are within the ASM, the NAM is a very different story. Although a small fraction of the NAM LCPs come from the NAM region, the majority of the LCPs lie within the ASM. This is an important finding since it emphasizes the dominant role of the Asian monsoon in controlling the moisture entering the stratosphere in boreal summer, while the North American monsoon is relatively speaking a bit player. This result could well be highlighted more explicitly in the Conclusions section.

Thank you for this valuable suggestion. We agree that this finding is significant and have revised both the Abstract and the Discussion section to better highlight it. However, given that the reconstruction does not perform well over the NAM region, it could well be that the inferred long-range transport may be overestimated, potentially contributing to the limited reconstruction performance there. We have emphasized these results more clearly and included a related balanced discussion in the revised manuscript.

Comment 3: In Section 4, the authors address the finding of Randel et al. (2015). They are able to repeat the Randel et al. results with the satellite water vapor observations but not with the reconstructed water vapor fields. They argue that the simple Lagrangian approach fails to properly capture the effects of convection and ice injection in monsoon regions. This is not a convincing argument given that Konopka et al. (2023) did not find that convective processes played a significant role in determining the final stratospheric water vapor entry values in the circulation around the "dehydration carousel" in the Asian summer monsoon anticyclone.

Thank you for your comment. Based on our results in Fig. 1 and the newly added bars in Fig. 2, which present the anomalies of both observations and reconstructions, we now provide a clearer comparison. Additionally, we have included the heights of the cold point tropopause and lapse rate tropopause derived from ERA5 (the cyan and yellow lines in Fig. 2) for better understanding. Our analysis shows that the reconstruction performs well from about 16.5km upwards, capturing nearly the full magnitude of the anomalies in the ASM despite the systematic dry bias. This finding aligns with Konopka et al. (2023), who demonstrated that convection plays a limited role in setting final stratospheric water vapor concentrations within the Asian summer monsoon anticyclone. However, our reconstruction is less accurate below the tropopause. To enhance clarity, we have also added tropopause heights to Fig. 7, similar to Fig. 2, which makes it evident that below 16.5 km (in the upper troposphere, where the reconstruction method becomes less effective), convective processes significantly impact water vapor transport, and our method cannot capture this effect, explaining the discrepancies between reconstructed and observed water vapor. We acknowledge that this distinction was not emphasized clearly in our previous discussion. To address this, we have revised the second paragraph in Section 3.3 to explicitly state the limitations of our approach in capturing convective influences in particularly the upper troposphere.

Comment 4: As a general comment, I found the narrative flow of the text choppy and confusing, particularly in the Introduction. The Introduction certainly recognizes the long-standing consensus that the dominant control on the concentration of water vapor entering is through slow horizontal transport. However, this is restated in various ways multiple times, suggesting a controversy that does not exist. At minimum, I would recommend a revision of the Introduction to make it shorter and read more smoothly.

Thank you for your feedback. We have removed the overly long introduction and comparison of the Lagrangian and local methods and have adjusted the narrative sequence to enhance readability.

Minor Comments

Comment 1: I found the discussion of the methodology of the water vapor reconstructions (Section 2.3.3) incomplete. They have adopted three types of reconstructions ("experiments"): two obtaining water vapor values from the CPT along back trajectories ("LAG_single" and "LAG") and a third based upon local CPTs ("LOC"). The first two types of reconstructions appear to be similar in approach to the Lagrangian trajectories used in similar studies going back at least two decades. However, the method by which the "LOC" reconstructions are carried out is unclear, especially since it lumps all three of the reconstruction approaches into one paragraph.

We appreciate this comment and have revised Section 2.3.3 to clarify the methodology regarding the LOC reconstruction.

Comment 2: It would have been helpful if the captions for Figs. 1 & 2 specifically stated that the reconstructions were obtained through the LAG "experiment."

Thank you for this suggestion. We have updated the captions for Figures 1 and 2.

Comment 3: (line 31) Pan et al. (2018) did not introduce the Lagrangian Cold Point, although they do provide a number of references to the Lagrangian approach to determining the effective dehydration temperature for air parcels entering the stratosphere.

We appreciate this correction and have revised the text.

Comment 4: (L.25–36) Taken together, these sentences comprising the latter half of the first paragraph in the Introduction restate the importance of the concept of the transport history of air parcels entering the stratosphere several times over. The paragraph gives little sense of what new insights the Lagrangian perspective has provided since earlier papers.

Thank you for highlighting this issue. We have revised the paragraph to streamline the discussion and focus on the new insights provided by the Lagrangian perspective.

References

Konopka, P., Rolf, C., Von Hobe, M., Khaykin, S. M., Clouser, B., Moyer, E., Ravegnani, F., D'Amato, F., Viciani, S., Spelten, N., Afchine, A., Krämer, M., Stroh, F., and Ploeger, F. (2023). The dehydration carousel of stratospheric water vapor in the asian summer monsoon anticyclone. *Atmospheric Chemistry and Physics*, 23(20):12935 – 12947.

Ploeger, F., Fueglistaler, S., Grooß, J.-U., Günther, G., Konopka, P., Liu, Y., Uller, R., Ravegnani, F., Schiller, C., Ulanovski, A., and Riese, M. (2011). Insight from ozone and water vapour on transport in the tropical tropopause layer (ttl). *Atmospheric Chemistry and Physics*, 11(1):407–419. cited By 54.

Poshyvailo, L., Müller, R., Konopka, P., Günther, G., Riese, M., Podglajen, A., and Ploeger, F. (2018). Sensitivities of modelled water vapour in the lower stratosphere: Temperature uncertainty, effects of horizontal transport and small-scale mixing. *Atmospheric Chemistry and Physics*, 18(12):8505–8527. cited By 18.

Schiller, C., Groob, J.-U., Konopka, P., Plöger, F., Silva Dos Santos, F., and Spelten, N. (2009). Hydration and dehydration at the tropical tropopause. *Atmospheric Chemistry and Physics*, 9(24):9647–9660. cited By 73.

Schoeberl, M. R., Dessler, A. E., and Wang, T. (2013). Modeling upper tropospheric and lower stratospheric water vapor anomalies. *Atmospheric Chemistry and Physics*, 13(15):7783–7793.