Response to Referee 2

We thank Referee 2 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, related to specific comment 5. This, along with the original discussion regarding the convection, has been reorganized and is now presented in Section 3.3.

General comment: This study employs a Lagrangian method to reconstruct water vapor over the Asian Summer Monsoon (ASM) and North American Monsoon (NAM) regions, investigating their contributions to stratospheric water vapor. While the introduction emphasizes that ”In this study, we aim to further investigate the physical processes responsible for the enhanced water vapor over the ASM and NAM regions,” I believe that the majority of the article primarily focuses on describing the distribution characteristics of water vapor and offers speculative suggestions regarding the underlying physical processes, rather than providing a thorough analysis of these processes and mechanisms.

Thanks for this critical general comment which shows us that overall our process analysis was not presented clear enough. However, we think that our paper indeed presents new insights into processes, and also into sources of biases for modelling approaches. In the revised version we tried to be much clearer in the description of processes and new results. In addition, we thoroughly addressed all specific comments below, which in our opinion helped to significantly improve the paper (in particular comment 5 - Thanks for that!). Therefore, we think that we could improve the paper so much that we can submit a revised and substantially improved new version.

Comment 2: The time periods for the MLS (August 2017 to 2019) and SAGE (August 2017 to 2022) datasets differ. Which time period was actually used in the study? In Figure 1, the differences in water vapor concentration between the two datasets—are these due to the different time periods being used? What is the rationale for using different time periods for the two datasets?

Thanks for the comment. We agree that the reason for the different periods needs to be explained. The extended period for SAGE was chosen to ensure sufficient coverage of the considered region. On the other hand, the large volume of MLS data makes it challenging to perform all trajectory calculations for a too long period - in particular because we launch large trajectory ensembles for each measurement point (we have included the specific numbers of trajectories that are calculated now in Section 2.3.1). However, if we confine the SAGE data to the MLS period, our results do not change significantly (see Fig. R1). We have included a short related discussion in the revised text (Section 2.1.2).

Comment 3: Fig. 1: The reconstructed water vapor over the NAM region does not reflect the observed features, such as the high water vapor values seen in the observations, unlike the ASM region. What is the underlying reason for this discrepancy? In the figure, the reconstructed water vapor uses the Lagrangian CPT method. If the tracing period were extended, for example, to 180 days as shown in Figure 3, would the reconstructed water vapor better capture the observed characteristics?

As Figures 1 and 2 use the maximum trajectory length of 180 days to determine the Lagrangian cold point, our finding that the reconstruction of water vapor above NAM is less accurate than over ASM is a robust result of our study. We think that this discrepancy is most likely due to the greater relevance of convective moistening events in the NAM compared to the ASM region which are not represented in the simplified Lagrangian reconstruction method. Also, the large circulation at around tropopause above the NAM shows stronger the year-to-year variability compared with that above the ASM (Park et al., 2007). A more thorough discussion of these issues is provided in the revised manuscript (Sect. 4).

Comment 4: Fig. 2: The reconstructed water vapor primarily relies on the CPT in the UTLS region. Why, then, do the differences in water vapor become smaller at higher altitudes?

At higher altitudes, the fraction of TST becomes smaller as backward trajectories need more than 180 days to reach the CPT, which is the maximum time of our backward calculations.

Hence, the fraction of non-TST trajectories, which are originating in the lower stratosphere and therefore represent climatological stratospheric mixing ratios. In this way, climatological mixing ratios start to dominate the reconstructed water vapor. A new related discussion paragraph is now included in Sect. 3.1. On the other hand, we agree that including climatological values in Fig. 2 could cause confusion, so we have revised the figure to show only the results based on TST trajectories. In the updated Fig. 2, we observe that in the deep stratosphere, the dry bias remains relatively constant at around 1.5 ppmv for both the entire tropics and the ASM. In contrast, the NAM again shows a different behavior, with a less consistent bias pattern, further indicating that the reconstruction performs less reliably for the NAM region.

Comment 5: Line 205: The authors attribute the discrepancies between the reconstructed and observed water vapor to issues with ERA5 temperature data or the absence of convective transport processes in the reconstruction model. This issue requires further analysis and diagnosis. If the difference between the observed and reconstructed results is calculated, does the time series of the difference align with the changes in the intensity of the convection (OLR)? If referring to the results in panels (b) and (d) of Figure 6, it seems likely that convective transport plays a significant role in the observed differences.

Thanks you for this insightful comment. Based on this suggestion, we have conducted further analysis and examined potential relations between the biases in reconstructed water vapor concentrations at 16.5 km and the time series of OLR indices as a proxy for convective intensity, as shown in Fig. R2. Our results indicate a significant correlation between the bias in the reconstruction and the OLR-West index, as a proxy for the strength of convection in the western monsoon region, particularly after applying a half-monthly mean to smooth out daily fluctuations. This new finding strongly supports that convection is a major influencing factor for the bias in the reconstruction. The analysis also reveals that convection in the western region has a stronger impact on reconstruction biases compared to the eastern region. This difference between the effect of convection in the western and eastern monsoon regions could have been expected given the result by Randel et al. (2015) that only convection in the Western region causes moistening of the UTLS. Hence, it is the moistening effect of convection which is likely underrepresented in the simplified Lagrangian reconstruction method and causing a large part of the reconstruction dry bias. Additionally, the correlation varies with altitude, with the strongest correlation observed at 16.5 km, indicating the complexity of atmospheric processes at different levels. To present this information in the revised manuscript we show the scatter plots of the relation between the reconstruction dry bias and convective intensity in the new Fig. 8 and added a detailed discussion in Section 3.3 to specifically address this issue. We think that these new findings provide a much clearer relation between the bias in the reconstruction and the relevant atmospheric process of convection and significantly improve the paper.

Comment 6: Line 235: How should we interpret the influence of the minimum saturation mixing ratio (or the cold point temperature) from three months prior on the lower stratospheric water vapor in August?
This time lag is related to the water vapor tape recorder signal propagating upwards. Due to the very weak tropical upwelling, especially during the boreal summer (on the order of less than 0.5 K per day in the TTL), the water vapor values imprinted at the Lagrangian cold point propagate upward. Additionally, as mixing is weak, this memory effect propagates along the upward-moving trajectories within the ASM anticyclone, also referred to as the upward spiraling (Vogel et al., 2019). Of course, for air masses with Lagrangian cold points occurring before the onset of the monsoon (around beginning of June) the dehydration process is not related to the monsoon circulation. We have added some related text in the revised version to clarify this interpretation, in Section 3.1.2 where we discuss about the increasing of correlations.

Comment 7: Line 292: If the dehydration process occurs in the vicinity of the monsoon region, how can we understand that the internal region of the anticyclone over Asia acts as the upward pathway for the material?
According to Konopka et al. (2023), the ASM anticyclone acts as a major transport pathway for air ascending into the stratosphere, while dehydration predominantly occurs at its southern vicinity where air encounters the coldest temperatures near the tropopause. This process does not contradict the role of the anticyclone as an upward pathway; rather, it reflects the interplay between circulation and dehydration. As described in the ”dehydration carousel” mechanism, air can recirculate within the anticyclone, lose moisture at its edges, and subsequently ascend into the stratosphere. We have included the related discussion in the second paragraph in Section 3.2.

Comment 8: Line 303: If the water vapor in the NAM region is transported from South Asia after undergoing dehydration, how is the moisture transmitted to the NAM region, and how does it form a high-value center in the NAM region (as shown in Figures 1a and 1b), given that the tropical summer region is dominated by an easterly wind belt?

The ERA5-based trajectory calculation clearly shows frequent transport from Asia to the NAM region via the subtropics, related to the westerly subtropical jet flow. However, these water vapor mixing ratios originating from freeze-drying (related Lagrangian cold points) over Asia are oviously too low and the NAM region in the reconstruction is significantly dry-biased. Hence, other processes not included in the reconstruction are likely responsible for moistening the NAM UTLS. The most likely process is local deep convection, which is known to frequently occur in the NAM region, though this process not necessarily involves direct injection into the stratosphere. An additional related discussion, including relevant recent literature has been added at the end of the Section 3.2 to address this point.

Comment 9: There are not many figures in the main text, so I suggest placing Figures S1 and S2 directly in the main text.

We appreciate this suggestion. However, we have added Fig. 8 in the main text, which is related to the comments 5, and have split the original Fig. 5 into Fig. 5 and 6 to include the locations of LCP for the entire tropics, allowing for a direct comparison with those in the monsoon regions. To maintain a balanced presentation and avoid overcrowding the main text, we will keep Figures S1 and S2 in the Supplementary Information.

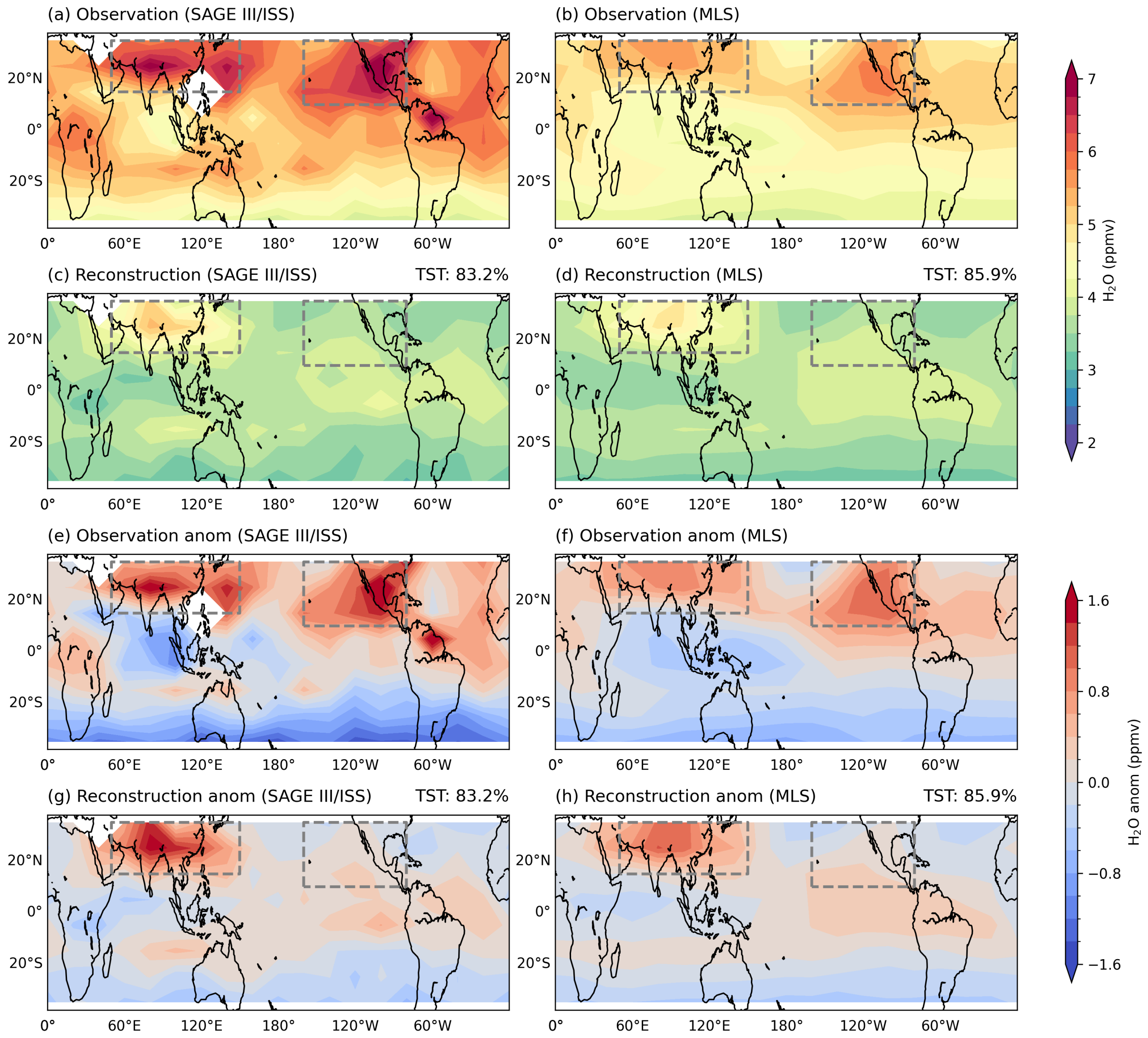

Figure R1: Same as Fig. 1, but using SAGE III/ISS data from 2017–2019. The gaps in the left panels are due to limited sampling, where fewer than two profiles are available.

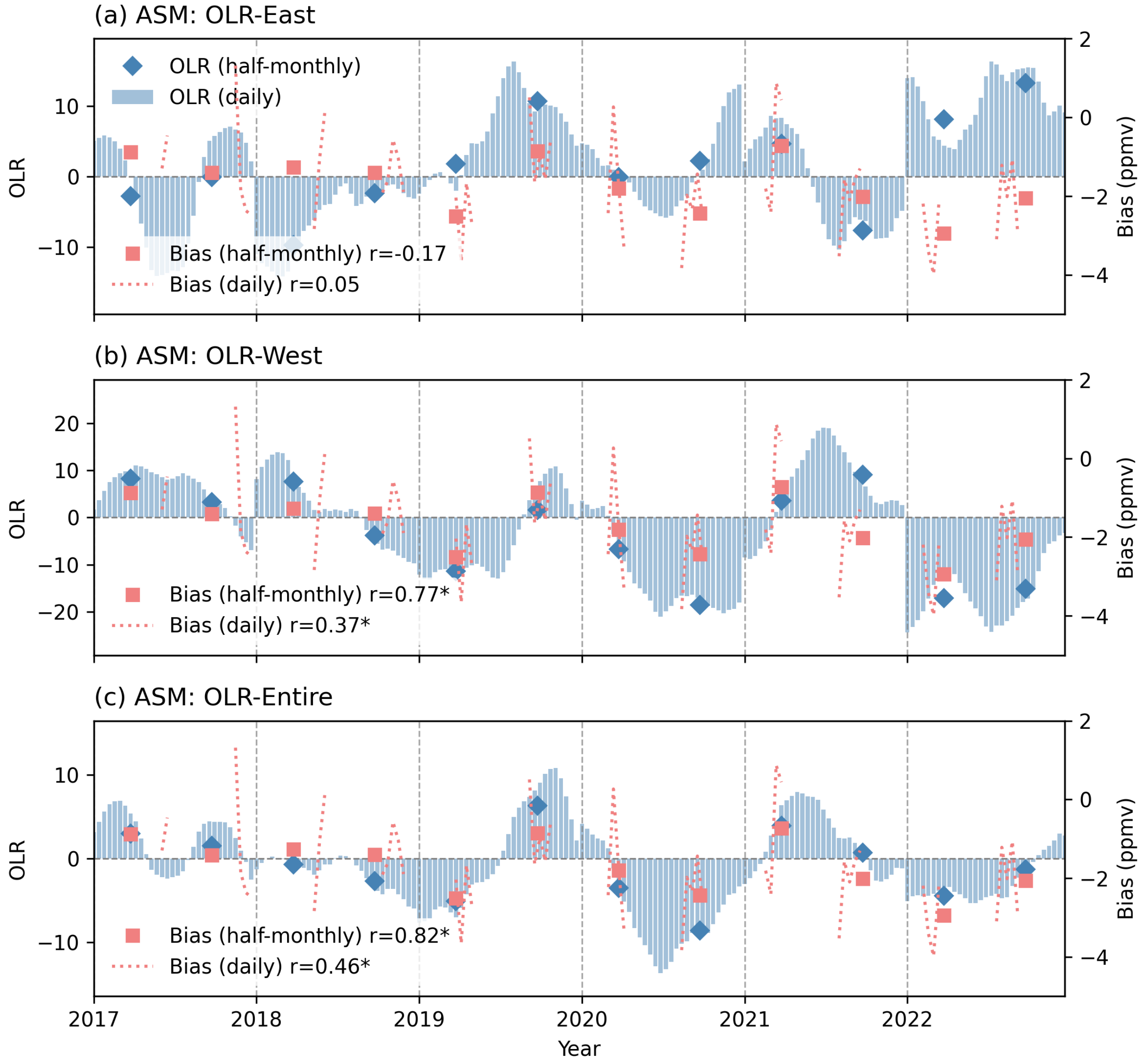

Figure R2: Time series of OLR indices and biases of reconstructed water vapor concentrations at 16.5 km for the ASM. The three panels correspond to results using OLR-East (a), OLR-West (b), and OLR averaged over both regions (c) as OLR indices. Blue bars represent daily OLR indices, while blue diamonds indicate half-monthly means. Red lines and squares show daily and half-monthly reconstruction biases based on SAGE III/ISS. The OLR indices are averaged over the 0–10 days preceding each date. Correlation coefficients between OLR and biases are shown in the legends, with a star indicating statistical significance at the 95% confidence level based on the Student's t-test.

References

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