Response to Referee 1

We thank Referee 1 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 examining the relationship between reconstruction bias and convection. This, along with the original discussion related to convection, has been reorganized and is now presented in Section 3.3.

General feedback: This paper aims to improve our understanding of lower stratospheric water vapor anomalies that occur over the Asian and North American summer monsoons, a problem that has implications for surface climate and stratospheric chemistry. This paper uses a Lagrangian trajectory method to identify the role of cold point temperatures in the vicinity of the monsoon in setting the water vapor content of air reaching the lower stratosphere. I believe that this is a valuable contribution that can be suitable for publication in ACP following revisions.

Comment 1: This work uncovers a correlation between Lagrangian cold point temperatures and water vapor anomalies over the Asian summer monsoon. However, the mechanism presented here can only explain a fraction of the overall water vapor anomaly. While the dry bias of the Lagrangian trajectory method has been noted before, the dry biases in Fig. 2 make it difficult to claim that elevated Lagrangian cold point temperatures contribute significantly to the water vapor anomalies. For example, at 15.5 km the ASM reconstructed anomaly is about 1 ppm, while the SAGE anomaly is about 5 ppm. Therefore, the current method only accounts for about 1/5 of the observed moistening in the ASM. In the NAM, the Lagrangian method does not show a moistening. In both regions, I feel that the current presentation of these results overstates the moistening that can be explained by this method. This framing needs to be improved prior to publication.

We agree with the reviewer that our Lagrangian reconstruction results in a dry bias and an underestimation of the monsoon moist anomaly. This is particularly so at lower levels, e.g. 15.5km. The main reason is that the Lagrangian reconstruction, which finds the Lagrangian cold point along the back trajectories, only works in the stratosphere, i.e., after the "true" Lagrangian cold point has been passed by an air parcel on its way from the troposphere to the stratosphere. This limitation is particularly relevant for altitudes below the cold point tropopause, such as the region over the ASM shown in Fig. 1 and the lower portions of the profiles in Fig. 2, where the reconstruction method cannot be expected to perform well, as these levels remain within the troposphere. Thus, we acknowledge that this constraint was not sufficiently emphasized in our earlier discussion. To better address this issue, we added the position of the climatological August cold point tropopause, as derived from ERA5, in Fig. 2. We also incorporated the observed moist anomalies in monsoon regions relative to the entire tropics (grey bars in the left sub-panels in Fig.2), along with the corresponding reconstructed anomalies (coral bars), to better evaluate the reconstruction's performance in capturing these features. Specifically, the reconstruction reproduces one-third of the observed anomalies in the ASM at 15.5 km, increasing to over two-thirds at 16.5 km and to an even higher contribution at levels above.

Comment 2: Moreover, I would argue that the central conclusion of this paper is that a small portion of moistening over the ASM is caused by an altered transport pathway through the UTLS, not that the moistening can be explained by the Lagrangian method. A secondary conclusion would be that the altered pathway is not significant for the NAM. In other words, the ASM allows some portion of air to avoid the "cold trap" and the dehydration that would occur within. This results in a water vapor anomaly that occurs regardless of direct injection of water vapor/ice into the lower stratosphere (although the majority of the anomaly is driven by these other processes). The correlation between the Lagrangian reconstructions and ASM observations suggest that this cold-trap-avoidance mechanism is robust, but it does not prove that the mechanism is the dominant source of water vapor anomalies.
We agree that the Lagrangian reconstruction method does not explain the entire anomalies observed by SAGE and MLS. However, the method works reliably well in the ASM region to reproduce the pattern of anomalies (Fig. 1), and also reproduces the main part of the anomaly at levels from the tropopause upwards (please refer to our reply to comment 1, and Fig. 2). However, since the number of TST trajectories decreases and the impact of the climatology on

the reconstruction increases at higher levels, we agree that these arguments should be considered carefully. Now in Fig. 2, instead of a mix of TST-based reconstructions and climatological values, we use the reconstructions only from TSTs, so that we can see a more 'systematic' dry bias. Nevertheless, the new figures of the reconstruction's contribution to monsoon anomalies in Fig. 2 and the high correlation coefficients shown in Fig. 3 show that in the ASM a significant part of the anomalies can be explained by the Lagrangian reconstruction method. For the NAM, we agree that the simple method does not capture the moistening processes sufficiently. We have included more detailed discussion about the capability of the Lagrangian method to reconstruct moist anomalies in ASM and NAM regions, and in particular we critically discuss the failure of the method in reconstructing the NAM anomaly now in Section 4.

Comment 3: The proposed mechanism would also gain meaning with additional discussion of other water vapor sources. For example, Smith et al. (2017) studied a summertime water vapor enhancement over North America and found that frequent deep convection can deliver water vapor to the lower stratosphere. O'Neill et al. (2021) also provide a mechanism by which water vapor injection occurs over intense convection. Studies like these would explain why the hydration captured by the Lagrangian trajectory method is smaller than the observed hydration, especially over the NAM.
Yes, we agree that deep overshooting convection plays an important factor in the anomalies in the monsoons, in particular over North America. We now incorporate a discussion (in section 4) of the results from Smith et al. (2017) and O'Neill et al. (2021), and also Homeyer et al. (2024) who demonstrated that frequent deep convection over North America and intense convection can deliver water vapor to the lower stratosphere. In particular, the new analysis on the relation between the reconstruction bias and the intensity of convection in Sect. 3.3 (suggested by the other reviewer) shows clearly that convective moistening is one of the key processes missed by the simplified Lagrangian method.

Comment 4: Additionally, the choice of the 6-hr resolution needs to be justified for two reasons. First, the monsoon can act on timescales shorter than 6 hours, so it is possible that the Lagrangian trajectories do not fully capture the effect of the monsoons. Li et al. (2020) found that the improved temporal resolution of ERA5 led to more rapid transport than ERA-i, so it is possible that the 6-hr data used here does not fully capture convective transport. Second, it has been shown that trajectories calculated with 6-hr data have transport errors and warm

CPT biases relative to those calculated with 1-hr data (Pisso et al., 2010; Bourguet and Linz, 2022). It is possible that the warm CPT biases cancel out when calculating anomalies, but it is also possible that the anomalies calculated with 6-hr data are larger than those that would be calculated with 1-hr data. This would mean that the mechanism presented here is actually smaller than these results would suggest.
We agree that enhancing the temporal resolution of the data could make the freeze-drying effect stronger in our calculations. However, generating the necessary high-resolution data in space and time and recalculating all trajectories is a major computational effort and beyond the scope of this paper. In the revised version, we discuss these issues in more detail in the last paragraph of the Section 4 as suggested by the reviewer, and with reference to the suggested publications. We also acknowledge that higher temporal resolution, rather than spatial resolution, has greater potential to refine the representation of Lagrangian dry points and deep convection.

Comment 5: I would also advise moving the LAG_single comparison to the Supplemental. It is well known that single trajectories are not meaningful and that ensembles should be used instead. As currently presented, the comparisons with LAG_single distract from the main results. I also feel that the MLS results could also be moved to the Supplemental to improve the focus on the comparison between reconstructed and observed water vapor. (The same conclusions are drawn when comparing reconstructions with MLS and SAGE.)
Thank you for your thoughtful suggestions. We acknowledge that single trajectories are generally less meaningful than ensemble-based approaches. However, we would like to clarify that even in the LAG_single experiment, the results presented (e.g., in Fig. 3) are not results of single trajectories but are averages over large trajectory ensembles. The key difference lies in how these ensembles are generated: in the LAG_single experiment, only one trajectory is initialized at each measurement point along the profile, whereas in the experiment LAG, a full ensemble of trajectories is initialized at each individual measurement point. Therefore, all presented results are derived from substantial trajectory ensembles, with the ensemble size varying between experiments. We appreciate your comment highlighting this potential source of misunderstanding and have clarified these points in the revised manuscript. Regarding the MLS results, we believe that keeping them in the main text is essential because SAGE III/ISS has much lower sampling compared to MLS. By presenting the MLS-based comparisons alongside SAGE III/ISS, we provide a stronger foundation for our conclusions and enhance the robustness of our analysis.

Minor Comments

Comment 1: Lines 2–4: “The amount of water vapor entering the stratosphere is sensitive to cold point temperatures, making NH summer monsoons more favorable for transporting water vapor into the stratosphere.” Water vapor enhancements over Northern Hemisphere summer monsoons do not follow from elevated cold point temperatures. Deep convection can lower the CPT, so this statement needs to be clarified.

Thank you for pointing this out. We have revised the sentence to clarify the relationship between cold point temperatures and water vapor transport in monsoon regions. Additionally, the abstract now is thoroughly rewritten, with consideration of all the comments related to the abstract.

Comment 2: Line 5: “investigating their contributions to stratospheric water vapor.” To my understanding, the water vapor reconstructions in this work are confined to the tropical lower stratosphere, and there is no evaluation of how monsoon water vapor anomalies contribute to the stratospheric water vapor budget. Therefore, I would avoid saying that the contributions to stratospheric water vapor are evaluated here.

Thank you for the suggestion. We agree and have revised the sentence to more accurately reflect our study’s scope.

Comment 3: Lines 9–11: “it effectively reconstructs UTLS water vapor (correlation coefficient 0.75), capturing moist anomalies in the ASM, but performing less well in the NAM.” Following from general feedback above, the high correlation here does not mean that the Lagrangian method can explain the magnitude of the water vapor anomalies.

Please refer our response to major comment 1 and 2.

Comment 4: Line 17: “The water vapor” -¿ remove “The.”

Thank you for pointing out. It has been removed.

Comment 5: Line 25: “Large-scale vertical transport enhances lower stratospheric water vapor. . . ” Is this meant to say that large-scale vertical transport spreads convectively-injected water vapor? Large-scale transport on its own does not enhance lower stratospheric water vapor.

Please refer to the new abstract.

Comment 6: Line 33: "Several studies have successfully reconstructed UTLS water vapor using Lagrangian methods…" I would argue that studies are able to capture UTLS water vapor anomalies, not total water vapor concentrations (e.g., Smith et al., 2021; Bourguet and Linz, 2022). This is an important distinction given the uncertainty surrounding the dry bias in Lagrangian reconstructions.

We agree with this distinction and have revised the sentence to make it more precise.

Comment 7: Lines 78–79: "within both Asian monsoon and North American monsoon regions" - tropical water vapor is also considered. Could be easier to say "across the tropics."

It has been revised according to your suggestion.

Comment 8: Lines 96–98: Clarify that 1-2-1 vertical smoothing is done on 1 km grid. (It's not currently clear if smoothing is done on 0.5 km grid or 1.0 km grid.)

We appreciate this point and have clarified in the text that the 1-2-1 vertical smoothing is applied on a 0.5 km grid.

Comment 9: Line 125: SAGE vertical resolution is reported as 0.5 km here. When is 0.5 km used, and when is 2.0 km vertical resolution used?

Thank you for pointing this out. We have clarified in the text that the native SAGE III/ISS vertical resolution is 2.0 km, but the profiles are retrieved on a 0.5 km vertical grid. This distinction is now explicitly stated.

Comment 10: Section 2.3: How many trajectories are calculated in total, and how many are with the ASM and NAM, respectively?

The relevant information is provided in Section 2.3: For each August from 2017 to 2022, SAGE III/ISS recorded 149, 203, and 2292 profiles for the ASM, NAM, and tropics, respectively. Taking the ASM as an example, the number of calculated trajectories is given by 149×10 (profiles × levels) for LAG_single and $149 \times 10 \times 51$ (profiles × levels × ensemble trajectories) for LAG. Accordingly, the total number of calculated trajectories for LAG_single is 1490 for the ASM, 2030 for the NAM, and 22,920 for the tropics, while for LAG, these numbers increase to 75,990, 103,530, and 1,168,920, respectively. For each August from 2017 to 2019, MLS provides 7801, 10,223, and 126,981 profiles for the ASM, NAM, and tropics, respectively. Since MLS calculations use five vertical levels, the number of trajectories for LAG_single is computed as $7801 \times 5 = 39,005$ for the ASM, $10,223 \times 5 = 51,115$ for the NAM, and

$126,981 \times 5 = 634,905$ for the tropics. For LAG, these values are further multiplied by 51, yielding the final trajectory counts.

Comment 11: Lines 171ff: "The large-scale patterns in the reconstructions are consistent with the observations…." I would argue that this is misleading, even with the acknowledgement of the dry bias that follows. The NAM anomaly is not present in reconstructions, so broad statements about large-scale patterns should be avoided. Similarly, in the following paragraph, the assertion that the "reconstruction captures the enhancements in water vapor concentrations and their locations" is misleading. The quality of the water vapor reconstructions in the ASM and the NAM should be discussed separately to avoid conflating the two.

Thank you for your comment. We agree that the statement was too broad and have revised it to more accurately describe the differences in reconstruction performance between the ASM and NAM. We also clarify that the quality of the reconstructions differs between the two regions and discuss them separately in the revised text.

Comment 12: Line 188: Specify that the cyan squares are in Fig. S1.

This point has been modified.

Comment 13: Lines 249–252: Please be more specific with what you mean by "exhibit no significant differences in overall structure" and explain how this suggests that the tropics and monsoon regions have the same primary controlling mechanisms. To me, the tropical scatter plots (Fig. 4d, g) appear qualitatively different than the NAM scatter plots (Fig. 4f, i). Also, although the ASM scatter plots appear more similar to the tropical scatter plots, these plots only consider the relationship between the CPT and observed water vapor, so it is possible that other mechanisms could contribute to the two separately.

We appreciate the reviewer's insights. In our revised text, we clarify that the similarity between monsoon regions and the deep tropics refers specifically to the correlation between lower stratospheric water vapor mixing ratios and LCP temperatures, not local cold point temperatures. This suggests that in both cases, water vapor is controlled by remote dehydration processes rather than local conditions, and that advection through the large-scale temperature field can explain water vapor mixing ratios above the tropopause in the ASM similarly well as in the deep tropics. While the scatter plots in Fig. 4 show some qualitative differences, the key takeaway remains that lower stratospheric water vapor in the ASM region, like in the deep tropics, is primarily governed by historical dehydration at LCPs. In the NAM region, we fully agree that the simplified Lagrangian reconstruction method does not explain the observed mist anomaly - and this is discussed in a more balanced way in the revised manuscript in Sect. 4 (see also our reply to comment 2). We acknowledge that additional mechanisms may contribute to differences, but our findings emphasize the dominant role of large-scale transport and freeze-drying in shaping water vapor distributions.

Comment 14: Lines 261–275: I would advise either removing this paragraph or moving it to the Discussion or Conclusion section.

Thank you for the suggestion. We have moved this paragraph to the Discussion section for better alignment with the overall flow of the paper.

Comment 15: Section 3.2: I suggest including a panel to Fig. 5 with the location of the LCP for all tropical trajectories. This would allow for a comparison of CPT locations between the monsoon regions and the tropics, which would support the idea that the monsoons alter the transport pathways through the UTLS.

We agree that this addition would be helpful. We have added a panel to Fig. 5 showing the LCP locations for all tropical trajectories and updated the discussion accordingly.

Comment 16: Lines 291–293: "This suggests that the increased water vapor in the ASM is primarily attributed to dehydration processes occurring in the vicinity of the monsoon over Asia." This needs to be clarified. The location of the highest reconstructed water vapor concentrations suggests that the increased water vapor captured by the Lagrangian reconstruction (about 1/5 of the observed increase) is primarily driven by changes to transport near the ASM. The remaining 4/5 of the observed anomaly is attributable to other processes.

Please refer to our response to Major Comment 1.

Comment 17: Lines 316–318: The contribution of distant CPTs to the reconstructed NAM water vapor anomaly does not imply significance of distant CPTs to the observed anomalies. Instead, the relative inability of the NAM reconstruction to capture observed water vapor anomalies implies that local processes (e.g., direct injection of water vapor) are crucial for explaining the final moisture composition within the anticyclone. However, the Lagrangian method cannot reproduce observations, so you cannot draw objective conclusions about the behavior of the atmosphere with this method.

Thank you for pointing to that potential misunderstanding. We fully agree that in the NAM other, local processes are likely important. Obviously, the related text was not clear. We have revised the text to clarify the role of distant CPTs and local convection in shaping water vapor anomalies in the NAM. The revised discussion now explicitly acknowledges that processes such as convective mixing and overshooting likely play a dominant role in enhancing water vapor in the NAM region, as the freeze-drying mechanism alone is insufficient to explain the observed anomalies (please also see our reply to major comment 2).

Comment 18: Line 351: "the ASM anomalies are nearly fully captured." The ASM observation and reconstruction patterns in Fig. 1 are qualitatively similar, but Fig. 2 shows that the ASM water vapor reconstruction does not capture a majority of the observed anomalies. Thus, I would caution against the quoted statement.
We have modified the statement to avoid this kind of unspecific comments.

Comment 19: Lines 370–372: Similar to the previous point, Fig. 2 shows that the Lagrangian water vapor reconstruction does not successfully capture the magnitude of the moist anomalies over the ASM. A portion of the moist anomalies can be explained by the Lagrangian reconstruction, but the large dry bias in the anomalies implies that a mechanism other than freeze-drying is needed to explain observations.
Please refer to our response to Major Comment 1.

References

Homeyer, C. R., Gordon, A. E., Smith, J. B., Ueyama, R., Wilmouth, D. M., Sayres, D. S., Hare, J., Pandey, A., Hanisco, T. F., Dean-Day, J. M., et al. (2024). Stratospheric hydration processes in tropopause-overshooting convection revealed by tracer-tracer correlations from the dcotss field campaign. *Journal of Geophysical Research: Atmospheres*, 129(16):e2024JD041340.