Author Reply to Reviewers

We thank Dr. Mengchu Tao and Reviewer 2 for raising a number of interesting questions. Addressing these questions has already helped tremendously to tighten the analysis and make it more incisive, as described below. The resubmission will be much stronger for your efforts. Initial responses to all general comments and selected technical comments are provided below.

1 Response to reviewer 1

Reviewer 1 evaluations: This paper focuses on analyzing water vapor variability in the Upper Troposphere–Lower Stratosphere (UTLS) region of the Asian Summer Monsoon (ASM) area. The authors use satellite data from Aura MLS and five atmospheric reanalysis datasets, including MERRA-2, M2-SCREAM, CAMS, ERA5, and JRA-3Q, to conduct a spatiotemporal mode analysis. The main results reveal three key modes of variability, including PC1, large-scale regional water vapor wetting or drying anomalies, PC2 and PC3, intraseasonal oscillations linked to quasi-biweekly variability.

A key conclusion in the paper, from my point of view, is the discrepancies between reanalysis products and Aura MLS data regarding spatial distribution and sign (positive/negative) of water vapor trends. While most reanalysis products show an increasing water vapor trend in the southeast of Asian monsoon during warm season, their spatial characteristics differ significantly from those derived from Aura MLS.

Overall, the paper is novel in design, well-written, and thorough in its data analysis, comparisons of methods, and results. I recommend minor revisions to address the following points for further improvement.

1.1 General comments

Comment 1.1

The analyses, particularly those focused on interannual variability and intraseasonal oscillations, are convincing and well-executed. My concerns are mainly about the analysis of PC1 trends. While the discussion clearly identifies the differences in trends between Aura MLS and reanalysis products, I would suggest a deeper exploration of the reasons behind these discrepancies.

Response:

Thank you for this suggestion. We have conducted further analysis and incorporated new results accordingly.

As documented by Wright et al., 2025 (see their Figure 1), the cold point tropopause (CPT) during our analysis period is located between 85–95 hPa. In the following, we adopt this estimate of the CPT pressure as the threshold to distinguish the upper troposphere (UT) from the lower stratosphere (LS). The partial column water vapor (PCWV) above the tropopause is defined as the water vapor integrated from 83 to 68 hPa, whereas PCWV below the tropopause is integrated from 147 to 100 hPa. Figure R1 presents the deseasonalized anomalies of PCWV above the tropopause regressed onto the first principal component (PC1), its trend ($\mathrm{PC1_{TREND}}$), and interannual variability ($\mathrm{PC1_{IAV}}$). Conversely, Figure R2 shows the deseasonalized anomalies of PCWV below the tropopause, regressed onto the PC1 interannual variability and the second principal component (PC2). Our analysis focuses on the reanalysis datasets from M2-SCREAM, JRA-3Q, CAMS, and ERA5, excluding MERRA-2 due to its inability to represent variability in the LS.

The spatial distribution of PCWV (Fig. R1) regressed onto PC1 above the tropopause (hereafter, $\mathrm{PC1^{strat}}$) aligns well with the spatial pattern regressed onto PC1 in the UTLS (i.e., Fig. 1 in the manuscript). Meanwhile, the spatial distributions regressed onto PC1 and PC2 below the tropopause (hereafter, $\mathrm{PC1^{trop}}$ and $\mathrm{PC2^{trop}}$, Fig. R2) correspond to anomalies regressed onto UTLS PC2 and PC3, respectively (i.e., Fig. 2 in the manuscript). This indicates that the PC signals identified within the UTLS (shown in the manuscript) encompass both the LS (represented by PC1 in the manuscript) and the UT (represented by PC2 and PC3 in the manuscript). Specifically, PC1 (in the manuscript) captures interannual variability in the lower stratosphere ($\mathrm{PC1^{strat}}$), above the tropopause, whereas PC2 and PC3 (in the manuscript) reflect subseasonal variability in the upper troposphere ($\mathrm{PC1^{trop}}$ and $\mathrm{PC2^{trop}}$), below the tropopause. The high correlations observed between the UTLS principal components and those above/below the tropopause further support this interpretation (Fig. R3). Consequently, the discrepancies in trend between Aura MLS and reanalysis products predominantly stem from different trends in water vapor in the lower part of the tropopause layer (i.e., 147 hPa to 100 hPa). All reanalysis products simulate a regional moistening trend in water vapor above the tropopause, consistent with Aura MLS (Fig. R1b,e,h,k,n).

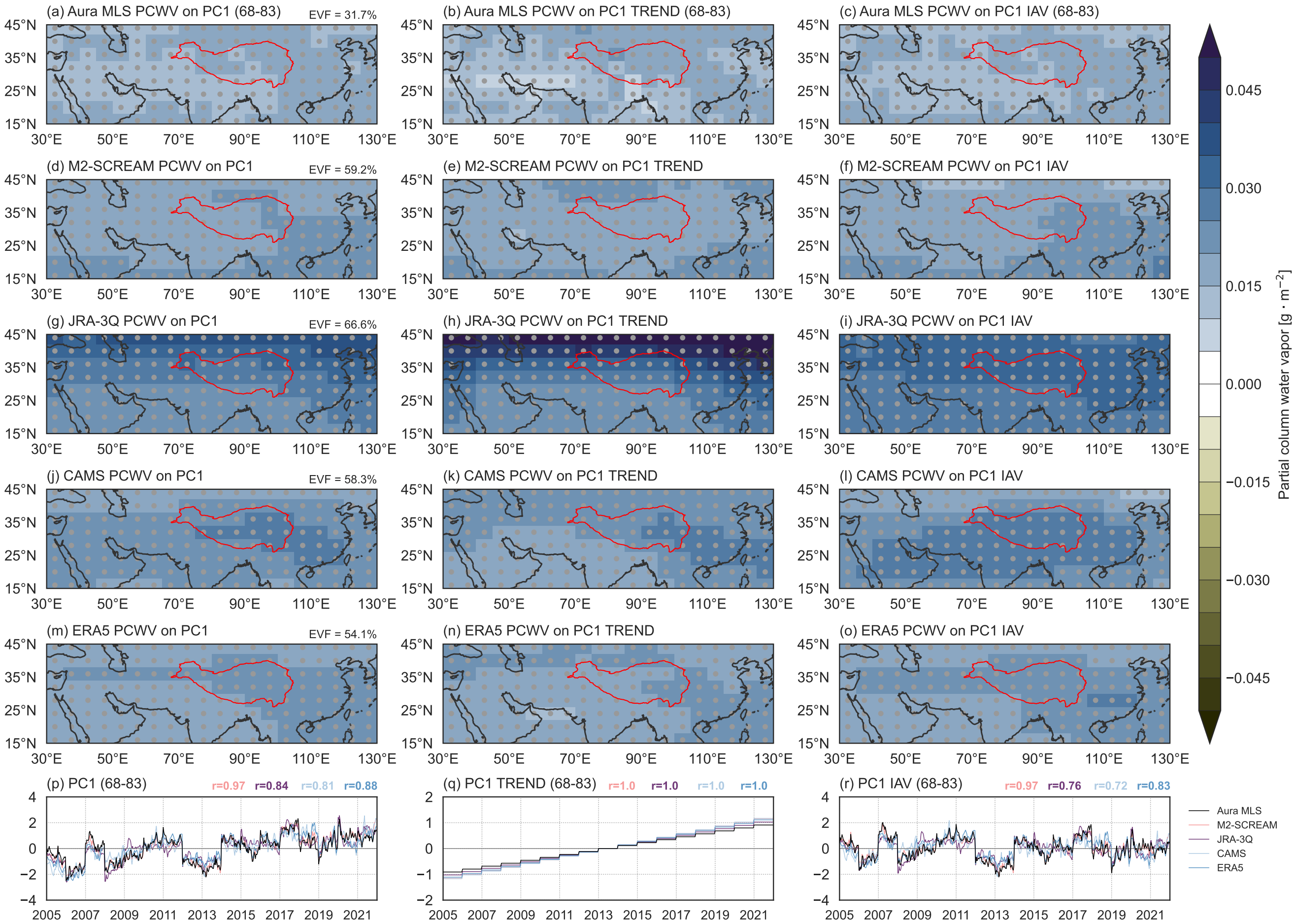

Figure R1: Deseasonalized partial-column water vapor (PCWV) anomalies integrated from 83 to 68 hPa regressed onto the (a) first principal component (PC1) from Aura MLS and its (b) trend ($\mathrm{PC1_{TREND}}$) and (c) interannual variability ($\mathrm{PC1_{IAV}}$) components; (d)–(f) same as (a)–(c), but for PC1 from M2-SCREAM; (g)–(i) same as (a)–(c), but for PC1 from JRA-3Q; (j)–(l) same as (a)–(c), but for PC1 from CAMS; (m)–(o) same as (a)–(c), but for PC1 from ERA5; and (p)–(r) the corresponding principal component time series. Principal components (PCs) are based on EOF analysis of vertical and horizontal variations in water vapor for the two Aura MLS pressure levels within 68 hPa–83 hPa, 30°E–130°E, and 15°N–45°N. Red contours mark the location of the Tibetan Plateau, with stippling indicating significance at the 95% confidence level based on Student's t test. The fraction of total variance explained by each mode is listed at the upper right of panels(a,d,g,j,m). Correlations between MLS-based PCs and those based on M2-SCREAM (light red), JRA-3Q (purple), CAMS (light blue), and ERA5 (dark blue) are listed from right to left along the tops of panels (p)–(r).

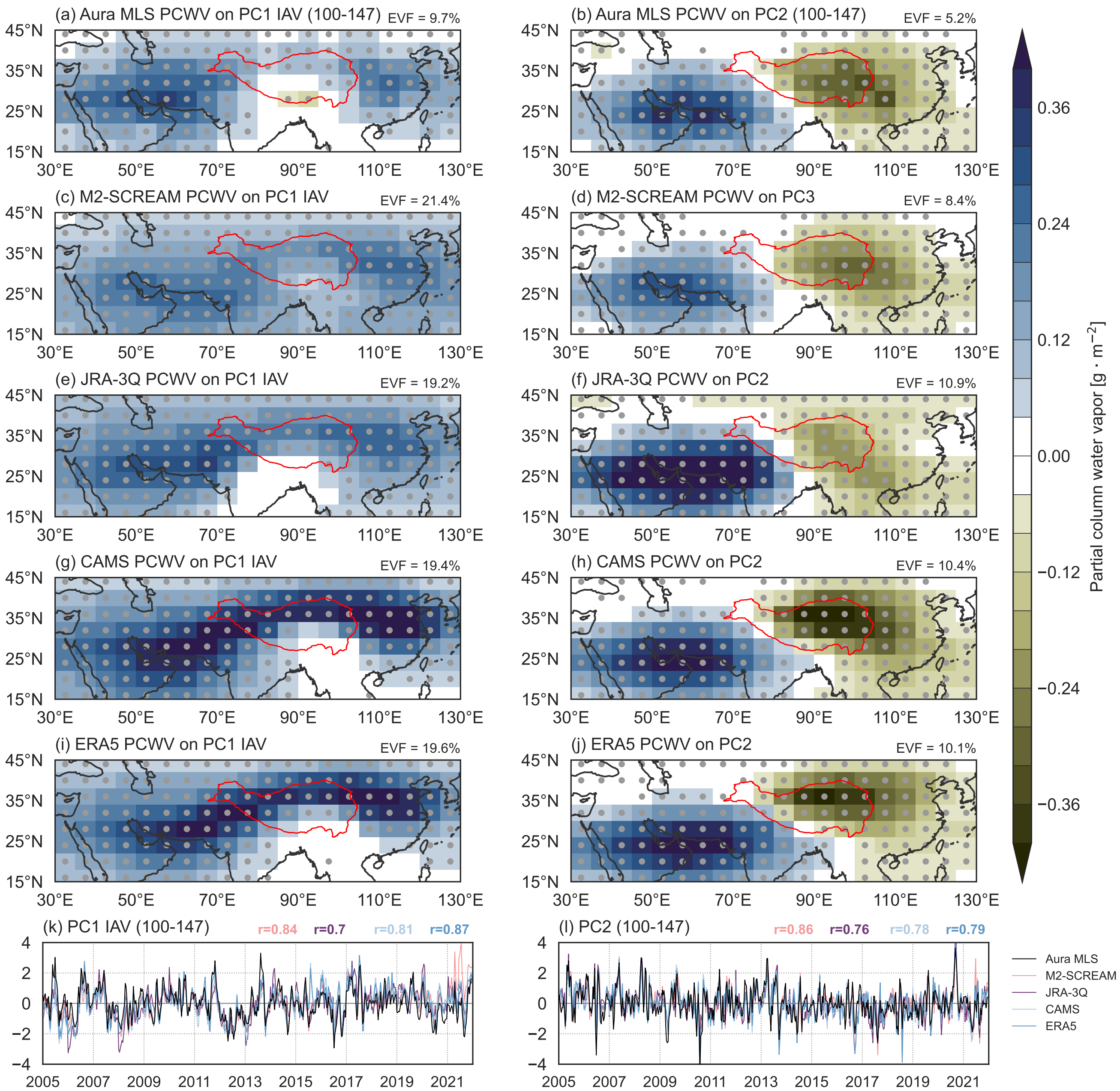

Figure R2: Deseasonalized partial-column water vapor (PCWV) anomalies integrated from 147 to 100 hPa regressed onto the (a) first principal component (PC1) interannual variability ($PC1_{IAV}$) and (b) the second principal component (PC2) from Aura MLS; (c)–(d) same as (a)–(b), but for $PC1_{IAV}$ and PC2 from M2-SCREAM; (e)–(f) same as (a)–(b), but for $PC1_{IAV}$ and PC2 from JRA-3Q; (g)–(h) same as (a)–(b), but for $PC1_{IAV}$ and PC2 from CAMS; (i)–(j) same as (a)–(b), but for $PC1_{IAV}$ and PC2 from ERA5; and (k)–(l) the corresponding principal component time series. Principal components (PCs) are based on EOF analysis of vertical and horizontal variations in water vapor for the three Aura MLS pressure levels within 100 hPa–147 hPa, 30°E–130°E, and 15°N–45°N. Red contours mark the location of the Tibetan Plateau, with stippling indicating significance at the 95% confidence level based on Student's t test. The fraction of total variance explained by each mode is listed at the upper right of panels(a–j). Correlations between MLS-based PCs and those based on M2-SCREAM (light red), JRA-3Q (purple), CAMS (light blue), and ERA5 (dark blue) are listed from right to left along the tops of panels (k)–(l).

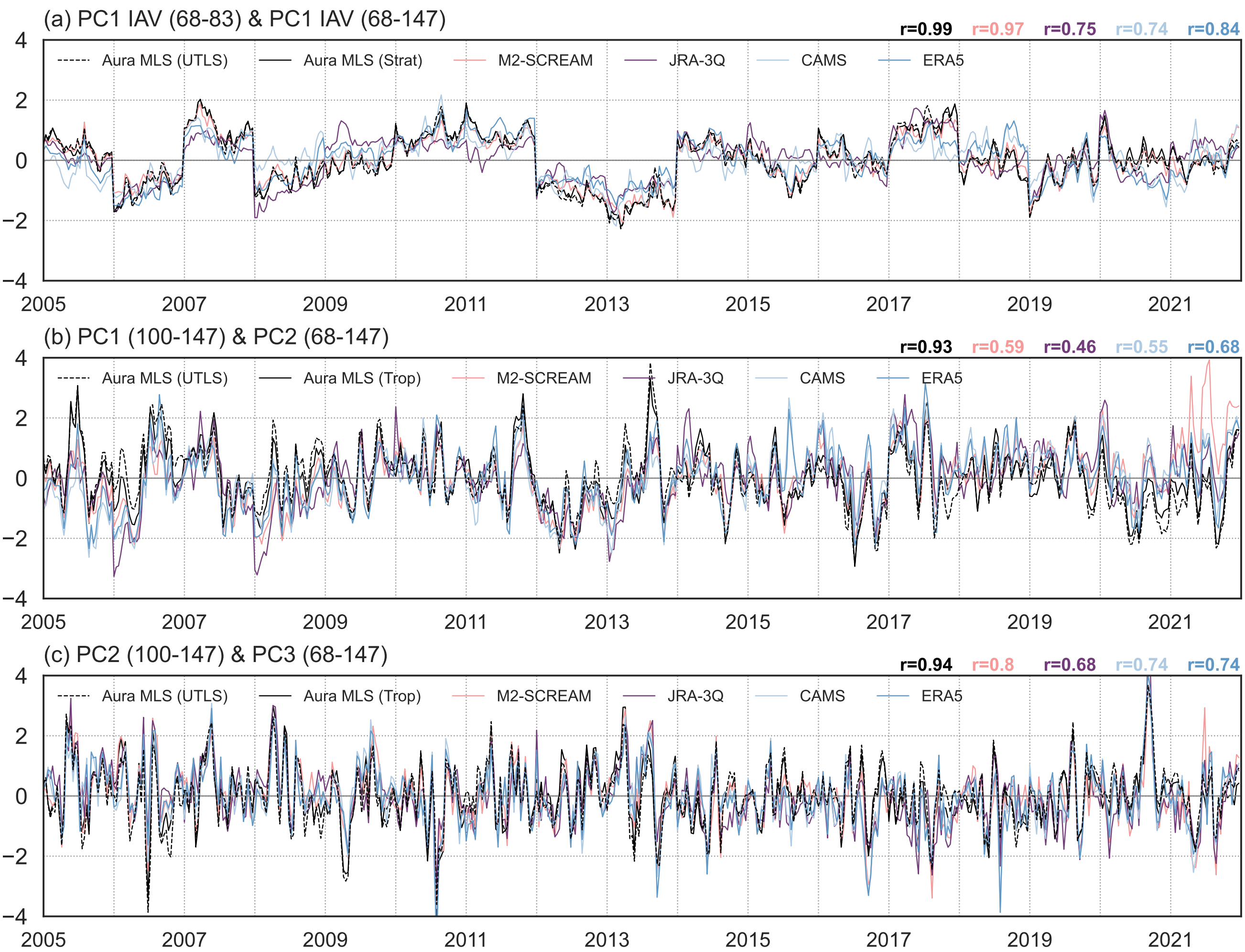

Figure R3: Principal component (PC) time series for the spatial patterns shown in Figs. R1 and R2 based on Aura MLS (black), ERA5 (dark blue), CAMS (light blue), JRA-3Q (purple), and M2-SCREAM (light red) and PCs shown in the manuscript based on Aura MLS (dashed black). Time series are shown for (a) the first principal component (PC1) interannual variability in the UTLS ($PC1_{IAV}$) and above the tropopause ($PC1^{strat}_{IAV}$); (b) the second principal component (PC2) in the UTLS and PC1 interannual variability below the tropopause ($PC1^{trop}_{IAV}$); and (c) the third principal component (PC3) in the UTLS and PC2 below the tropopause ($PC2^{trop}$). PCs in the UTLS are based on EOF analysis of vertical and horizontal variations in water vapor for the five Aura MLS pressure levels within 68 hPa–147 hPa, 30°E–130°E, and 15°N–45°N; PCs above the tropopause are based on EOF analysis of vertical and horizontal variations in water vapor for the three Aura MLS pressure levels within 68 hPa–83 hPa, 30°E–130°E, and 15°N–45°N; and PCs below the tropopause are based on EOF analysis of vertical and horizontal variations in water vapor for the three Aura MLS pressure levels within 100 hPa–147 hPa, 30°E–130°E, and 15°N–45°N. Correlations between MLS-based PCs in the UTLS and those based on MLS above/below the tropopause (black), M2-SCREAM (light red), JRA-3Q (purple), CAMS (light blue), and ERA5 (dark blue) are listed from right to left along the tops of panels (a–c).

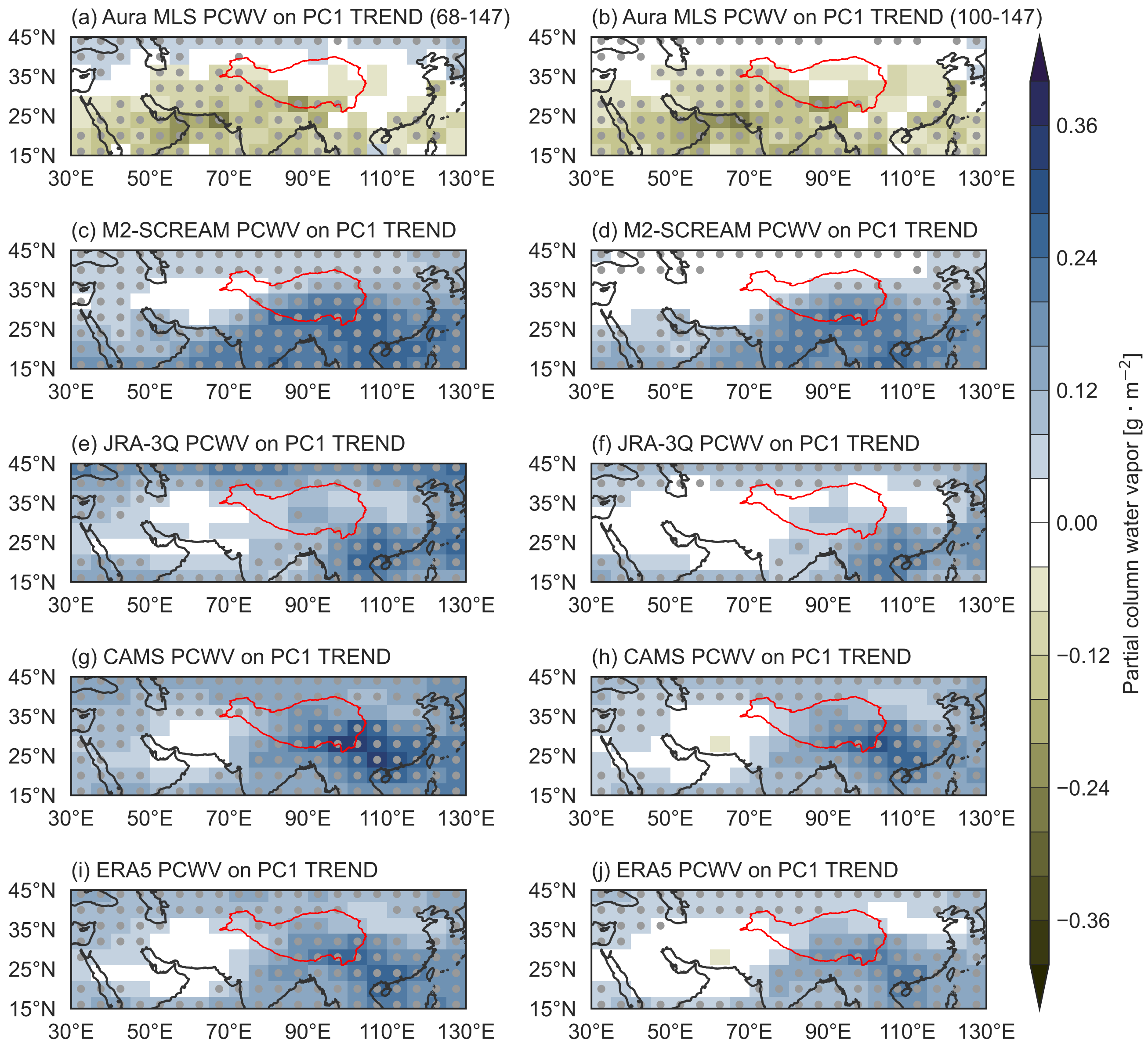

Figure R4: Deseasonalized partial-column water vapor (PCWV) anomalies integrated (a) from 147 to 68 hPa and (b) from 147 to 100 hPa regressed onto the first principal component (PC1) trend variability ($PC1_{TREND}$) from Aura MLS (Fig. R1q); (c)–(d) same as (a)–(b), but for PCWV from M2-SCREAM; (e)–(f) same as (a)–(b), but for PCWV from JRA-3Q; (g)–(h) same as (a)–(b), but for PCWV from CAMS; (i)–(j) same as (a)–(b), but for PCWV from ERA5. Principal components (PCs) are based on EOF analysis of vertical and horizontal variations in water vapor for the two Aura MLS pressure levels within 68 hPa–83 hPa, 30°E–130°E, and 15°N–45°N. Red contours mark the location of the Tibetan Plateau, with stippling indicating significance at the 95% confidence level based on Student's t test.

Comment 1.2

Another question from my side, whether the second reason to doubt the reanalysis-based trends are robust: "trends in cold point tropopause (CPT) temperatures are negative in the southeastern quadrant of the anticyclone where the reanalyses show the largest positive trends in water vapor" (in conclusion). If reanalysis WV increase mainly under the tropopause and thus increase the PCWV, it seems be consistent with OLR/cloud trend (convection increase pattern shown in Figure 6). It thus meets "criteria 3: a plausible physical mechanism". And WV decrease due to local CPT decrease is not a main driver since the mass of WV in the LS is much less than that in the UT. Surely, long-term warming of the tropical cold point tropopause increasing WV outside the monsoon region can be another reason. But I don't see the contradiction between CPT cooling and PCWV increasing over one region.
To shed more lights on this point, my suggestion could be:
1) the trends (and their spatial characteristics) be further decomposed into contributions above and below the tropopause;
2) further analysis of the "dyn" and "phy" terms individually (specifically their behaviours above and below the tropopause) in Fig. 7. This could potentially reveal whether convection is the primary driving factor in the trends observed. And this could uncover systematic patterns or consistencies within these two terms from reanalysis datasets.

Response:

Thank you for your detailed and insightful comment. We agree that the trend below the tropopause meets the third criterion (but not the second) and will work to make this clearer in the revised text. This possibility motivates our call for a more complete analysis of trends in UTLS composition and related fields in this region at the end of section 3.1.

As discussed in our response to Comment 1.1, PC1 in our manuscript primarily corresponds to interannual variability in the humidity of the lower stratosphere ($\mathrm{PC1^{strat}}$, see Fig. R1 and Fig. R3a). Both reanalysis products and observations indicate a regional moistening trend above the tropopause (Fig. R1, R5a). Although these moistening trends occur downstream of the positive anomalies in the cold point tropopause (CPT) (Fig. R5), consistent with the expectation that a warmer CPT should enhance water vapor content above the cold point, it is difficult to relate these to the enhanced convection in the southeast quadrant. The difficulty arises because there is a trend toward colder cold point temperatures co-located with that increase in convective activity. To evaluate this in more detail, we will examine the changes in tendency terms between these two regions. For example, if the positive trend in the CPT and the positive trend in LSWV are mechanistically related, then we may expect to see a positive trend in the physics term (less condensation drying) in the locations where the CPT has warmed, all else remaining equal.

In an area- and annual-mean sense, trends in resolved transport (DYN; $-\nabla \cdot (\mathbf{V}q) - \partial(\omega q)/\partial p$) are small but positive both above (Fig. R6) and below the tropopause (Fig. R7) in the reanalyses. However, the increases in these transports are offset by a decreasing trend in the physical tendencies (S_{phy}), and sometimes more than offset, as is the case in MERRA-2. The net changes in PHY + DYN trends are inconsistent across different products and are effectively offset by the data assimilation components (S_{ana}), regardless of the altitude relative to the tropopause. We interpret this lack of any significant trend in the ASM UTLS budget as indicating that the consistent moistening trend in LS water vapor is driven by processes outside the monsoon season or domain. Because the trend in the upper tropopause is more spatially heterogeneous, analysis of the area-mean budget is insufficient. We will investigate the mechanisms in the trend below the tropopause as we prepare the revised manuscript and include an update when we submit that revision.

1.2 Specific comments

Comment 1.3

Following EQ (2) in Line 160, the terms "Sphy" and "Sana" should be briefly explained. Specifically: What key physical processes related to water vapor are captured by "Sphy" (e.g., condensation, deposition, subsidence, etc.)? What is the role of "Sana," particularly in relation to the data assimilation process? I also wonder whether subgrid-scale mixing is included in the "Sres" term?

Response:

Thank you for this suggestion. We will explain these terms in more detail in the revised manuscript.

S_{phy} comprises the influences of parameterized physical processes, including cloud microphysics, convection, and turbulent mixing (see Wright et al. (2025), their Fig. 8). Subgrid-scale mixing is included in S_{phy}. S_{res} is a 'diffusive' residual, which we interpret this residual as primarily representing the transport due to high-frequency or small spatial scale motions resolved by the reanalysis model but not by our calculation of S_{dyn}, together with the effects of numerical diffusion. To reiterate, we calculate S_{dyn} on a coarser spatial grid (for ERA5, by a factor 4) and the analysis interval (1 h) is five times

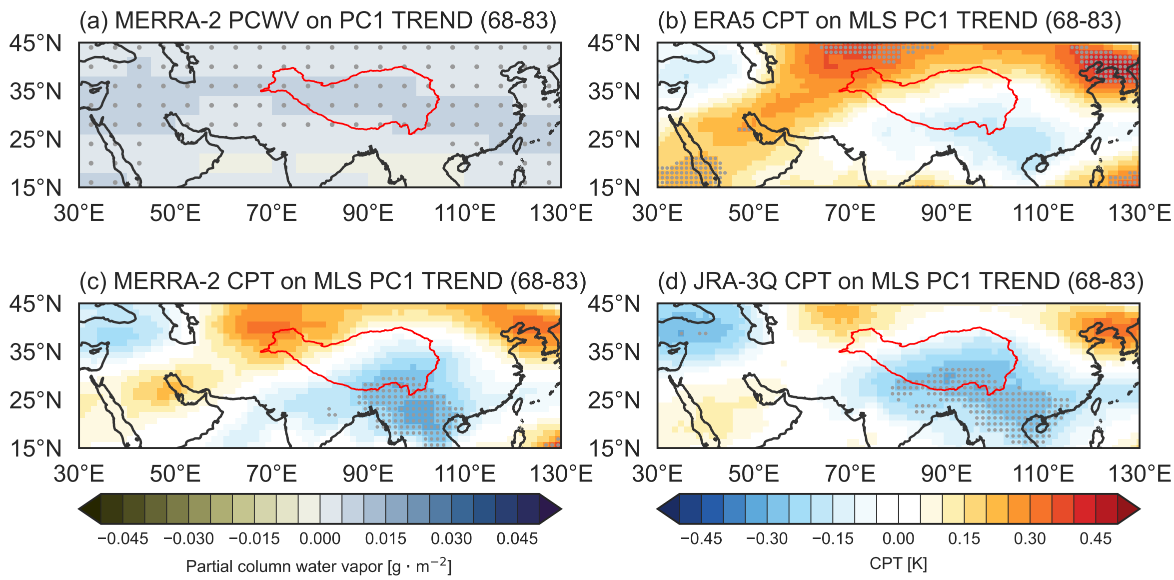

Figure R5: (a) Deseasonalized partial-column water vapor (PCWV) anomalies integrated from 83 to 68 hPa regressed onto the first principal component (PC1) trend variability ($\mathrm{PC1_{TREND}}$) from Aura MLS. Changes in cold point tropopause (CPT) temperatures based on (b) ERA5, (c) MERRA-2, and (d) JRA-3Q regressed onto $\mathrm{PC1_{TREND}}$. The location of the Tibetan Plateau is marked by a red contour in all panels. Stippling indicates locations where regression slopes are significant at the 95% confidence level based on Student's t test.

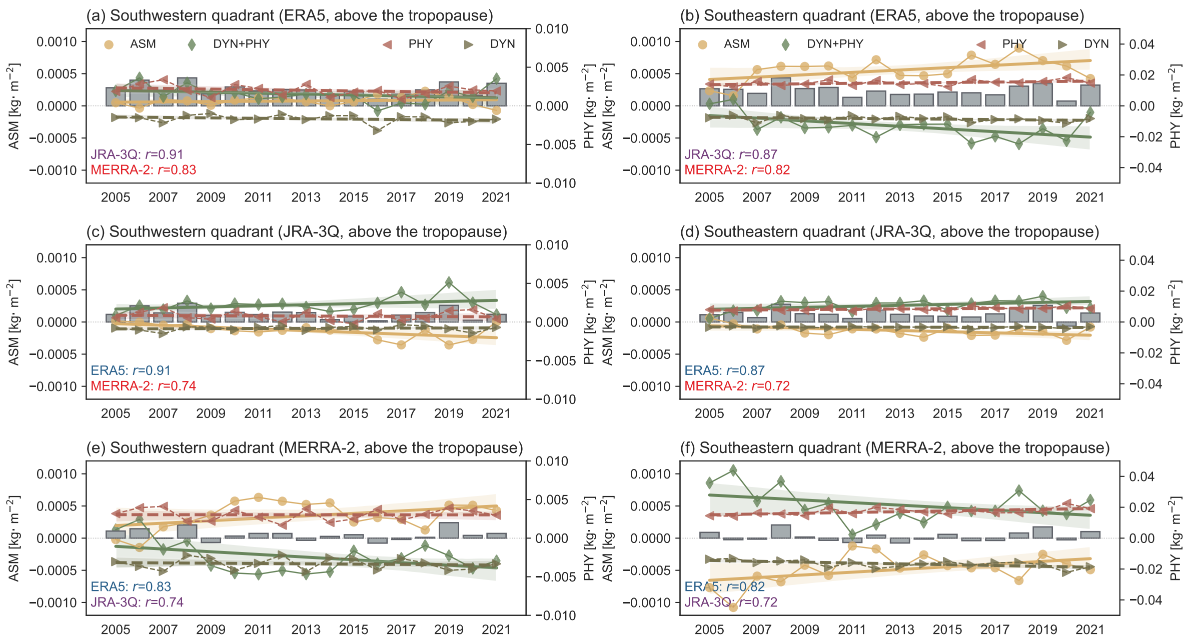

Figure R6: Yearly variations in the sum of the dynamics and physics terms (green lines), assimilation increments (yellow lines), dynamics terms (brown lines), physics increments (red lines), and time rate of changes in partial column water vapor (gray boxes) above the monsoon tropopause layer (68-83 hPa) based on (a,b) ERA5, (c,d) JRA-3Q, and (e,f) MERRA-2 over (a,c,e) the southwestern quadrant (15°N–30°N, 30°E–80°E) and (b,d,f) the southeastern quadrant (15°N–30°N, 80°E–130°E) of the monsoon anticyclone. Correlation coefficients between net water vapor tendency time series based on individual reanalyses are listed in the lower left corner of each panel.

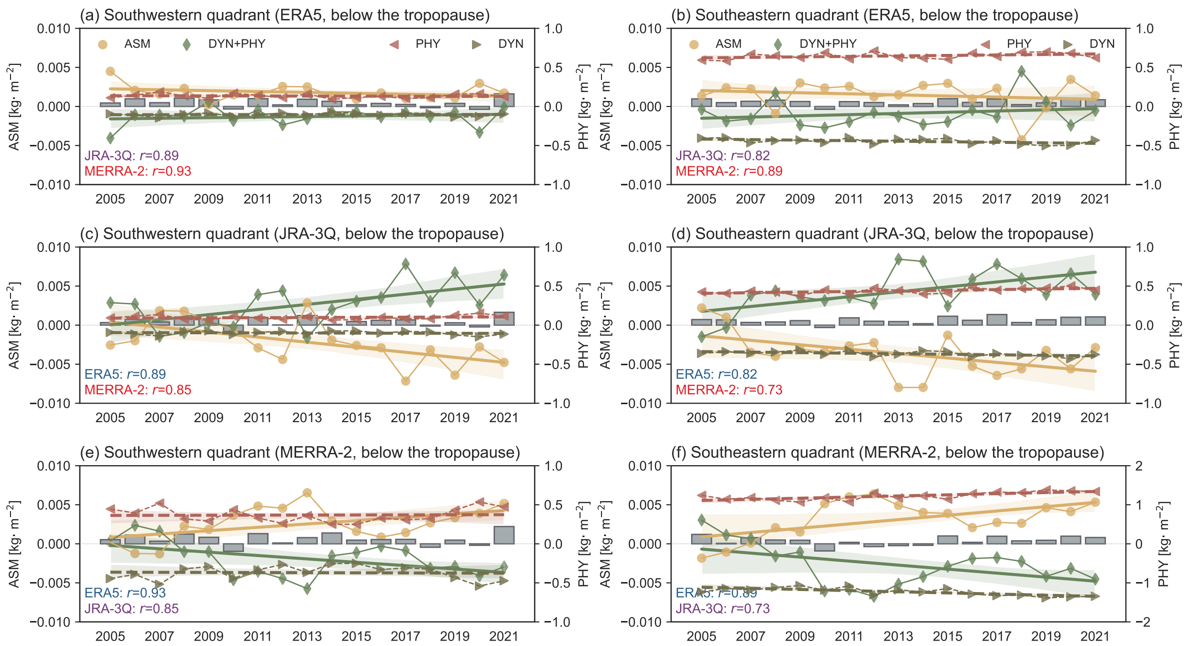

Figure R7: Yearly variations in the sum of the dynamics and physics terms (green lines), assimilation increments (yellow lines), dynamics terms (brown lines), physics increments (red lines), and time rate of changes in partial column water vapor (gray boxes) below the monsoon tropopause layer (100–147 hPa) based on (a,b) ERA5, (c,d) JRA-3Q, and (e,f) MERRA-2 over (a,c,e) the southwestern quadrant (15°N–30°N, 30°E–80°E) and (b,d,f) the southeastern quadrant (15°N–30°N, 80°E–130°E) of the monsoon anticyclone. Correlation coefficients between net water vapor tendency time series based on individual reanalyses are listed in the lower left corner of each panel.

longer than the model time step (every 12 minutes). As a result, our calculation is missing a chunk of the transport that the model resolves. Because the model resolves this transport, it does not appear in the physics term. Because our calculation of moisture flux divergence does not resolve this transport, it does not appear in the dynamics term. We have struggled to come up with a good name for this term that clearly conveys what it represents ('resolved mixing' as opposed to 'subgrid-scale mixing'? 'eddy transports'?) and would welcome suggestions. Finally, the residual term also includes the effects of numerical diffusion.

S_{ana} is the data assimilation term. MERRA-2 explicitly provides S_{ana}, but this component must be estimated for budgets based on ERA5 and JRA-3Q. We estimate S_{ana} for ERA5 and JRA-3Q by directly subtracting forecast specific humidities (the model-generated background state before data assimilation) from analysis specific humidities (the final reanalysis product after data assimilation). We then average this difference and multiply by the number of analysis cycles per day (two for ERA5 and four for JRA-3Q) to get an assimilation-related moistening rate in units of per day (alternatively we could divide by the length of the analysis cycle). More details on these terms and their interpretation have been provided by Wright et al. (2025) in their sections 2.1 and 4.

Comment 1.4

Figure 1: The titles of the three subplots for MERRA-2 (panels am-cm) are incorrect; they should refer to "PC1" instead of "PC2."

Response:

Thank you for your careful check. However, due to the distinct characteristics of different reanalysis datasets in the upper troposphere and lower stratosphere (UTLS), the principal components (PCs) derived from each dataset are not necessarily directly comparable on a one-to-one basis. We therefore attempt to match the modes in terms of their spatial signatures. Under this approach, PC2 in MERRA-2 corresponds to PC1 in other reanalysis datasets. The reason for this difference is that MERRA-2 relaxes stratospheric water vapor to a zonal-mean climatology with a 3-day relaxation time scale, washing out low-frequency variability in the lower stratosphere. PC1 based on Aura MLS is defined largely by the variance in lower stratospheric water vapor, so MERRA-2 does not represent this mode well.

Comment 1.5

Figure 3 (panel b): Please reduce the y-axis range to between -2 and 2 to allow for better visualization. Consider setting the y = 0 reference line to gray for improved clarity.

Response:

We appreciate your suggestion. The y-axes of all panels in the figure were set to a fixed range of -4 to 4 to ensure facilitate comparison across the panels. However, we acknowledge that this choice makes it more difficult to compare the line profiles in panel b effectively and will revise Figure 3 to address this issue.

Comment 1.6

I wonder why MLS trend show larger positive trend than merra-2 (Fig. 3)? It seems conflict with Fig.1. Does that mean MLS PC1 trend for the whole region is positive? And the positive trend is highly contributable from 35-45N latitude band according to Fig.1 (b)?

Response:

Thank you for raising this question, which highlights a logic error in our presentation of Fig. 1. MERRA-2 exhibits the smallest trend in the low-frequency PC among the datasets we examine, corresponding to $PC2_{\mathrm{TREND}}$ in MERRA-2. This is primarily because MERRA-2 damps lower stratospheric water vapor variability through relaxation toward a zonal-mean annually-repeating seasonal cycle, resulting in comparatively small year-to-year variability and trend signals. Because the trend in the lower stratosphere (the main point of consistency between Aura MLS and the reanalyses) is small, the low-frequency mode in MERRA-2 is dominated by variations below the tropopause and tilts more toward $PC2_{\mathrm{IAV}}$. Conversely, MERRA-2 shows larger PCWV anomalies when regressed onto the trend component compared to MLS. This is because all regressions were shown for $PC_{\mathrm{TREND}} = 1$. This approach is appropriate when the principal components are standardized, as in Fig. 2 and column (a) of Fig. 1. However, because we have not re-standardized $PC1_{\mathrm{TREND}}$ and $PC1_{\mathrm{IAV}}$ the magnitude of the water vapor anomalies associated with both modes is overstated in columns (b) and (c) of Fig. 1. This overstated amplitude is more pronounced for MERRA-2, because time variance in $PC2_{\mathrm{TREND}}$ based on MERRA-2 is smaller than that for $PC1_{\mathrm{TREND}}$ based on the other datasets. To correct this, we will keep the current time series of the trend and IAV parts of the low-frequency principal component but show regressions in columns (b) and (c) and Fig. 1 for the re-scaled trend and IAV time series.

Regarding your second question, yes, the positive trend in the full 147–68 hPa partial column is most robust along the northern edge of our analysis domain. However, Figs. R1 and R4 provide further insight on these spatial patterns as discussed in our response to comment 1.1 above. In our revised submission, we plan to use the differences in low-frequency modes for partial columns above and below the tropopause to clarify these details.

2 Response to reviewer 2

Summary evaluation: This work focuses on three leading modes of interannual variability in water vapor in the tropopause layer using the measurements from the MLS satellite and multiple reanalysis products. The first mode is linear trend and interannual variability in regional-scale anomalies, which show some differences in the satellite data and reanalysis. The second and third modes are related to anomalies within the monsoon anticyclone, such as, variabilities within the quadrants and a horizontal east-to-west dipole structure. The results show reanalysis captures the modes of variability in water vapor in the upper troposphere and lower stratosphere and the physical processes controlling them. The results shown here are based on comprehensive, thorough and very detailed analyses. However, I did not see clear motivation and goal of the work. Below are my comments for the authors might take into consideration.

2.1 General comments

Comment 2.1

L1 (Abstract): Rather than starting with 'we describe', I recommend start with some background information including why the Asian summer monsoon is important and what the goal of this study is. This will make the abstract more appealing.

Response:

Thank you for this suggestion. We removed this background information from the abstract at submission due to word count requirements, but will work to formulate a more appealing abstract that also meets the length requirement in the revised manuscript.

Comment 2.2

L16 (Introduction): It was mentioned that the goal of this study is to provide further insight into the mechanisms governing variations in water vapor. More specific information could be added here. What are examples of the mechanisms that we need to understand further? What variations in water vapor is discussed here? What is the science goal? A clear motivation and some scientific context of this work will be necessary. This work maybe relevant to the fact that there will be less observations of stratospheric water vapor available from satellites in the near future.

Response:

Thank you for raising these questions, which provide helpful guidance for us to present the work in a way that will be clearer and easier for readers to understand.

The research gaps and processes that we target in this work are articulated at the end of the first paragraph in the introduction: "Despite much progress in recent years, uncertainties remain regarding the relative influences and interplays among convective transport, the large-scale circulation, and thermodynamic structure near the tropopause in controlling humidity and composition in the upper troposphere and lower stratosphere (UTLS) above the ASM." We revisit this in the closing paragraph of the introduction, in the sentence following the one you reference: "We pay particular attention to characteristic patterns of covariability among convective activity, circulation patterns, and trace gas concentrations [as represented in current reanalysis systems]". To this, we should add that we evaluate the roles of data assimilation relative to those of parameterized physics and large-scale dynamics in allowing reanalysis systems to reproduce recurrent patterns of water vapor variability in the UTLS above the ASM.

Comment 2.3

In depth and very detailed analyses and descriptions of the results are presented in this work. I found it rather hard to understand all the detailed descriptions of figures. Many of the sentences are long and the description of results contains some speculation, besides facts. It would be helpful if some of the long sentences are split into multiple short sentences and simplify the descriptions.

Response:

We appreciate your suggestion and will make changes to the text accordingly.

Comment 2.4

It would also be helpful to include some context of the results from this work relative to previous studies throughout the main text. How is the result shown here different from previous work? Are they consistent with or different from previous work? This will help understand the results more scientifically. Is EOF analyses giving us new information that has not been discovered?

Response:

Thank you for this suggestion. Although direct comparisons are not always possible due to methodological differences, we have provided a discussion of our results in the context of previous work in section 4. It is also worth noting that the EOF analysis is primarily an exploratory tool. The first question we address with this tool is: are recurrent patterns similar between high-quality observations and reanalysis products? Having established that they are largely similar and delineated areas of disagreement, we address a second question: do these recurrent patterns derive from clear physical and dynamical mechanisms?

The decision to use EOF decomposition in this work was motivated by both the widespread use of this procedure in climate science and the platform it provides for us to identify and analyze recurrent patterns of water vapor anomalies. The EOF approach has known limitations (non-stationary, unable to cleanly identify propagating patterns) and many other statistical tools could provide a similar platform. Moreover, EOF patterns in isolation can be difficult to interpret and are often not physically meaningful. Although the use of vertically resolved information in identifying these patterns has not to our knowledge been applied to this region before, it is not the EOF analysis itself that provides new information, but rather our detailed decomposition of how the reanalyses generate the recurrent anomaly patterns identified by the EOF decomposition.

We will work to clarify these distinctions in the revised manuscript.

Comment 2.5

I think it would be helpful to provide some outlook. For instance, information about which reanalysis products represent dynamical or thermodynamical processes near the monsoon region well so that we can trust?

Response:

Thank you for this suggestion. We will collect and collate this information from the manuscript and include a summary of outlook recommendations in the final section.

2.2 Specific Comments

Comment 2.6

L39 – “The smooth boundaries and distinct shape of the climatological anticyclone” can be explained further with specific descriptions here. What does ‘smooth’ mean? Does ‘distinct shape’ refer to eddy shedding event?

Response:

In this case we use “smooth” and “distinct shape” to refer to the clear, smooth, oblong boundary around the time-mean Asian summer monsoon anticyclone as often shown in the literature. This is often shown in isobaric geopotential height (see, e.g., Nützel et al. 2016), isentropic Montgomery streamfunction (see, e.g., Manney et al. (2021)), or potential vorticity (Fig. 14 of our manuscript). We will add some additional context to set the stage for this sentence in our revised submission.

Comment 2.7

L65 – A brief mention of why all these species are analyzed together will be useful here.

Response:

The rationale for examining these species together is outlined in detail in the preceding paragraph. We will clarify this relationship in the revision.

Comment 2.8

L66 – Here 'further insight' sounds vague. Consider replacing it with more specific terms. For instance, 'analyzing seasonal behaviors or interactions between various processes that have not been analyzed before'.
L68 – Instead of 'pay attention', mentioning what is new in this work compared to the related work (Tegtmeier et al. and Wright et al.) would be recommended.

Response:

We apologize for the misunderstanding. Here we feel that "further insight" is appropriate because what we provide is a new perspective (via the reanalysis-based budget decomposition) on processes that have been extensively analyzed but remain incompletely understood and poorly quantified. More specifically, as outlined in the first two paragraphs of the introduction, many previous studies have examined variability in the composition of the monsoon UTLS from a variety of perspectives, yielding a good qualitative understanding and situational quantitative information on how these processes and covariations contribute. Although the ability of reanalysis products to represent the processes previous studies have shown to be important is an open question, it is important to us to respect the effort and body of work that have established a foundation for us to address that question.

Comment 2.9

L81 – What horizontal grids are used in the gridding?
L112 – Is the 'replay' technique commonly used or specific to this study?

Response:

L81: We adopt the coarsest grid among the evaluated datasets and interpolate all dataset onto this grid for the analysis. This grid corresponds to the Aura MLS Level 3 products on a 2.5°×2.5° regular latitude–longitude grid.

L112: "Replay" is a technique developed by NASA GMAO. In addition to M2-SCREAM, it has been used in a number of specified dynamics-type model simulations (e.g., Orbe et al. 2017). It is not specific to this study.

Comment 2.10

L140 – The meaning of this sentence is unclear as well. Are specific humidity tendencies produced by parameterized physics and data assimilation?

Response:

Specific humidity tendencies ($\partial q/\partial t$) are decomposed into contributions from parameterized physics (S_{phy}), data assimilation (S_{ana}), and moisture flux convergence due to resolved dynamics ($\nabla \cdot (\mathbf{V}q) + \frac{\partial(\omega q)}{\partial p}$). Please see Section 2.2 for details.

Comment 2.11

L176 - What does 'weighted equally' mean here?

Response:

In the most common applications of EOF analysis, time variations of two-dimensional (latitude-longitude) spatial patterns are evaluated. In our analysis, we instead flatten the horizontal dimensions and apply the EOF decomposition to vertical-horizontal distributions. One dimension corresponds to both latitude and longitude, while the second corresponds to pressure within the 147 hPa–68 hPa layer. In this context, "weighted equally" means that anomalies in all vertical layers are given the same weight in the decomposition, so that the only weights that apply to the input data are the area weights in the horizontal dimension.

Comment 2.12

L207 – Instead of stating 'no prior expectation', one can try to find if there is a known trend in water vapor.

Response:

"No prior expectation" is meant in a roughly Bayesian sense: when developing the analysis, we did not consider whether a linear trend was likely or unlikely to exist in the data. However, as the analysis proceeded, it became clear that the low-frequency principal component exhibited a significant trend, and that the spatial pattern of this trend was distinct from that of interannual variability. Although we are unaware of any previous study highlighting a trend in this region, there have been reports of trends in adjacent regions, such as water vapor in the extratropical lowermost stratosphere (e.g., Dessler et al 2013) or the trend in cold point tropopause temperatures referenced in the discussion (Zolghadrshojaee et al., 2024).

Comment 2.13

Figure 5 – It is striking to see how the left panel (MLS) and the right panel (CAMS) look very different for all the species. It is not easy to understand the explanations of this figure.

Response:

This is a key point we wish to emphasize in our manuscript: the observed and reanalysis trends differ, and therefore, caution must be exercised when interpreting these trends. At the suggestion of Dr. Tao (reviewer 1), we have conducted new analysis demonstrating that stratospheric variability associated with PC1 is largely consistent between Aura MLS and the reanalysis products. The differences illustrated in Figure 5 between MLS and reanalysis data thus attributable to different trends in water vapor below the tropopause, in the 147–100 hPa layer. For more details, please refer to our response to comment 1.1 above.

Comment 2.14

L303 – I am not sure how much we can assume that the drift correction for Aura MLS water vapor contributed to the trend. Is it just a speculation or based on some findings?

Response:

This an alternative hypothesis, namely: "the drift correction causes Aura MLS to miss a real moistening trend in this region". Because M2-SCREAM includes a positive trend, we have strong confidence that there is a (statistical but not necessarily meaningful) difference in the trend between MLS version 4 and MLS version 5.

We do not assume that this hypothesis is correct, and have largely discounted it because (1) other lines of evidence (like disagreements in the spatial patterns of trends in ozone and CO as remarked in the next sentence) suggest that the alternative hypothesis (i.e., that trends in reanalysis products are unreliable) is more likely and (2) we have a stronger prior expectation that trends in reanalysis products are unreliable. However, it remains a plausible if unlikely alternative hypothesis that thus deserves a place in the discussion. We will make sure that our skepticism about this hypothesis is made clear in the revision.

Comment 2.15

L571 – 'Concurrent variations. . . ' -> This sentence seems to be based on speculations.

Response:

Actually not, there are some studies results.