Response to Comments of Reviewer 1

*The authors thank all reviewers for their constructive comments and suggestions, which have helped us to improve the quality of this paper both in sciences and writing. All comments are carefully considered and responded to. The response in italic letters follows each comment.*

This manuscript presents a well-structured and scientifically significant study on air mass transport pathways over the Tropical Western Pacific (TWP), with a particular focus on the role of the cold trap in the upper troposphere and lower stratosphere (UTLS). Using lidar and balloon-borne observations from Koror, Palau, combined with trajectory simulations, the authors provide valuable insights into seasonal variations in air mass ascent and dehydration processes.

The study is particularly relevant as it enhances our understanding of how air masses transition from the troposphere to the stratosphere, a process fundamental for stratospheric water vapor balance and global climate dynamics. The authors effectively demonstrate the stark contrast between winter (December 2018) and summer (August 2022) conditions, showing that upward transport through the cold trap occurs primarily in winter, while summer air masses tend to descend. The inclusion of quantitative metrics, such as the fraction of air masses reaching above 380 K potential temperature, strengthens the findings and makes a compelling case for the seasonal dependency of stratospheric entry pathways.

Overall, this is an important and well-executed study that deserves publication. I only have a few minor suggestions regarding clarity, phrasing, and data presentation that could further improve the manuscript. These are detailed below:

(151). The use of two case studies (December 2018 and August 2022) allows for a seasonal comparison, adding depth and clarity to the analysis. However, in both case studies there is no description of the meteorological conditions that would have provided additional information about the local context in which the measurements were taken.

*Response:*

*Thank you for your comment. We agree that the meteorological context is important for interpreting the case studies. In our analysis, we use radiosonde data to provide temperature and humidity profiles that are directly matched to the observation time and location. These profiles capture the local atmospheric conditions relevant to our study, including tropopause temperature and moisture distribution, which are key factors influencing cirrus cloud formation and stratospheric transport. Given that the radiosonde measurements offer high temporal and spatial relevance to our case studies, we chose not to include additional meteorological field data. However, we will clarify this in the text to ensure that the role of the radiosonde data in providing meteorological context is explicitly stated.*

*We rewrote the following sentence:*

*"We analyzed two typical cases of cirrus cloud layers measured in December and August, combining meteorological conditions including temperature and RH profiles obtained from the radiosonde, measurements of cirrus clouds in the tropical tropopause layer (TTL), and trajectory simulation results."*

(176). There is no information here on where precisely the backtrajectories are initiated. Midcloud maybe? One trajectory per cloud? Clusters? You may consider to shift here (if appropriate) lines 417-420 from appendix A.

*Response:*

*We initiated the HYSPLIT trajectory from the cirrus cloud layers, specifically 5 trajectories between the cloud top and base height in each layer. The trajectories are started every hour corresponding to measurement time from ComCAL lidar observations. For ATLAS, trajectory starting points are spaced at 100 m interval within each cloud layer. The releasing time is the same as HYSPLIT with 1 h interval. The info are given in L115-122 and as you've mentioned L417-420.*

*We add some details about the trajectory setup and add a reference note here to the method section, in L178:*

*"To further analyze the STE pathways for different cloud types on this day, we present 20-day backward and forward trajectories from the upper and lower cloud layers in Fig. 3. Ascent is shown in red, while descent is shown in blue. Additionally, for long-lasting cirrus clouds, one back and one forward trajectory is initiated every hour. So within each cloud layer, multiple trajectories are initiated to capture variations. The trajectory setup details are described in Sect. 2.3 and Appendix A."*

Fig2. It would be nice that panel 2a, 2c and 2d could share the same vertical axes. This can be done by removing panel 2 b. The latter is cited in the text but not further discussed so it might be sufficient to state in the text the amount, variability and trends (if any) of the COD, and skip the figure. By the way, in the figure 2b there appear to be a lack of COD data between 11.5 and 12.5 and 13.15-14.15. Why? Moreover, in fig2a the colors are coded in a.u. Why? Can you plot explicitly the BR?
Response:

*We appreciate the reviewer's suggestions regarding Figure 2. However, we believe that keeping panel 2b is important for the following reasons:*

- *Scientific Context: Panel 2b provides essential information for cirrus cloud classification based on COD values. As COD is critical for distinguishing different cirrus types—ETTCi (extremely thin cirrus, COD < 0.005), SVC (subvisible cloud, COD < 0.03), thin cirrus (COD < 0.3), and thick cirrus (COD > 0.3)—this panel allows readers to understand the variability and distribution of cloud types directly from the figure. We updated the plot (Panel 2b) and marked the different cirrus types based on COD.*

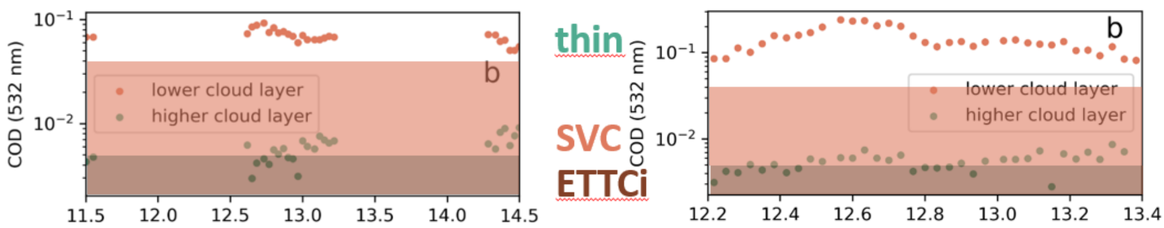


*Figure 1 (Fig.2b and Fig. 4b in the manuscript). The backscatter ratio (BSR) at 532 nm as a function of time and altitude. Thin cirrus (COD < 0.3), SVC (Sub-visible cirrus, COD < 0.03) and ETTCi (extremely thin cirrus, COD < 0.005) are marked.*

- *Trajectory and Seasonal Analysis: Panel 2b also supports the discussion of how different cirrus types, identified through their COD values, exhibit distinct seasonal patterns when combined with trajectory analysis. Removing this panel would weaken the connection between COD-based classification and the cloud variability discussed later, for example in Sect. 4 L295 "Different cloud types, such as SVC…".*

*Based on the reviewer's suggestions, we have added more descriptions and discussions of cloud COD in the text, clarifying its importance for cloud classification and seasonal variations.*

*Regarding the reviewer's specific questions:*

*Missing COD Data in Figure 2b: The absence of COD data between 11.55–12.61 and 13.21–14.28 is because the lidar was turned off during these intervals, as confirmed by our measurement records. The apparent continuous coloring in the pcolormesh plot of BSR (panel a) results from interpolation between available time points. We masked these time periods in the revised manuscript to avoid confusion.*

*Color Coding and BSR in Figure 2a: we thank the reviewer for the question regarding the units of the backscatter ratio (BSR) in Figure 2a. BSR is a dimensionless quantity because it is defined as the ratio of the total backscatter coefficient $\beta_{total}(\lambda)$ to the molecular (Rayleigh) backscatter coefficient $\beta_{Ray}(\lambda)$ :*

$$BSR = \frac{\beta_{total}(\lambda)}{\beta_{Ray}(\lambda)} = \frac{\beta_{par}(\lambda) + \beta_{Ray}(\lambda)}{\beta_{Ray}(\lambda)} = 1 + \frac{\beta_{par}(\lambda)}{\beta_{Ray}(\lambda)} \quad (1)$$

*where $\beta_{par}(\lambda)$ is the backscatter coefficient of particles, and the total backscatter is simply the sum of the contribution of the individual components. When the BSR value is greater than 1, there is more backward scattering in the atmosphere in addition to Rayleigh scattering. This is the amount available for assessing the strength of atmospheric backward scattering, which in this study is cirrus cloud.*

*Since both $\beta_{total}(\lambda)$ and $\beta_{Ray}(\lambda)$ have the same units (typically $m^{-1}sr^{-1}$) their ratio is unitless. Therefore, BSR does not have a physical unit and is expressed in arbitrary units (a.u.) on the color scale, indicating relative intensity rather than an absolute physical measurement.*

Fig.3. : See the remarks on Fig. 2

*Please see the response to Fig. 3 above.*

(205-207). In this sentence, it almost seems as if dehydration is a cause for upwelling, and it could be rephrased to avoid giving this impression. The Brewer-Dobson Circulation provides the dominant large-scale upwelling mechanism in the TTL, and deep convection and cold trap dehydration regulate the water vapor content, influencing the efficiency of air entering the stratosphere. While it is true that latent heat release from cirrus formation enhances local ascent, the radiative effects of cirrus can either amplify or dampen vertical motion depending on cloud properties. Therefore, the role of latent heat release by condensing cirrus in TTL ascent can be complex and not straightforward.

*Response:*

*Thank you for your suggestion. We see how the wording might imply a causal relationship between dehydration and upwelling, which was not our intention. We will revise the sentence to clarify that the Brewer-Dobson Circulation (BDC) is the primary driver of large-scale upwelling in the TTL, while deep convection and cold trap dehydration regulate water vapor content, thereby influencing stratospheric entry efficiency. We also appreciate the note on the radiative effects of cirrus clouds, and we will refine the discussion to better capture the complexity of their role in TTL ascent.*

*We rewrote and added the following sentences in L207:*

*"The lower and sub-saturated RHi below the CPT suggests that the cold trap during this period is not cold enough to further dehydrate the air parcels passing through it. Cloud formation in the cold trap releases latent heat, which may influence local temperature and stability. However, the radiative effects of cirrus clouds can either amplify or suppress vertical motion, depending on the ice crystal shape and size (Spang et al., 2024). Specifically, ultrathin cirrus clouds composed of spherical ice crystals tend to warm the atmosphere, while aggregated or hexagonal ice crystals lead to cooling. These cloud microphysical effects interact with large-scale circulation, potentially influencing the vertical transport patterns observed in the trajectories."*

*We also added the following sentences in L240 to strengthen the connection between the BDC and our analysis:*

*"A comparison of observed SVC and ETTCi and the associated trajectories shows that clouds with similar optical depth nevertheless ascend in winter and descend in summer. This contrast aligns with the seasonal variability of the BDC, which is stronger in NH winter, supporting enhanced upwelling over the TWP due to an extremely cold trap. In contrast, during NH summer, the BDC is weaker over Palau, and there is no evident large-scale upward motion shown in trajectory results. This implies that seasonal differences in the strength of the BDC play a key role in modulating the transport pathways, rather than cloud microphysical processes alone. …"*

(229). The potential influence of Kelvin waves is a valuable addition to understanding the August case. Is there direct observational evidence, as temperature anomalies or reanalysis data that confirm the presence of such waves?

*Response:*

*We have not yet conducted a specific analysis using reanalysis data over Palau for this study. Here, we propose Kelvin waves as a possible explanation based on previous studies, e.g. Immler et al., 2008, that have demonstrated their connection with cirrus clouds using reanalysis data. We plan to investigate this relationship over Palau in greater detail soon, leveraging targeted reanalysis data and cloud observations.*

(243-261) The section nicely extends the previous case studies by performing trajectory analyses for all cirrus clouds in two seasons. The inclusion of potential temperature analysis strengthens the transport pathway discussion. However, there is no information on where the trajectories are initiated in case of geometrically thick clouds. Midcloud? Or if the geometrical thickness is large, more than a backtrajectory is used for the same cloud? And for long lasting cirrus observation, do you launch a trajectory every 3 hrs? The sentence at (248) "The trajectories are initialized at the observed time and altitude of cirrus clouds above Palau, consistent with the case study methodology." should be expanded to provide such information explicitly. This has an impact on the understanding of the AEF afterward.

*Response:*

*Thank you for your thoughtful comments. The details regarding the trajectory initialization are already described in the Methods section (Sect. 2.3). As noted there, in our HYSPLIT simulations, we divide the cirrus cloud layer into five levels, and in the ATLAS simulations, back trajectories are released every 100 m. Therefore, for geometrically thick clouds, multiple back trajectories are indeed used. Additionally, for long-lasting cirrus observations, we initiate one back or forward trajectory per hour. These settings are consistently applied to both the case study and the full-month analysis. We will expand the sentence at line (248) to explicitly clarify this information in the Results section.*

*We will refer to the method section (Sect. 2.3) at the beginning of this section to enhance the clarity.*

*This is the rewritten sentences:*

*"Similar as the case studies, the trajectories are initiated for the time and altitude of cirrus clouds measured above Palau. Within the cloud layers detected by lidar, multiple trajectories are used to capture variations. The trajectory setup details are described in Sect. 2.3 and Appendix A."*

(265) How are different box regions (1-6) defined? In terms of continental/maritime convection? Presence of monsoon? Please explain in further detail the reason for this boxing choice.

*Response:*

*Thank you for your question. We use the regional definitions (regions 1–6) following Sun et al. (2022), which extended the tropical-based definitions of Fueglistaler et al. (2004) to ±60° latitude. However,* *since this study specifically focuses on tropical regions, we restrict our analysis to ±30° latitude, maintaining the original definitions and boundaries adapted from Sun et al. (2023).*

*We added the following sentences:*

*"The regional definitions (regions 1–6) used here follow Sun et al. (2023), adapted from Fueglistaler et al. (2004), but restricted to ±30° latitude to maintain a tropical focus."*

(267). What does N represent? Total trajectory points? Please state that explicitly.

*Yes, the total trajectory points. We rewrote this as following:*

*"where N (x,$\vartheta$) represents the total number of trajectory points in the specified box region. Here, x ranges corresponding to different geographic regions, and $\vartheta$ represents potential temperature, ranging from ≤ 350 K to ≥ 370 K in 10 K intervals. For instance, N (1, $\vartheta$ > 400 K) represents the number of trajectory points in the central east Pacific region within the vertical layer above 400 K (as indicated by the dark green box in Fig. 7b. The AEF is then calculated as the fraction of trajectory points in each box region to the total number of trajectory points."*

(275) The text presents a strong seasonal contrast (46% vs. 5%) but does not explicitly explain why December favors stratospheric entry. My suggestion: "The significantly higher AEF in December (46% reaching 380 K is consistent with stronger upwelling over the TWP during NH winter. This aligns with the seasonal phase of the Brewer-Dobson Circulation, which facilitates upward transport of TTL air into the stratosphere."

*Response:*

*Thank you for your insightful comment. We agree that the seasonal contrast in AEF suggests a stronger upwelling in December (NH winter). The suggested explanation aligns well with the seasonal phase of the Brewer-Dobson Circulation, which enhances the upward transport of TTL air into the stratosphere during NH winter. We have rewritten the text as you suggested to explicitly state this connection and clarify why December favors stratospheric entry.*

(279) The reference to the easterly upper-level winds and QBO connection need more clarity: The role of QBO-driven zonal wind patterns should be briefly explained. My suggestion: "The dominance of easterly winds in both months corresponds to the observed QBO phase during December 2018 and August 2022 (Diallo et al., 2018). Easterlies in the lower stratosphere favor upward transport by reducing mixing with mid-latitude air, enhancing tropical stratospheric entry."

*Response:*

*Thank you for your suggestion. We agree that the connection between QBO-driven zonal wind patterns and stratospheric entry should be more clearly stated. The proposed explanation aligns well with our* *findings, as the dominance of easterly winds during both months is consistent with the observed QBO phase in December 2018 and August 2022. We have revised the text here as you suggested to explicitly clarify that easterlies in the lower stratosphere reduce mixing with mid-latitude air, thereby enhancing the upward transport of tropical air into the stratosphere.*

(289). A better Explanation of the Chemical Equator (CE) is here needed. Add a brief sentence explaining what the CE represents and why it matters for tropical atmospheric composition.

*Thank you for your comment. We agree that a clearer explanation of the Chemical Equator (CE) would improve the readability of the text. We will add a brief sentence to define the CE and explain its significance in tropical atmospheric composition, particularly its role in distinguishing between air mass origins from NH or SH. We rewrote L289-291 as the following sentences:*

*"The inter-hemispheric mixing controls the origins of air masses from the northern or southern hemisphere in the tropics. The seasonal movement of the Chemical Equator (CE) (Hamilton et al., 2008, Sun et al., 2023) marks the boundary where air from both hemispheres converges and mixes, distinguishing air mass origins and influencing trace gas distributions. This dynamic separation reflects differences in anthropogenic and natural emissions between hemispheres, characterizing the tropical atmospheric composition. Figure 9 summarizes the results of our study in a schematic diagram of transport pathways, considering the seasonal shift of the temperature structure and inter-hemispheric mixing over the TWP. …"*

(330-337) Here consider to quote "Khaykin, S. M., Moyer, E., Krämer, M., Clouser, B., Bucci, S., Legras, B., Lykov, A., Afchine, A., Cairo, F., Formanyuk, I., Mitev, V., Matthey, R., Rolf, C., Singer, C. E., Spelten, N., Volkov, V., Yushkov, V., and Stroh, F.: Persistence of moist plumes from overshooting convection in the Asian monsoon anticyclone, Atmos. Chem. Phys., 22, 3169–3189, https://doi.org/10.5194/acp-22-3169-2022, 2022." and the dual role of overshooting convection, which may lead to hydration or dehydration depending on the synoptic-scale tropopause temperatures.

In general, this paragraph needs more clarity on the role of overshooting tops: First, explain why overshooting convection bypasses the cold trap and directly injects air into the stratosphere. Then, explain the impact of short-lived species.

*Response:*

*Thank you for your insightful comment. We agree that the dual role of overshooting convection in regulating stratospheric hydration and dehydration should be more clearly explained. We've revised the paragraph to explicitly describe how overshooting convection bypasses the cold trap, depending on the synoptic-scale tropopause temperature, as highlighted in Khaykin et al. (2022). We added the following sentences to L351 regarding the role of overshooting convection:*

*"The overshooting top is a rare but important pathway for tropospheric air entering the stratosphere, as shown in Fig. 9 in the white dashed line. During intense convection, such as severe thunderstorms, strong updrafts can propel warm, moist air above the CPT, forming a dome-shaped overshooting top that intrudes into the stratosphere (Wu et al., 2023; Fueglistaler et al., 2009). Although cold point overshooting tops account for only 1%-2% of all cirrus clouds above the CPT (Nugent et al., 2023), they play a key role in stratosphere-troposphere exchange (STE) by injecting air directly into the lower stratosphere.*

*The impact of overshooting convection on stratospheric humidity depends on the synoptic-scale tropopause temperature (Khaykin et al., 2022). As Fig. 9 shows, the overshooting top bypasses the CPT towards the warmer hemisphere. When the tropopause is cold, strong ice scavenging removes moisture, leading to dehydration of air parcels and cloud formation before they reach the stratosphere, as we measured in December. Conversely, when the tropopause is relatively warm, convective overshooting can bypass the cold trap and inject ice-rich air, leading to stratospheric hydration referring to the August case we measured. However, our measurements do not directly observe deep convection using ComCAL, as these clouds are too optically thick for backscatter detection. Instead, we infer the presence and effects of deep convection from seasonal comparisons of upper-level cirrus clouds combined with trajectory analyses. These cirrus clouds likely represent cloud detrainment after deep convection or dehydrated ice crystals formed from water vapor entering the TTL (Sun et al., 2024). This process influences the radiative balance and cirrus cloud formation. Additionally, overshooting convection rapidly transports short-lived species (NOx, CO, and hydrocarbons) into the lower stratosphere, bypassing tropospheric oxidation processes, particularly over the TWP, where the oxidizing capacity is low. These chemical injections impact ozone chemistry and the stratospheric oxidation capacity, further altering the stratospheric composition."*