Response to Editor comments on 2nd revision

We sincerely appreciate your careful review and the time you took to read our manuscript again. Your insightful comments and suggestions have helped us improve the clarity and accuracy of the paper. We have carefully addressed each of your comments, and we believe the revised version is now clearer and more robust.

Specific comments:

P1, L7: The statement: "Latent heat released during cloud formation drives the ascent of air

masses." is not correct. I guess you mean that the latent heat release causes a cooling that can lead to further ascending of air masses. However, if an air mass ascends or not is driven by the stability of the atmosphere. Latent heating has (if there is an impact) only a minor impact.

P1, L8: "A case study in December" -> could that be rephrased as well. You are doing a case study, but the measurements are available not only for December 2018.

Response to comments to abstract:

Thank you very much for your thoughtful comments and questions. Please find our responses regarding the abstract below:

1. Regarding latent heat and air mass ascent (P1, L7):

Thank you for highlighting this important point. We agree with your suggestion that latent heat release alone does not directly drive the ascent of air masses. To avoid any misunderstanding, we have removed this statement from the abstract. We revised the sentence as follows:

"These conditions lead to water vapor condensation, forming thin cirrus clouds which can be measured as an indicator of the ascent of air masses".

2. Regarding the wording "A case study in December" (P1, L8):

Thank you for pointing out the ambiguity here. We agree this wording can imply measurements are limited to December 2018, which is not the case. We revised this sentence for clarity as follows:

Revised sentence: "A representative example from December 2018 shows a subvisible cirrus cloud layer (optical depth < 0.03) measured by lidar, coinciding with high supersaturation observed by radiosonde."

P2, L32-33: "These cold temperatures significantly modify the pathways of air masses by dehydrating air and by the release of latent heat" -> they do not modify the pathways it is rather the amount of clouds or cirrus that are formed.

P2, L34 and throughout the manuscript: The term "dehydration" is misused. Dehydration is usually caused by sedimenting ice particles. Either you have to write this more clearly or you should omit the term dehydration here and at some other places in the manuscript. Note, while reading your paper and checking again on this processes in the TTL, I realized that the term that is missing here is "freeze-drying". This is the process that causes the dehydration in the TTL (see e.g. Uemura et al., https://doi.org/10.1002/2013JD021381, 2014).

Response to P2, L32-34 and the following paragraph:

1. Regarding the term "modify pathways" (P2, L32-33):

We thank the reviewer for this insightful comment. We agree that the phrase “modify the pathways” is not precise, as the cold temperatures primarily influence the formation and persistence of cirrus clouds rather than directly altering air mass pathways. We have revised the sentence to clarify:

Revised sentence (P2, L32-33): “These cold temperatures significantly influence the formation of cirrus clouds and thus the humidity in TTL.”

2. Regarding the term “dehydration” (P2, L34):

We thank the reviewer for this insightful comment. We agree that the term *“dehydration”* should be used with greater precision, particularly to emphasize the underlying microphysical processes. In the revised manuscript, we clarify the cloud formation via the *freeze-drying* process and that it is related to dehydration in the TTL. Air slowly ascending through the cold tropical tropopause forms ice particles that may sediment out of the airmass, reducing its water vapor content. Thank you for providing the literature by Ueyama et al. (2014), which stated that “air is dehydrated via the ‘freeze-drying’ process.”

We removed the sentence (P2, L34-35) where we misuse the term “dehydration”.

We have clarified this “freeze-drying” process in our revised manuscript accordingly (P2, L34):

“As air masses move horizontally within the TTL for long distances, they slow ascent, experiencing the coldest temperatures. Moisture is removed via condensation in a freeze-drying and subsequently sedimentation process (Ueyama et al., 2014).”

We have checked the paragraph accordingly (P2, L30-40) to keep this paragraph clearly stating the terms “freezing-drying” and “dehydration”. We also checked for misuse throughout the manuscript to ensure that “dehydration” is used in the context of the freeze-drying mechanism. We appreciate the reviewer’s guidance in helping us improve the clarity and accuracy of our terminology.

P3, L58: here you should replace “dehydration” rather by cloud formation processes. Using CALIOP cloud observations you observe when and where clouds occurred and in combination with models you are able to investigate the formation processes. You could also write “cloud formation and related processes as dehydration”.

Response:

Thanks. We replaced the “***dehydration***” with “***cloud formation and related dehydration processes,***” as you suggested.

P5, L124: “……potentially leading to associated dehydration of air masses through the removal of water vapor by ice particle formation.” Add “and subsequent sedimentation of the ice particles” since there will be no dehydration of the air mass if the ice particles haven’t sedimented. Note, same here as for P2, L34 while reading your paper and checking again on this processes in the TTL, I realized that the term that is missing here is “freeze-drying”. This is the process that causes the dehydration in the TTL (see e.g. Uemura et al., https://doi.org/10.1002/2013JD021381, 2014).

Response:

Thanks, we added “and their subsequent sedimentation.”

P5, L129-130: "……..with a hybrid vertical coordinate within the TTL changing from kinematic to diabatic." I hope you compare the kinematic versions of the model and use the diabatic version for further analysis. Could you rephrase the sentence as well to be more precise which versions of the models you actually compare?

Response:

We thank the reviewer for this important observation. In our study, the HYSPLIT trajectories were driven by the GDAS1 meteorological dataset using a kinematic vertical coordinate, while the ATLAS trajectories were driven by ERA5 reanalysis using a hybrid vertical coordinate that gradually changes from kinematic to fully diabatic above 100 hPa. So, we admit that the comparison between HYSPLIT and ATLAS reflects the combined influence of differences in reanalysis data, trajectory model, and vertical coordinate approach.

Our intention was not the thorough inter-comparison of models and to isolate the effect of vertical coordinate alone but rather simply to demonstrate the sensitivity of TTL trajectory pathways to different common modeling frameworks and inputs. We suggest clarifying this and revising the sentence (L129-130) in the manuscript to more precisely reflect this scope.

In a later specific comment in this response, we continue our answer to this question with more detail, also in the context of the Appendix.

Revised sentences (P5, L129-130):

"To investigate the sensitivity of trajectory pathways calculated with HYSPLIT setup, we conducted additional simulations using the Alfred-Wegener-InsTitute LAgrangian Chemistry/Transport System (ATLAS) transport model (Wohltmann and Rex, 2009), driven by ERA5 reanalysis data and applying a hybrid vertical coordinate that gradually changes from kinematic to fully diabatic above 100 hPa."

We suggest adding the following sentence (P5, L130) to clearly state the aim of using two models:

"In this study, a thorough inter-comparison between the two models is not the focus. Instead, the relative distributions of different pathways are of main interest. In this sense, the example case study results between the two models are given, and the differences in reanalyzing data inputs are neglected."

P8, L167: "….air mass to release latent heat and subsequently rise into the stratosphere" you mean from deep convective clouds? Here of course the latent heat may have a higher impact and may have an influence on the ascent of air masses.

Response:

Thank you for your comment. We did not intend to refer to deep convective clouds here. Instead, we are describing the large-scale ascent of air masses into the stratosphere. As the air ascends and passes through the cold trap near the tropopause, water vapor tends to condense out. This condensation is not the cause of ascent but rather a consequence of the cooling during ascent, and it serves as an indicator of the vertical transport.

We revised the sentence (P8, L167) as follows: "…the low-temperature conditions cause water vapor to condense and form cirrus clouds, which in turn indicate vertical transport into the stratosphere."

P8, L167-169: "This supersaturated and cold environment near the CPT suggests a condition that led to further dehydration of the air mass flow in the altitude range above 14 km up to the CPT." If the process of freeze-drying is explained somewhere before in the manuscript, this sentence may ok as it is now, but otherwise it should be improved as well.

Response:

Thank you for the suggestion. We revised the sentence to clarify the freeze-drying process in this context, specifically referring to cirrus cloud formation and ice particle sedimentation as the mechanism for further dehydration near the CPT.

We revised the sentence (P8, L167-169) as follows**: "***This supersaturated and cold environment near the CPT suggests a condition favorable for cirrus cloud formation and further dehydration of the air mass via ice particle sedimentation in the altitude range above 14 km up to the CPT.***"**

P9, L195-196: "We have compared and validated the HYSPLIT results with those of ATLAS shown in

Appendix A." This sentence is obsolete since you have mentioned this already several times before and a few lines later you write again "The comparison between the two model results is described in detail in Appendix A." This paragraph should be improved.

Response:

Thank you for the comment. We revised the paragraph (P9, L195-198) to remove the redundancy and improve clarity:

"We compared and validated the HYSPLIT results with those of ATLAS. In comparison, ATLAS trajectories do not show this extreme uplift. Otherwise, the results of the two models are comparably consistent, especially regarding the NH winter air uplift. A detailed comparison between the two model results is described in Appendix A."

P11, L236: "……dispersion of the vertical coordinates of stratospheric kinematics." Sentence not clear, please rephrase.

Response:

We revised the sentence (P11, L236) for clarity as follows: "… dispersion in stratospheric trajectory calculations."

P11, L237: "The comparison details between the results of the two models are in Appendix A."

Obsolete here since this has been mentioned several times, just add "see Appendix A" in parenthesis.

Response:

We removed this sentence (P11, 237).

P18, L378-379:" …. bringing high concentrations of species related to human activities, such as O3,

CO." Text part uncomplete. Add something like "to this/other region". Not clear what you actually mean here, if the pollutants are coming to Southeast Asia or transported away from there.

Response:

Thank you for the suggestion. We revised the sentence to clarify that the pollutants are transported from Southeast Asia into the TWP.

"During NH winter, the dominant air mass origins are within the NH (red arrows and circles in Fig. 9, specifically Southeast Asia, transporting high concentrations of species related to human activities, such as O_3 and CO to the TWP."

P19, L398: What is meant with "consistent with other studies"? Same type of study or deriving the same/similar results? Please rephrase the sentence.

Response:

Thank you for the comment. We revised the sentence to clarify that the studies cited derive similar results regarding air mass transport pathways toward the TWP.

We rephrased the sentences (P19, L398) as follows: "Similar results from other studies (e.g., Randel et al., 2019, Pan et al., 2016) also highlight potential air mass transport routes toward the TWP."

P19, L415: "Latent heat can be released due to the condensation of water vapor, resulting in the dominant ascent of air in this region." Please improve this sentence and make clear that you mean latent heat release in connection with deep convection.

Response:

Thank you for the helpful comment. We revised the sentence to improve clarity and better reflect the physical processes involved. In this section, our intention is to describe the condensation of water vapor as a result of large-scale uplift and cooling rather than to suggest that latent heat release is the primary driver of the convective ascent. Since the sentence should focus on large-scale transport during winter, we have revised the sentence (P19, L415) to improve the clarity as follows:

"Latent heat can be released because of the condensation of water vapor, which occurs as a result of the dominant ascent and extremely low temperatures in this region."

P22, L455-456: "All trajectories within a cirrus cloud are initiated simultaneously every hour during the time of the lidar observation." Do you really start every hour new trajectories or do you use an hourly output for the trajectories? Please add this information as well. In the former case, over how many hours are trajectories started and how many trajectories have you calculated in total? In the latter case, please rephrase the sentence to be more clear.

P22, L456ff: You are comparing two trajectory models with different vertical coordinates for trajectory calculation. However, both consider diabatic processes. Nevertheless, due to the different approaches differences occur. What I miss in your manuscript is a clear statement what you want to achieve with comparing these two models. Do you want to investigate which method produced the more reliable results? Since the calculations are also based on different reanalysis this makes an assessment quite difficult.

Response to these questions regarding P22 L455-456 and 456ff:

1. Regarding initiation of trajectories (P22, L455-456):

We appreciate your request for clarification. To clarify, trajectories are indeed initialized every hour independently during periods when the cirrus cloud is continuously observed to persist for more than one hour. Trajectories are initiated simultaneously every hour in time within the detected cirrus cloud, vertically spaced at 100 m intervals in the output vertical coordinate of the lidar measurement and converted to pressure levels using the closest radiosonde data in time. The total number of trajectories calculated depends on the duration of cloud presence, with each hour producing an independent set of trajectories. To reflect this clearly, we revise the sentence in P21, L454 as follows:

"Trajectory starting points within a cirrus cloud layer are vertically spaced at 100 m intervals in geometric height and converted to pressure levels using radiosonde data from the PWS, taken closest in time to the cirrus cloud observation. All trajectories within a cirrus cloud are initiated simultaneously every hour during the time of the lidar observation and with an output time step of 1 h."

We suggested adding an explicit statement of the number of trajectories we initialized in this paragraph:

"For a detected cloud layer case, the number of trajectories is thus the cloud thickness divided by 100m times the durations of the cloud observation in hour."

2. Purpose of comparing two trajectory models (P22, L456ff):

Thank you for emphasizing the importance of clearly stating our objectives when comparing these two trajectory models. The inter-comparison of the ATLAS-HYSPLIT models is not our intention. Instead, we acknowledge that there have been discussions about these two vertical velocity approaches, and we want to justify the sensitivity of the trajectory calculation by HYSPLIT through the simple case study comparisons.

We revised sentences (P22, L443) to state the aim of using the additional model clearly as follows:

"To investigate the sensitivity of trajectory pathways calculated with HYSPLIT setup, we use the additional …"

However, we must clarify that a detailed comparison between different Lagrangian models is beyond our scope due to significant computational and practical constraints. We could theoretically extend our comparison of HYSPLIT and ATLAS by using the same reanalysis dataset, but this would require more time and computational effort than we originally intended for the paper. We suggest clarifying this in the paper on P22, L470:

"In the scope of this study, the inter-comparison between the two models was not the focus. The examples of case study simulations are given here to show the similar relative distribution of pathways over the TWP, which is the focus of this study. In this sense, differences in reanalysis data inputs were neglected when comparing the sensitivity of trajectory calculations through case studies. "

It is not our intention to establish the superiority of one model over the other. There are discussions about the performances of these two velocity approaches (e.g., Honomichl and Pan 2020), but we do not aim to solve this. With our additional case study using the ATLAS setup, we contributed to this discussion. Our comparison suggests that the different vertical velocity approaches are important to the study of long-time transport in UTLS, and further study is needed.

We revised sentences (P22, L484): “Both models provide evidence of the predominance of ascending air masses over Palau in Case 1 (the winter case) …… A thorough model inter-comparison accounting for differences in both vertical velocity and reanalysis datasets would further clarify remaining uncertainties and add new insights to the discussion of transport studies in the TTL (Honomichl and Pan 2020).”

We thank you once again for these important suggestions, which have significantly improved the clarity of our manuscript.

Technical corrections:

P9, L186: cold traps -> cold trap

Corrected.

P9, Figure 2 caption: Add “for” so that it reads “Lidar and radiosonde observations for a typical case of cirrus cloud measurements on 13 December 2018.”

Corrected.

P9, Figure 2 caption: remove second full stop after “marked” and Section 2 -> Sect 2.

Corrected.

P11, L218: “this case” -> which case? Please be more precise.

Corrected as: “Case 2 (summer)”.

P11, L240: “Case 2” a bit lost year. Either put this in parentheses with the reference to Fig 4 or include this in the sentence.

Corrected as: “(Case 2, Fig. 4b)”.

P11, L248: Since you mean “an extremely cold ‘cold trap’ you should write it also like this.

Corrected.

P13, L259: “capture variations” variations of what? Please be more precise.

Corrected as: “capture variations in time and vertical positions of the air masses initialized within the cloud layers.”

P13, L259: “Although trajectories were calculated hourly” Not the trajectories are calculated hourly, you calculate these with an hourly output time step. Please rephrase the sentence to be more clear.

Corrected as: “Although the output time step of the trajectory is 1 hour”.

P14, Figure 6 caption: cloud layer -> cirrus cloud layer

Corrected.

P14, L287: Remove parenthesis around the reference of “Sun et al., 2023a”.

Corrected.

P15, L295: "the ascending air masses higher than the 400 K level account……" you mean the air masses "that" ascend higher than the 400 K level? Please correct the sentence.

Corrected.

P15, L299: "……., enhancing tropical stratospheric entry." This sentence part feels uncomplete.

Corrected as: "enhancing the entry of tropical air masses into the stratosphere."

P18, L368: dynamics -> dynamical processes

Corrected.

P18, L373: Research -> Recent research studies ……. (e.g. Rao et al.) if there are several studies or

A recent research study …… (Rao et al.) if this is only discussed in Rao et al.

Corrected.

P18, L383: vast -> west (?)

Corrected.