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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Transport model diagnosis of the mean age of air derived from stratospheric samples in the tropics" *by* Hanh T. Nguyen et al.

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Reply to Referee 1

We sincerely appreciate Referees 1 and 2 for their review of the manusc and valuable comments and criticism on it. We understand the problem and ha made substantial changes to the manuscript in response to the comments from b Referees. These revisions have significantly improved the manuscript, and we ho we have answered all of the concerns. Our reply to Referee 1 is shown below in b

following the comments cited in italics.

In their paper, Nguyen et al. apply two methods (BIR and backward trajectory cal lation) to model age of air (spectra) as well as mole fractions of CO_2, SF_6 and wa vapour. In the paper, first the model results are evaluated and subsequently some sults are compared with data from a measurement campaign. The comparison wo reasonably well, with some discrepancies that mostly can be explained. The ove idea of the paper is good and the method is elaborate. Some of the results are a interesting and can contribute to foster science in this field, although it is for exam expectable that chemical SF_6 depletion will not allow direct comparison in the up stratosphere if it is not included in the model. It is good to carve out which of modelling methods is suitable to tackle which science question.

However, the paper is chaotic and does not provide the necessary information to low. Almost nothing is reported about the measurements of that campaign and w are the points that were supposed to be investigated with them. The model desc tion is unclear, I do not understand why sometimes nudging is described, while authors apply a CTM, which usually is driven (not nudged) by reanalysis data. Tha very confusing. The evaluation of the results is pretty lengthy and should be redu to about two figures. If need be, the rest can be banished to a supplement (ma together with the appendix). I like the idea of explaining measurements with mode AoA spectra, but at the end, that is only a minor part in the paper and is only pa successful (partly due to the sinks). However, my main point really is that the st does not follow a clear research question. The reader can be lost due to that. Wha it exactly that is puzzling you about the measurements? Why do you think the appr method can help to answer that question and how do you plan on pursuing that? H can additional information about transport processes be gained through that? Wha your contribution to improve the understanding of the underlying processes at the e and how does that fit into existing literature? Some of this information informatio

lacking, some is spread somewhere across the manuscript, and the reader has to the pieces together. Further, so many different points are applied, AoA, its spec the CO_2 and SF_6 mole fractions as well as water vapour and the cold point are thro together, but it does not clearly shine through that all these measures are needed make the conclusions that are drawn at the end. Also, different models, free runni nudged simulations and/or the CTM and the two diagnostic methods, all that lea to confusion and does not help to get to the point. Additionally, intense use of n intuitive abbreviations complicate reading and also in the results section, many poi are thrown together and a clear focus is missing.

Hence, I would suggest the authors to completely revise the manuscript and then s mit it again. I think the study can help to advance our understanding of stratosphe transport and the methods that can be used to investigate it if it is presented and str tured properly. Please start with one or more clear research questions that can answered with this method and build everything around that. Use only the meth needed, describe them clearly, and then take the reader point by point towards conclusion. Please also consider my additional comments that I am making below.

In response to the above comments, the manuscript has been completely vised by setting clear research questions. Before explaining them briefly, let us reso the confusion on the use of "ACTM" and the application of nudging in the present stu ACTM is an abbreviation of an Atmospheric General Circulation Model (AGCM)-bas Chemistry Transport Model (CTM), which was used in the past literature such as Is jima et al. (2010, JGR, 115, D20308, doi:10.1029/2009JD013322). We would like maintain the use as the continuation of previous studies. The application of ACTM w data assimilation is motivated by our hope that realistic transport field is better rep sented than the direct use of (re)analysis field, such as ERA-Interim, in higher tempo resolution. We choose nudging as the simplest way for data assimilation. Nudging frequently applied for the diagnosis of model performance in AoA studies as can

seen from Krol et al. (2018, Geosci. Model Dev., 11, 3109–3130). The improvem attained by the use of ACTM with nudging is discussed in Section 4.

We agree to the comment that the study must follow a clear research question. have revised the manuscript to state it clearly in Introduction. That is, how can interpret the vertical profiles of CO_2 and SF_6 ages obtained by cryogenic air sampl in CUBE/Biak campaign, especially from the aspect the shape of age spectra wh is often parameterized by Δ^2/Γ ratio since Hall and Plumb (1994). We employ t methods, boundary impulse response (BIR) method and Lagrangian backward traj tories, both replying on ACTM wind field. The whole manuscript has been revis along the line to answer the question under a unified story. The description on evaluation of the results and the number of figures are reduced. Due to the additio description such as the measurements of that campaign, however, the total lengt the manuscript remains almost the same. Some of the contents are moved to app dices and supplementary material following the suggestion. The use of abbreviat has also been revised. The details are given below.

The manuscript has been reorganized as follows:

1. Introduction
   Our research questions are stated clearly to meet the comments from Refe 1. Recent publications in related topics are also added. Some more descriptio on our campaign CUBE/Biak have been given as well. An introduction of atmospheric general circulation model-based chemistry transport model is ma with its abbreviation ACTM. The use of "clock tracers" is eliminated in respor to the comments by Referee 2.

2. Model experiments

   2.1 Description of the model and simulation design

We try to interpret the vertical profiles of observationally estimated CO_2- a SF_6-ages referring to transport model calculations. The use of ACTM is th a key to our analysis. Explanation on the use of ACTM is given here.

2.2 Evaluation of the model performance
Our results deeply rely on the performance of the transport model. T model performance is briefly investigated by looking at the distribution tracers that are released as a "pulse" at the tropical surface. This metho tracer release constitutes the basis of the BIR method.

2.3 Estimation of age spectra and mean age of air
We employ BIR method and back trajectories to estimate age spectra a mean age of air in the stratosphere. A brief review of the theoretical fo dation of both methods are given here before their application to the tropi stratosphere.

3. Application to CUBE/Biak observations

3.1 BIR method
The mean age estimation relies on unobservable age spectrum. The a spectra estimated from BIR method are described.

3.2 Lagrangian method
Back trajectory calculations are often conducted to describe the tracer tra port from a Lagrangian point of view. The method is one of the import tools to study stratospheric tracers including water vapor. The use of o hour averaged one-hour interval wind field, together with additional press levels assigned near the tropical tropopause, proved useful to better rep duce the observed profiles of CO_2, SF_6, and water vapor "tape recorder."

3.3 Assessment of the mean age profiles
The mean age profiles derived by applying above two methods are co

pared against those estimated by using observed CO_2 and SF_6 mole fr tions.

4. Discussion
The results obtained above are discussed focusing on the interpretation of the ferences between the ACTM-derived and observationally estimated mean ag Δ^2/Γ-ratio and the shape of age spectra, and the advantage of using one-h averaged one-hour interval data available from ACTM in trajectory calculation

5. Summary
The overall results are summarized.

Appendix A: Supplementary notes on the age spectra
The effect of tail correction and fine structure reflecting the pathway differer are discussed emphasizing the importance of using accurate age spectrum mean age estimation.

Appendix B: The effect of quasi-biennial oscillation (QBO)
The modulation of BIR map over the equator due to QBO is briefly described.

Figures are rearranged and reorganized as follows:

Section 2

Fig. 1: Latitude-height section of the mixing ratio of January-released pu tracers in (a) February of the first year, (b) February of the second ye and evolution of pulse tracer concentrations (c) over the equator and (d) some representative latitudes on 50 hPa pressure surface. Panels (a) a (b) come from original Fig. 1, and panel (c) comes from the upper pan of original Fig. 3. Panel (d) consists of lower panels of original Fig. 3. T original Fig. 2 is deleted.

Fig. 2: Zonal mean distribution of three-year averaged mean age in NH wir (DJF) and summer (JJA). This comes from original Fig. 5. Original Fig goes to Fig. A1 in Appendix A.

Section 3

Fig. 3: (a) BIR map at 50 hPa over the equator, and (b) latitude-height sectior the mean age in March 2015. Panel (a) comes from original Fig. 6 (a), wl panel (b) is original Fig. 7. Original Fig. 6 (b) goes to Fig. B1 in Appendix

Fig. 4: Age spectra derived from BIR method corresponding to the altitudes eight cryogenic air samples acquired during CUBE/Biak 2015. This is same as original Fig. 8.

Fig. 5: Examples of (a) age spectrum and (b) water mixing ratio spectrum e mated from back trajectory method. These panels come from original Fig (a), (b). Those of original Fig. 9 (c), (d) are deleted.

Fig. 6: Vertical profiles of mole fractions of (a) CO_2 (ppm), (b) SF_6 (ppt), and water vapor mixing ratio (ppmv) estimated by back trajectories. This fig comes from original Fig. 10. Original Fig. 11 appears in snapshots i movie provided by Supplementary Material.

Section 4

Fig. 7: Comparison of the vertical profiles of (a) mean age and (b) ratio of r ments (Δ^2/Γ) estimated by the BIR method, back trajectories, and cryoge samples. Panel (a) comes from original Fig. 13 after removing horizor bars for Γ_{bir} and Γ_{trj}. Panel (b) is newly plotted from Table 2.

Fig. 8: Time series of the zonal (u), meridional (v), and vertical (ω) wind com nents at grid points 0° longitude near the equator. This figure comes fr original Fig. 12.

Appendix A

Fig. A1: Multi-year averaged age spectra with tail correction estimated by E method. This comes from the original Fig. 4.

Fig. A2: (Left) age spectra and (right) meridional projection of back trajectori This comes from the original Fig. A1.

Appendix B

Fig. B1: A time-height section of mean zonal wind over the equator. This con from the original Fig. 6 (b).

A supplementary material has been attached with the revised manuscript. It conta an animated GIF showing a meridional projection of air parcels associated with backward trajectory calculations for one year since the initialization on 27 Febru 2015.

We believe that the application of two independent methods, BIR and back trajectori to the ACTM wind field successfully achieved our research goal of interpreting vertical profiles of CO_2 and SF_6 ages obtained by cryogenic air sampling in CUBE/B campaign. We hope we have made necessary revisions so that the manuscript h reached the required quality for publication in ACP. Detailed revisions associated v Additional comments follow.

Additional comments:

P1, L2: *A CTM is not nudged! A CTM uses some meteorological fields for describ transport. This is totally confusing and it is not clear to me what is actually don this study, because later also you talk about GCM and CTM. Please clarify w that is and what you do throughout the paper.*

As was mentioned at the beginning of our reply, we use an Atmospheric g eral circulation model (AGCM)-based Chemistry Transport Model (CTM), wh is named "ACTM" in previous publications. ACTM employs nudging to reprodu realistic transport for atmospheric chemical/non-chemical components in moc

P1, L4: *Change "a single" to "the chemistry transport model"*

We have changed "a single model" to "the ACTM."

P1, L3–5: *The sentence is unclear. Are there discrepancies between the two moc or between models and observations? And the following sentence starts w a "This", but it is unclear what the "this" refers to, to the usefulness, or to discrepancies.*

This sentence was rewritten together with the following sentence without us the word "discrepancies" and "This.": "Since the BIR method is capable of tak unresolved diffusive processes into account, while the Lagrangian method c distinguish the pathways the air parcels took before reaching the sample site, application of the two methods to the common transport field simulated by ACTM is useful in assessing the CO_2 and SF_6 derived mean ages."

P1, L7: *But where is the connection between the water vapour tape recorder and mean age here?*

This sentence is revised saying that the advantage is "The capability to exam the reproducibility of the observed values of CO_2, SF_6, and water vapour".

P1, L8: *Change "the reality" to "good quality" or something alike.*

The phrase "confirming the reality of the trajectory calculations" is deleted.

P2, L12: *Please consider also the newer publication by Engel et al. from 2((10.5194/acp–17–6825–2017)*

Thank you for the suggestion. We have updated and cited the suggested pa in the revised manuscript.

P2, L18: *observations and models*

The sentence is revised as "to resolve this discrepancy by reducing uncertaint in both observational and model estimates".

P2, L18: *With "sampling of clock tracers" do you mean SF_6 and CO_2? Or m tracers? Can you elaborate a little more on the campaign, please, like what, h how long...?*

Yes, they are CO_2 and SF_6. However, we revised the manuscript distinguish CO_2 and SF_6 from ideal "clock tracers" following the comments from Referee The sentence is deleted and a brief description about CUBE/Biak campaigr added.

P2, L21: *What exactly is it that is puzzling you about these measurements? T should be central in all parts of the paper.*

We are sorry that we did not explain well about our research question. As w mentioned in our reply to your major comments above, our research questior clearly written in Introduction.

P2, L25: *But that is why the Green's function is used to flatten out these n linearities. Please see and possibly mention Fristch et al. 2020 (10.5194/ac 2019–974) and citations therein.*

Thank you for the suggestion. We have added the suggested paper for a disc sion in the revised manuscript.

P3, L17–18: *So is it a CTM or a GCM now?*

We are sorry for the confusion, but we do hope this question has been alrea resolved from our reply at the beginning.

P3, L23: *It would be easier to use the name of the model from here on, instead "ACTM", if the model has a name.*

Again we hope this question has been resolved already; "ACTM" is the name the model used in this study.

P3, L27: *How did the model perform in that inter-comparison? Was it somewh around the multi-model mean or was it an outlier?*

As the ACTM was nudged to JRA-25 (not to ERA-Interim) in the inter-comparis by Krol et al. (2018), the results need to be interpreted carefully. They found t ACTM showed the strongest convective mixing in the tropics and the young air at the high-altitude poles among the models participated in the comparis This is stated in Sect. 2.3.

P4, L5: *"several years". Please be precise, for the sake of reproducibility. Did you u ERA-I data of year 2004 for that and repeat that year for ? years?*

Our simulation has been conducted for the period from 1 January 2000 to March 2015 by nudging horizontal winds and temperature to ERA-Interim da The first five years (January 2000 to December 2004) are regarded as the spin period. This information is given in Sect. 2.1.

Sects. 2.3 and 2.4 are just the evaluation of the model. Firstly, this should be flected in the section headers, and secondly, these sections should be consid ably shortened and/or moved partly to the supplement. I suggest to reduce number of figures from 5 to 2.

Thank you for your suggestions. The whole Sect. 2 has been rewritten by ducing the number of figures to 2. Fig. 4 is moved to Appendix for the sake readability. Sect. 2.2 is entitled "Evaluation of the model performance" follow the suggestion.

These abbreviations, particularly "AF" and "AN" do not make much sense to me.

We are sorry for the confusion but these follow our precedent use in BAMS pap For clarity and readability, those abbreviations have been changed to ACT FREE (for AF) and ACTM-NUDG (for AN). Additionally, "EI" is also changed "ERA-Interim".

Fig. 2: I do not fancy that the streamfunction is shown again here, it was sho in Fig. 1 already and does not help much, instead, it disturbs the view on tendencies. I suggest to remove it.

Thank you for the comment. As suggested by the reviewer, this figure has be removed.

P5, L15: *What do you mean by "selected tracers"?*

The term "selected tracers" was intended to identify pulse tracers released a specific month such as January. The term is no longer used in revis manuscript: "The transport features described above are limited to those a specific time in the Northern winter." (Sect. 2.2)

P7, L1: *...temperature move upward over time.*

The sentence has been removed associated with the revision of the paragrap

P7, L6: *backward*

Done.

P7, L15–17: *Unclear and awkward phrasing, please rephrase. Plus, what is meant "not simple"?*

The sentence has been rephrased to the following without using "not simp "Therefore, it is necessary to address the difference in the definition of the re ence time from which age counting is started before making direct comparis between the two. As is evident from Fig. 1, the excursion of the tropospheric ai the stratosphere depends on tropospheric transport features, including isentro mixing with the air in the extratropical LS, and thus the mean age counted fr the tropical surface is not always a sum of the tropospheric residence time a the mean age counted from the TTL."

P7, L25–26: *Remove parentheses around dates*

Thank you for the comment. The parentheses are used to identify tw dimensional coordinates on the BIR map in the form (source time, field tim Thus, we would like to retain the parentheses around dates with the follow modification: "at (t', t) = (March 2007, October 2007) and (November 2009, J 2010)."

P7, L28: *change "drives the tracers upward" to "intensifies the upward tracer tra port"*

This sentence is moved to Appendix B and rephrased to: "the upward tra transport driven by extratropical pumping is intensified by the secondary circu tion"

P7, L31: *"The vertical axis is ...." What is that sentence supposed to mean? It mak no sense to me.*

This sentence has been removed.

P7, L32: *What is a latitudinal split? Please explain clearly what you talk about. Mo over, why is that important now, you explained the QBO topic already before.*

Again, we are sorry for the confusion. The sentence has been rephrased to: "T deformation of the contours at 3.0, 3.5, and 4.0 years showing wavy structures the tropics are due to the downward motion associated with the westerly shea the QBO (Appendix B)." (Sect. 3.1)

P8, L5: *...the spread of the transit times (Δ)...*

"(Δ)" has been inserted as suggested.

P8, L9: *A bundle! Please be more quantitative.*

The sentence has been revised referring to Table 1 for the details of the mo parameters of trajectory calculations.

P8, L9: *the spectra of AoA, CO_2 and SF_6 mole fractions? You are mixing up sor thing here, please be specific.*

In this work, the trajectories are used to estimate not only the spectra of stra spheric AoA, but also the CO_2 and SF_6 mole fractions as well as the water va mixing ratio by tracking the position of air parcels advected by the 3D wind. T sentence and panels (c) and (d) of Fig. 9 are deleted following the revisions the manuscript.

P8, L11: *Can you still give a very brief description of the method of analysis pleas*

Some descriptions are made: "In the Lagrangian method, the age spectra estimated by counting the transit time τ during the advection along each ki matic trajectory since the last passage through the top of the troposphere (Tr_{to} (Sect. 2.3) and "The present study tries to resolve disagreements between

estimates from trajectory calculations and CUBE/Biak observations by incre ing the number of trajectories and extending the integration period (Table (Sect. 3.2).

P8, L12–14: *I do not understand what this sentence is supposed to mean. Plea rephrase it and sharpen the message.*

It is an important advantage of using the ACTM and is rephrased to: "In dition to using the ERA-Interim analysis directly as 6-hour interval snapsh the assimilated meteorological field created by nudging its horizontal winds a temperature to the ACTM are also used for trajectory calculations. In this ca one-hour averaged values are used at one-hour intervals (ACTM-NUDG)."

P8, L14: *Where do these additional levels come from?*

Additional pressure levels are set to better represent the Lagrangian cold-p temperature that controls the water transport to the stratosphere. All pressu level data, not restricted to the additional levels, are interpolated from model le data.

P8, L21: *What is CONTRAIL data? Please describe!*

The citation of CONTRAIL data is deleted as the name is not absolutely imp tant. The description is revised to: "The tropospheric reference was derived fr direct measurements of air samples collected onboard commercial airliners d ing the cruise within the area 5° S–5° N and 142° E–150° E at an altitude of 10 km".

Fig. 9 Water "vapour"! Or is ice included too? (Throughout the paper!)

Water vapour is an important constituent to describe the ascending motion the equatorial stratosphere, although total hydrogen (=H_2O + 2CH_4) is a be quantity (Waugh and Hall, 2002, Rev. Geophys.). Trajectory calculations

frequently used to estimate stratospheric water variations (e.g., Fueglistaler a Haynes, 2005, JGR). The top right panel for water vapour is retained as the ri panel of Fig. 5 with description in Sect. 3.2. We have never mentioned ice.

P9, L2 and L5: *You already defined these abbreviations above.*

Thank you for the comment. We have deleted the redundant information.

P9, L3: *But what were the problems in H18? Can you provide a quick introductio Without that, it is almost impossible to follow.*

The following descriptions are given in Sect. 3,2: "The present study tries resolve disagreements between the estimates from trajectory calculations a CUBE/Biak observations by increasing the number of trajectories and extend the integration period (Table 1). Improvements are not limited to these simulat settings. In addition to using the ERA-Interim analysis directly as 6-hour inter snapshots, the assimilated meteorological field created by nudging its horizon winds and temperature to the ACTM are also used for trajectory calculatio In this case, one-hour averaged values are used at one-hour intervals (ACT NUDG)."

P9, L18: *"It is interesting". Does that mean the other results are not interesting?*

Thank you for the comment. Figure 11 is replaced by a movie provided a Supplementary Material. Related descriptions are made in Sect. 4: "The ti evolution of the meridional location of air parcels corresponding to Sample 8 visualized as a movie in Supplementary Material. We can see that air parc gradually descend in reverse time sequence, and stay mostly inside the "tropi pipe" without appreciable latitudinal dispersion during the Northern winter (J uary and February 2015). The vertical advection is fastest in ACTM-FREE a slowest in ACTM-NUDG. By June 2014, an appreciable number of ACTM-FR air parcels has descended back into the troposphere. In contrast, scarcely a

air parcels are found in the troposphere in ACTM-NUDG. ERA-Interim sho features intermediate between the two."

P9, L18–32: *Using these abbreviations this way make it almost impossible to follo*

The abbreviations "EI", "AN", and "AF" follow the use in our project paper (H1 Now we have changed AN to ACTM-NUDG, AF to ACTM-FREE and EI to EF Interim.

P9, L25: *How is that question linked with the general idea of the paper?*

Our purpose is to attain a better understanding on the vertical profiles of C and SF_6 ages obtained by cryogenic air sampling in CUBE/Biak campaign. tried to reproduce the observed age profiles by applying the BIR and Lagrang methods to the meteorological fields simulated by ACTM. The question, "W is the advection velocity in EI and AN different in spite of nudging?" is link to the reproducibility of the observations. It is natural for us to expect that (ACTM-NUDG) gives similar results to EI (ERA-Interim), as AN is nudged to The related descriptions are made in Sect. 4 as described in our reply to y comment on P9, L18.

P10, L5–9: *Even more abbreviations that totally disturb readability.*

Following this comment, we stoped using Γ^* and Γ_{adj} in the revised manuscr However, we want to retain the use of Γ_{corr}, Γ_{bir}, Γ_{trj}, Γ_{Cobs}, and Γ_{Sobs} better readability of the manuscript. We don't think it wise to write, for examp "mean age estimated by BIR method having been applied the tail correction a source-region adjustment" every time for Γ_{bir}.