Authors' responses

We thank the reviewers for their constructive feedback. We have revised the manuscript according to the suggestions provided. In addition, we made two minor updates to Section 4.1. First, the temperature evolution during the idealized descent used in the coagulation sensitivity calculation was modified to be consistent with dry-adiabatic warming. This change produced nearly identical results, with differences not visually perceptible in Fig. 6. Second, to provide additional observational context, we added a mean vertical profile of aerosol number mixing ratio from the CAFE-Brazil campaign in Fig 6b. The inclusion of these new data necessitated an update to the author list.

Below, we provide detailed responses to each point raised.

Anonymous Referee #2

1. The motivation of the paper is to understand whether the downward transport of the tropical upper troposphere aerosols is a source of boundary layer aerosols. Therefore, I am surprised that the authors only show results in the middle troposphere (500 hPa). I strongly suggest showing results in the boundary layer, e.g., repeating all the figures for the lower troposphere.

   Response: We agree that an important aspect of the relevance of UT aerosol formation is whether UT-origin particles can ultimately influence lower-tropospheric and boundary-layer aerosol populations. However, our aim in this study is not to quantify the complete boundary-layer aerosol budget. Transport all the way to the boundary layer likely involves cloud-scale, mesoscale, and boundary-layer processes that are not the primary target of our global-model setup. For example, Bardakov et al. [2022] showed that convective downdrafts can efficiently transport tracers from the middle troposphere, around 5 km, to the boundary layer, whereas direct downward transport from upper-tropospheric levels to the boundary layer within a single convective event was not evident in their simulations. This motivated our focus on the pathways and timescales by which large-scale circulation can transport UT-origin tracers into the mid-troposphere, where subsequent processes may become important.

   We have revised the Introduction section to clarify this motivation and to state more explicitly that the study focuses on large-scale transport into the mid-troposphere, rather than on a complete UT-to-boundary-layer aerosol budget.

   We also note that the manuscript does not rely solely on 500 hPa diagnostics. Figure 5 includes vertical cross-sections and area-averaged vertical profiles extending below 500

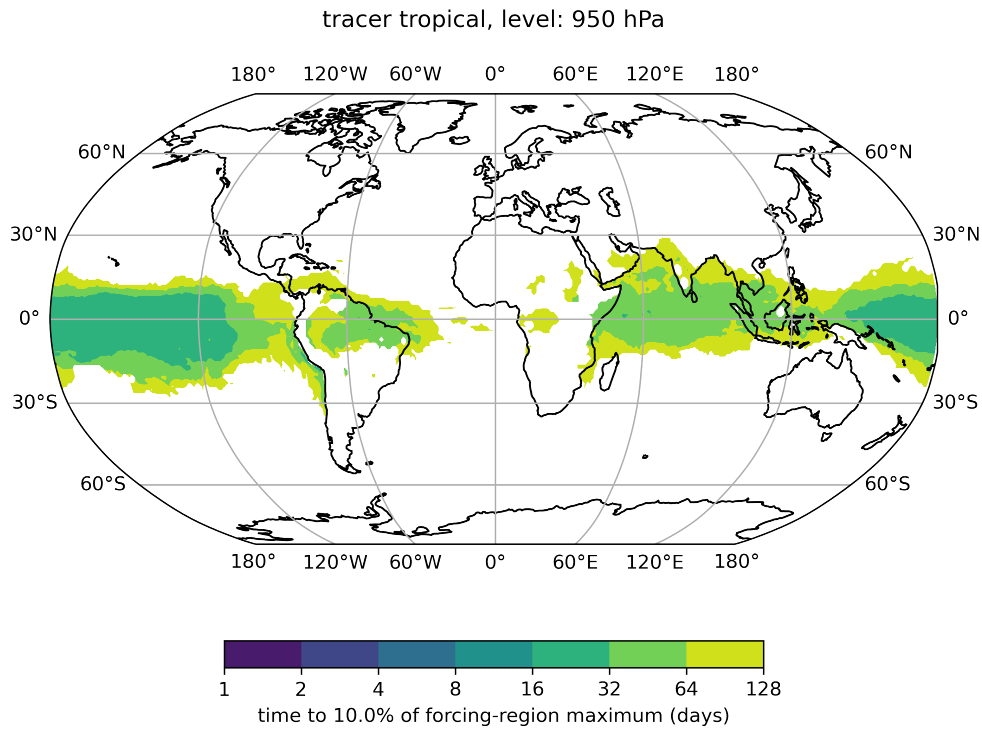

Figure 1: Same as Fig. 3a, but at 950 hPa. Average time to reach 10% of the mean mixing ratio in the forcing region, diagnosed from the twelve staggered Tropical tracers initialized on the first day of each month in 1999. Regions where the threshold is not reached are masked.

hPa, which show the rapid weakening of the tracer signal at lower levels. In addition, to address the reviewer's concern, we examined the same time-to-threshold diagnostic as in Fig. 3a at 950 hPa; this figure is included above for reference. The 950 hPa result shows that the UT-origin signal is much weaker near the surface compared to the signal at 500hPa. Repeating all horizontal figures in the boundary layer would therefore add limited interpretive value, because the signal is substantially diluted and increasingly affected by near-surface removal, topography, and boundary-layer processes that are outside the main scope of the present idealized tracer analysis.

2. Lines 171-172: The "staggered" tracer are used to produce the age spectrum, right? I would suggest showing and explaining the age spectrum, for example, over the entire tropics and the three chosen land regions.

   Response: The staggered tracers are not intended to reconstruct the full age spectrum. Rather, they are step-like tracers initialized at different months and used to estimate the time required for the tracer number mixing ratio to exceed a prescribed fraction of the forcing-region reference value. In other words, they provide a threshold-arrival diagnostic, t_p, which samples the timing of the fast-arriving part of the transport signal, but they do not contain sufficient temporal information to retrieve the full age spectrum $\Gamma(\tau)$.

Recovering the full age spectrum would require a different experimental design, for example a set of pulse tracers released with sufficiently high temporal resolution and integrated over a sufficiently long period. This was not computationally feasible in the present multi-year global simulations, particularly given the number of source regions and sensitivity experiments considered. We have reworded the Methods section to clarify this distinction and to avoid implying that the staggered tracers are used to retrieve the full age spectrum.

3. Line 215: Explain why young air is predominately near the Equator. It appears that the large-scale sink motion is dominated by the subsidence of the Walker Circulation. But how about meridional transport of the Hadley Cell? I would expect that the sinking branches of the Hadley Cell bring young air to the subtropics. Why are the effects of Hadley Cell not seen in the timescales?

   Response: Since the forcing region is confined to ±20° latitude, with a Gaussian decrease toward the edges, the largest tracer source is located near the Equator. Consequently, the shortest and least diluted pathways to 500 hPa are expected to occur within the deep tropics, where zonal overturning associated with the Walker circulation and regional subsidence can transport tracers downward within or near the source latitudes.

   The Hadley circulation is still likely reflected in the poleward spreading of relatively young air. For example, in Fig. 3a, $t_{10\%}$ values as low as about 16 days occur near ±30°, indicating that UT-origin air does reach the subtropics on relatively short timescales. However, meridional transport into the Hadley-cell descending branches requires additional poleward displacement before descent and is therefore expected to be slower and more affected by dilution and removal than descent occurring closer to the forcing latitudes. Thus, we would not necessarily expect a separate subtropical minimum in t_p, especially given the prescribed source geometry. Such a feature would likely be more pronounced if the forcing region extended farther into the subtropics.

   We have added text to clarify that the young-air pattern near the Equator reflects the combination of the imposed source distribution and the dominance of the fastest detectable transport pathways, while the Hadley circulation likely contributes to the broader poleward extension of the tracer signal.

4. The authors attribute the much longer transport timescales for the regional emission sources to mixing and dilution. This explanation is not complete. I think an important implication is that for a given region, downward transport directly from the upper troposphere of that region is not an important pathway. In other words, most of the downward transport comes from outside of that region. Therefore, I suspect that the 3 regional upper tropospheric emissions would have stronger downward transport influences on areas downstream of the emission regions than areas directly below the emissions. To test this, I suggest showing mean age over the entire tropics for the regional emissions. This will show what region is mostly sensitive to the downward transport for each of the regional emissions.

Response: We note that Fig. 2b already shows the mean age over the tropical band for the three regional emissions, which is the diagnostic suggested by the reviewer.

We agree that the longer transport timescales for the regional tracers should not be attributed only to dilution, but also to the fact that the pathways of fastest descent are not perfectly collocated with the center of each source region. However, we do not interpret our results as indicating that downward transport directly below the regional source regions is unimportant. In Fig. 2b, the minima in mean age remain within the regional source boxes, although they are displaced relative to the source centers and extend preferentially downstream. Similarly, Fig. 5a shows that the maxima in normalized number mixing ratio occur below and slightly east of the Amazon and Africa source regions, and slightly southwest of the Maritime Continent source region. Thus, the simulations indicate a tilted descent pathway within or near the source regions, rather than a complete decoupling between the UT source region and the lower-level region of influence.

We have modified the discussion to clarify that the longer regional-source mean ages arise from both stronger dilution/mixing, due to the smaller source area, and the spatial structure of the descent pathways. However, given the relatively small horizontal displacement of the minimum-age regions with respect to the regional sources, this displacement is unlikely to fully explain the much larger mean ages compared with the tropical source. We therefore retain mixing and dilution associated with the smaller source-region area as an important part of the explanation.

Anonymous Referee #3

1. Why do the authors choose 500 hPa, instead of lower troposphere, as the target receptor region?

   Response: Response: As discussed in more detail in our response to Anonymous Referee #2, we chose 500 hPa as the primary receptor level because it represents an intermediate "gateway" level in the hypothesized pathway from the UT toward the lower troposphere. Transport all the way to the boundary layer likely involves cloud-scale, mesoscale, and boundary-layer processes that are not the primary target of our global-model setup. For example, Bardakov et al. [2022] showed that convective downdrafts can efficiently transport tracers from the middle troposphere, around 5 km, to the boundary layer, whereas direct downward transport from upper-tropospheric levels to the boundary layer within a single convective event was not evident in their simulations. This motivated our focus on the large-scale pathways and timescales by which UT-origin tracers reach the mid-troposphere, where subsequent smaller-scale processes may become important.

   We have revised the Introduction to clarify this motivation and to state more explicitly that the study focuses on large-scale transport into the mid-troposphere, rather than on a complete UT-to-boundary-layer aerosol budget. We also note that the manuscript does not rely solely on 500 hPa diagnostics: Fig. 5 includes vertical cross-sections and area-averaged vertical profiles extending below 500 hPa, which show the rapid weakening of the tracer signal at lower levels. In addition, in response to Anonymous Referee #2, we examined the same time-to-threshold diagnostic as in Fig. 3a at 950 hPa. This diagnostic, included above for reference, shows that the UT-origin signal is much weaker near the surface than at 500 hPa, supporting our choice of 500 hPa as the main level for interpreting coherent large-scale transport pathways.

2. Could the authors comment on how uncertainties in the related EMAC parameterizations (e.g., deposition, turbulent mixing, etc.) may affect their results?

   Response: We acknowledge that uncertainties in EMAC parameterizations may affect the quantitative values of the diagnosed tracer mixing ratios and timescales. The main parameterization-related uncertainty in our setup is likely associated with wet scavenging, which is the dominant sink for the tracers with removal. Uncertainties in dry deposition and sedimentation are expected to be less important for the particle sizes considered here, whereas uncertainties in turbulent mixing and convective transport may affect the detailed vertical redistribution of the tracers.

   Some of these sensitivities are already partly constrained by our experimental design. We compare tracers with and without sedimentation, wet scavenging, and dry deposition, and we include sensitivity experiments in which parameterized convection or turbulent diffusion is disabled. These experiments suggest that, for the 500 hPa diagnostics analyzed here, large-scale advection dominates the resolved transport pathways, while removing parameterized convection increases $t_{10\%}$ by only about 10% and removing turbulent diffusion changes it by about 1%. However, these tests should not be interpreted as a full quantification of parameterization uncertainty, because they represent idealized on/off sensitivity experiments rather than perturbations within the plausible uncertainty range of each scheme.

   In the revised version, we have emphasized this point further by noting that the absolute magnitudes of $N_{\mathrm{cnt}}/N_{\mathrm{ref}}$ and the diagnosed time-to-threshold values should be regarded as model-dependent, particularly because of uncertainties in parameterized removal, especially wet scavenging. In contrast, the broader spatial patterns and the conclusion that large-scale advection provides the dominant mid-tropospheric transport pathway appear more robust across the sensitivity tests considered here.

3. Title: This study mainly examines the transport from upper troposphere (200-300 hPa and 150-250 hPa) to 500 hPa. Therefore, "Downward transport" may be more suitable than "Global transport" for the title.

   Response: We have changed the title to: "Downward transport of tropical upper-tropospheric aerosols: multi-year insights from idealized simulations."

4. L84, L152, and others: Is sedimentation part of dry deposition?

   Response: In the model setup used here, while sedimentation contributes physically to the downward motion of particles toward the surface, dry deposition it is treated separately. Sedimentation, represented by the MESSy submodel SEDI, accounts for gravitational settling of particles through the atmospheric column relative to the surrounding air. Dry deposition, represented by DDEP, describes removal at the surface through land/ocean-atmosphere exchange processes. We have clarified this distinction in the Methods section.

5. L102: Since it is mentioned that the simulations start from a specific date (1/1/1998), are the meteorology of the two simulations driven by or nudged to reanalysis data? Or do the authors just use the initial conditions from this date (L112)?

   Response: The simulations were not nudged to reanalysis meteorology. ERA5 was used only to provide the initial atmospheric conditions on 1 January 1998. After initialization, the model evolved freely, with prescribed climatological sea surface temperature and sea ice concentration boundary conditions. We have revised the Methods section to make this clearer.

6. L172-173: It is not clear how Nstgrd is set. My understanding is that the staggered tracers are initialized twelve times on the first day of each month in 1999. If so, the description that "t0 is the first day of each month ..." is not accurate. According to Eq. 3, this sounds more like Nstgrd is initialized after the first day of each month (when t ¿ t0). Also, one may need to assume that t only ranges from the beginning to the end of the month.

   Response: The staggered tracers are not released only during individual months, nor is a single tracer reinitialized every month. Rather, each set consists of twelve independent tracers, each with a different source start time $t_{0,m}$, corresponding to the first day of month m in 1999. After $t_{0,m}$, the tracer is continuously maintained at the prescribed value inside the forcing region until the end of the 2.5-year simulation, following the same formulation as Eq. 3. Thus, t is the absolute simulation time and does not range only from the beginning to the end of each month.

   The staggered start times are used to reduce the dependence of the diagnosed time-to-threshold metric on the arbitrary choice of release month. In the analysis, we diagnose t_p separately for each of the twelve tracers and then use the arithmetic mean of the twelve monthly estimates. We have revised the Methods section to clarify the definition of N_{stgrd} and the role of $t_{0,m}$.

7. L195-197: The τ for regional tracers is five times older than the tropical tracer. This comparison may be misleading. Does it indicate the regional tracers have five times weaker downward transport than the tropical tracers? Also, this difference is ascribed to stronger dilution in the manuscript. Is this right? I think the larger τ of the regional tracers is possibly because the regional source is smaller compared to the tropical tracer, and the corresponding receptor at 500 hPa also receives aerosols from other tropical sources.

   Response: We agree that the comparison between the tropical and regional tracers should not be interpreted as indicating that downward transport is simply five times weaker for the regional sources. The mean age of air is a source-specific diagnostic: it reflects the first moment of the transit-time distribution from the prescribed source region to the receptor region, and is therefore sensitive not only to vertical transport rates, but also to the spatial extent of the source region, as well as to mixing and dilution by air that has not recently been in contact with that source.

In this sense, the referee's interpretation is consistent with our intended explanation. For the tropical tracer, air arriving at 500 hPa from any tropical longitude contributes to the source-tagged signal. For a regional tracer, however, the receptor region may receive air from many other tropical longitudes that are not part of the prescribed source. This non-source air dilutes the regional tracer signal further and broadens the effective age distribution, increasing $\langle\tau\rangle$. Therefore, the larger $\langle\tau\rangle$ values of the regional tracers reflect the combined effects of smaller source-region area, horizontal mixing, dilution, and source-receptor geometry, rather than a simple reduction in vertical transport efficiency.

We have revised the Results and Discussion sections to clarify this interpretation and to avoid implying that the factor-of-five difference in $\langle\tau\rangle$ corresponds directly to a factor-of-five difference in downward transport strength.

8. Fonts are too small for Figures 5 and 6.

   Response: We have increased the font sizes in the figures as much as possible while preserving the current layout and readability of the panels. Some labels may still appear relatively small because of the figure dimensions used in the discussion/preprint version, but these can be further adjusted during journal production if needed.

References

Roman Bardakov, Radovan Krejci, Ilona Riipinen, and Annica M. L. Ekman. The role of convective up- and downdrafts in the transport of trace gases in the amazon. *Journal of Geophysical Research: Atmospheres*, 127(18):e2022JD037265, 2022. doi: https://doi.org/10.1029/2022JD037265.