Author Comment to Referee #1

Egusphere-2023-1026, 'Evaluation of vertical transport in the Asian monsoon 2017 from CO2 reconstruction in the ERA5 and ERA-Interim reanalysis' by B. Vogel et al.

We thank Referee #1 for the positive review and for further guidance on how to revise our manuscript. Our reply to the reviewer comments is listed in detail below. Questions and comments of the referee are shown in italics. Passages from the revised version of the manuscript are shown in blue.

Review of Vogel et al., Evaluation of vertical transport in the Asian monsoon 2017 from CO2 reconstruction in the ERA5 and ERA-Interim reanalysis.

The paper by Vogel et al aims at quantifying vertical transport in the UTLS of the monsoon region. They combine in-situ measurements of CO2 with simulations of the Chemical Lagrangian model of the stratosphere (CLaMS) driven by ERA-Interim, ERA5, and 1x1 regridded ERA5 reanalysis data.

They apply backward trajectory transport analysis extending backward by more than a year with age of air derived from CLaMS for the different driving reanalysis data sets and compare these with long-lived tracers to infer ascent time scales.

They use surface CO2 observations in different regions and combine these with the trajectories and show that the reconstruction using ERA5 gives a good agreement of reconstructed CO2 and measurements up to 410K, Above the reconstruction is affected by mixing with stratospheric air.

The authors conclude, that the results are highly sensitive to the representation of vertical transport in the troposphere in the different reanalysis data sets. According to their methods ERA5 yields the most reliable results compared to the observations. Using quasi-inert tracers (C2F6, HFC-125) they their results indicate a good agreement with ascent rates from ERA5 (also 1x1) with large mean age differences at 470 K between ERA-Interim derived age and ERA5 (1x1) of about one year.

The paper is well written and the methodology is clearly given. The results regarding the different reanalysis data sets are important for the community, since *a lot of conclusions on stratospheric transport were based on ERA-Interim before the release of ERA5. The reconstruction with CO2 is impressive and balanced discussed. Therefore the paper clearly merits publications and I have only a few comments, which are minor.*

We thank Referee #1 for this very positive review. A detailed discussion about the reviewer's minor comments follows below.

Minor Comments:

1. *Since a large number of species have been measured at the STRATOCLIM mission, I wondered, if one could include other shorter-lived species to further support the transport time results above the tropopause. In general shorter-lived species should fade out (NMHC) or decrease to background (CO) when being uplifted. I wondered, if the authors thought about including such constituents, which would strengthen their estimates at least above the tropopause.*

   Many thanks for this comment. Yes, it is correct that during StratoClim several shorter-lived species were measured (e.g. Adcock et al., 2021; von Hobe et al., 2021). In our study we focus on trace gases with a very long chemical life time (CO_2, HFC-125, C_2F_6, SF_6) to exclude any chemical effects (e.g chemical reduction) and thus concentrating on transport and mixing. During Stratoclim short-lived species such as dichloromethane, 1,2-dichloroethane and chloroform were measured by the air sampler. The mixing ratios of all three trace gases are decreasing strongly above the tropopause (see Fig. 3 in Adcock et al., 2021). However, for all three substances no published stratospheric life times are available. Further, air samples at the ground and in the troposphere (e.g. Fig. 3 in Adcock et al., 2021) of these trace gases show a very high variability up to tropopause altitudes. This variability make it very difficult to infer transport times (ascent rates) just above the tropopause because of the strong variability of the trace gases around tropopause altitudes.

2. *Fig.2: Could you add the Mauna Loa curve and the classical tropical boundary condition for CO2 at the tropopause as given by e.g. Andrews et*

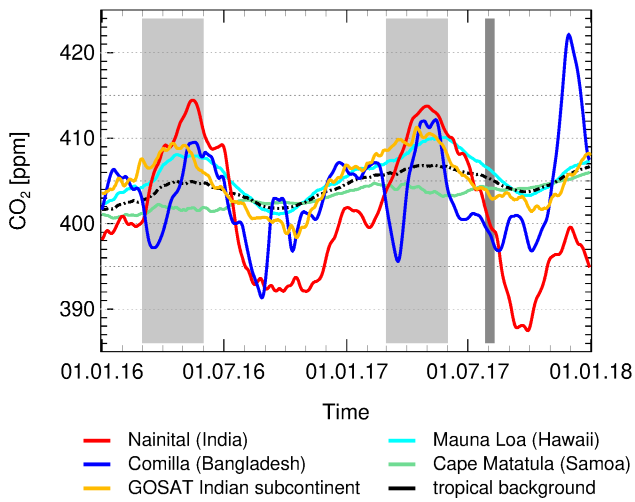

Figure 1: Temporal variability of ground-based CO_2. The variability of ground-based CO_2 is shown at Nainital and Comilla (geographical positions see Fig. 3 of Vogel et al. (2023b)). In addition, the seasonal variability of CO_2 over the northern Indian subcontinent (mean value between 20–30°N and 75–95°E) of the lowest model level at 975 hPa of the GOSAT-L4B product for comparison to ground-based CO_2 measurements is shown. Further, ground-based CO_2 measured in Mouna Loa (Hawaii) and in Cape Matatula (Samoa) as well as their average (black dashed-dotted line) as reference for the tropical background are given. The pre-monsoon period (March–May) when a seasonal CO_2 maximum is expected is high-lighted (light-grey) as well as the period of the StratoClim aircraft campaign during monsoon 2017 (dark-grey).

al., 1999, which is the mean of American Samoa surface cycle and Mauna Loa?

We agree that it is helpful to add the Mauna Loa and the Samoa CO_2 surface cycle as well as the mean of both as shown in Fig. 2 in Andrews et al. (1999). The Mauna Loa and the Samoa CO_2 surface cycles are already shown and discussed in Fig. 1 in Vogel et al. (2023a). To avoid too much repetition of Vogel et al. (2023a) in Vogel et al. (2023b), we didn't show the Mauna Loa and the Samoa CO_2 surface cycle in Vogel et al. (2023b). However, we agree with Reviewer #1 and added this information to the revised version of the manuscript as shown in Fig. 1 of this reply. Particularly, the mean of Mauna Loa and the Samoa representing the tropical background is an added-value for our paper. We added the following text to Sect. 3.2 of the revised version of the manuscript.

Ground-based CO_2 (provided by the World Data Centre for Greenhouse Gases (WDCGG), `https://gaw.kishou.go.jp`) measured in Mouna Loa (Hawaii) and in Cape Matatula (Samoa) (Thoning et al., 2021, `http://doi.org/10.7289/V5X0659V`) as well as their average (black dashed line) are also shown in Fig. 1 (of this reply) as reference for the tropical background (e.g. Boering et al., 1996; Andrews et al., 1999). The comparison of the different seasonal cycles of the ground-based CO_2 measurements demonstrates that the seasonal CO_2 maximum over the Indian subcontinent during pre-monsoon is much larger than the CO_2 maximum of ground-based CO_2 of the tropical background.

3. *l.315-335: Ascent rates: Would it be possible to support the ascent rates (20days) with measured vertical gradients of short-lived species, which should show a considerable decrease over 20 days? This would complement the stratospheric analysis based on the very long-lived species presented in Fig.10.*

   See discussion above to point #1.

4. *Was SF6 available for age calculations?*

   SF_6 was measured during the StratoClim campaign by the multi-tracer in situ instrument HAGAR operated by the University of Wuppertal (see Details in Sect. 2 in Vogel et al., 2023b) as well as by the whole air sampler (Adcock et al., 2021). In Asia, SF_6 has strong sources, therefore it is difficult to use SF_6 as a tracer for mean age of air. Nevertheless we show mean age of air deduced from SF_6 measured by the whole air sampler in the revised version of the paper (details see below point #6).

5. *l.392: How reliable is the use of just one location at the surface to derive*

mean transport time? The authors state in l.400 ff that a detailed CO2 reconstruction using comprehensive data is needed, which makes more sense. I'd recommend to skip l.392-397.

Following the advice of both reviewers, we removed Sect. 4.5 (L382-402 and Fig. 13) in the revised version of the manuscript. Parts of the text included in Sect. 4.5 as well as Fig. 12 are revised and shifted to Sect. 3.2 and 4.6.

6. *Fig. 10 (and general discussion of mean age of air): How well does CLaMS age of air resembles the observational derived age of air (either by the species in Fig 10, or by CO2 itself or eventually SF6 or N2O)?*

   We agree that this is an important question. Therefore, we added a more detailed discussion as well as Fig. 2 (of this reply) comparing observation-based age of air derived from N_2O measurements to simulated age of air to Sect. 4.1 in the revised version of the manuscript:

   To validate clock-tracer mean age of air as well as trajectory-based transport times from CLAMS we use N_2O measured by the HAGAR instrument during the StratoClim research flights. We compute mean age of air (Γ) from measured N_2O using $\Gamma - N_2O$ correlations by Andrews et al. (2001) and Engel et al. (2002) based on aircraft and balloon measurements. We use Eq. 3 by Andrews et al. (2001) derived for N_2O mixing ratios of the year 1997:

$$\Gamma = 0.0566 \times (313 - N_2O[1997]) - 0.000195 \times (313 - N_2O[1997])^2. \quad (1)$$

   This $\Gamma - N_2O$ correlation is adapted to N_2O mixing ratios (in ppb) for the year 2017 as follows:

$$N_2O[1997] = N_2O[2017] \times (313/335). \quad (2)$$

   In addition, the mean age of air is calculated using a correlation by Engel et al. (2002) which is based on measurements from 1997 and 2000 and is also adapted to N_2O mixing ratios for the year 2017.

$$\Gamma = 6.03 - 0.0136 \times N_2O[1997] + 8.5892 \times 10^{-5} \times N_2O[1997]^2 - 3.376968 \times 10^{-7} \times N_2O[1997]^3 \quad (3)$$

Figure. 2b shows the Γ – N_2O correlations (valid above 375 K) from Andrews et al. (2001) and Engel et al. (2002) compared to clock-tracer mean age of air derived from global 3-dimensional CLaMS simulations driven by ERA-Interim and ERA5 $1° \times 1°$ reanalysis. In the Asian monsoon region, clock-tracer mean age of air based on ERA-Interim is lower than observation-based estimates while mean age of air based on ERA5 $1° \times 1°$ is somewhat older, but a little closer to the observations. For N_2O larger than ~310 ppb (between 380 K and 410 K) simulated mean age of air for both ERA5 $1° \times 1°$ as well as ERA-Interim is somewhat older than the observation-based mean age of air, likely related to an underestimation of subgrid-scale convective transport processes in the model (see Konopka et al., 2019, and discussion above).

Measured N_2O profiles indicate strong mixing with older stratospheric air only above ~400 K (Fig. 2a), therefore we can also compare trajectory-based transport times with observation-based mean age of air below 400 K. In Fig. 2b, trajectory-based mean transport times (back to 1 June 2016) for potential temperature levels between 375 K and 400 are added. At these altitudes, a very good agreement between observation-based mean age of air and trajectory-based transport times is found using both ERA-Interim as well as ERA5 to drive the trajectories. Therefore, CLaMS back-trajectories are very well suited for CO_2 reconstruction in particular below 400 K (Sect. 4.5). CLaMS mean age of air above 400 K will be further used for comparison to observation-based mean age from HFC-125 and C_2F_6 which are used to derive ascent rates (Sect. 4.3) .

Further, we discussed the observation-based mean age derived from HFC-125 and C_2F_6 as well as from SF_6 in comparison to CLaMS mean age of air derived from 3-dimensional calculations in more detail in Fig. 3 (of this reply) and added it in Sect. 4.3 to the revised version of our manuscript:

The observation-based mean age of air based on HFC-125 and C_2F_6 at 470 K is about ~2-2.5 years (Fig. 3), clock-tracer mean age of air inferred from 3-dimensional CLaMS simulations driven by ERA-Interim is younger

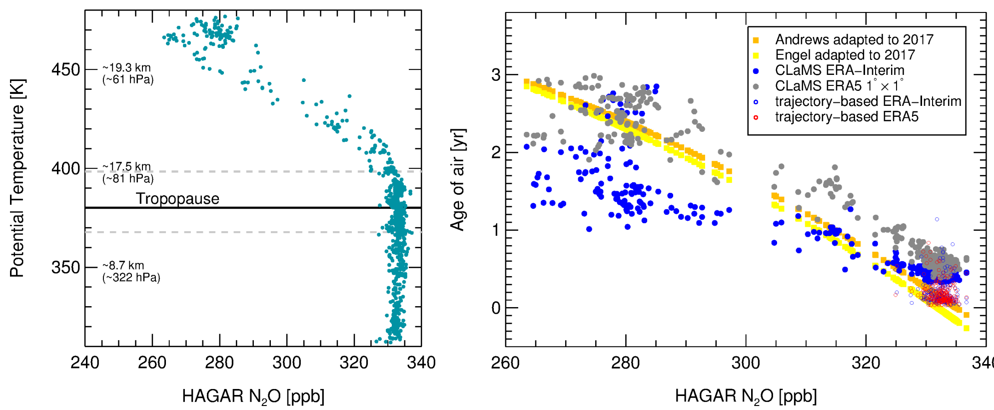

Figure 2: Airborne N_2O measurements from the StratoClim campaign in Kathmandu (Nepal) during July and August 2017 (left). In addition, the mean WMO tropopause using ERA5 (Hoffmann and Spang, 2022) as well as the lowest and highest tropopause (grey dashed lines) over Kathmandu during the flight days are shown. Mean age versus N_2O from Andrews et al. (2001) and Engel et al. (2002) adapted to the year 2017 compared to clock-tracer mean age of air derived from global 3-dimensional CLaMS simulations driven by ERA-Interim and and ERA5 $1^\circ \times 1^\circ$ reanalysis (right). Only N_2O measurements from the HAGAR instrument above 375 K potential temperature are shown. Further, trajectory-based transport times using ERA5 and ERA-Interim (back to 1 June 2016) are added for potential temperature levels between 375 K and 400 K.

than 2 years and ~2-3 years using ERA5 $1^\circ \times 1^\circ$ at this altitude (Fig. 3). Observation-based mean age of air inferred from HFC-125 and C_2F_6 is based on a reference level of 390 K, while clock-tracer mean age of air is based on the Earth's surface. From trajectory-based transport times, a time lag of about 2-3 months between Earth's surface and 390 K can be estimated. Taken this time lag into account, mean age of air driven by ERA-Interim is too young at this altitude, whereas mean age of air from ERA5 $1^\circ \times 1^\circ$ is somewhat too old at 470 K. Further, observation-based mean age of air based on SF_6 is compared to observation-based mean age of air based on HFC-125 and C_2F_6 (Fig. 3), however observation-based mean age of air based on SF_6 is about half a year older at 470 K than from HFC-125 and C_2F_6 caused by SF_6 sources in Asia (Adcock et al., 2021). Therefore, SF_6 is a rather unsuitable chemical age tracer for the Asian mon-

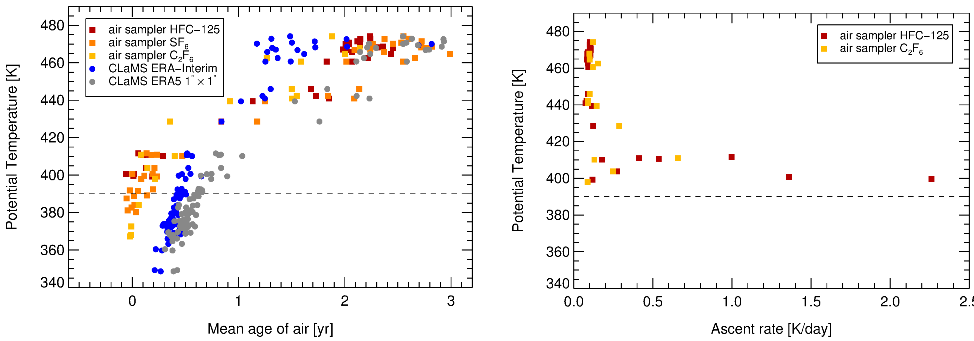

Figure 3: Observation-based mean age of air (left) and observation-based mean ascent rates above 390 K (right) derived from trace gas measurements of air samples collected with the whole air sampler (WAS) of Utrecht University during the eight StratoClim research flights over the Indian subcontinent in summer 2017. Note that negative observation-based mean age of air (< -0.1 year) found below 390 K are not shown. In addition, clock-tracer mean age of air for each air sample is shown derived from global 3-dimensional CLaMS simulations driven by the ERA-Interim and ERA5 $1^\circ \times 1^\circ$ reanalysis (right).

soon region.

7. *Fig.7: Looking at Theta > 430K: Which role plays transport and mixing from the TTL and tropical lower stratosphere for the calculation of fractions and further below the transport time estimates, also for the age of air and the CO2 reconstruction?*

In the stratosphere at potential temperature levels above 430 K, the fraction of air originating on the Indian subcontinent is low compared to contributions from other regions in the tropics and of aged air (older than 1 June 2016) from the stratosphere (Fig. 7). This has to be considered in both the CO_2 reconstruction and the calculation of age of air. At these altitudes it is important to consider 3-dimensional global long-term CLaMS simulations to calculate mean age of air (Sect. 3.3), because trajectory-based transport times inferred in our study do not cover time scales older than 1 June 2016. This issue is discussed in detail in Fig. 5 in Vogel et al. (2023b). Ditto for the CO_2 reconstruction at these altitudes it is important to include source regions from outside the Indian subcontinent as well as aged air from the lower stratosphere using the GOSAT-L4B CO_2 product (for more details see Vogel et al., 2023a).

8. *The CO2 cycle at the tropical tropopause is probably similar as at the monsoon tropopause, but how does this affect the reconstructed values and times?*

   Air masses in the Asian monsoon anticyclone are strongly separated by a horizontal transport barrier from the background air of the residual tropical tropopause region (e.g. Ploeger et al., 2015; Vogel et al., 2015, 2019). In the Asian monsoon anticyclone very young air from Asia is transported very fast upwards by convection. Therefore during the Asian monsoon season the CO_2 cycle at the Asian monsoon tropopause is dominated by Asian emissions (e.g. measured in Nainital and Comilla) and their seasonal cycle. However, in other regions at the tropical tropopause (outside of the monsoon systems) the air is much more a composite from different tropical surface regions in the Inter-Tropical Convergence Zone. However, here the transport times to UTLS altitudes are in general longer than within the Asian monsoon anticyclone. Fig. 1 of this reply, shows the seasonal variability of ground-based CO_2 at different sites in the tropics.

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