Author Comment to Referee #3

ACP Discussions doi: 10.5194/acp-2018-724 (Editor - Peter Haynes) ‘Lagrangian simulations of the transport of young air masses to the top of the Asian monsoon anticyclone and into the tropical pipe’

We thank Referee #3 for further guidance on how to revise our paper. Following the reviewers advice we have elaborated the relation of our findings to previously published work regarding the ‘longstanding debate’ and introduced an extended discussion of the presented results with respect to previous publications. 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.

The manuscript ‘Lagrangian simulations of the transport of young air masses to the top of the Asian monsoon anticyclone and into the tropical pipe’ investigates transport pathways in the monsoon region from the boundary layer into the stratosphere. The authors use both Lagrangian backward trajectory calculations and three-dimensional simulations including irreversible mixing with the Lagrangian transport model CLaMS. Artificial tracers of air mass origin are compared to measurements of chlorodifluoromethane (HCFC-22; CHClF2) by the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS). The methods are similar to those in Vogel et al. (2016) but in addition to horizontal transport they address vertical transport pathways out of the Asian monsoon anticyclone and subsequent upward transport into the lower stratosphere. The chosen period is a normal monsoon season in terms of medium rainfall over India in summer 2008. The paper presents an interesting description of the ‘spiralling staircase’. Consistency with MIPAS data supports the model results. The paper is well written and I support publication after a few comments have been addressed. The heavy focus on a particular day is didactical, but the analysis of different meteorological situations would provide stronger evidence. In certain passages the phrasing could be improved in order to more clearly distinguish what is the particular contribution of this *study to the 'longstanding debate about the transport mechanisms at the top of the Asian monsoon anticyclone and beyond into the stratosphere'. The debate is mentioned again in the discussion but the different arguments about 'the exact transport mechanism' could be more clearly stated. Otherwise it is difficult to distinguish if some very general assertions have been stated before in the literature or are novel to this work. The figures could be improved and the description thereof clarified in the text.*

We revised the paper following the referee's advice and added an extended discussion section to the revised manuscript to point out the relation of our findings to the existing literature.

Minor comments:

1. *p1 l19 'However, this upward transport': Make 'this' more clear (the upward spiralling range).*

   We revised this part in the abstract as follows.

   Moreover, the vertical transport of air masses from the Asian monsoon anticyclone into the tropical pipe is weak in terms of transported air masses compared to the transport from the monsoon anticyclone into the northern extratropical lower stratosphere.

2. *p2 l20 Briefly mention the sides in the debate and state where the authors stand.*

   We revised this part in the introduction as follows.

   The Asian monsoon circulation provides an effective pathway for tropospheric trace gases such as pollutants, gaseous aerosol precursors, as well as aerosol particles into the lower stratosphere which could play an important role in the formation of ATAL layer (e.g., Vernier et al., 2015, 2018; Höpfner et al., 2016; Brunamonti et al., 2018). There is also export of monsoon air quasi-isentropically out of the monsoon and a certain fraction of monsoon air may reach greater altitudes in the stratosphere. There is a longstanding debate about the transport mechanisms at the top of the Asian monsoon anticyclone and beyond into the stratosphere (e.g., Bannister et al., 2004; Park et al., 2009; Randel et al., 2010; Bergman et al., 2012, 2013; Randel and Jensen, 2013; Uma et al., 2014; Orbe et al., 2015; Garny and Randel, 2016; Tissier and Legras, 2016; Ploeger et al., 2017). In the literature different aspects of the complex interplay between convection, large-scale upward transport (driven by radiative heating), and the anticyclonic flow in the UTLS are highlighted. Randel et al. (2010) pointed out that the monsoon circulation provides an effective pathway for pollution from Asia to enter the global stratosphere. Vertical upward transport into the deep stratosphere occurs within the tropical pipe, where tropical air masses are isolated to some extent from isentropic mixing with mid-latitude air (e.g., Plumb, 1996; Volk et al., 1996). Bourassa et al. (2012) analysed the eruption of the Nabro volcano in northeastern Africa and reported that the volcanic aerosol enhancement from the Nabro eruption was not injected directly into the stratosphere. They conclude that volcanic aerosol only attained stratospheric altitudes through subsequent transport processes associated with deep convection in the region of the Asian monsoon anticyclone. Pan et al. (2016) highlight that the Asian monsoon anticyclone is an isolated 'bubble' of tropospheric air above the global mean tropical tropopause that isentropically sheds tropospheric air into the stratosphere. Further, they argue that the vertical transport of Asian monsoon air into the deep stratosphere is inefficient during summer..

3. *p5 l3 $\zeta < 120K$? p5 l 17 'is quantified.' What will be the quantitative measure?*

In CLaMS a pressure-based coordinate system (σ coordinates) is used for pressure levels greater than 300 hPa with a hybrid vertical coordinate (ζ) (for more details, see Konopka et al., 2012; Pommrich et al., 2014). The model boundary layer is defined $\approx$ 2–3 km above the surface following orography corresponding to $\zeta < 120$ K. The emission tracers are set in the model boundary layer every 24 hours and are transported (advection and mixing) into the free troposphere and stratosphere during the course of the simulation. The fraction of different emission tracers of an air parcel, e. g. in the tropical pipe, is a measure to quantify the transport from the source region into the tropical pipe during the course of the simulation.

4. *p6 l8 Dee et al. (2011) already cited in the first reference to ERAI in p4 l11*

   Yes, Dee et al. is cited twice. However, for clarification we think it is good to cite once again Dee et al. in Sect. 2.2.

5. *p7 l20 make more explicit the dates of the monsoon and the pulse releases to clarify the 6 month age.*

   We revised the sentence as follows.

   To analyse the transport pathways at the top of the Asian monsoon anticyclone during the monsoon season 2008, we use only the tracers of air mass origin for the time pulse for Summer 08 (started on 1 May 2008 until end of October 2008).

6. *l22 'have strong variability from day to day' please rephrase*

   The geographic position and shape of the Asian monsoon anticyclone show a strong day-to-day variability.

7. *p8 l1 mention the 360 theta level before in the text to streamline the reading*

   Thanks for the this comment. We agree that the 360 K level was introduced too abruptly. We added the following paragraph at the beginning of Sect. 3.1.1.

It is known that the Asian monsoon anticyclone has a strong horizontal transport barrier at about 380 K (e.g., Ploeger et al., 2015), however this transport barrier is not well defined at higher levels of potential temperature. The less strong transport barrier at higher levels has consequences on the vertical transport at the top of the anticyclone. Before the transport at the top is discussed we show the horizontal distribution of different emission tracers at 360 K and then their subsequent transport to the top of the anticyclone up to 460 K. Vogel et al. (2015) showed that the emission tracer for India/China is a good proxy for the location and shape of the Asian monsoon anticyclone using pattern correlations with potential vorticity (PV), and MLS O_3 and CO satellite measurements between 360 K and 400 K. Therefore here we use the India/China tracer as a proxy for the location of the anticyclone.

8. *p8 l10 'simulated horizontal gradients': is there an objective metric or visual inspection? How is the top of the asian monsoon precisely defined?*

   We removed this statement about tracer gradients. The objective metric is the tracer distribution of air masses released by the time pulse for Summer 08 (India/China tracer and tropical adjacent regions). A precise definition of the top of the Asian monsoon does not exist in the literature. In our simulations we use the contribution of the emission tracers for India/China and the tropical adjacent regions to infer the top of the Asian monsoon.

9. *p8 l17 Fig. 2 (3rd row), to be consistent with previous paragraph.*

   done

10. *p10 l15 When are the trajectories started? How many? What release pattern? It would help for understanding what was done to state this clearly in the text. 40 days could be analysed statistically, bur for individual trajectories is a little bit too long.*

We agree that the description of the initialisation procedure of the trajectories is a bit short. The 40-day backward trajectories are presented to illustrate the main transport pathways. A more statistical analysis is presented in Sect. 3.2.2 for global 20-day backward trajectories. We revised this paragraph as follows.

To analyse the transport pathways to the top of the anticyclone in more detail, 40-day backward trajectories are calculated starting in the western (20–50°N,0–70°E) and eastern (20–50°N,70–140°E) modes of the anticyclone. The trajectories are started at the position of the air parcels from the 3-dimensional CLaMS simulation at different levels of potential temperature ($\Theta = 380, 400, 420, 440\,\mathrm{K} \pm 0.25\,\mathrm{K}$) on 18 August 2018. Note that the air parcels in the 3-dimensional CLaMS simulation are distributed on an irregular grid. To take into account the distribution of the boundary emission tracer at the top of the Asian monsoon anticyclone, only air parcels are selected with contributions of young air masses (age $<$ 6 months, Summer 08) larger than 70% (380 K), 50% (400 K), 20% (420 K), and 5% (440 K) (not all levels of potential temperature are presented here). The percentages are chosen in a way to obtain a number of trajectories (less than 30) that can be reasonably visualised. The results of the 40-day backward trajectories are similar at different levels of potential temperature; therefore we show a selection of trajectories to demonstrate the main transport pathway to the top of the Asian monsoon. A larger set of 20-day backward trajectories analysed statistically will be discussed below in Section 3.2.2.

11. *p10 l20 describe the panels of fig 5 in the text.*

We revised the text as follows. Note that Fig. 5 from the ACPD version of the manuscript is Fig. 6 in the revised version.

Fig. 6 shows trajectories started in the eastern and western part of the Asian monsoon anticyclone around the thermal tropopause at 380 K on 18 August 2018. Air masses are uplifted to approximately 360 K very rapidly by various convective events occurring at different times and locations. Our 40-day backward trajectories show that preferred regions for fast uplift are continental Asia (mainly the region of the south slope of Himalayas and the Tibetan Plateau) and the western Pacific (not shown here). A lower fraction of trajectories originates in the free troposphere. The trajectories in Fig. 6 demonstrating convection below 380 K are only a snapshot for 18 August 2018. There are several previous studies (e.g., Randel and Park, 2006; Park et al., 2007, 2009; Wright et al., 2011; Chen et al., 2012; Bergman et al., 2013; Fadnavis et al., 2014; Tissier and Legras, 2016) quantifying the contribution of different source regions to the composition of the Asian monsoon anticyclone during the course of the monsoon season (see discussion in Sect. 4).

12. *p10 last paragraph. At this point the reader would feel satisfied with a statistical analysis of a larger number of days to support the case study results. Maybe some additional results such as those later presented in A1 could be mentioned.*

    As mentioned above a statistical analysis of 20-day backward trajectories for the 18 August 2018 is presented in Sect. 3.2.2.

13. *p11 l4 what do you mean with 'single selected trajectories'?*

    We revised the text as follows:

    In the previous section, the transport pathways for a restricted number of trajectories were discussed. Here, for a broader view 20-day backward trajectories for the entire region of the Asian monsoon anticyclone are presented.

14. *p11 l32 'In the previous sections, we could show that the Asian monsoon is an effective circulation pattern in the UTLS that transports very young air masses (< 6 months) from the surface into the lower stratosphere up to ≈ 460 K.' This may have been mentioned before in the literature. You could rephrase this as 'we could show how the effective circulation pattern in the UTLS can be seen with CLaMS and MIPAS data', for example. Also it seems that all your conclusions will be drawn*

from a single day case study. Additional statistical evidence from more modelling cases could help.

As proposed by referee #3, we revised the text as follows.

In the previous sections using CLaMS model simulations and MIPAS HCFC-22 measurements, we could show that the circulation of the Asian monsoon is effective in transporting very young air masses ($<$ 6 months) from the surface into the lower stratosphere up to $\approx$ 460 K.

We agree that the most of the analysis is focused on 18 August 2008 as a case study. However, the results of the 3-dimensional CLaMS simulation for 18 August 2008 is a result of the interplay between convection, large-scale upward transport (driven by radiative heating), and the anticyclonic flow in the UTLS during the last weeks of the simulation. The same is true for the 40-day and 20-day backward trajectories as well as for the MIPAS measurements. Thus our results are representative for August 2008. To give a broader view, we already include 20-day backward trajectories showing different days during the monsoon season 2008 within the Appendix.

15. *12 4 is it a CLaMS simulation?*

    Yes, it is a CLaMS simulation as described in Sect. 2.1.

16. *Fig 8. The figure is difficult to read. The label at the color bar is very small and takes time to find. You could replace the title of the subplots '08081812 at 90 E' that is the same for all and put is in the cation. 'horizontal winds (black lines)', do you mean horizontal wind absolute value isolines? 'corresponding levels of pressure' corresponding to what? 'Pressure levels as white lines' would be better. Are the values really zero in W07 (lower left panel) or is the color scale?*

    Following the referee's advice we revised the figure caption as shown in Fig. 1 of this author comment (= Fig. 9 of the revised version of this

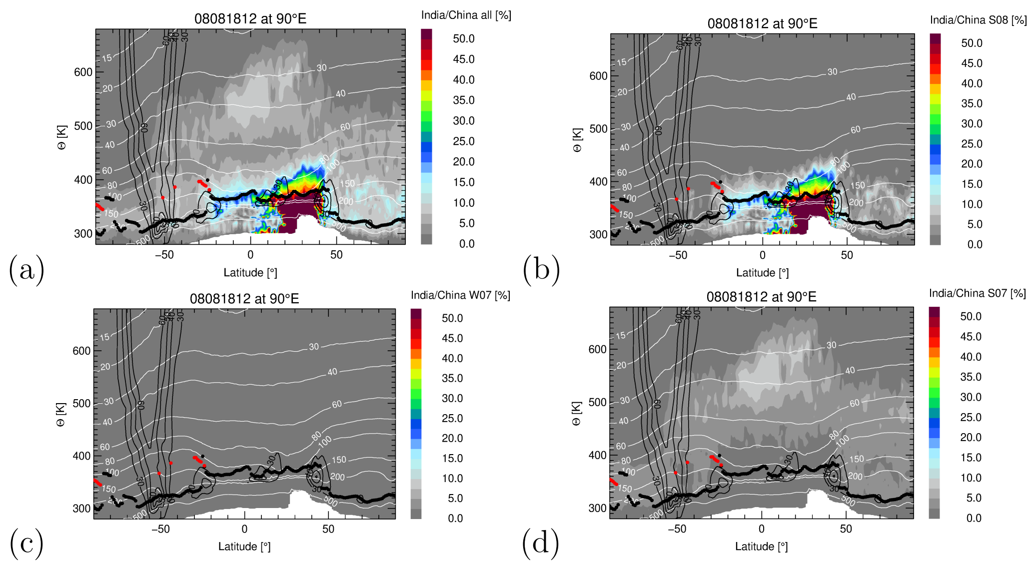

Figure 1: Latitude–theta cross sections at 90°E for the fraction of the India/China tracer for the simulation period (1 May 2007 - 18 August 2008 labeled as 'all') (a), for the Summer 08 (S08) pulse (b), for the Winter 07/08 (W07) pulse (c), and for the Summer 07 (S07) pulse (d) on 18 August 2008. The thermal tropopause (primary in black dots and secondary in red dots) and absolute horizontal winds (black lines for 30, 40, 50, and 60 m/s) are shown. The levels of pressure are marked by thin white lines. Note that the maximum value for the Winter 07/08 (W07) pulse (c) is 2.4%.

manuscript).
Further we removed 'corresponding' in all figure captions of the revised manuscript. The 'horizontal winds (black lines)' are calculated by $\sqrt{u^2 + v^2}$ and isolines for 30, 40, 50, and 60 m/s are shown and labelled. The maximum value for W07 is 2.4%.

17. *'demonstrating' may sound a bit strong for this context. 'Suggesting' or 'indicating' could fit better.*

We revised the sentence as follows.

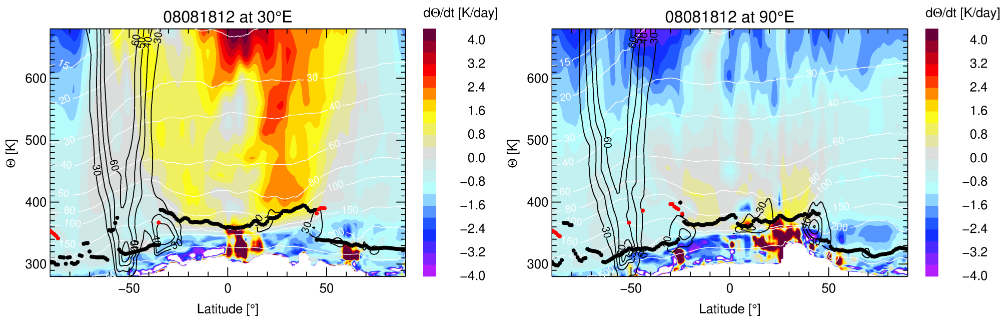

Figure 2: Latitude–theta cross section of dΘ/dt showing the radiative heating above the Asian monsoon anticyclone for the western (30°E) and eastern mode (90°E) of the anticyclone on 18 August 2008. The thermal tropopause (primary in black dots and secondary in red dots) and absolute horizontal winds (black lines for 30, 40, 50, and 60 m/s) are shown. The pressure levels are marked by thin white lines.

Fractions of air from the India/China tracer for the time pulse for Winter 07/08 are below 2.4%, indicating that during winter in the absence of the Asian monsoon anticyclone the transport of boundary layer emissions from India/China into the stratosphere is insignificant weak.

18. *p12 l14 If still describing Fig. 9 better to keep the same paragraph.*

    done

19. *Figure 10: again, wind speed contours, 'pressure levels' instead of 'corresponding levels of pressure'*

    Following the referee's advice we revised the figure caption as shown in Fig. 1 of this author comment (= Fig. 11 of the revised version of this manuscript).

20. *p13 l11: attract the attention of the reader to the vertical dashed line immediately here.*

We added in the figure caption of Fig. 12 of the ACPD version (=Fig. 13 of the revised manuscript) the following explanation.

Top: The contribution of the three different time pulses S07, W07, and S08 (each set for a time period of 6 months marked the vertical doted lines) for the entire Earth's surface (Ω_{S07}, Ω_{W07}, Ω_{S08}) to the tropical pipe between 30°S and 30°N at 550 K potential temperature from 1 October 2007 until the end of the simulation period (31 October 2008) (top, black lines).

21. *Fig 13 what is the dashed line?*

The dashed line marks the tropical pipe as described in the revised figure caption as follows.

The dashed line marks the tropical pipe which isolates tropical air masses largely from isentropic mixing with mid-latitude air (e.g., Plumb, 1996; Volk et al., 1996).

22. *p15 l12 please refer to the published version.*

The paper Hanumanthu et al., 2018 is not as yet published, therefore we refer here to Vernier et al. (2015, 2018); Brunamonti et al. (2018).

23. *p16 l17 'Thus, air masses in the upward spiral range are uplifted by diabatic heating across the (lapse rate) tropopause, which does not act as a transport barrier against this diabatic vertical transport process.': This assertion is likely to be 'consistent with previous studies'.*

We added the following references in the revised version of the paper.

Thus, air masses in the upward spiralling range are uplifted by diabatic heating across the (lapse rate) tropopause, which does not act as a transport barrier against this diabatic vertical transport process. This transport across the tropopause is consistent with previous studies (e.g., Bergman et al., 2012; Garny and Randel, 2016; Ploeger et al., 2017).

24. *p16 l 22 occurs where?*

    We revised this paragraph as follows:

    Above 380 K, within the upward spiralling range above the anticyclone, young air masses from along the edge of the anticyclone originating in the tropical adjacent regions are mixed with air masses from inside the anticyclone mainly originating in India/China. Therefore, a significant fraction of air masses from the tropical adjacent regions is found within a widespread area around the anticyclone and above caused by the large-scale anticyclonic flow in this region, acting as a large-scale stirrer. This transport pattern up to 460 K is consistent with previous results focused on lower levels of potential temperature (up to ≈400 K (Vogel et al., 2014, 2016; Li et al., 2017).

25. *The last paragraph is a nice summary of the mechanism but it undoubtedly draws from the conclusions of many previous studies. This should somehow be acknowledged.*

    We added within the conclusions in the revised version of the manuscript some additional references.

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