Author Comment to Referee #2

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(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 #2 for further guidance on how to revise our paper. Following the reviewers advice we have elaborate the relation of our findings to previously published work 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 study "Lagrangian simulations of the transport of young air masses to the top of the Asian monsoon anticyclone and into the tropical pipe" investigates transport processes from the boundary layer to the monsoon anticyclone and further into the stratosphere by employing 3-D CLaMS simulations with mixing and additional backtrajectory data. Further, comparisons with satellite data (MIPAS) are included, which increase the confidence in the presented results. Overall, the manuscript is well written and the figures and analyses are well composed. Further, the study contains interesting results suitable for publication in ACP. Nevertheless, I think that the following comments need to be addressed before the manuscript can be published. In particular, the manuscript would benefit from (and in my opinion needs) an extended discussion of the presented results with respect to previous publications.

General Comments

In the abstract and in the text, you distille the transport processes from the boundary layer to the tropical stratosphere into 3 separate regimes. In my opinion, this result is in agreement with previous notions on transport of

ASM air massse, i.e. I think it is known that the upper troposphere in the Asian summer monsoon region is strongly affected by convection (e.g. Randel and Park, 2006, show a strong impact from convection at 350- 360K), slow upward movement within the anticyclone is addressed e.g. in Park et al. (2007, 2009; see also the schematic Fig. 14 in the latter publication). Further, Ploeger et al. (2017) show slow upward transport of Asian summer monsoon air masses in the tropical pipe (cf. also Randel et al. 2010) and also presents an overview of transport processes in the ASM region in its introduction. There are also other studies addressing transport in the Asian monsoon and some that also mention slow ascent in the UT in the monsoon region: e.g. Wright et al. (2011), Bergman et al. (2012) and Garny and Randel (2016). Nevertheless, it is indeed interesting to have a single study (and model) that shows all of the transport regimes and your study includes additional information. Please, relate your results to these previous findings or suggestions and carve out how your study differs/agrees with the processes described there. How do your results complement these previous suggestions/findings? Maybe you could commet also on the influence of extremely deep (or even overshooting) convection on air masses within the UTLS in the Asian monsoon region.

Following the reviewer's advice we introduced an extended discussion of the presented results with respect to previous publications within the Discussion Section 4 in the revised version of the manuscript (see below). Further, we introduced in the Conclusion Section 5 additional references to better link to previous published work.

It is well known that the composition of the Asian monsoon anticyclone is strongly affected by convection over continental Asia (e.g. the south slope of the Himalayas and the Tibetan Plateau), Bay of Bengal, and the western Pacific, (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). However there is a debate about the contribution of different source regions to the composition of the Asian monsoon anticyclone. Further, there are differences in the conclusions in the literature about the contribution of different source regions depending on the used reanalysis data (e.g., Wright et al., 2011; Bergman et al., 2013). Findings by Vogel et al. (2015) show that there is a strong intraseasonal variability of boundary source regions to the composition of the Asian monsoon anticyclone during a particular monsoon season. We would like to emphasise that the trajectories presented in Fig. 6 demonstrating convection below 380 K are only a snapshot for 18 August 2018 with convection over the western Pacific and continental Asia mainly in the region of the south slope of the Himalayas and the Tibetan Plateau.

Here, in contrast to earlier studies, we focus on transport at the top of the anticyclone at altitudes greater than 380 K potential temperature (≈100 hPa) reaching up to 460 K (≈60 hPa). Further, in addition to previous studies (e.g., Garny and Randel, 2016; Ploeger et al., 2017), we relate the transport of air masses from inside the Asian monsoon anticyclone to air masses uplifted outside the anticyclone. Subsequently these air masses are jointly transported upwards to the top of the anticyclone at ≈460 K. ... (further see revised version of the manuscript).

We added in Sect. 3.3.1 the following discussion:

It is known that the radiative heating rates in the tropical UTLS are different in current reanalysis models (e.g., Wright and Fueglistaler, 2013) and are most likely overestimated in ERA-Interim (e.g., Ploeger et al., 2012; Schoeberl et al., 2012). Therefore, the rates of diabatic heating in the upward spiralling found in our study are most likely somewhat too high, however slow upward transport in the UTLS in the region of the Asian monsoon anticyclone associated with positive heating has been addressed previously (e.g., Park et al., 2007; Bergman et al., 2012; Garny and Randel, 2016; Ploeger et al., 2017).

Regarding the influence of extremely deep convection, note that in CLaMS convection is driven by ERA-Interim reanalysis data. We introduced the following paragraph within Section 2 to explain convection in CLaMS in more detail. Small-scale overshooting convection is not included in ERA-Interim, however the focus of our paper is to understand the main transport pathways at the top of the anticyclone higher than 380 K up to 460 K (≈100-60 hPa) which is above the main level of tropical deep convection (e.g., Devasthale and Fueglistaler, 2010; Bergman et al., 2012).

The upward transport and convection in CLaMS (in both three-dimensional simulations as well as in trajectory calculations) is driven by ERA-Interim reanalysis data in which changes are implemented to improve deep and mid-level convection compared to previous reanalysis data (Dee et al., 2011). However, small-scale rapid uplift in convective cores is not included. Therefore convection over Asia is most likely underestimated in ERA-Interim. However, the focus of our paper is to understand the main transport pathways at the top of the anticyclone greater than 380 K and up to 460 K (≈100-60 hPa) which is above the main level of tropical deep convection (e.g., Devasthale and Fueglistaler, 2010; Bergman et al., 2012). Further, previous studies demonstrated that the vertical transport in CLaMS allows the spatio-temporal distribution of CO within the Asian monsoon anticyclone measured by the Aura Microwave Limb Sounder (MLS) to be reproduced (Vogel et al., 2015; Ploeger et al., 2017).

Related to this issue, you state a convective regime and I wonder how convection is treated in your simulations and backward trajectory calculations. Please incorporate some notion on how the setup of your simulations/trajectories will affect your results.

We revised this paragraph in Sect. 2 regarding convection in CLaMS as already stated above (see previous comment).

P.8 L.31-31: "...how can air masses...?": you pose this question, however, to me it is not clear where it is anserwered. Are you thinking about inmixing from the outside to the inside/edge of the AC and subsequent vertical transport. Please connect to the parts in the text where this question is answered and/or e.g. repeat the question and give the answer to it in the conclusion. Would it be possible to include the transport of air masses from adjacent regions above 380K also in your Fig. 13?

We agree it would be helpful to revisit to these questions posed within the introduction. Therefore, we refer to these two questions within the conclusions as follows.

Further between 420 K and 460 K, highest contributions from young air masses are found around the edge of the anticyclone, indicating a spatially strongly inhomogeneous ascent in the monsoon with strongest ascent at the edge. The higher in the upward spiralling range the more air masses from the stratospheric background are mixed with the young air masses transported upwards within this upward spiralling range. Thus in this paper, we could answer the question of what are the transport pathways of young air masses at the top of the Asian monsoon into the stratosphere by the concept of the upward spiralling range.

To answer our second question of how boundary layer source regions in Asia affect the composition of the middle stratosphere within the tropical pipe at 550 K, the transport times from the Earth's surface up to this level of potential temperature need to be taken into account. In a two-monsoon-season simulation...

Moreover, following the reviewer advice we added Fig. 1 (= Fig. 15 of the revised version of the manuscript) to our manuscript.

Most of the analysis are focused on one day (18 August 2008), only. For some of the analyses this might not be important, however, other analyses might depend on the specific conditions (e.g. the split of the anticyclone) during that date/period as for example the trajectory analysis in Fig. 5. Please include some additional discussion regarding that issue. Partly, you have already addressed this issue, e.g. to complement Fig. 7 you additionally include Figure A1. I would guess that in particular the backward trajectories results are affected by the choice of the starting date and might vary throughout the monsoon season. This issue also extends to the comparison with MIPAS data and to the inferred transport on the eastern/western side of the anticyclone.

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.

Fig. 8 in Garny and Randel (2016) shows kinematic and diabatic vertical velocities and Fig. 12 a) in Park et al. (2007) shows pressure tendencies.

These figures show ascent on the eastern side of the anticyclone and descent on the western side at levels close to (but still mostly below) the tropopause. How do your statements and your Fig. 10 relate to that? How does the climatological picture of Fig. 10 look like? Is there always (i.e. on a climatological basis) stronger heating above the western side of the anticyclone above the tropopause but cooling below? How is it on the eastern side?

Fig. 10 (= Fig. 11 of the revised version of this manuscript) shows in agreement with Garny and Randel (2016) and Park et al. (2007) downward transport (negative radiative heating) below ≈360 K in the western mode of the anticyclone and upward transport (positive radiative heating) above ≈360 K in the eastern mode on 18 August 2008. Fig. 8 in Garny and Randel (2016) shows monthly mean vertical velocity for July 2006 at 360 K using ERA-Interim data. Fig. 12a in (Park et al., 2007) shows July–August average ERA40 vertical velocity for 2000-2002 at 104 hPa. Further, also Fig. 10a in Pan et al. (2016) confirm ascent on the eastern side of the anticyclone and descent on the western side showing June–July–August vertical velocity from WACCM4-SD at 100 hPa for 2014. Thus, ascent in the eastern side of anticyclone and descent on the western side in the upper troposphere is a common feature found in our case study for the 18 August 2008 as well as in a more climatological picture reported in the literature (Park et al., 2007; Garny and Randel, 2016; Pan et al., 2016).

The focus of our study is to demonstrate that in the upward spiralling range (above 360 K) a slow upward transport is found over the region of entire anticyclone (west and east mode) with diabatic heating rates of up to 1–1.5 K inferred from ERA-interim. Our 40-day backward trajectory calculations (see Fig. 6 and 7 of the revised version of this manuscript) demonstrate that a diabatic heating above 360 K is found at both the western and eastern side of the anticyclone during August 2008. A broader climatological analysis about differences in heating rates between the western and eastern side of the anticyclone above the tropopause would be an additional project and is therefore not included in this paper.

Additionally, I think it would be very helpful if you relate the results of your tracer pulses shown in Figs. 8 and 9 to the results in Ploeger et al. (2017). In particular with respect to transport of air masses from the anticyclone to the deep stratosphere.

We extended the discussion regarding the paper by Ploeger et al. (2017) within the Discussion Section 4 as follows below. Our results agree in general with findings by Ploeger et al. (2017), however in our paper in addition the contribution of the tropical adjacent regions to the tropical pipe are quantified. Further, the tracer approach is different between Ploeger et al. (2017) and our paper.

In Ploeger et al. (2017) the anticyclone tracer is initialised with unity inside the PV contour enclosing the anticyclone core in the 370-380 K layer on each day during July-August of the years 2010-2013 and is advected as an inert tracer during the following year. On 1 July of the year thereafter, the tracer is set to zero everywhere and is then reinitialised for the following monsoon season. Thus, the anticyclone tracer is set to zero during the monsoon season in July.

In our paper, the boundary emission tracers are released within the model boundary layer each day during the course of the two-monsoon-season simulation from 1 May 2007 until 1 November 2008. Thus, the transport from the troposphere through the Asian monsoon anticyclone into the tropical pipe is continuously covered over two succeeding years.

It has been proposed that the Asian monsoon constitutes an effective transport pathway from the surface, through the Asian monsoon anticyclone, and deep into the tropical pipe based on satellite observations of hydrogen cyanide (HCN) (Randel et al., 2010). HCN is a tropospheric pollutant produced mainly by biomass burning with a strong sink on ocean surfaces. Therefore tropical ocean regions cannot be the source for HCN found in the tropical pipe. Ploeger et al. (2017) addressed this issue using CLaMS simulations marking air masses within the Asian monsoon anticyclone by a PV-gradient criterion (Ploeger et al., 2015). They find that the air mass fraction from the anticyclone correlates well with satellite measurements of HCN within the tropical pipe.

In our study, we found a similar behaviour for contributions of the India/China tracer within the tropical pipe as Randel et al. (2010) for HCN and Ploeger et al. (2017) for the simulated anticyclone air mass fraction. Ploeger et al. (2017) found a maximum anticyclone air mass fractions around 5% in the tropical pipe using 3-dimensional CLaMS simulations for 2010-2013. This is consistent to our simulations finding about 6 % contributions of the India/China tracer within the tropical pipe at 550 K in 2008.

However in addition to Randel et al. (2010) and Ploeger et al. (2017), we show that the contributions from emissions from Southeast Asia and the tropical Pacific during summer are larger than the contribution from India/China within the tropical pipe. This demonstrates that the Asian monsoon anticyclone is a more effective transport pathway for the tropical adjacent regions than for air masses from inside the anticyclone itself (India/China). From the tropical adjacent regions air masses can be transported to the edge of the Asian monsoon anticyclone and then further into the tropical pipe.

Specific comments

P1 L19-20: Regarding the effectiveness of horizontal mixing and vertical transport, Garny and Randel (2016) seem to come to a different conclusion. Please discuss (e.g. in Sect. 4) how your results agree and differ. In case of the latter please also discuss why they differ.

Many thanks for this comment. This shows that we have to be more precise in our formulations to avoid any misunderstandings. Our statement on P1 L19-20 is related to the vertical transport of air masses into the tropical pipe compared to the transport from the monsoon anticyclone into the northern extratropical lower stratosphere. In contrast, Garny and Randel (2016) compares the difference of vertical transport into the lower tropical stratosphere in the anticyclone directly above the tropopause with the isentropic transport from the monsoon anticyclone into the northern extratropical lower stratosphere. Garny and Randel (2016) found only a few percent 3%/8% (360 K/380 K) by isentropic transport, however 15% of trajectories from the Asian monsoon anticyclone reach the northern extratropical lower stratosphere after 60 days. Most of them by upward transport into the tropical stratosphere and subsequent transport into the northern extratropical lower stratosphere. In Vogel et al. (2018), we found a contribution of the India/China tracer up to 16% (at 380 K) in the northern extratropical lower stratosphere during fall 2008. The transport of the India/China tracer within the 3-dimensional CLaMS simulations includes both transport pathways: direct isentropic transport as well as vertical transport in the region of the anticyclone into the tropical stratosphere and subsequent northward transport. Therefore, the value of 15% in Garny and Randel (2016) is comparable with the value of 16% (at 380 K) in Vogel et al. (2018) and therefore in good agreement.

We revised the abstract as follows.

In the upward spiralling range, air masses are uplifted by diabatic heating across the (lapse rate) tropopause, which does not act as a transport barrier under these conditions. Further, in the upward spiralling range air masses from inside the Asian monsoon anticyclone are mixed with air masses convectively uplifted outside the core of the Asian monsoon anticyclone in the tropical adjacent regions. Further, 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. Air masses from the Asian monsoon anticyclone (India/China) contribute a minor fraction to the composition of air within the tropical pipe at 550 K (6%), the major fractions are from Southeast Asia (16%) and the tropical Pacific (15%).

The paragraph related to the issue within the Discussion Section 4 is revised as follows.

Vogel et al. (2016) performed a CLaMS simulation for the year 2012 using similar tracers of air mass origin as in this work and found a flooding of the northern extratropical lower stratosphere with young air masses from the region of the Asian monsoon anticyclone. The transport of young air masses (age < 6 months) into the northern extratropical lower stratosphere is calculated, resulting in up to 44% at 360 K (up to 35% at 380 K) end of October 2012, with the highest contribution from India/China up to 15% (14%) (see Fig. 14 in Vogel et al. (2016)). Here, the same analysis is performed for the simulation for 2008 and a slightly higher impact on the northern extratropical lower stratosphere is found for the year 2008, up to 48% young air at 360 K (up to 41% at 380 K) end of October 2008 and up to 18% (16%) from India/China compared to 2012 (see Appendix B). This difference is most likely caused by the interannual variability of the monsoon system. However, within the tropical pipe at 550 K, in 2008 the contributions from India/China are about 6 %, demonstrating that the transport of air masses from the Asian monsoon anticyclone into the northern extratropical lower stratosphere during boreal summer and fall is more effective than the vertical transport into the tropical pipe during the course of one year. This is consistent with Ploeger et al. (2017), who found maximum anticyclone air mass fractions around 5%

in the tropical pipe and 15% in the northern extratropical lower stratosphere using 3-dimensional CLaMS simulations for 2010-2013. In a study releasing trajectories within the Asian monsoon anticyclone, Garny and Randel (2016) found a similar values of 15% of trajectories released in the anticyclone that reach the northern extratropical lower stratosphere after 60 days (for 2006).

P3 L7-10: Regarding the connection of El Nino and La Nina with the Indian summer monsoon. You argue that 2008 was (in terms of rainfall) normal because of La Nina in the winter before, although, in the previous sentence you claim that El Nino and La Nina events tend to be connected to unusual rainfall in the following Indian summer monsoon season. This seems contradictory to me! Further, Kumar et al. (2006) show a relation of concurrent SSTs with rainfall in India (during a quick search I could not find that they are stating a connection with previous winter SSTs). Also, in Webster et al. (1998) I could not easily find to which SST anomaly they refer, i.e. previous/following winter or concurrent summer. Please comment on this and revise if necessary.

Thanks for the comment, we revised these sentences as follows and introduced a further reference to the connection between ENSO to Indian rainfall.

Further, in 2008 there was a normal monsoon season in terms of normal rainfall over India in summer 2008[1]. It is established that the Indian monsoon is influenced by the El Niño Southern Oscillation (ENSO) (e.g., Kumar et al., 2006). There is evidence that a strong La Niña in winter (e.g. 2007/08 (DJF) according to the Oceanic Niño Index[2]) in combination with La Niña conditions during the subsequent summer (as in 2008) is correlated with normal rainfall over India with a certain variability in precipitation between different Indian regions (e.g., Chakraborty, 2018).

P5 L3-5: Is the sum of the tracers for all parcels in the boundary layer really always equal to 1 as you describe on page 5 L3-4. What if unmarked parcels from above the BL are transported into the BL? Are they removed? Otherwise, they might not be marked in the BL as marking takes place every 24h, only. Does the time step of 24h release play an important role? As

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[1] see e.g. `http://www.tropmet.res.in/~kolli/mol/Monsoon/Historical/air.html`

[2] see e.g. `http://ggweather.com/enso/oni.htm`

an example, Bergman et al (2013) use backward- trajectories started every 6 hours. Why don't you mark/emmit the tracer "continuously", i.e. at every time step of the simulation? Is there a scientific or technical reason for this setup

Thanks for the comment, in fact we have to be more precise at this point and revised the sentence as follows. We adapted also Table 1 by introducing the emission tracer for the background.

Within the model boundary layer, the sum of all the different emission tracers (Ω_i) including the emission tracer for the background (remaining surface) is equal to 1 ($\Omega = \sum_{i=1}^{n} \Omega_i = 1$, see Table 1) .

Air parcels in the free troposphere and stratosphere are not unmarked. They are marked with ‘zero’ in contrast to air parcels in the model boundary that are marked with ’one’. If air parcels from the free troposphere are transported downward into the model boundary layer, they will be overwritten by the boundary conditions every 24 hours. The setting of the emission tracers is adjusted to the mixing in CLaMS which is every 24 hours. The mixing in CLaMS is coupled to the integral deformations in the flow over the time step of transport. The critical deformation parameter λ_c can also be expressed in terms of a critical Lyapunov exponent γ_c (with $\gamma_c = \lambda_c \times \Delta\mathrm{t}$) which depends on the advection times step (Δt). The mixing procedure in CLaMS is optimised using a γ_c equal to 1.5 for a $\Delta\mathrm{t} = 24\,\mathrm{h}$ (Konopka et al., 2007), therefore we use here a time step of 24 hours to set the boundary emission tracers. It is possible that an air parcel from the free troposphere is transported downwards into the model boundary layer and subsequently upwards out of the model boundary layer into the free troposphere within a time period lower than 24 hours without mixing. In that case the air parcel is not marked by an emission tracer. However, we think the impact of this issue is small compared to the uncertainties of the trajectory calculations itself at the lowest model levels.

P6 L1: Please add whether the trajectories described in this section are calculated using heating rates (as I would assume) or kinematic vertical velocities.

Yes, we use heating rates. We revised the sentence to be more precise as follows. Moreover, we added some further information to the vertical transport in the model within the general CLaMS description in Sect. 2.0 (see above).

Within this study, 20-day and 40-day backward trajectories are calculated driven by wind data (with a horizontal resolution of $1^\circ \times 1^\circ$) from the ERA-Interim reanalysis (Dee et al., 2011) and using the diabatic approach to analyse the transport pathways of air parcels at the top of the Asian monsoon anticyclone and beyond into the tropical pipe.

P7 L6-9: Has the same method for interpolating MIPAS HCFC-22 data been used in Vogel et al. 2016? Then you could add a note so it is clear.

The same synoptic interpolation of MIPAS HCFC data has been used in Vogel et al. (2016) (see Fig 13). However, in Fig. 13a in Vogel et al. (2016) three-monthly mean values of HCFC for July, August and September 2008 are shown in contrast to the Figures in Vogel et al. (2018). In Vogel et al. (2018), MIPAS HCFC-22 data are shown synoptically interpolated for 18 August 2018 (see Fig. 3 and Fig. 11). Because of this difference, we think here it it better to make no reference to Vogel et al. (2016) to avoid any misunderstanding.

P8 L16 and following as well as P9 L26-27: Either in the description of Fig. 2 2nd row and Fig. 3 2nd row left or in the discussion you should draw a relation to Pan et al. (2016), who showed that upward transport (e.g. of CO) is mainly focused on the eastern side of the AC.

We added the following sentence in Sect. 3.1.1 to the discussion of Fig. 2 (2nd row):

The horizontal transport of air masses from the eastern to the western mode of the anticyclone indicated by the India/China tracer is consistent with simulations of carbon monoxide (CO) using the Whole-Atmosphere Community Climate Model (WACCM4-SD) (Pan et al., 2016).

P10 L13: Please state that you are starting trajectories only on 18 August 2018 for the analyses in Sect. 3.2.1. Or have you analysed other dates as well?

In our paper (Vogel et al., 2018), 40-day backward trajectories started on

18 August 2018 are only presented. We add the date (see below). For your information, we also performed for other days 40-day backward trajectories with similar results as for 18 August 2018. However, we decided to only present the results for the 18 August 2018 as a case study.

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.

P10 L22-23: How do you know that the transport occurs above the Tibetan Plateau? From Fig. 5 only the longitudinal range is visible but not where in latitude the parcels ascend. If you have made additional analyses to check that they are indeed from the Tibetan Plateau just note that you have analysed this but chose to not include a figure or the analysis here.

Fig. 2 (of this author comment), shows the location of the strongest updraft along the 40-day backward trajectories shown in Fig. 5 of the revised version of the manuscript. There is a cluster of trajectories in the region of the south slope of Himalayas and the Tibetan Plateau as well as in the western Pacific. We revised the sentence as follows.

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).

P10 L32: At some instances (e.g. here at P10 L32) you refer to inside or outside the anticyclone but do not give a reliable definition or state what you consider as inside or ouside. Would it be an option to include PV contours for that purpose? Also on P11 L5 you should probably rephrashe to "entire Asian monsoon region" because you do not start only within the anticyclone.

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 missing at higher levels of potential temperature. Therefore, it is difficult to define inside/outside the anticyclone for all levels above 380 K. Here we use the emission tracer for India/China is a proxy for the location and shape of the Asian monsoon anticyclone as introduced as follows in the manuscript.

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 proxy for the location of the anticyclone.

P11 L14: Maybe you should rephrase this part stating "At 380..." instead of "Above 380K,..." because at 400K the structures are not as inhomogeneous anymore and above 400K there is also considerable upward transport in the tropics.

As proposed we revised this paragraph as following including also comments by reviewer #1.

Above 360 K, air parcels that experienced strong upward transport larger than 20–30 K within 20 day (corresponding to a mean value of 1–1.5 K per day) are largely found in the region of the anticyclone. This rate of upwelling is much slower compared to convective upwelling shown at 360 K. Air parcels that experienced strong upward transport are mainly grouped in curved elongated filaments, reflecting a rotating movement of the air parcels at the top of the anticyclone. Often air parcels with strong $\Delta\Theta$ above 360 K are located more at the edge of the eastern and western modes of the anticyclone and at the edge of the eastward-migrating eddy at the eastern flank of the anticyclone. Thus the upward transport in the region of the anticyclone is inhomogeneous and not homogeneously distributed over the entire anticyclone as suggested from climatolgical studies (e.g., Randel et al., 2010; Ploeger et al., 2017). This is consistent with results presented above in Sect. 3.2.1 demonstrating that for single selected trajectories the transport at the top of the Asian monsoon anticyclone is a slow upward transport of about 1–1.5 K per day in a large-scale spiral above the anticyclone caused by diabatic heating. In the backward trajectory calculations mixing processes are not included, however the results of the trajectory calculations are consistent with patterns found in the 3-dimensional CLaMS simulation including mixing as discussed in Sect. 3.1.3, demonstrating that young air masses above 400 K are found at the edge of the anticyclone. Above 400 K, air masses in the tropics also experienced upward transport, but the vertical uplift is in general lower than 20 K within 20 day, (i.e. lower than 1 K per day).

P. 12 L14 and L17: Two times 25% instead of 15% is mentioned, as I assume would be correct. If I am correct, the 25% are the contribution of the winter pulse (W07) at 450K, right?

Yes, we agree. However, we changed Fig. 9 (of the manuscript) showing TAR instead of SEA. For TAR 25% is correct. We changed this sentence as follows (see Figure 9 in the revised version of the manuscript.

Many thanks for this comment. 15 % is correct. We corrected the percentages in the manuscript.

P14 L6-8: Do you really mean "Asian monsoon air masses from the anticyclone" or rather air masse from your India/China tracer? I think your findings show the claimed relation only for the latter.

We agree that the India/China tracer and air masses from the anticyclone are not the same, however we found in Vogel et al. (2015), that India/China tracer 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 as explained in Sect. 2.1 in Vogel et al. (2018). We clarified the sentence as follows:

Further, our findings show that air masses from India/China, thus mainly from the Asian monsoon anticyclone, contribute to a smaller fraction of the composition of air within the tropical pipe at 550 K; the major part is from Southeast Asia and the tropical Pacific.

P14 L30-31: I think slow upward transport has been proposed earlier (see my general comment). Please clarify if you are referring to some specific point of the upward transport process that was not published earlier.

We revised the Discussion Section 4 as discussed above and clarified that our focus is the relation of transport of air masses from inside the Asian monsoon anticyclone to air masses uplifted outside the anticyclone in an altitude range higher than 380 K potential temperature (≈100 hPa) up to 460 K (≈60 hPa).

Here, in contrast to earlier studies, we focus on transport at the top of the anticyclone at altitudes greater than 380 K potential temperature (≈100 hPa) reaching up to 460 K (≈60 hPa). Further, in addition to previous studies (e.g., Garny and Randel, 2016; Ploeger et al., 2017), we relate the transport of air masses from inside the Asian monsoon anticyclone to air masses uplifted outside the anticyclone. Subsequently these air masses are jointly transported upwards to the top of the anticyclone at ≈460 K.

Further we added in Sect. 3.3.1 the following discussion.

It is known that the radiative heating rates in the tropical UTLS are different in current reanalysis models (e.g., Wright and Fueglistaler, 2013) and are most likely overestimated in ERA-Interim (e.g., Ploeger et al., 2012; Schoeberl et al., 2012). Therefore, the rates of diabatic heating in the upward spiralling range found in our study are most likely somewhat too high, however slow upward transport in the UTLS in the region of the Asian monsoon anticyclone associated with positive heating has been addressed previously (e.g., Park et al., 2007; Bergman et al., 2012; Garny and Randel, 2016; Ploeger et al., 2017).

I think it would be good to label all panels of all figures with (a), (b), (c) and so on as you do for example in Fig. 3 but not in Figs. 4, 5 etc. This is just a suggestion, but would definitely help to increase the readability. Then you could refer directly to the individual panels of the figures and it would be *consitent throughout the manuscript.*

done

Also, consider to add additional references to the individual panels in the text when you draw a conclusion or describe something that is based on the respective panel.

done

Minor suggestions/corrections:

1. *P1 L11: Either change to "Second, these air masses..." or "Second, air masses are uplifted within the anticyclone..." or something similar.*

   done

2. *P1 L14: As before, maybe clarify by changing your sentence to something like: "Third, transport of air masses affected by the Asian monsoon (anticyclone)..." or something similar.*

   done

3. *P2. L1: This probably needs some additional restriction to where the the Asian monsoon is the "most pronounced circulation pattern". Do you refer here to the tropospheric flow or the UTLS anticyclone?*

   We revised the sentence as follows:

   The Asian summer monsoon is associated with deep convection over the Indian subcontinent and is the most pronounced circulation pattern in boreal summer with an anticyclonic flow that extends from the upper troposphere into the lower stratosphere (UTLS) region (e.g., Li et al., 2005; Randel and Park, 2006; Park et al., 2007).

4. *P2 L21-22: Order references according to year of publication.*

   done

5. *P3 L1: Would it be better to change "defined regions" to "specific regions"?*

   We prefer ‘defined regions’.

6. *P3 L2: Shouldn't this read: "covering Earth's entire surface". Then it would need to be changed throughout the manuscript.*

   We don’t think so.

7. *P3 L32-33: Maybe change to "...a total simulation period of 18 months)."*

   done

8. *P4 L2-6: The two sentences starting with "With this approach..." and "This model setup..." seem somehow repetitive. If they are not, please try to clarify.*

   done

9. *P9 L4-5: Repetition of "in particular". Please rephrase.*

   done

10. *P13 L6: "exists" should be "exist". Also consider to rephrase, e.g. to "... pathways exist. On these horizontal pathways, air masses are transported isentropically..."*

    done

11. *P13 L10: I would suggest to shift the first sentence of the paragraph ("On 18 August....") behind the current second sentence ("To analyse...") or/and adapt as it seems to be doubled at the moment.*

    no

12. *P13 L33: Probably this should be "...from the tropical...".*

    done

13. *P14 L13: Are "Asian monsoon anticyclone" and "Asian monsoon" switched here?*

    done

14. *P32: In the caption of Fig. 8 it should state "...(1 May 2007 - 18 August 2008)..." instead of "...(1 May 2007 - 31 October 2008)...", because you show the tracer distribution on 18 August 2008. This is also how you describe the figure in the text.*

    done

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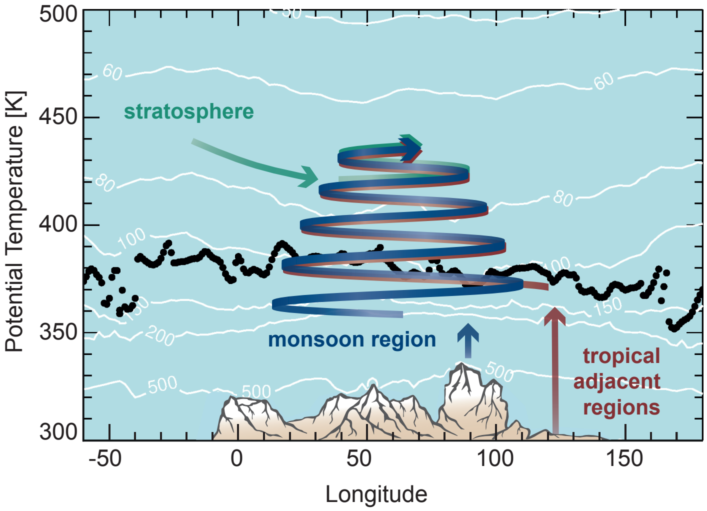

Figure 1: Longitude-theta cross section at 30°N: At the top of the Asian monsoon anticyclone (above ≈360 K) air masses circulate around the anticyclone in a large-scale upward spiral extending from northern Africa to the western Pacific. In the upward spiralling range air masses from inside the Asian monsoon anticyclone (shown in blue) are mixed with air masses convectively uplifted outside the core of the Asian monsoon anticyclone in the tropical adjacent regions e.g. uplifted by tropical cyclones in the western Pacific ocean (shown in red). The higher above the thermal tropopause the larger is the contribution of air masses from outside the Asian monsoon anticyclone from the stratospheric background coming into the upward spiralling flow (shown in green). The levels of pressure are marked by thin white lines and the thermal tropopause is shown by black dots.

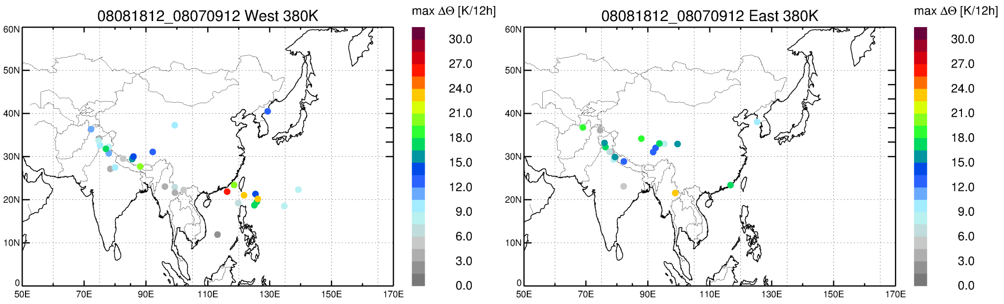

Figure 2: The geographical position of the strongest updraft along the 40-day backward trajectories in the western and eastern mode of the anticyclone (started at 380 K) shown in Fig. 5 of the revised version of the manuscript.