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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Transport of aerosol pollution in the UTLS during Asian summer monsoon as simulated by ECHAM5-HAMMOZ model" *by* S. Fadnavis et al.

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Replies to Reviewer-I

Fadnavis et al. presents transport of aerosols in the Asian monsoon region based on the simulations of global chemistry transport model with detailed analyses of their impact on various physical and dynamical processes in the upper troposphere and lower stratosphere. Aerosol extinction coefficients obtained from the HALOE and SAGE II instruments are also used to compare with the model simulations. I found the results interesting and would like to suggest following comments for the authors might take into consideration.

Reply: We thank the reviewer for the encouraging comments and critical remarks which we have carefully analyzed. These comments helped to improve our manuscript (the revised manuscript is attached as a supplement). Detailed answers to the individual comments are inserted below.

Major Comments 1. The focus of this paper is not clear. The authors have to present not only the changes in various processes due to aerosols but also their interaction and mechanisms that are responsible for the feedbacks. This article contains a lot of information but they do not offer one big picture, i.e., what is the main result of this paper?

Reply: To increase clarity and focus of the manuscript, we have changed the abstract and the text to highlight the new results in our paper. The new results in this paper are: 1) The formation of a transport conduit into the upper TTL between 20N and 30N around 100E in the presence of aerosols, and 2) the formation of an aerosol arch spanning from the northern hemisphere subtropics to the southern hemisphere subtropics around the tropical tropopause due to large scale mixing processes. This is not a trivial result as other models, e.g. WACCM (see Figure 13 in Park et al., 2013) fail to produce such a transport pattern in the case of HCN which has localized ASM source regions and is a good proxy for aerosol transport. The aerosol arch feature is consistent with mixing by synoptic scale Rossby waves around the 380 K isentrope as found by Homeyer and Bowman (2013). The paper is now re-organized under a suitable title. The big picture the authors want to focus on is "Transport of aerosol pollution due to ASM convection and impact of aerosols over the Asian monsoon region". The aerosol interaction mechanisms which are responsible for the convective transport feedback are a topic of interest. However, to restrict the length of the paper we will postpone detailed analysis for the next paper. Nevertheless a few results pertaining to aerosol effects merit inclusion in the paper without extensive analysis. For example aerosol induced circulation changes causes weakening of the main branch of the Hadley circulation. This leads to reduction of monsoon precipitation over India.

Homeyer, C. R., and Bowman, K. P.: Rossby wave breaking and transport between the tropics and extratropics above the subtropical jet, J. Atmos. Sci., 70, 607–626, doi:10.1175/JAS-D-12-0198.1, 2013.

Park, M., W. J. Randel, D. E. Kinnison, L. K. Emmons, P. F. Bernath, K. A. Walker, C. D. Boone, and N. J. Livesey: Hydrocarbons in the upper troposphere and lower stratosphere observed from ACE-FTS andcomparisons with WACCM, J. Geophys. Res. Atmos., 118, doi:10.1029/2012JD018327, 2013.

2. Discussions about changes in large-scale circulations, including Brewer-Dobson circulation, Hadley circulation, and the Asian monsoon circulation, are somewhat misleading. The authors might want to focus on the Asian monsoon circulation and only the relevant features of the large-scale circulations in the UTLS should be included to minimize any confusion. A separate paper can be written on the subject of impacts of large-scale circulation on dynamics of the Asian monsoon.

Reply: We have revised several sections of the manuscript and hope the focus of the paper on the ASM circulation is now clearer.

3. I am not convinced with the discussion of QBO and Rossby wave breaking influencing the transport. First of all, the amplitude of QBO decreases rapidly below $\sim$24 km and the Asian monsoon circulation does not extend above $\sim$18 km. So, in my opinion, there is little overlap between those two and also there is little evidence that QBO has any impact on the Asian monsoon circulation. In addition, the references (Randel and Park, 2006; Bowman, 2006) have little relevance to QBO. I would suggest that discussions about QBO, Rossby wave breaking, and wave drag all have to be presented with convincing evidence or figures.

Reply: We have added more references to back up our discussion of dynamics and removed the unrelated references (a revision mistake in our manuscript). We have removed discussion of the QBO since our simulations are not nudged to observed winds (at one stage we looked at nudged simulations). Additional references have been

added pertaining to Rossby wave transport in the tropical and subtropical UTLS and wave mixing near the equator. Our results are consistent with the findings of Homeyer and Bowman (2013) based on ECMWF ERA-Interim reanalysis data to characterize synoptic Rossby wave breaking in the tropical and subtropical UTLS.

Homeyer, C. R., and Bowman, K. P.: Rossby wave breaking and transport between the tropics and extratropics above the subtropical jet, J. Atmos. Sci., 70, 607–626, doi:10.1175/JAS-D-12-0198.1, 2013.

4. Changes in convection due to aerosol loadings over the Asian monsoon region can be a foundation for the responses in transport and the hydrologic cycle in the UTLS. However, little analysis of convection is presented in this paper (except Fig. 6).Convection in the model (including horizontal and vertical extent) has to be shown with detailed analyses with figures to support all the results presented in this paper.

Reply: Detailed analysis of aerosol interaction with convection is beyond the scope of our paper. However, we feel that we have provided sufficient information about the circulation impact of aerosols in several Figures. Other than figure 6 (Figure 7 in the revised manuscript), changes in convection due to aerosol leading are shown in figure 9 (figure 10 in the revised manuscript) (see discussion on page 30096 and 30097). Also Figures 8 and 10 make it rather clear that there is enhanced convection over the southern slopes of the Himalayas due to aerosol loading. This is consistent with the findings of Bollasina et al. (2008). Figure 2 offers further evidence of this convective feature being a major transport conduit for aerosols into the UTLS, in particular Figure 2(d). We have added a new Figure 4 to highlight the structure of the large scale circulation and cloud condensate distribution in the ASM region. From this figure it is clear that there is a region of enhanced deep convection around 100OE between 20ON and 30ON. This enhanced convection is associated with a resolved circulation upwelling anomaly extending into the TTL.

Bollasina, M. A., Ming, Y., and Ramaswamy, V.: Anthropogenic Aerosols and the

Weakening of the South Asian Summer Monsoon, Science, 334, 6055, 502-505, doi: 10.1126/science.1204994, 2011.

5. This paper can be shortened significantly by simplifying discussions and reducing detailed explanations of previous studies, which can simply be cited. Also, section 3.2 can be divided into multiple subsections for clarity.

Reply: Thank you for the suggestion. Discussions related to previous studies are now reduced. As suggested, section 3.2 (now section 4) has been reorganized and it is divided into multiple subsections. We believe that the new structure has improved the readability and clarity of the paper.

6. Most of the quantitative comparisons are cited from the references (e.g., Liu et al., 2009). Instead, the authors should present the quantitative results from their work first and just mention how these results agree or disagree with the previous studies. More quantitative analyses on the impact of aerosols in multiple variables in the model used in this study can be included.

Reply: As suggested, quantitative results from present work and its comparison with references (e.g., Liu et al., 2009) are now included in the revised manuscript. Quantitative analysis on the impact of aerosols for almost all the variables considered in this study is now incorporated in the revised version. e.g Ice Cloud water (ICW), Ice Crystal Number concentration (ICNC), cloud ice.

7. The satellite data (HALOE and SAGE II) can be valuable tools to validate the model results quantitatively and add credibility to the work presented here. For instance, adding a figure showing average vertical profiles in the NH subtropics both from the satellite and the model can be useful. Are the aerosol concentrations reasonable/ underestimated/overestimated in the model compared to the satellite data?

Reply: Figures 5 (a) and (b) (Figures 6 (a) and (b) in the revised manuscript) show the evidence of enhanced aerosol concentrations in the lower stratosphere transported into

the southern hemisphere across the equator with descent over the southern subtropics. The ECHAM5-HAMMOZ simulation produced similar transport (see Figure 6(c) in the revised manuscript). The extra aerosol features seen in the observations and not in the model in the lower TTL are likely due to a combination of sampling bias and under-representation of overshooting convection in the model due to the coarse resolution. The aim of Figure 5 is to have a qualitative comparison between simulated and observed aerosol distribution patterns. Due to the aerosol extinction wavelength dependency, a quantitative comparison of aerosol extinction obtained from HALOE at 5.26μm with SAGE II at 0.525 μm does not convey whether aerosol concentrations are reasonable/ underestimated/overestimated in the model (at 0.550μm).

Minor Comments

The title does not necessarily represent the content of this paper. It should include more specific information, for instance, ‘Impact of aerosol increase over the Asian monsoon region as seen in the global model simulation:’ to better represent this work.

Reply: As suggested title of the paper is changed to represent content of the paper.

P30082, L12 – The impact of aerosols (on the hydrologic cycles?) in the UTLS region is:

Reply: In order to highlight our results we have changed the abstract. In this process above sentence is reframed.

P30082, L24 – dramatic levels ! dramatic increase in the levels?

Reply: Above suggestion is now incorporated in the revised manuscript.

P30083, L28 – associated with the ASM (references?).

Reply: References (Chen et al 2012; Randel et al., 2010; Li et al., 2005) are now added in the revised manuscript.

Chen, B., Xu, X. D., Yang, S., and Zhao, T. L.: Climatological perspectives of air transport from atmospheric boundary layer to tropopause layer over Asian monsoon regions during boreal summer inferred from Lagrangian approach, Atmos. Chem. Phys., 12, 5827–5839, 2012.

Randel, W. J, Park, M., Emmons, L., Kinnison, D., P. Bernath, P., Walker, K. A., Boone, C.: Pumphrey, H., Asian Monsoon Transport of Pollution to the Stratosphere, Science 30 April 2010, Vol. 328 no. 5978 pp. 611-613, DOI: 10.1126/science.1182274

Li, Q., Jiang, J. H., Wu, D. L., Read, W. G., . Livesey, N. J., Waters J, W., Zhang, Y., Wang, B., Filipiak, M. J., Davis, C. P.,Turquety, S., Wu, S., Park, R. J., Yantosca, R. M., and Jacob D. J.: Convective outflow of South Asian pollution: A global CTM simulation compared with EOS MLS observations, Geophy. Res. Lett., VOL. 32, L14826, doi:10.1029/2005GL022762, 2005.

How does the precipitation change in this study compare with the result of Ramanathan et al. (2005)?

Reply: The study by Ramanathan et al. (2005) analyzed five member ensemble runs (for 200 years) of general circulation model (GCM). Whereas present study is based on 8 member ensemble runs for the year 2003. As precipitation shows high spatiotemporal variability, we have not compared precipitation changes obtained in the present study with results of Ramanathan et al. (2005). However both studies report that increase in aerosols loading causes weakening of the Hadley circulation and reduction in precipitation over North India.

P30084, L6-24 – Is this section about cirrus clouds directly related to this work?

Reply: This section gives details of earlier studies on impact of cirrus clouds on radiation and large scale circulations. This is related to present study as ECHAM5-HAMMOZ model simulations show that the transport of boundary layer aerosol and water vapour rich air by ITCZ may enhance cloud ice formation in the Northern Hemisphere subtropics. High amounts of ICW and ICNC (see figures 7a-d) (figures 8a-d in

the revised manuscript) near the tropical tropopause layer indicate that uplifted boundary layer aerosols trapped by the Tibetan anticyclone may elevate cloud ice formation. Also Figure 8(a) (figure 9(a) in the revised manuscript) shows enhancement in cloud ice due to aerosol. We have added to the text the references of clouds ice and cirrus parameterization used in the model.

P30086 – more details on the sources of aerosols should be included as they are the main focus of this paper aerosols should be included as they are the main focus of this paper:

Reply: The emission inventories used for anthropogenic aerosols and aerosol precursors are referenced in the text. Adding more information on this subject would unnecessarily expand the manuscript. We added the references of natural aerosol emissions (e.g. mineral dust and sea salt). In the original text is also shown the distribution of emissions over the region of interest for the main aerosol species.

P30086, L28 – This is a very general statement and I do not know if this statement is necessary.

Reply: As suggested, the above mentioned statement is removed.

P30087, L5 – What are the advantages or reasons of carrying out eight-member ensemble? Reply: In order to converge model output obtained from free runs, we carried out eight member ensemble. The set-up of the ensemble is now discussed in more detail in the revised manuscript. Various other studies, for example Ramnathan et al. (2005), Meehl et al. (2008), also reported results from five and six member runs respectively.

Meehl, G.A., Arblaster ,J.M., and. Collins , W.D: Effects of Black Carbon Aerosols on the Indian Monsoon, J. of Clim., 21, 2869-2882., DOI: 10.1175/2007JCLI1777.1, 2008.

P30087, L15 – 'Although similar features are : : : year 2003' – This sentence is very vague. What are the similar features and what is the effect of monsoon circulation on aerosol distributions?

Reply: Here we wanted to say that aerosol transport due to Brewer-Dobson circulation which appears as arch feature is observed every monsoon season during 2000-2004. Since it was creating confusion it is now removed from the revised manuscript.

P30089, L16-18 – The horizontal extent and the center of the maxima in Figs. 1a-d vary quite a bit. It would be necessary to define a boundary of the Asian monsoon anticyclone and show it on top of the aerosol distributions.

Reply: Wind fields plotted in figure 1(a) shows boundary of Asian summer anticyclone. Maxima of aerosol fields vary due to many reasons as the aerosols are not all the same and are removed by sedimentation and wet scavenging in different ways. In addition their emission distributions vary. However all four aerosols fields clearly show a collocated maximum in the anticyclone core.

P30089, L19-P230090, L6 – This paragraph seems to be repeated from Introduction without adding new information.

Reply: It is now eliminated from revised manuscript.

P30090, L11 – satellite observations (references?)

Reply: As suggested references are now incorporated in the revised manuscript.

Fig. 2 (and 3) – Adding velocity vectors to at least one of the four plots (as shown in Fig. 1) and also showing the location of the monsoon anticyclone on each plot would be helpful. It is not easy to make connections between transport and the aerosol maxima without the velocity vectors.

Reply: Velocity vectors are now plotted in Figure 2(a) and also the approximate location of monsoon anticyclone is shown via the negative 10-5 vorticity surface averaged between 15 and 35°N. Velocity vectors are added to the new Figure 4(b) in lieu of one of the Figure 3 panels.

P30091, L5-7 – I do not think the relationship between monsoon convection and the vertical transport is presented either in Fig. 2 or Fig. 3.

Reply: As suggested by the above comment the relationship between monsoon convection and vertical transport is now shown via velocity vectors plotted over figure 2(a). It shows evidence of large scale transport of aerosols into the anticyclone and to the TTL in the region of enhanced convection (see new Figure 4) around 100°E and between 20°N and 30°N. It should be emphasized that convective transport is sub grid-scale and will not appear in the resolved circulation field. There is indication from Figure 2 that aerosols are being stripped from the column around 100°E below 180 hPa and transported above where they are detrained into the anticyclone. The manuscript text has been changed to make this point.

Fig. 5 – Tropopause and isentropes can be added to this figure for a better presentation. It is hard to tell how well the model reproduces the data. What are the differences between HALOE-model and SAGEII-model?

Reply: Figure 5 (figure 6 in the revised manuscript) exhibit latitude-pressure section (averaged over 60-120°E) of aerosols extinction mostly above the tropopause (from 16 to 32 km). As can be seen from figure 3, a small part of tropopause crosses 16 km (∼100 hPa) over 60°S-60°N region. Hence when we tried to added tropopause, fractured pieces of tropopause appears on the figure. This may not give meaningful representation. Aerosol extinction is wavelength dependent. Wavelength of HALOE (5.26 μm), SAGE II (0.525 μm) and Model (0.550 μm) are different. Hence comparison of aerosol extinction obtained from HALOE, SAGE II and model simulations is not appropriate (Also see reply to comment 7).

Fig. 6 – The longitude ranges used for the OLR and the aerosol averages are identical. However, their maxima are not necessarily collocated (see, Fig. 1 and other literatures for the location of convection).

Reply: It is clear from Figure 7 (figure 8 in the revised manuscript) that there is a prominent region of deep convection over the southern flanks of the Himalayas in our simulations. This convective feature is quite well correlated with mineral dust and carbonaceous aerosols (Figure 1). This convective feature is also the main injection point for water vapour into the stratosphere in our simulations (Figure 10). In addition, aerosols are transported to the deep convection regions over the Bay of Bengal and South-East Asia. Figure 6 (7 in the revised manuscript) shows a time series (averaged over 20-30°N, 60-120°E) so that aerosol maxima are not required to be spatial maxima. Consistent with our results, using Aura-MLS observations, Park et al. (2007) also observed correlation (0.77) between OLR averaged over the region 15-30°N, 60-120°E and CO (ppb) at 100 hPa averaged over the region 15-30°N, 20-100°E. Randel and Park (2006) also show evidence of collocation of maxima in OLR (averaged over the region 15-30°N, 60-120OE) and water vapour (averaged over the region 20-30°N, 60-120°E).

Fig. 9 – The arrows are too small to recognize their direction except in the NH subtropics. Any descending motion is not obvious in this figure due to too many small arrows.

Reply: Figure 9 (now figure 10) has been re-plotted to include a panel showing the vertical wind field. It is clear that there is a diabatic circulation cell around the subtropical flank of the tropopause in the lower stratosphere which involves upwelling on the equator side and downwelling on the pole side. Peak values are over 0.3 mm/s, which is significant compared to the typical upwelling above the tropical tropopause according the results of Mote et al. (1998) and this point is now included in the text.

Mote, P. W., Dunkerton, T. J., McIntyre, M. E., Ray, E. A, Haynes, P. H., and Russell III, J. M.: Vertical velocity, vertical diffusion, and dilution by mid latitude air in the tropical lower stratosphere. J. Geophys. Res., 103(D8), 8651-8666, doi: 10.1029/98JD00203, 1998.

P30095, L17-26 – It is not clear if this paragraph is just based on Fu et al. (2006) or

based on this paper. The proposed transport mechanism presented by the authors in this paragraph should be supported by either their own results or previous studies.

Reply: The text has been revised to make the parts relevant to Fu et al. and Park et al. more clear. We have also changed text regarding our results to highlight that the deep convective transport over the southern flanks of the Himalayas seen in our results are consistent with the Fu et al. (2006) picture. While the Park et al. (2009) picture remains valid, there is persistent deep convection that extends to the tropopause above the southern flanks of the Himalayas that is missing from their CTM results. This aerosol-laden air will be entrained in the Monsoon anticyclone in addition to being transported into the lower stratosphere by the Brewer-Dobson circulation and tropopause level mixing processes.

P30096, L12 – What is the evidence of ‘aerosol induced enhancement of the convection’ in this work?

Reply: Bollasina et al. (2008) find a strong correlation between aerosols and deep heating and precipitation over the southern slopes of the Himalayas (cf. their Figure 4). Our model results support this picture. The origins of this correlation and not straightforward and involve large scale circulation and moisture changes in addition to convective microphysics impacts. Analysis of the mechanisms is beyond the scope of our paper.

Bollasina, M., Nigam, S., and Lau, K-M.: Absorbing Aerosols and Summer Monsoon Evolution over South Asia: An Observational Portrayal. J. Climate, 21, 3221–3239. doi: 10.1175/2007JCLI2094.1, 2008.

P30097, L1-5 – This section is very confusing and it is not clear what the authors are trying to say. Are the discussions based on Elliassen (1951) paper?

Reply: The discussion of circulation non-locality has been removed and we have changed the text as follows: “The meridional circulation anomaly between the equator and 30°N seen in Figure 10 can be interpreted as the result of increased convective heating around 20-25°N. It drives a thermally direct circulation (like the Hadley circulation) and is subject to the same asymmetry that is discussed by Lindzen and Hou (1988). Namely, that a localized heating anomaly centered off the equator but still in the tropics has a two-cell circulation pattern with a dominant circulation cell on the equatorward side. The convective heating on the southern flanks of the Himalayas is such a tropical heating anomaly."

P30100, L19 – : thermal structure (references?) Reply: The relevant reference is added.

Please also note the supplement to this comment:
http://www.atmos-chem-phys-discuss.net/12/C13590/2013/acpd-12-C13590-2013-supplement.pdf

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Interactive comment on Atmos. Chem. Phys. Discuss., 12, 30081, 2012.