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Reply on RC1

Suvarna Fadnavis et al.

Author comment on "Tropospheric warming over the northern Indian Ocean caused by South Asian anthropogenic aerosols: possible impact on the upper troposphere and lower stratosphere" by Suvarna Fadnavis et al., Atmos. Chem. Phys. Discuss., <https://doi.org/10.5194/acp-2021-969-AC2>, 2022

Replies to the Reviewer-I

Fadnavis et al. present simulations with the chemistry-climate model ECHAM6-HAMMOZ to investigate the transport pathways and impacts of anthropogenic aerosols during spring. They perform five model simulations, one control run and four sensitivity runs. From their simulation results, they find that the carbonaceous aerosols cause an increase in heating rates and an increase in water vapor.

Reply: We thank the reviewer for their thorough assessment of our study and the valuable suggestions to improve the manuscript. We have now incorporated all suggestions in the manuscript at the line numbers mentioned in the replies below. The changes are also indicated in blue color in the revised manuscript.

General comments:

- The manuscript is generally well written and structured, but leaves several questions open. For example, the title states "possible implications". What exactly do you mean with that? The society, the atmosphere or a specific process? This is not answered throughout the paper (or if it is answered the message does not come across).

Reply (1): Thank you for pointing this out. We have changed the title of the manuscript as "Tropospheric warming over the North Indian Ocean caused by the South Asian anthropogenic aerosols: possible impact on the upper troposphere and lower stratosphere"

- I have difficulties to understand the connection between the heating rates and the increases in water vapour as well as the connection between aerosols and convection. Both seems to be essential for this study, but the underlying processes are not really explained. Thus, this needs definitely to be elaborated in more detail.

Reply (2): To highlight this connection more clearly, we have now performed an additional analysis on isentropic levels. The transport pathways of aerosol to the Southern Hemisphere are now therefore better illustrated. Our analysis shows that South Asian aerosols are transported to the North Indian Ocean. These aerosols are then lifted into the

upper troposphere and lower stratosphere (UTLS) by the ascending branch of Hadley circulation. In the UTLS, they enter the westerly jet. They are further transported to the Southern Hemisphere ($\sim 15^\circ \text{S} - 30^\circ \text{S}$), and downward (320 – 340K) via an equatorial Atlantic westerly duct ($5^\circ \text{S} - 5^\circ \text{N}$, $10^\circ \text{W} - 40^\circ \text{W}$) and shifted Pacific westerly duct ($5^\circ \text{S} - 5^\circ \text{N}$, $95^\circ \text{E} - 140^\circ \text{E}$). The shifting of a Pacific westerly duct may be due to higher Rossby wave breaking caused by the South Asian aerosols. (See discussion in section 3.3)

The carbonaceous aerosols (mainly BC) produce short wave heating along the transport pathway. This leads to an increase in temperature and therefore water vapour concentrations. We have now removed the discussions on the connection between aerosols and convection. (See discussion in section 3.4).

- Additionally, I have the feeling that the connections between these specific processes and the according changes in heating and water vapour are overrated. Since the numbers are quite low.

Reply(3): Since the gradient of water vapor is very large between troposphere and stratosphere we have expressed it in percentage change. Our analysis shows an enhancement in water vapor by $1 \square 10 \%$ in the UTLS over tropical and sub-tropical latitudes ($45^\circ \text{S} - 45^\circ \text{N}$). While we agree with the reviewer that the numbers are not extremely large, a change in UTLS water vapor of 10% is not negligible. (L39-40 and section 3.4)

- Are the AODs only used for model evaluation? If yes, this could be provided in the supplement. How good are the heating rates, aerosol distributions etc. simulated in the model? Are the model simulations reliable? Wouldn't it be worth to generally compare the model simulations with observations?

Reply (4): We agree with the reviewer's point and, as suggested, we have now moved the AOD analysis to Supplementary Material. We have also expanded the discussions on the comparison of observations with the model as follows:

"The model simulations show high amounts of AOD over the Indo-Gangetic plain ($25^\circ \text{N} - 35^\circ \text{N}$, $75^\circ - 95^\circ \text{E}$), consistent with MODIS and MISR observations, despite quantitative differences (Fig. S1). Compared to observations, the model underestimates AOD over the Indo-Gangetic plain by $\sim 18 \%$ than MODIS and overestimates by 14% than MISR. While it underestimates over central India ($15^\circ - 24^\circ \text{N}$, $75^\circ - 82^\circ \text{E}$) by 20 – 23 % compared to MODIS and MISR. There are differences among satellite observations and between the model and observations. The differences are due to (1) uncertainties in the model transport processes, the emission inventory, and the parameterizations. (Fadnavis et al. 2014, 2015, 2018, 2019) and (2) there are uncertainties in the satellite measurements (Bibi et al., 2015). The comparison of AOD from Aerosol Robotic Network (AERONET), MODIS and MISR show error of 0.03 to 0.05 (**Kahn et al., 2007**). With model biases present in both the CTL and the perturbed simulations, investigating anomalies removes some of the model bias." (see section S2, L36-48)

Specific comments:

- Title: "possible implications" what do you mean with that? Implications on what? The atmosphere? The society? This is also not at all explained/discussed throughout the paper.

Reply (5) Thank you for pointing this out. We have changed the title of the manuscript to " Tropospheric warming over the North Indian Ocean caused by the South Asian

anthropogenic aerosols: possible impact on the upper troposphere and lower stratosphere"

- P2, L32 and 35: The numbers alone are not helpful without any further explanations. Are these changes severe or negligible?

Reply(6): Heating rates are small since they are expressed per day. Now we have changed them to Kmonth^{-1} . We have now added percentage changes of heating rates to show their impact. (See L36-L37 and section 3.4).

- P2, L37: Please clarify and state more precisely if these increases in heating are due to heating or due to transport.

Reply(7): The above sentence is re-written as "The increase in tropospheric heating due to aerosols results in an increase in water vapor concentrations, which are then transported from the North Indian Ocean-Western Pacific to the UTLS over $45^{\circ}\text{S} - 45^{\circ}\text{N}$ (increasing water vapor by $1 \pm 10\%$), L37-40.

- P4, L70: Are the here mentioned increases based on observations or model simulations? Please add.

Reply (8): It is from AEROCOM-ACCMIP-II emission inventory. It is stated at L70-L71.

- P5, Figure 1: Where is the data shown coming from? Inventory, model simulation or observation?

Reply(9): It is from AEROCOM-ACCMIP-II emission inventory. It is mentioned at L100.

- P6, L115: Add here some references. There are some studies that have investigated the impact of increases in water vapour on the polar stratosphere (e.g. Khosrawi et al., 2016; Thölix et al. 2016; Thölix et al., 2018).

Reply(10): We have repeated the analysis on isentropic levels. The new figures show water vapor enhancement in the UTLS between $45^{\circ}\text{S} - 45^{\circ}\text{N}$. Hence, we could not cite the above references.

- P6, L116: Add some sentences on the structure on the paper and what you are going to do in this paper? Especially since you keep this kind of information quite short in the abstract and introduction it would be worth to give here some more details.

Reply (11): As suggested we have added an outline of the paper at L119-122 as "The paper is structured as follows: the ECHAM6-HAMMOZ model simulations are provided in section 2, in section 3 we discuss the results on the transport of South Asian aerosols to the North Indian Ocean, radiative forcing, transport into the UTLS, and associated impacts on heating rates, while conclusions are summarised in section 4."

- P6, L124: Why seven? Either skip this information or provide more details.

Reply(12): It is provided at L130-132 as "Nucleation mode, soluble and insoluble Aitken, soluble and insoluble Accumulation and soluble and insoluble Coarse modes.

- P6, L125: Same here. What does M7 mean? Either skip this information or provide more details on what this module does or is.

Reply (13): It is deleted now.

- P7, L140ff: Here definitely a motivation for your experiments is missing. Why are you switching of the aerosols? What kind of insights you can get from each simulation experiment?

Reply (14): The motivation is to understand (1) the transport pathways of South Asian anthropogenic aerosols, and (2) their impact over the Indian region, and UTLS (340K - 400K). It is mentioned at L160-161.

- P9, L170: That you use the satellite data sets for model evaluation should be mentioned already in the beginning of the section.

Reply (15): It is moved to supplement as suggested in a comment (4).

- P9, L182: Is AOD a unitless number? What is the typical range of AOD? What do these numbers tell me? How strong is the over-/underestimation? Something the reader should worry about? I would suggest to add differences in percent so that it is easier to follow if this is a large or small over-/underestimation.

Reply (16): Yes AOD is a unitless number. We have added values in percentages and discussion given below:

"The model simulations show high amounts of AOD over the Indo-Gangetic plain (25° - 35°N, 75° - 95° E), consistent with MODIS and MISR observations, despite quantitative differences (Fig. S1). Compared to observations, the model underestimates AOD over the Indo-Gangetic plain by ~18 % than MODIS and overestimates by 14% than MISR. While it underestimates over central India (15° - 24° N, 75° - 82° E) by 20 - 23 % compared to MODIS and MISR. There are differences among satellite observations and between the model and observations. The differences are due to (1) uncertainties in the model transport processes, the emission inventory, and the parameterizations. (Fadnavis et al. 2014, 2015, 2018, 2019) and (2) there are uncertainties in the satellite measurements (Bibi et al., 2015). The comparison of AOD from Aerosol Robotic Network (AERONET), MODIS and MISR show error of 0.03 to 0.05 (Kahn et al., 2007). With model biases present in both the CTL and the perturbed simulations, investigating anomalies removes some of the model bias." (see section S2, L36-48)

- P9, L190: Give more information on the uncertainties of the satellite data. I guess there are validation studies that provide some uncertainty estimations so that you could provide some numbers for errors or biases of the satellite data.

Reply (17): We have now added numbers for errors of the satellite data as mentioned in Reply (16) (section S2, L45-47).

- P10, L195: How reliable is the ECHAM6-HAMMOZ simulation? Is the model good enough for the here anticipated study?

Reply (18): We thanks for pointing this out. The ECHAM6-HAMMOZ model has previously been evaluated in several studies in the past, indicating its suitability for studies of this type. This is now more clearly mentioned in section S2, L48-51. Furthermore, we provide a comparison with model simulations (see Reply (14))

- P10, Figure 2: The differences between model and observations are quite large. For me it looks like that there are serious problems in deriving AOD correctly in the model. Could provide this figure once again changing the scale of the mode so that it is possible to check if there is a qualitative agreement (thus to see if the model at least gets the AOD generally right).

Reply(19): We have changed the color scale in Figure-2 and zoom-in over the South Asian region. The revised figure shows qualitative agreement of the model with MODIS and MISR. As mentioned in Reply (16) differences in model are -23 to 18 %. It should be noted that there are differences among the observations.

(20)P12, L249: Why significant? What is the measure for rating a change significant or not significant?

Reply(20): We agree the use of this word here is confusing. We have now reworded this at L210-211 as: "The RF estimates show that the aerosols have produced cooling at the TOA and surface over the Arabian Sea".

(21)P15, L320: To my opinion it is misleading to talk about convection. I think from the CNDC and ICNC distribution you see where you have clouds.

Reply(21): Thank you for pointing this out. As suggested, we have now removed the discussion on CNDC and ICNC and we repeated and expanded the analysis on isentropic levels. As mentioned in the reply (2) there are two pathways for South Asian aerosol.

(22)P15, L327-328: This is not clear at all. How do aerosols induce a circulation? This relationship needs to be better elaborated.

Reply (22): As per the new analysis on isentropic levels above discussion is obsolete and hence removed.

(23) P17, L367: Compared to heating rates in the tropics that reach several K d⁻¹ these changes are quite low. I cannot follow why this should be a severe or significant change in heating rates.

Reply (23): Heating rates are now expressed in K month⁻¹ and percentages to indicate their impact.

(24) P18, L392: As stated above. This is really difficult to believe since the numbers are so low. It would be worth to give the changes additionally in percent so that is easier to follow what this means.

Reply(24): Heating rates are now expressed in K month⁻¹ and percentages to indicate their impact.

(25) P18, L412: Same holds for water vapour. Please add also changes in percent.

Reply (25): As suggested, water vapour is now expressed in percentage change.

(26) P20, L444 and Figure 8: I do not see a connection between aerosols in the LS and water vapour entry into the LS. The entry usually appears where you have overshooting convection. Why have you then such a huge amount of aerosols in the LS, but much less water vapour entering in the LS? Have you taken into account that there are also natural processes for aerosols? Especially sulfate aerosols are formed naturally in the UTLS (Brock et al., 1995). What kind of aerosols are left if you switch off all aerosols? The natural ones? Unfortunately, it is not clear what exactly is shown in this figure since it is nowhere clearly stated what you derive when you switch off certain aerosols in your model experiments.

Reply (26): See reply(2). In this study, we have perturbed South Asian anthropogenic aerosols only. The major changes are due to anthropogenic aerosols and partly by secondary aerosols which are produced by changes induced by changes of the anthropogenic aerosols It is described L148-155 and in Table-1.

(27) P20, L445: References should be added here.

Reply(27): The above lines are deleted in the revised manuscript hence we could not add a reference.

(30) P21, L464: A correlation of 0.57 is not that good. It seems the correlation is generally higher for the Antarctic than the Arctic. Why?

Reply(30): Our analysis on isentropic levels show transport to the Arctic only. The new analysis shows correlation values varying between 0.55 to 0.85.

(31)P21, L464: Only because there is a correlation it does not mean that there is necessarily a connection.

Reply(31): In our model simulations, aerosols are switched on and off over South Asia. Hence variation of aerosol/heating rates at the Arctic is a response of South Asian aerosols. Therefore the correlation between aerosol and heating rates indicates a connection.

(32) P21, L466: transported \square increase in aerosols?

Reply(32): It is corrected at L436.

(33) P21, L467: It not good to cite only the own papers. Here, definitely also some independent studies should be cited.

Reply (33): We have now added the below mentioned references (See L413-414).

Zheng, C., Wu, Y., Ting, M., Orbe, C., Wang, X., and Tilmes, S.: Summertime transport pathways from different northern hemisphere regions into the Arctic. *Journal of Geophysical Research: Atmospheres*, 126, e2020JD033811. <https://doi.org/10.1029/2020JD033811>, 2021

Shindell, D. T., Chin, M., Dentener, F., Doherty, R. M., Faluvegi, G., Fiore, A. M., Hess, P., Koch, D. M., MacKenzie, I. A., Sanderson, M. G., Schultz, M. G., Schulz, M., Stevenson, D. S., Teich, H., Textor, C., Wild, O., Bergmann, D. J., Bey, I., Bian, H., Cuvelier, C., Duncan, B. N., Folberth, G., Horowitz, L. W., Jonson, J., Kaminski, J. W., Marmor, E., Park, R., Pringle, K. J., Schroeder, S., Szopa, S., Takemura, T., Zeng, G., Keating, T. J., and Zuber, A.: A multi-model assessment of pollution transport to the Arctic, *Atmos. Chem. Phys.*, 8, 5353–5372, <https://doi.org/10.5194/acp-8-5353-2008>, 2008.

(34) P22, L489 and 491: References should be given for these statements. Why do South Asian aerosols enhance water vapour globally?

Reply(34): As per the new analysis on isentropic levels above discussion is obsolete and hence removed.

(35) P23, L518-519: For me these increases in heating seem to be not that strong. Is this really a severe change? From where do you got these numbers? From your study or from the literature. A 2% change in cloud cover anomalies seems to be negligible for me, however, the 12% are rather non-negligible. Here, it also needs to be elaborated more when the changes are significant and when not.

Reply (35): Heating rates are now expressed in K month^{-1} and percentages. The values of heating rates vary between 4 - 60 % which indicates their impact. We have also shown 95% significance level to show changes are significant.

(36) P23, L524: What is the process behind that? Give also here a short explanation.

Reply(36): The above stated text is removed in the revised manuscript.

(37) P23, L527: How do aerosols increase evaporation? Can they also have an effect on condensation? If they affect heating I would rather expect a connection to condensation than evaporation.

Reply(37): As per the new analysis on isentropic levels above discussion is obsolete and hence removed.

(38) P23, L531: Until the end, it is not really explained why BC or other aerosol increase water vapour.

Reply(38): The heating of the troposphere by the carbonaceous aerosol (mainly BC) increases temperature and thereby tropospheric water vapor amounts over the North Indian Ocean and adjoining regions. It is mentioned at L487-489.

Technical corrections:

P3, L63 and throughout the manuscript: south Asia or South Asia? You should choose one way of writing and use this consequently throughout the manuscript.

Reply: It is corrected throughout the manuscript.

P4, L76: compared to rest of the Indian region -> compared to "the" rest of the Indian region

Reply: It is corrected, now at L76.

P5, Fig. 1 caption: of year 2016 -> for the year 2016

Reply: It is corrected, now at L99.

P5, L105: Based -> based

Reply: It corrected, now at L106.

P5, L110: delete "the" so that it reads "by convection"

Reply: It corrected, now at L111.

P6, L119: Change sentences as follows: "We use the state of the art aerosol-chemistry-climate model ECHAM6-HAMMOZ."

Reply: It corrected, now at L125.

P6, L127: Instead of just ice-nucleating particles, I would suggest to write (to be more precise) "as kernel for ice-nucleating particles"

Reply: It corrected, now at L135.

P7, L134: replace "the" by "a" □ the model simulations are performed with a T63 spectral resolution

Reply: It corrected, now at L142.

P7, L137: at a time step □ with a time step

Reply: It corrected, now at L145.

P8, L162: add "are used" at the end of the sentence.

Reply: It corrected, now at Section S1, L19.

P8, L163: add "a" twice □measures a radiance.....at a spectral resolution.....

Reply: It corrected, now at Section S1 L20.

P9, L173: add "a" and "of" □ at a spatial resolution of $0.5^\circ \times 0.5^\circ$

Reply: It corrected, now at Section S1 L30-31.

P9, L178: add "the" □ We evaluate the model performance.....

Reply: It corrected, now at Section S2 L36.

P9, L188: rephrase sentence as follows: The differences are due to uncertainties in the model transport processes, the emission inventory, and the parameterizations.

Reply: It corrected, now at Section S2 L42-44.

P9, L190: add "the" □ uncertainties in the satellite measurements

Reply: It corrected, now at Section S2 L45.

P11, Figure 3: Figure size should be increased, so that the scale is better readable.

Reply: We improved the size of figure 3, now scale is better readable.

P11, Figure 3 caption: during □ "for the years" or "for the time period from".....

Reply: It corrected, now at L260.

P11, L231: in □ of

Reply: It corrected, now at L195.

P12, L246: "and at the surface" or "and the surface"

Reply: It corrected, now at L208.

P12, L249: add "the" and "a" □ show that the aerosols have produced a significant cooling

Reply: It corrected, now at L211.

P12, L254: add "an" □ an atmospheric warming

Reply: It corrected, now at L216.

P12, L261: add "the" twice □ at the TOA (...) and the surface

Reply: It corrected, now at L224.

P13, L267: add "a" □ lead to a heating

Reply: It corrected, now at L228.

P13, L269: Analyses of the □ The analyses of the

Reply: It corrected, now at L230.

P14, Figure 4 caption: replace twice "during" by "for the years" or "for the time period"

Reply: Now it is Figure 3 and it corrected at L260.

P15, L318: add "from" □ from north India

Reply: As per the new analysis on isentropic levels above sentence is removed.

P18, L409: add "the" □ on the water vapor distribution

Reply: It corrected, now at L391.

P18, L417: abortion □ absorption

Reply: As per the new analysis on isentropic levels above sentence is removed.

P19, L432: add "the" □ over "the" Arabian Sea

Reply: It corrected, now at L403.

P19, L432: add "over" □ averaged over

Reply: It corrected, now at L406.

P19, L433: during □ "for the years" or "for the time period"

Reply: It corrected, now at L407-408.

P20, L448: it □ This figure

Reply: It corrected, now at L420.

P20, L449: add "the" □ during spring and the monsoon seasons

Reply: It corrected, now at L421.

P21, Figure 21: add "in the" □ "in the UTLS"

Reply: It corrected, now at L446.