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Atmospheric Chemistry and Physics Discussions

Interactive comment on "The impact of increases in South Asian anthropogenic emissions of SO_2 on sulfate loading in the upper troposphere and lower stratosphere during the monsoon season and the associated radiative impact" *by* Suvarna Fadnavis et al.

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Replies to Anonymous Referee #1

Review of the paper: "The impact of increases in South Asian anthropogenic emissions of SO2 on sulfate loading in the upper troposphere and lower stratosphere during the monsoon season and the associated radiative impact", by S. Fadnavis et al., Atmos. Chem. Phys. Discuss., acp-2019-81, 2019. This study focuses on the impact that

rapidly increasing anthropogenic emissions of SO2 in South Asia may have on the distribution of UTLS sulfate. This is an important topic and the manuscript deserves publication on ACP, after two major points (in my opinion) have been correctly addressed in the revised version.

Reply: We thank the reviewer for the positive comments on our paper and all valuable suggestions. We have performed additional experiments and tried to incorporate suggestions given by the reviewer.

Major points

(1) The most important conclusions of the present study (changes in ATAL and related radiative forcing both at the surface and TOA, as well as feedback processes on UTLS dynamics and clouds) are based on the model calculated distribution of sulfate aerosols following the increasing anthropogenic SO2 emissions at the surface over South Asia. This distribution is not only determined by local convective uplift, but also by the lower stratospheric coupling of aerosol transport and microphysics. From this point of view, the quasi-biennal oscillation (QBO) plays a major role in determining the rate of large-scale isentropic transport from the tropics to the extra-tropics. A different SO2 and SO4 lifetime in the tropical reservoir may, in turn, affect the aerosol size distribution, thus modulating the sedimentation rate and the strat-trop exchange. Nothing is said in the manuscript on how the QBO is treated in the model simulations. Internally generated? External nudging? What is the different level of sulfate export from the tropical reservoir during E/W phase years? I think the authors should clarify and produce some evidence of the model predicted variability in the horizontal gradient of the sulfate loading between tropics and extra-tropics (maybe in the supplementary material).

Reply(1):. We agree these are important points that need to be clarified. The focus of our manuscript is to understand the convective transport of Asian sulfate aerosols during the monsoon season. Therefore free simulations (10 member ensemble) were performed for the year 2011 with a one-year spin-up for the year 2010. The analysis is presented for the year 2011. These experiments are canonical in design as their aim is to understand the radiative impact of Asian sulfate aerosols. The model results do not include the influence of QBO, which has a periodicity of 22-24 months. Also, the QBO is not internally generated in the model. We now clarify this in the manuscript at L231-232.

We thank the reviewer for the valuable suggestion about analyzing the role of the quasi-biennial oscillation (QBO) in understanding the large-scale isentropic transport from the tropics to the extra-tropics. QBO can be generated in the model by the external nudging. To understand the influence of enhancement of sulfate aerosols on QBO, we have now performed external nudging experiments for the years 2008 - 2016 (CTRL and Ind48 simulations). Our model simulations show that the enhancement of sulfate aerosols slows down the QBO propagation (Figure 1a-b below). There is interannual variability in transport sulfate aerosols by the phases of QBO (Figure 1c). It affects the transport out of the tropics (Figure 1d). Since the focus of the present paper is to highlight the seasonal transport and associated radiative impacts, we plan to provide detail analysis of the interaction of QBO and sulfate aerosol in a separate paper which will focus on "Influence of sulfate aerosol on QBO: implications on Asian summer monsoon convection".

Following the reviewer's suggestions, we have now added a discussion about sulfate export from the tropical reservoir during E/W phase of QBO (section 6 in the manuscript).

(2) Some recent studies have focused on this topic, looking at model simulations for SO4 aerosols from sulfate geoengineering (e.g., Aquila et al., 2014; Visioni et al., 2018). It is true that in this latter case, as well as for aerosols from major tropical volcanic eruptions (e.g., Pinatubo; Trepte and Hitchman, 1992) the aerosols are located a few kilometers above those convectively uplifted from the surface, but the QBO impact on the latitudinal transport of aerosols in the lower stratosphere should be significant,

anyhow. The link between tropical UTLS sulfate (convectively uplifted from South Asia) and its poleward transport is mentioned in several places in the manuscript (lines 22-23, 77-79, 309-314, 321-325, 344-345, 398-399, 450-453) and is one of the key points in the discussion. For this reason, need to be addressed.

Reply(2): Thank you for this important point. As mentioned in the reply(1), the QBO is not internally generated in the model (L231-232). To see the influence of QBO on the transport in our model, nudge simulations need to be performed. However, the model simulations used in the manuscript are 10-member ensemble free runs. These runs show poleward transport of the Asian sulfate aerosols by the lowermost branch of the Brewer-Dobson circulation.

We have also added a discussion about sulfate export from the tropical reservoir during East-West phases in discussion section 6.

3) Proper acknowledgment of previous works in the literature is needed. The authors cite the review paper of Kremser et al. (2016), but they should do the same for the SPARC assessment of stratospheric aerosol properties (ASAP, 2006), as well. Here, in the uncertainties section of Chapter 6, a detailed discussion is made on the potential impact of future trends of stratospheric sulfate aerosols due to increasing anthropogenic sulfur emission in South Asia. A citation to SPARC-ASAP would be appropriate, for example, at lines 76-77 and line 287.

Reply(3) : We agree. As suggested citation of SPARC-ASAP is added at L81 and L315.

4) Minor points Both in the abstract (line 19) and in the conclusions (line 447) the authors write: ". . .experiments with SO2 emissions enhanced by 48% over South Asia. . .". For the reader, it is not clear (mainly in the abstract) with respect to what the emissions are enhanced by 48%. Later on in the text this is made clear (lines 210-213).

Reply(4) : As suggested, SO2 emissions enhancement by 48% over South Asia in the model experiment is made clear in abstract and conclusion (L18-21 and L567-570).

(5) Line 66: “economy and agriculture” instead of “economy, agriculture”.

Reply(5) : The above-said sentence is removed from the manuscript.

(6) Line 78 and 399: “poleward” is one word, not two.

Reply(6) : Above mentioned suggestion is incorporated at L66, L87, L320, L359, L379, L380, L397, L473.

(7) A reference is missing at line 202: “AMIP (add reference) sea surface temperature”.

Reply(7) : We have incorporated the reference (Taylor et al., 2002) at L211.

(8) Line 340: is likely to be caused.

Reply(8) : Above mentioned phrase is not used in revised manuscript.

(9) Lines 370-371: Ozone absorption of the increasing diffuse radiation by sulfate aerosols may also play a role.

Reply(9): The above sentence is now removed from the revised manuscript.

(10) At line 443 the Kuebbeler et al. (2012) citation is not appropriate for the cirrus cloud formation response to volcanic eruptions, but it should be moved at line 444 together with Visioni et al. (2018). On the other hand, the effects of non-explosive volcanic eruptions on UTLS aerosols and cirrus ice clouds were explored in Pitari et al. (2016).

Reply(10): The citations of Kuebbeler et al. (2012) and Visioni et al. (2018) are moved to L535-536. Pitari et al. (2016) is added at L536.

(11) References Aquila et al.: Modifications of the quasi-biennial oscillation by a geo-engineering perturbation of the stratospheric aerosol layer, Geophys.

Reply(11) : The above reference is added at L546.

(12) Visioni et al.: Sulfur deposition changes under sulfate geoengineering conditions: QBO effects on transport and lifetime of stratospheric aerosols, Atmos. Chem. Phys., 18, 2787-2808, doi: 10.5194/acp-18-2787-2018, 2018.

Reply(12) : The above reference is added at L547.

(13) Pitari et al.: Sulfate aerosols from non-explosive volcanoes: chemical radiative effects in the troposphere and lower stratosphere, Atmosphere, 7, 85, doi:10.3390/atmos7070085, 2016.

Reply(13) : The above reference is added at L536, L493.

(14) SPARC: Assessment of stratospheric aerosol properties (ASAP), L. Thomason, and Th. Peter, Eds., www.sparc-climate.org, 2006.

Reply(14) : The above reference is added at L315, L834.

Please also note the supplement to this comment:
https://www.atmos-chem-phys-discuss.net/acp-2019-81/acp-2019-81-AC2-supplement.pdf

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