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Atmospheric Chemistry and Physics
Discussions

Interactive comment on "Spatial distributions and seasonal cycles of aerosol climate effects in India seen in global climate-aerosol model" *by* S. V. Henriksson et al.

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We thank Dr. Lau for his expert comments, which give credit to our study and which for the more critical parts have helped to improve the manuscript. Below are our replies together with action taken to address the comments as well as the original comments in Italics.

Comments on paper " Spatial distributions and seasonal cycles of aerosol climate effects in India seen in global climate-aerosol model" by Henriksson et al

In this paper, the authors used the ECHAM5-HAM model together with GAINS inventory of anthropogenic aerosols emissions to study the impact of aerosols on temperature and rainfall of the Indian monsoon. They first presented model results on seasonal distribution of aerosols and aerosol radiative forcing over India. Then they conducted various sensitivity experiments, to elucidate the climate effects of respectively, total aerosol, anthropogenic aerosols, absorbing aerosols, direct and indirect effects, as well as aerosol induced SST effects, to determine the relative importance of each effect in contributing to monsoon rainfall changes over India. The study should be commended as a first step towards a comprehensive understanding of aerosol-Indian monsoon interaction. It has added new perspective to the ongoing debate on the possible impacts of aerosols on monsoon.

We thank Dr. Lau for the positive feedback.

However, as is, there are major weaknesses. The authors went through a laundry list of figures, some of them with very brief discussions. The discussions were not particularly enlightening, and at times confusing. Overall, the paper lacks in-depth analyses and discussions of physical processes. Given the wealth of information in the experiments, this paper can be significantly improved, if the authors can focus on one or two key messages, and conduct more in-depth analyses to support them. I recommend publications with major revisions along the following suggested lines.

We thank Dr. Lau for the suggestions for improvement. The comments of Dr. Lau and other reviewers have helped us to recognize the physical processes worth to discuss in more depth. We have decided to focus on the following two key messages:

1. EHP and SDM both affect rainfall in India in opposite ways, with the total aerosol effect on monsoon precipitation seeming to be negative, now also suggested by mixed-layer ocean simulations 2. Making conclusions about EHP and SDM effects from observed correlations between aerosols and precipitation is risky as illustrated by a few examples

(for repetition EHP stands for Elevated Heat Pump and SDM for Solar Dimming Mechanism)

Naturally, it is good to keep in mind that the phenomena studied are extremely complex and that conclusions might be modified when more information is obtained. We have added discussion about model evaluation and possible sources of bias and error.

Replies to the more detailed comments are below as well as actions taken to address them.

1. A main result of the paper is that decreasing the meridional SST gradient between the northern and equatorial Indian Ocean seems to have the largest impact in decreasing monsoon rainfall. The problem with this conclusion is that the aerosol SST gradient modification which followed Ramanathan et al 2005 is artificial and arbitrary. If anything, this is simply the model's response to SST cooling in the northern Indian Ocean/Arabian Sea due to any number of reasons such as increased surface wind, ocean upwelling, and others, but not necessarily aerosols. To obtained more realistic SST cooling estimate, one possibility is to estimate from mixed layer ocean, with realistic mixed layer depth, the temperature cooling caused by the model's aerosol radiative cooling over the North Indian Ocean. This has not been done. Here, the magnitude of the 20% reduction in rainfall by SST is likely to be strongly dependent on the magnitude of SST gradient which is arbitrarily set and not internally consistent with the model aerosol surface radiative forcing. The SST experiment is not in the same class as the other experiments, which are consistent internally (as far as I can tell) with the aerosol physics of the model, and hence should not be a main conclusion of this paper. If included, it should be accompanied by discussions of the caveats of such artificially modified SST.

Simulations with a mixed-layer ocean have now been undertaken. The equilibrium SST response in those simulations is somewhat different than that estimated using the reference Ramanathan et al. (2005), with more cooling of the near-equator ocean as well and not only in the more northern parts. The simulation with modified fixed

SST is now treated as a sensitivity analysis and the mixed-layer ocean results lifted to the article results as an internally consistent, but in many ways limited (for example because of fixed horizontal and vertical ocean heat fluxes, as discussed in the article), estimate of the aerosol aggregate effect on the Indian climate.

2. Another major conclusion of this paper is that increased SDM may cause reduced evaporation, leading to reduced humidity and reduced rainfall which over compensates EHP. However, the authors did not show where and how much the reduction in evaporation occurs. Is it mainly over the NIO, due to SST cooling? Increased monsoon surface wind over the NIO from increased rainfall over India due to EHP could increase evaporation. As shown in previous studies (e.g. Lau and Kim 2006, 2010, Meehl et al, 2008), increase rainfall in northern India in late spring or early monsoon due to EHP can result in increased cloudiness, leading to surface cooling, and weakening of the monsoon in later stages. Hence the SDM effect may not be all aerosols, but amplified by cloud feedback. Including a discussion of this effect will be helpful.

Spatial distribution figures showing evaporation changes have been added to the supplementary material. The suggested discussion on the mentioned cloud feedback effect has been added. Complications are brought by the fact that evaporation not only leads, but can also lag precipitation and from separating initial climate response and more delayed feedbacks. However, the feedback might have had an effect for example in the mixed-layer ocean simulations.

3. The authors show TOA and surface aerosol radiative forcing. For EHP, strong radiative heating of the atmosphere is essential to excite the large scale circulation, moisture and latent heating feedback processes. It is more instructive to show in Fig. 3-6, the atmospheric heating , i.e., difference in TOA and surface, to indicate changes in potential for EHP initiation as a function of the season. In Fig. 7-8, the tropospheric temperature anomalies should also be shown to see if the change in rainfall is consistent with the change in the tropospheric merdional temperature gradient, which is the key to drive the monsoon and with direct linkage to EHP, more so than SST gradient. Any SST or *surface thermal gradient has to be translated into tropospheric temperature gradient to drive monsoon wind and rainfall changes. Additional analyses along these lines, will greatly help the reader to understand the model results.*

Atmospheric heating and tropospheric temperature anomaly plots have been added to the supplementary material and the related discussion to the text. The TOA and surface plots are left in the article itself for readers interested in radiative forcing and the connections with aerosol distributions, even though from the point of view of studying monsoon winds and rain, we agree that atmospheric heating and tropospheric temperature plots are more infomative.

4. The discussions for Fig. 9 in Section 5 (P.18040) are very confusing. From Fig. 9b, it is obvious that absorbing aerosol has the largest effect in increasing rainfall in June through August, when cloud activation is included. The effect absorbing aerosol seems to be even stronger than the modified SST. According to the caption, the plot is for all-India (5-35N) rainfall. But a following statement states that total rainfall reduced by -20% in northern India due to modified SST. Is it all-India or northern India?. The next statement on the lack of statistical significance of the JJA rainfall seems to contradict or weaken the conclusion of reduced rainfall due to SDM is more important than EHHP. Then the following statement said that absorbing aerosols increases rainfall EHP with 97% significance suggesting the robustness of EHP in the model response. Yet, this result is not reflected in the conclusion or in the abstract. From observations (Lau and Kim 2010), EHP should be more effective in northern India in late spring and early summer, and over northern India. I would like to see a plot of rainfall change similar to Fig. 9b, but for northern India, i.e., (20N-35N).

Figure 9 was precipitation for northern India (20N-35N) and we apologize for the typo in the caption of the original manuscript (in the text itself, the information was correct). As for the statement on statistical significance, it did indeed focus only on the effect of aerosol light absorption. The point was to emphasize that the EHP is clearly seen in the results, even though the SDM effect seems to be stronger. Reformulating: both the

EHP and the SDM effects have significant effects on rainfall according to the simulations. In the revised manuscript, both the effect of absorption and the aggregate effect is discussed in a more balanced way.

5. They authors attribute the increased in aerosols and precipitation in July as a hygroscopic growth in aerosols associated with increased in humidity in July, but the increase can also be due to increase southwesterly monsoon flow, bringing more moisture and dust to northern India. These effects should be further examined from the model outputs.

This is indeed what happens and we apologize that the formulation was perhaps not too clear regarding this fact. The westerly flow, increased humidity, hygroscopic growth and dust transport to large parts of northern India are all connected and this is now formulated more clearly. Supplementary Figure 7 in the original manuscript illustrated the hygroscopic growth due tue increased humidity and now an additional subfigure showing mean wind speed has been added to further illustrate the phenomenom.

6. It will be very helpful to better understand the model results, if the authors could show model AOD spatial distribution and compare with MODIS observations. For proper simulation of EHP, realistic distribution in space and time of increased aerosol in northern India piling up against the Himalayas is essential. Coarse resolution model will have problems simulating realistic distribution of AOD over India. This could be a reason of the SDM over-compensating EHP in the present model results. A discussion of the inability of coarse model resolution to resolve topography effects in transporting and trapping aerosols over the Indo-Gangetic Plain will be very useful.

A comprehensive comparison of simulated AOD spatial distributions as well as seasonal cycles was done in an earlier paper (Henriksson et al., ACP 2011). We have updated the discussion by showing the AOD seasonal cycle obtained with the GAINS emission inventory in Supplementary Figure 1b.

Yes, a realistic distribution of aerosols piling up against the Himalayas is essential for making correct conclusions of the EHP effect. Discussion regarding the limitations of coarse-resolution simulation of topography effects has been added to Section 2. However, the evaluation of BC concentrations against measurements at Mukteshwar on the Himalayan slopes (Figures 1 and 2 and related discussion) is meant to provide the reader with some additional information on the model's ability to resolve regional effects and we think the correspondence is satisfactory.

Interactive comment on Atmos. Chem. Phys. Discuss., 13, 18031, 2013.