Interactive comment on “Suppression of warm rain by aerosols in rain-shadow areas of India” by M. Konwar et al.
Anonymous Referee #2
Received and published: 2 September 2010

Review on "Suppression of warm rain by aerosols in rain-shadow areas of India" by Konwar et al.

The authors thank the reviewer for the helpful comments. The paper is restructured keeping in mind proper use of English language and grammar. Please find below the reviewer's comments in *italics*, followed by our responses.

The paper deals with the question of how aerosol affects precipitation over the rain shadow area in central India. They use in-situ measurements collected during the Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX) to show aerosol effects on the clouds' properties. The topic of the paper is important and interesting and the data looks of high value. However the quality of the presentation and the way the paper is organized are not meeting the same standards of the data. As a non native English speaker I could hardly follow the story of the paper so a general editing should be done. The authors miss important details about the analysis results on one hand and derive many conclusions that are not linked to what they show in the analysis on the other hand. For example they discuss in the abstract two aerosol effects that are not clearly shown in the data namely 1) they write “This might invigorate the very deep clouds on expense of the smaller clouds. “ And they further discuss invigoration in other places in the paper but nowhere invigoration is shown or hinted by the analyzed data. 2) They discuss in the abstract as well as in other places aerosol radiative effects but show very little evidence to it in the analysis.

Response: A general editing is done to the manuscript, which was mostly rewritten. We focus more on the cloud microphysical effect of aerosols. We however, kept the discussion on invigoration of the very deep clouds in the manuscript as we have shown that polluted clouds suppress formation of rain droplets even at the altitude of 7 km. This means that clouds that do not grow deep fail to precipitate. We reference the possibility that aerosols delaying warm rain can lead to invigoration of deep clouds with warm bases (around 20°C), but we do not claim that this is actually happening in the study area. The likelihood of invigoration is reduced because the observed clod base temperatures are not so warm (around 12-15°C).

As suggested the discussion of aerosol radiative effect is minimized in the abstract, however the importance of aerosol radiative effect is referenced in the manuscript.

My recommendations are: *1) Focus only on aerosol effects on droplets evolution (microphysical effect) hence warm rain suppression.*

Response: This is the primary objectives of the manuscript i.e. aerosols effect on droplets evolution. Now this issue is addressed for two contrasting cases in detail i.e. polluted case on 21 June and less polluted case on 22 June 2009 under similar synoptic conditions. It is also demonstrated that in case of the polluted clouds warm rain was suppressed with little coalescence process (for detail please see Figure 7).

2) Convince better that the shown differences between clouds are mostly aerosol effect (and not different environmental conditions represented by different profiles over several locations and measurement times). This can be done by testing meteorological parameters (other than CAPE) to convince that apart from aerosols loading all the other environmental conditions are similar.

Response: The synoptic conditions on 21 and 22 June 2009 were found to be quite similar except the difference in aerosol and CCN concentration. The cloud base temperature on 21 and 22 June was 15 ºC and 15.5 ºC respectively while the cloud base height was 2.40 and 2.02 km respectively (please see table 1). The RH % on 21 and 22 June was around 50 % from the surface to nearly 5 km (please see Figure 3). The stable layers in presence of large aerosol concentrations found to delineate dry and wet air for the more polluted case. Also the wind shear between 850 and 500 mb were nearly identical for these two cases (please see table 1).

3) Reduce the discussion on invigoration and absorption or show clear evidence related to these processes in your data analysis.

Response: We do not claim to have documented invigoration in our measurements. As suggested by the reviewer, discussion on absorption is reduced but still referenced in the manuscript.

It is much more difficult to document dynamic effects of aerosols compared to microphysical effects. Our study shows that warm rain is suppressed by aerosols in the polluted clouds, reducing the coalescence processes and converting the cloud droplets into ice crystals (Please see Figure 10). The suppression of warm rain is a major component of the invigoration hypothesis. Therefore, we do not need to document actual cloud invigoration for it to be warrant a discussion in this paper. Furthermore, Goswami et al. (2006) has shown that there is an increasing trend of heavy showers over the central India. Also the report of lightning by Lal and Pawar (2009) is related to aerosols in their study.

Specific comments related to the figures (and to the related text):

Fig 1: In the figure you simply show the southern part of India with no other additional information. It would be informative to highlight the location of the Western Ghats, the rain shadow area, the general circulation there (during the data collection time) and the measurement location in a clearer way.

Response: We provide in the revised manuscript the June-September mean rainfall over India (please see Figure 1 of the revised manuscript). The location of the rain shadow area is evident on the rain map. The locations of Maharashtra and Andhra Pradesh are marked on Figure 2.

The cloud base temperature and wind shear between 850 and 500 mb are provided in table 1. It can be seen that identical wind shear, cloud base temperature existed for the cases on 21 and 22 June inferring similar meteorological conditions.

Fig 2: 1) Please explain what is the meaning of measuring more ccns than aerosols.

Response: The aerosol concentration we presented here measured by the PCASP, which counts the aerosols within 0.1 to 3 μm. Many aerosols <0.1 μm, which are not counted by the PCASP, can still serve as CCN.

2) Also, it would be more informative if all figures would have the same scale.

Response: As suggested the figures are in the same scale.

3) The thermal profiles are shown to follow the wet-adiabatic lapse rate apart from the stable parts. Given that the RH is lower than SS for all the profiles, how should we guess where the clouds are? There should be clear evidence in the figure for the clouds location based on the presented parameters.

Response: As suggested we included the lines of moist and dry adiabatic lapse rates in the revised manuscript. Now the cloud bases could be inferred from the diagrams. The measured cloud bases by the aircraft are provided in the manuscript (please see table 1).

Fig 3: It is hard to take home messages from such scatter plot. The author should test the correlations with other meteorological parameters to make the point that the effect is due to aerosol.

Response: Figure 3 is now removed from the revised manuscript. It is mentioned in the manuscript that the year 2009 was a draught year, as the monsoon circulation was weak.

The meteorological parameters were examined for the observational days (please see table 1). In case of 21 June and 22 June, the wind shears and cloud base temperature were nearly identical, while the aerosol loading were different.

Fig 4: The LWC units are not clear

Response: In the revised manuscript the legends are enlarged for clarity.

Fig5. Would help to tie the different profiles to their aerosol loading in one plot Interactive

Response: We have shown here that heavy aerosol loading can suppress formation of warm rain. With increase in CCN concentrations the cloud droplet concentrations found to increase and are of smaller sizes. For the clouds over the rain shadow areas, warm rain was suppressed below the freezing level when CCN concentration below cloud base was greater than 1500 cm^{-3}.

References:

Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanan, M. S. and Xavier, P. K.: Increasing Trend of Extreme Rain Events Over India in a Warming Environment. Science, 314, 1442-1445. DOI: 10.1126/science.1132027,2006.

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