Authors' Response to Reviewer #3

This paper examines the relationship that exists between aerosols and precipitation through aerosolcloud-interaction. In general the paper is written well, analysed with all the available techniques for separation from meteorological effects, and necessary references have been cited properly, but it can be improved further by correcting the comments and concerns. Though the authors have taken efforts in doing such a laborious analysis, the anticipated results are more qualitative in nature due to the complexity with decoupling the meteorology. Hence, I suggest the reviewers to take up a major revision of the same by considering the comments given below.

Response: We are very grateful to the Dr Manoj M. G. for his thorough reading and useful suggestions for improvement of our manuscript. We have addressed all the comments and suggestions provided by the reviewer. Our point-to-point responses for the specific comments are mentioned below in blue color. The subsequent changes and additions in the revised manuscript against each comment are shown in red color.

The detailed review comments are provided below.

Major Comments

1. Page 4, Line 4: For a comprehensive review, discuss briefly on other studies which report evidences for increase in rainfall as a result of enhanced warming over IGP region due to aerosol radiative effects and associated dynamical feedbacks (Lau et al, 2006; Manoj et al., 2011 etc.).

Response: We have added a detailed discussion on aerosol radiative impact on Indian monsoon rainfall in Introduction (Page 4 Line 6) as mentioned below.

Recent studies based on aerosol direct effect have shown different plausible pathways of aerosol impact on rainfall. Lau and Kim (2006) [*Lau and Kim*, 2006] have shown that aerosol-induced atmospheric heating over Himalayan slopes and Tibetan plateau during monsoon onset period, intensifies the northward shift of Indian summer monsoon, causing reduction in rainfall over ISMR. On the other hand, high aerosol loading also induces a solar dimming (absorbing) effect at surface [*Ramanathan and Carmichael*, 2008; *Ramanathan et al.*, 2001], which can alter the land-ocean thermal gradient and weaken the meridional circulation, resulting in a drying trend in seasonal rainfall during Indian summer monsoon [*Bollasina et al.*, 2011; *Ganguly et al.*, 2012]. Presence of higher concentrations of absorbing aerosols over North India is shown to induce a stronger north–south temperature difference which fosters enhancement in moisture convergence from ocean and a transition from a break spell of ISM to an active spell of ISM [*Manoj et al.*, 2011]. Further, this aerosol radiative effect causes increase in the moist static energy, invigoration of convection and eventually more rainfall over India during the following active phase [*Hazra et al.*, 2013; *Manoj et al.*, 2011].

2. Page 9, line 5: Why 25th and 75th percentile between high and low AOD conditions were used? In section 2.3, the authors had adopted 33 and 67 percentiles. Why are these cut offs different, and what is the condition which these limits have been based up on?

Response: The criteria for low and high AOD categories are same in the entire study as is mentioned in Page 8 Line 20. The concerned sentence at line 5 Page 9 does not state the criteria of segregating CLOUDSAT profiles into low and high aerosol bins. It is meant to describe the variability of the microphysical variables (e.g. thin lines representing the 25^{th} and 75^{th} percentile within each of the two AOD bins in Figure 5B). We have modified the sentence in the revised manuscript (Page 9 Line 19) as below for clarity.

The mean microphysical variables along with their variability (profiles indicating 25^{th} and 75^{th} percentile) for low and high aerosol bins were plotted against altitude to visualize the net increase or decrease in liquid-phase water content, ice-phase water content and size of ice-phase hydrometeors at different altitudes with increase in aerosol loading.

3. Page 11, Line 3: Since the authors have all the relevant meteorological profiles at hand from CAIPEEX experiment, why the assumption regarding exponentially decreasing temperature pulse of 3° C was used?

Response: CAIPEEX experiment was localized over Bareilly during 23rd August 2009, but we intend to simulate a storm over Patna, so we have not used CAIPEEX meteorological conditions in our simulation. We have used CCN spectra from CAIPEEX measurements only as a guideline for probable CCN concentrations over the region. For the SBM simulation Radiosonde-obtained initial thermodynamic conditions from Patna IMD station were used as initial conditions to simulate the environment and microphysical variability. An exponential 3^0C temperature pulse is employed intrinsically in the SBM model instantaneously to trigger the initiation of parcel rise from surface as mentioned in the basic papers of the model. We have included references for this in the revised manuscript.

4. Page 13, Lines 20-23: 'The height above the LCL where the theoretical temperature of a buoyantly rising moist parcel (following wet adiabatic lapse rate) becomes equal to the temperature of the environment is referred to as equilibrium level'. This statement is not exactly correct. The Level of Free Convection (LFC) also satisfies the above criteria. Hence it is correct to change as: 'The height above the LFC…. to as equilibrium level'.

Response: We have replaced LCL with LFC as suggested.

5. Page 17, Lines 5-6: (a) 'Thus, the aerosol indirect effect could be twice as high as aerosol direct effect over ISMR'. How did the authors estimate the indirect radiative effect? The Reviewer is doubtful about this statement here. Cloud formation is not simply as a result of aerosol indirect effect alone; however, it requires conducive thermodynamical and dynamical atmospheric processes too. Hence, the reported cooling by 30 Wm-2 cannot be attributed to aerosol indirect effect alone, if the authors estimate the indirect effect by simply sorting AODs under cloudy conditions, and estimate the indirect forcing. (b) Reported cutoff values of AOD ≈ 0.3 illustrates that up to 0.3 AODs, the indirect effect dominates and beyond this limit the aerosol-radiation interaction effect dominates. No mention about this cut off is mentioned in this paper.

Response:

(a) We have removed this interpretation in the revised manuscript. The main focus of the AOD-CERES analysis is to illustrate the deepening of cloud systems with depth. So we have modified the sentence in **Page 19 Line 22** accordingly. We have also removed similar interpretation from the conclusions.

Quantitatively, the net cooling per unit increase in AOD (Figure 4B) under clear sky scenario was ~13 W/m^2,whereas the net cooling for same change in AOD under cloudy condition was twice more than that under clear sky scenario i.e. ~30 W/m^2.

(b) A discussion in this context is present in the manuscript on Page 17 Line 17.

Aerosol-cloud studies have reported reduction in cloudiness under high AOD for regions with high absorbing aerosol loading [*Koren et al.*, 2004; *Small et al.*, 2011]. Widespread cloud coverage over ISMR (CF of ~0.75 for AOD ~0.3 in Figure 3) induces substantial reduction in the incoming solar radiation [*Padma Kumari and Goswami*, 2010], which may result in reduced interaction between absorbing aerosols and shortwave radiation. This explains that, despite the high emission rate of absorbing aerosols over ISMR [*Bond et al.*, 2004], the aerosol-induced cloud inhibition effect seemed to have been reduced to a second order process during Indian summer monsoon.

6. Figure 6. Each line colour in Figure Caption given for Ex1 is wrong compared with those given in the Figure itself. Please correct. Same for other figures too (e.g. Figure 8)

Response: These mistakes are corrected in the revised manuscript.

7. Page 21, Line 5: Is the vertical updraft velocity only 0.2 cm/s, when the convection is strong? Or is it in the unit of meter/second (instead of cm/s)?

Response: The vertical velocity is indeed in m/s. We have corrected this in the revised manuscript.

8. Page 26, Lines 15-19: Give a discussion on whether aerosol invigoration leads to increase in total rainfall averaged over all grids and time, or if it leads to a redistribution of rain with suppressed rain at initial time, and enhanced precipitation at a later stage so that total surface precipitation is nearly conserved.

Response: Aerosol-induced cloud invigoration leads to increase in accumulated rainfall throughout the storm domain as seen in the Figure below. The initial suppression of warm rain favors transport of more water mass to higher altitudes and the formation of bigger and deeper clouds, which eventually result in enhanced rainfall. In this context, we have added a description as below at **Page 24 Line 22.**

However, the increase in rainfall amount with increase in CCN concentration in later stage of simulation was manifold compared to the initial suppression of warm rainfall eventually leading to the enhancement of accumulated rainfall throughout the storm domain(Figure not shown).

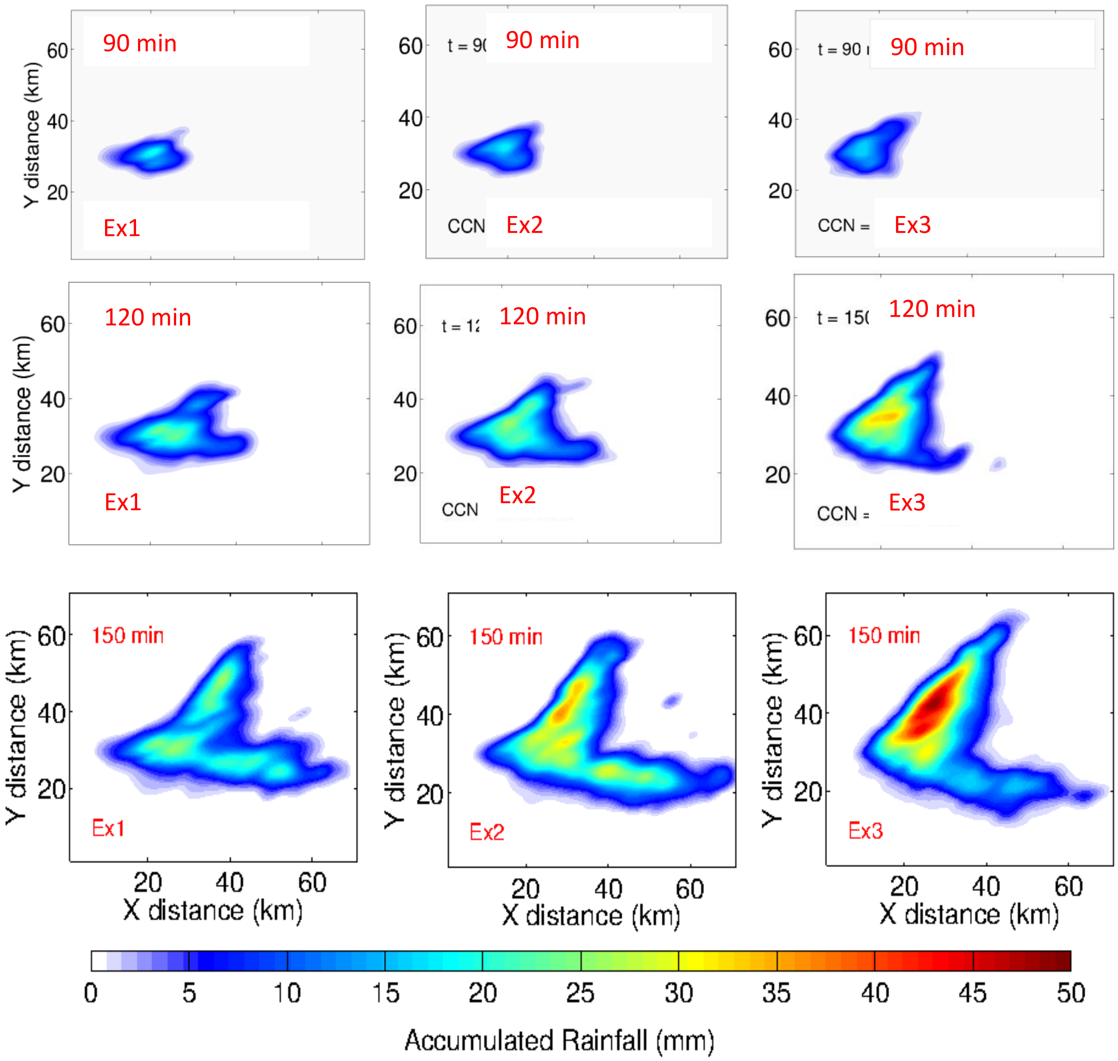

Figure: Accumulated rainfall after t=90 min (top row) , t=120 min (middle row) and t=150 min (bottom row) for Ex1 (left col.), Ex2 (middle col.) and Ex3 (right col.) simulations

9. Figure 10 needs precise description for a general reader to comprehend the basic idea, especially about the x-axis, and the shaded region.

Response: We have revised the caption of figure 10 as mentioned below to improve clarity.

Figure 10: Correlation coefficients of accumulated daily rainfall, AOD and cloud fraction with various GDAS meteorological variables over ISMR. Different color shades along the x-axis illustrate different meteorological variables and each color shade has 21 divisions which represent corresponding 21 model pressure levels from 100 hPa to 1000 hPa. Correlation analysis was performed at each model pressure level with all collocated samples (of the two variables used in the analysis) over ISMR region for JJAS, 2002-2013.

10. Page 26, Lines 22-25: A major drawback of the correlation analysis here is that it represents simultaneous correlation. However, aerosol build up might have taken place prior to cloud

maturity and rain initiation, and subsequently could have reduced due to cloud scavenging and wet removal. A lag correlation analysis at cloud formation time scales could have been more meaningful here.

Response: The reviewer is correct in stating that a lag correlation analysis at cloud formation/rainfall time scale will be interesting and insightful about the effect of wet scavenging and subsequent aerosol build-up effect. In the revised manuscript we have used long-term aerosol-rainfall ground based measurements over Kanpur to redo the analysis at hourly time scale and check the impact of wet scavenging. We have also added this analysis to results and discussion in our revised manuscript as suggested by Reviewer 1. The results and additions are mentioned below. We found that positive aerosol-rainfall association persisted even when wet scavenging effect was explicitly present in the sampling which strengthen our prime results.

Section 2.5

(3) Underestimation of wet scavenging effect on satellite retrieved AOD values [Grandey et al., 2013;2014].

Section 2.5.3

Aerosols present below cloudy pixels are not visible to satellite. To circumvent this limitation in investigating aerosol-cloud-rainfall association, it would be reasonable to assume that the mean aerosol distribution below the non-raining cloudy pixels is similar in magnitude to the aerosol distribution of the non-cloudy pixels within a 1^o x 1^o grid box. Nevertheless, aerosols below cloudy pixels, where rainfall occurs, are subject to depletion due to wet scavenging effect. Thus, wet scavenging effect might not be accurately represented in the MODIS retrieved AOD dataset used in our study. Modeling studies suggest that this artifact in the satellite retrieved AOD values can significantly affect the magnitude as well as the sign of the aerosol-cloud-rainfall associations [*Grandey et al.*, 2013; *Grandey et al.*, 2014;*Yang et al.*, 2016]. At the same time, *Gryspeerdt et al.*, (2015) [*Gryspeerdt et al.*, 2015] have recently illustrated that the aerosol in neighbouring cloud-free regions may be more representative for aerosol-cloud interaction studies than the below-cloud aerosol using a high resolution regional model, justifying the methodology used in their study.The main limitation in investigating the impact of probable inaccuracy in representing wet scavenging effect on our analysis is lack of collocated measurements of aerosol-cloud-rainfall at temporal resolution of rainfall events from space-borne measurements. Hence, we used collocated hourly measurements of aerosol and rainfall over Indian Institute of Technology, Kanpur (IITK) as a representative case study dataset to investigate the possible effect of wet scavenging on aerosol-rainfall associations within ISMR.

AErosol RObotic NETwork (AERONET), is a global network of ground based remote sensing stations that provides quality-controlled measurements of aerosol optical depth with high accuracy[*Dubovik and King*, 2000; *Holben et al.*, 1998]. Hourly averages of AOD (550 nm) used in this analysis were obtained from the quality ensured Level-2 product of AERONET site deployed in the IITK campus. Rainfall events were identified from collocated rain gauge measurements near AERONET station within IITK campus between April-October; 2006-2015. We have also included the months of April, May and October to increase the number of sample points. Rainfall amount of all the rainfall events were sorted as a function of collocated AERONET-AOD values (mean of AERONET-AOD measurements within ± 4 hour of the start/end of the rainfall) into 5 equal bins of 20 percentiles each. As AERONET-AOD measurements were available only between sunrise and sunset, we have used AOD values of late evening measurements as representative of aerosol loading during the first rainfall event (if any) at night-time. However, in case of more than one rainfall events at night, only the first rainfall event is considered in this analysis. Nearly half of the AOD-rainfall samples used here included AOD measurements within 4 hours after the end of any rainfall event, and therefore, this includes a wet scavenging effect of rainfall on AOD measurements. To reproduce another specific scenario, only the rainfall-AOD samples with availability of AOD measurement before start of rainfall events were collected and sorted as a function of AOD into 5 equal bins of 20 percentiles each. This restricted sampling does not include the wet scavenging effect as only the AOD-values before the start of rainfall in each rainfall event were used. The average of rainfall amount for each bin was plotted against mean AOD values under both scenarios to illustrate the difference in aerosol-rainfall association due to exclusion of wet scavenging effect within ISMR.

Section 3.3.3

Contrary to the positive aerosol-cloud-rainfall associations shown by many satellite data studies across the globe, recent studies have illustrated a negative aerosol-rainfall association mainly over tropical ocean region based on reanalysis dataset and global model simulations. This difference in sign of the association in modeling studies is mainly attributed to inclusion of wet scavenging effect in models and probable lack of the same in satellite samples [*Grandey et al.*, 2013; *Grandey et al.*, 2014; *Yang et al.*, 2016]. However, global modeling studies have their own inherent limitations and uncertainties in addressing aerosol-cloud-rainfall associations. Due to computational constraints, the global model simulations use grids with coarse spatial resolution (~ 200 km) and fall short of explicitly resolving the fine-scale cloud processes. Moreover, the convection parameterizations used to simulate cloud formation generally do not parameterize the aerosol indirect effect on clouds and thus, on rainfall. On the contrary, the observed relations using satellite datasets are at fine scale and inclusive of the aerosol indirect effect. As a representative analysis, collocated AOD-rainfall measurements at hourly temporal resolution over IITK was used to illustrate the association between aerosol-rainfall with and without wet scavenging effect. Positive association was found between rainfall amount and mean AOD values measured before the start of rain events over IITK (NWS_IITK; red line in Figure 12). Similar association was also found when all the available collocated AOD-rain amount samples over IITK were correlated (Cyan color line in Figure 12), but the gradient was reduced by almost 50 % when compared to that of NWS_IITK. Thus, positive association between aerosol-rainfall was evident even with the inclusion of wet scavenging effect in the sampling. Grandey et al., 2013 [*Grandey et al.*, 2013] have also shown similar amount of contribution of wet scavenging effect on the positive aerosol-cloud association. Correlation of MODIS-AOD with RF (black line in Figure 12) and PR (blue line in Figure 12) values over the IITK grid also illustrated positive association between aerosol and rainfall similar to the observed associations in Figure 3. High anthropogenic aerosol emission rate at surface [*Bond et al.*, 2004] and the rapid aerosol buildup within a few hours after the individual rainfall event over ISMR [*Jai Devi et al.*, 2011] might contribute towards reducing the impact of wet scavenging effect on the aerosol-cloud-rainfall analysis over ISMR. This argument is also supported by a pattern seen in model results that negative aerosol-cloud-rainfall associations were usually prominent over ocean regions and positive aerosol-cloud-rainfall associations were found over continental conditions in global simulations [*Grandey et al.*, 2013; *Grandey et al.*, 2014; *Gryspeerdt et al.*, 2015; *Yang et al.*, 2016]. Unlike continental conditions, lack of high emission rates at the ocean surface might also contribute to the dominant effect of wet scavenging on aerosol-cloud-rainfall association. In addition, the cloudy pixels where rainfall actually occurs under continental conditions are usually a small fraction of the total area within a 1^{o} x 1^{o} box, and therefore, the reduction in mean AOD value of the 1^{o} x 1^{o} box due to wet scavenging might not be a dominant phenomena affecting the aerosol-cloud-rainfall gradients in Figure 3. IITK-AERONET data analysis offers confidence to the observed positive association for aerosol-cloud-rainfall, and confirms that it was not a misrepresentation due to possible uncertainties involved for wet scavenging effect in using satellite retrieved AOD values. It indeed also showed that a more accurate representation of wet scavenging effect is essential to reduce uncertainty about the magnitude of the positive aerosol-rainfall gradient observed over ISMR.

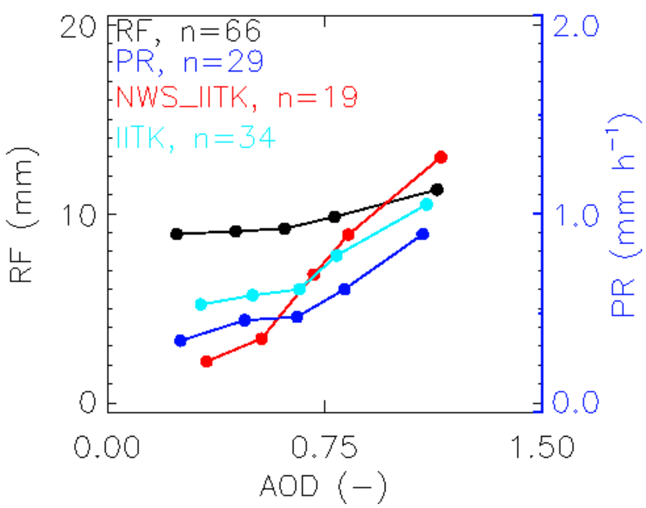

Figure 12: Associations of rainfall with collocated AERONET-AOD measurements (within ± 4 hours of the start/end of rainfall event) over IITK. The Cyan color line illustrates the scenario with inclusion of wet scavenging effect (IITK) and the red color line illustrates the scenario with no wet scavenging effect (NWS_IITK). The association between daily rainfall and precipitation rate with MODIS-AOD over IITK grid is also shown in black and blue color lines, respectively. In each case, all the rainfall-AOD samples were sorted as a function of corresponding AOD values into 5 bins of 20 percentiles each. Each scatter point is the average of each bin and have *n* number of data points.

Section 4:

As a future scope, more observational studies at cloud formation and rain event time scales are warranted to accurately quantify the magnitude of aerosol-cloud-rainfall association over ISMR.

11. Section 3.4 could be merged with an earlier description of AOD retrieval errors associated with contamination due to RH. This section is a repetition.

Response: As suggested we have reorganized Section 3.4 as subsection 3.3.2

Minor Comments

1. Title: ‘Association’ instead of ‘Associations’.

Response: We have modified this word.

2. Abstract, Line 31: Change to ‘Simulated microphysics also illustrated that the…’

Response: We have revised as suggested.

3. Abstract, Line 36: Correct as: ‘While the meteorological variability influences’

Response: We have corrected the word.

4. Abstract, Line 37: Change to ‘association’ instead of ‘associations’.

Response: We have corrected it as suggested.

5. Page 2, Line 9: Remove comma (,) after ‘cloud base’.

Response: We have removed the comma as suggested.

6. Page 3, Lines 4 & 15; Page 9, Line 20, and many places: Correct ‘AP Khain et al.’ to ‘Khain et al.’.

Response: We have modified the references as suggested.

7. Page 4, Line 2: Replace ‘as well as’ by ‘and’.

Response: We have modified as suggested.

8. Reference required: ‘…lower available spatial resolution (i.e. 0.25o×0.25o) was in general biased to smaller clouds..’.

Response: We have removed the sentence.

9. Page 9, line 1: Correct: ‘CLOUD-aerosol Lidar and infrared pathfinder SATellite (not CloudSat, but CALIPSO)’.

Response: Corrected

10. Page 22, line 18: Correct: ‘droplet spectral’.

Response: Corrected at Page 26 Line 11

11. Page 30, Lines 5: Remove ‘other’.

Response: Removed

12. Page 33, Lines 5: Change to ‘found to be in-line…’

Response: Changed at Page 39 Line 9.