Author's Response to Reviewer #1

The authors used 12 years of in-situ and satellite observations combined with model simulations to examine association of aerosol loading with cloud fraction, cloud top pressure, cloud top temperature, and daily surface rainfall over Indian summer monsoon region (ISMR). They found high aerosol loading might induce cloud invigoration and thereby increasing surface rainfall over the ISMR. This study contributes to address aerosol-cloud-rainfall associations over ISMR. Before this manuscript can be considered for publication, I have a few comments that need to be addressed by the authors.

Response: We are grateful to the reviewer for the thorough reading of our manuscript. We have addressed all the comments and suggestions provided by the reviewer. Our point-to-point response to each comment is indicated below in blue color. The subsequent changes and additions made in the revised manuscript in response to each comment are shown in red color.

My major concern of this paper is that the author found that impact of aerosols on cloud and rainfall dominated the aerosol-cloud-rainfall relationship over ISMR. However, many previous studies found that wet scavenging of aerosols by rainfall control this relationship, while aerosol indirect effect could only perturb it (Grandey et al., 2013, 2014; Yang et al., 2016a,b). Why they are different from the results shown here?

Response: We agree with the reviewer's concern about the difference in results between the two broad approaches (modeling analysis and data analysis using satellite retrievals) used for studying aerosol-cloud-rainfall associations. However, many studies (as mentioned in the Introduction section) have shown the aerosol induced changes to coupling between the microphysical and dynamical processes in the cloud and in the cloud field to explain the positive link while wet scavenging could not explain most of the effect. We have included a discussion in this context in the revised manuscript about the possible causes of these differences as well as about the limitations and uncertainties involved in both approaches regarding the competing effects of wet scavenging and aerosol microphysical modifications. Additionally, we have also analyzed aerosol-rainfall association with and without wet scavenging effect over Kanpur using AERONET-measured AOD and rain gauge measured rainfall at an hourly resolution. This analysis illustrated that the positive aerosol-rainfall association exists despite exclusively including wet scavenging effect thereby further strengthening our argument. Nevertheless, in agreement with the reviewer’s statement, it has reduced the gradient of the association.

The added discussion and results in manuscript in response to the reviewer's comment for "Page 12 Line 10" are mentioned below.

Specific comments:

Page 1 Line 24: What is the seminal role? It needs to be expressed more specifically.

Response: We have included the following statement in the revised manuscript (Page 1 Line 22):

A decrease in outgoing longwave radiation and increase in reflected shortwave radiation at the top of the atmosphere with an increase in aerosol loading further indicates a possible seminal role of aerosols in deepening of cloud systems.

Page 3 Line 16: Aerosols interact with clouds and rainfall two ways. Aerosols impact clouds and precipitation, and clouds and precipitation can influence aerosols through wet scavenging processes (Quaas et al., 2010; Grandey et al., 2013, 2014; Gryspeerdt et al., 2015; Yang et al., 2016a,b,c). In introduction section, the authors only discussed aerosol impacts on cloud. They might add the cloud and rainfall influence on aerosols here.

Response: We have included the following discussions about wet scavenging effect on aerosols in the revised manuscript (Page 3, Line 16):

Moreover, clouds and precipitation can also interact with aerosols through wet scavenging process [*Grandey et al.*, 2013; *Grandey et al.*, 2014;*Yang et al.*, 2016]. Global model simulations illustrated that wet scavenging can cause a strong negative cloud fraction-AOD correlation over the tropics [*Grandey et al.*, 2013]. Wet scavenging effect can also generate similar negative rain rate-AOD association in the tropical and mid-latitude oceans [*Grandey et al.*, 2014].

Page 4 Line 11: Also, please also add description about impact of monsoon on aerosols (e.g. Corrigan et al., 2006; Lou et al., 2016).

Response: We have included the following discussions in the revised manuscript (Page 5, Line 1):

Conversely, summer monsoon plays an important role in determining variation in aerosol loading over India by bringing clean marine air and wet scavenging, which are as important as emission in determining aerosol concentration [*Li et al.*, 2016]. It has also been shown that aerosols over the Indian Ocean interplay with seasonal changes over ISMR[*Corrigan et al.*, 2006].

Page 6 Line 8: This sentence is hard to follow. Please make it clear.

Response: We have revised the following sentence in the revised manuscript for clarity (Page 7, Line 1).

RF as well as PR datasets were linearly re-gridded to the $1^{o}\times1^{o}$ grid for consistency in our correlation analysis.

Page 6 Line 15: Could you also calculate the ratio of AODs>1.0 as same as 7% shown below?

Response: The percentage of AOD values > 1 was ~5%. We have included this information in the revised manuscript Page 6 Line 21.

Page 8 Line 20 and Page 9 Line 5: Why high and low AOD categories are different here?

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 for segregating CLOUDSAT profiles into low and high aerosol bins. It is meant to describe the variability of the microphysical variables (thin lines representing the 25th and 75th 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 25th and 75th 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.

Page 12 Line 10: aerosol humidification effect is not the only effect that causing covariation of AOD- and rainfall. Engström and Ekman (2010) and Yang et al. (2016a) found wind speed also lead to co-variation of AOD-cloud and rainfall, it impact could be larger than aerosol humidification effect.

Response: The correlation of AOD, RF and CF with wind speed at different heights is shown in Figure 10. The analysis over ISMR illustrates that wind speed in the lower troposphere is not a dominant factor. Moreover, positive correlation between AOD-wind speed is associated with a negative correlation between CF/RF- wind speed at the same altitude. This is different from the findings of Engström and Ekman (2010) and Yang et al. (2016a), where, increase in wind speed at 10m height is strongly correlated with increase in both AOD and accumulated rainfall/precipitation rate. A possible reason for this may be that unlike our study, both, Engström and Ekman (2010) and Yang et al. (2016a) were performed exclusively over oceans. Wind speed can increase the aerosol loading over the ocean (more production of sea-spray aerosol) but over polluted land regions with local sources it could dilute the aerosol concentration.

We found a strong impact of wind shear on AOD-cloud-rainfall association, consistent with aerosol-induced cloud invigoration as shown by previous studies (Fan et al., 2009). So we have considered wind shear as a key meteorological factor over ISMR and have analysed its effect on observed aerosol-cloud-rainfall analysis.

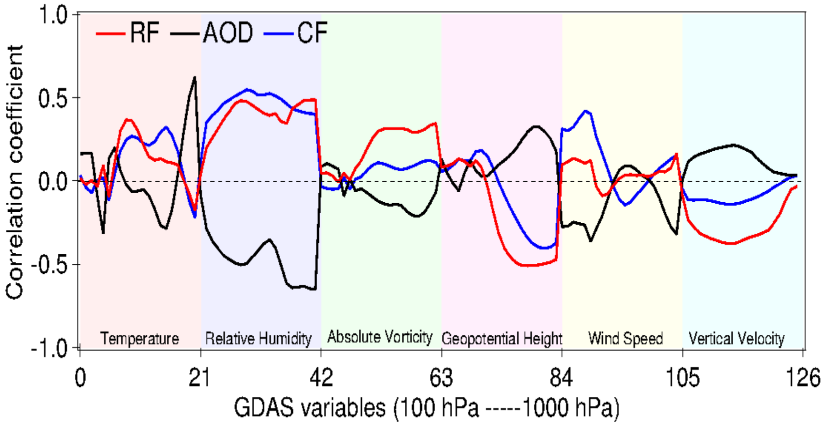


Figure 10.Correlation coefficients of accumulated daily rainfall, AOD and cloud fraction with six GDAS meteorological variables over ISMR. Different color shades along the x-axis indicate corresponding meteorological variable and each color shade has 21 divisions which represents corresponding 21 model pressure levels from 100 hPa to1000 hPa (left to right). Correlation analysis was performed at each model pressure level with all collocated samples between two variables (e.g. temperature and RF for x-axis values of 1-21 in case of red color line) over ISMR region for JJAS 2002-2013.

Page 12 Line 10: Also, I suggest adding impact of cloud-rainfall on AOD here as (3) and analysising it in result section.

Response: As per your suggestion, we have added analysis and discussion on the wet scavenging impact of cloud-rainfall on AOD. Corresponding modifications in each section are mentioned below in red color.

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. Modelling 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.

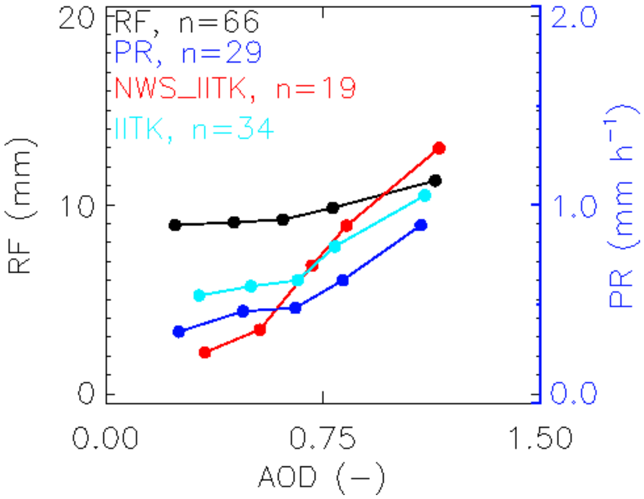


Figure 12: Associations of rainfall with collocated AERONET-AOD measurements (within ± 4 hours of the start/end of rainfall event) over IITK. The Cyan color line illustrates the scenario with inclusion of wet scavenging effect (IITK) and the red color line illustrates the scenario with no wet scavenging 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.

Page 14 Line 17: Figure 3A. Is this figure the JJAS daily data for 2002–2013 (total 1464 samples)? How did you treat intra-seasonal variability of these variables? Please make it clear here or in figure caption.

Response: We have modified the caption of Figure 3 in the revised manuscript to provide information about the sampling used in these correlations. The modified caption is shown below

Caption of **Figure 3.**Associations of (A) daily rainfall, (B) precipitation rate, (C) cloud fraction, (D) cloud top pressure, and (E) cloud top temperature with AOD. The collocated data points for these five variables (A-E) were sorted as a function of AOD over ISMR during JJAS 2002-2013. The total number of collocated data points are then used to create 50 bins with 'n' numbers of data points (2 percentile) each and averaged. These 50 scatter points are shown in the respective panels.

Moreover, we have also created figures similar to Figure 3, but separately for June, July, August and September. The comparison of these plots illustrate that the positive aerosol-cloud-rainfall association exists in each month separately, however, the range and variability in the association varies. As our focus is to illustrate the qualitative association, we have merged the data from all the four monsoon months into one plot to examine the seasonal pattern. This also reduces the spread of the regression by increasing the number of samples (n) per AOD bin. We have stated this information in the modified manuscript as below (in red) at **Page 18 Line 7**.

Analysis of individual months viz; June, July, August and September also illustrated similar positive associations as seen in Figure 3 indicating negligible intra-seasonality in the observed associations.

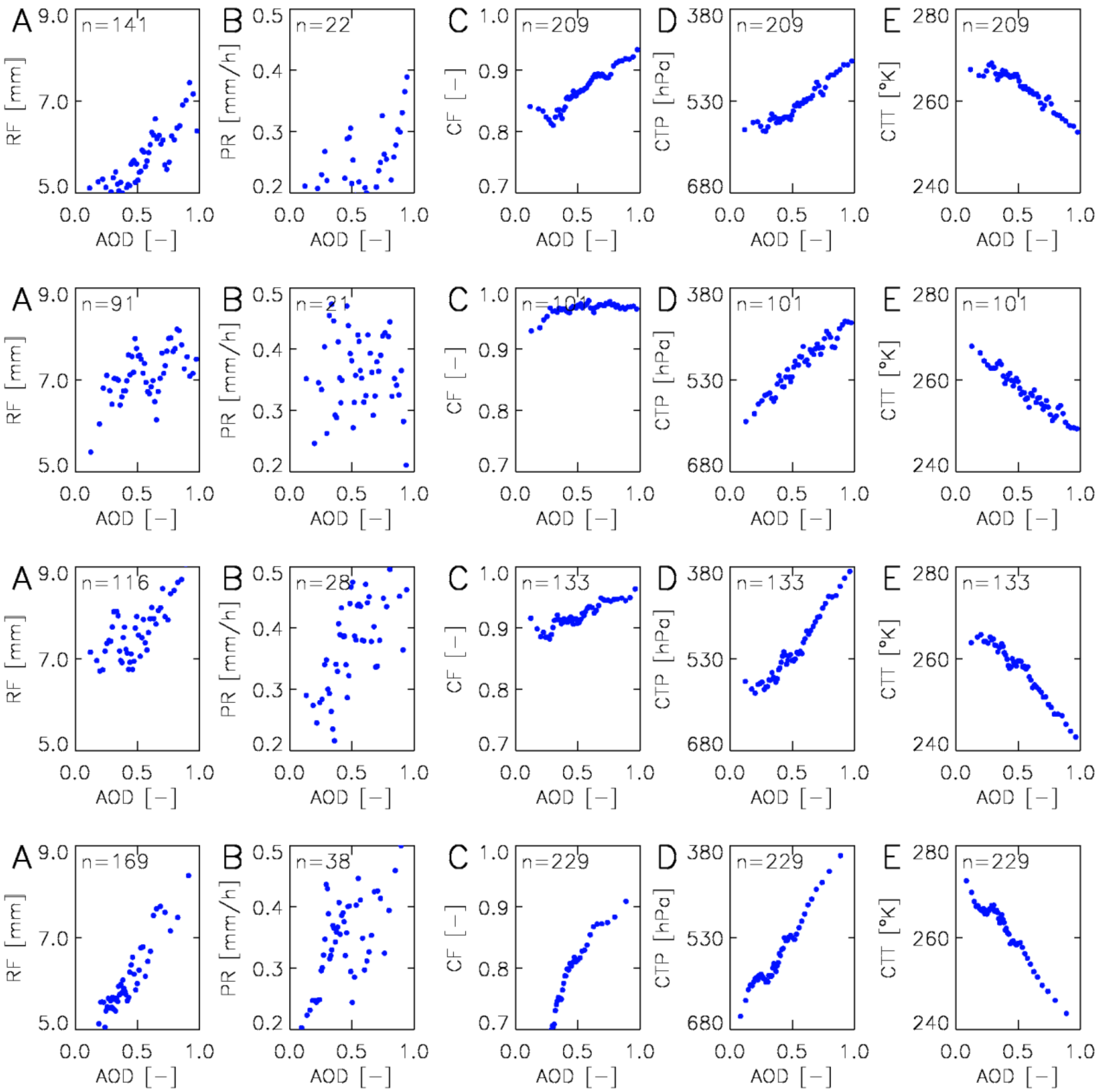


Figure: Associations of daily rainfall (A), precipitation rate (B), cloud fraction (C), cloud top pressure (D) and cloud top temperature (E) with AOD. The daily collocated measurements of these five variables with AOD from all the grids within ISMR during June (Row1; top row), July (Row2), August (Row3), and September (Row4; bottom row) monthsof 2002-2013 are used. They are sorted as a function of collocated AOD values (each variable separately).The total number of collocated data points are then used to create 50 bins with 'n' numbers of data points (2 percentile) each and averaged. These 50 scatter points are shown in the respective panels.

Figure 4: Again, please make clear how data used. What are these radiative fluxes, net, upward or downward?

Response: We have modified the caption of Figure 4 as shown below to incorporate the suggested information.

Figure 4. Association of CERES retrieved incoming shortwave (SW) and outgoing longwave (LW) radiation with AOD for (A) all-sky and (B) clear-sky scenario over ISMR during JJAS 2002-2013. The collocated data points for both SW and LW as a function of AOD were first sorted. The total number of collocated data points are then used to create 50 bins with 'n' numbers of data points (2 percentile) each and averaged. These 50 scatter points are shown in the respective panels.

Figure 7: Why not show Ex2?

Response: We have included Ex2 in Figure 7. We had not included Ex2 previously to reduce the density of the figures as the results are proportional between Ex1, Ex2 and Ex3.

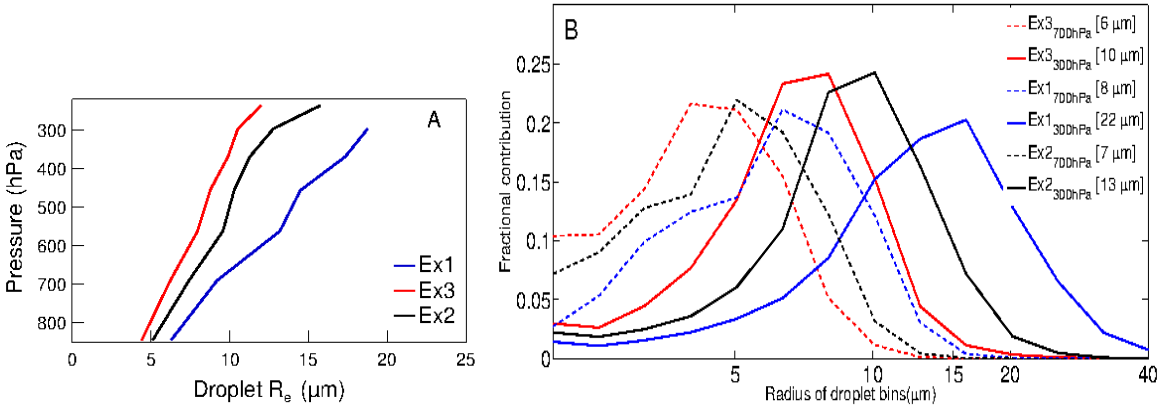


Figure 7: A) Mean droplet R_e versus CTP for low (Ex1; blue), medium (Ex2; black) and high (Ex3; red) CCN scenario. B) Droplet size distribution spectra of Ex1 (blue), Ex2 (black) and Ex3 (red) simulations at 700 hPa (dashed lines) and 300 hPa (solid lines). The corresponding effective radius values are mentioned in the legends in square brackets. Fractional contribution is calculated by dividing the mass concentration of each bin with the total mass concentration.

Page 26 Line 21: The authors did not consider the impact of combination of meteorological fields. They may dampen each other. And the correlation in Figure 10 between different meteorological fields did not take into account the correlation among the meteorological variables.

Response: We agree with the reviewer that many of the meteorological variables are not orthogonal to all others and therefore can have significant correlation between them. Nevertheless, when classifying the atmosphere in accord to its cloud formation potential, most of the variables indicate the same trend, i.e. for deeper clouds we will find higher CAPE levels, low geopotential height, stronger updrafts, higher relative humidity in the cloud layers, stronger moist conversion, etc. Conflicting trends are possible but based on our analysis the trend is quite uniform in all key variables.

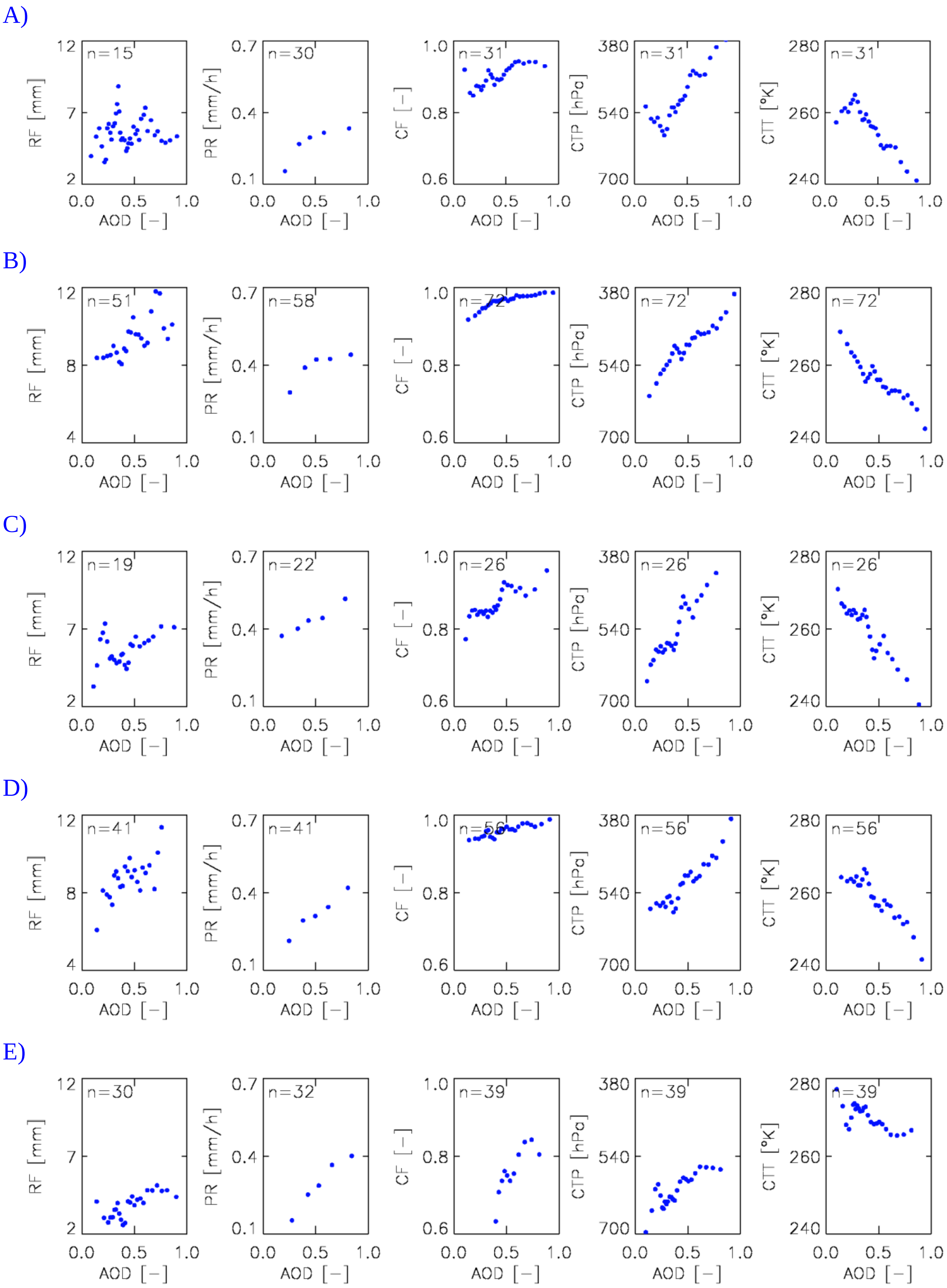
As per suggestion of the reviewer, we have also analysed the impact of combining the key meteorological factors in our analysis. The results are shown in Figure A below. The entire dataset was divided into meteorological slices to represent 8 regimes as shown in the table below. The positive association between aerosol-cloud-rainfall existed in each sub regime, however, the relationship indeed dampened due to the orthogonal effect of ambient meteorological conditions as also discussed in the manuscript. We have included information about this analysis in the revised manuscript at **Page 31 Line 16**

Page 31 Line 16

We have also considered the combined effect of all the three key meteorological variables by dividing the datasets into 8 regimes (alternate combination of higher and lower bins of RH,WS and GPH). Our analysis illustrated (Figure not shown) similar results as seen in Figure 11; positive aerosol-cloud-rainfall association was evident in all the 8 sub-regimes along with distinct orthogonal effect of ambient meteorological conditions.

Table: Segregation criteria of the 8 regimes created for investigating the orthogonal effect of meteorology on aerosol-cloud-rainfall analysis combining all the three key factors. The association in each regime is shown in figure B below.

Regimes	RH	Wind shear	GPH
R1	High (>67 percentile)	High (>67 percentile)	High (>67 percentile)
R2	High (>67 percentile)	High (>67 percentile)	Low (<33 percentile)
R3	High (>67 percentile)	Low (<33 percentile)	High (>67 percentile)
R4	High (>67 percentile)	Low (<33 percentile)	Low (<33 percentile)
R5	Low (<33 percentile)	High (>67 percentile)	High (>67 percentile)
R6	Low (<33 percentile)	High (>67 percentile)	Low (<33 percentile)
R7	Low (<33 percentile)	Low (<33 percentile)	High (>67 percentile)
R8	Low (<33 percentile)	Low (<33 percentile)	Low (<33 percentile)


A)
n=15
n=30
n=31
n=31
n=31
B)
n=51
n=58
n=72
n=72
n=72
C)
n=19
n=22
n=26
n=26
n=26
D)
n=41
n=41
n=56
n=56
n=56
E)
n=30
n=32
n=39
n=39
n=39
RF [mm]
PR [mm/h]
CF [–]
CTP [hPa]
CTT [°K]
AOD [–]
0.0
0.5
1.0
2
7
12
4
8
0.1
0.4
0.7
0.6
0.8
1.0
380
540
700
240
260
280

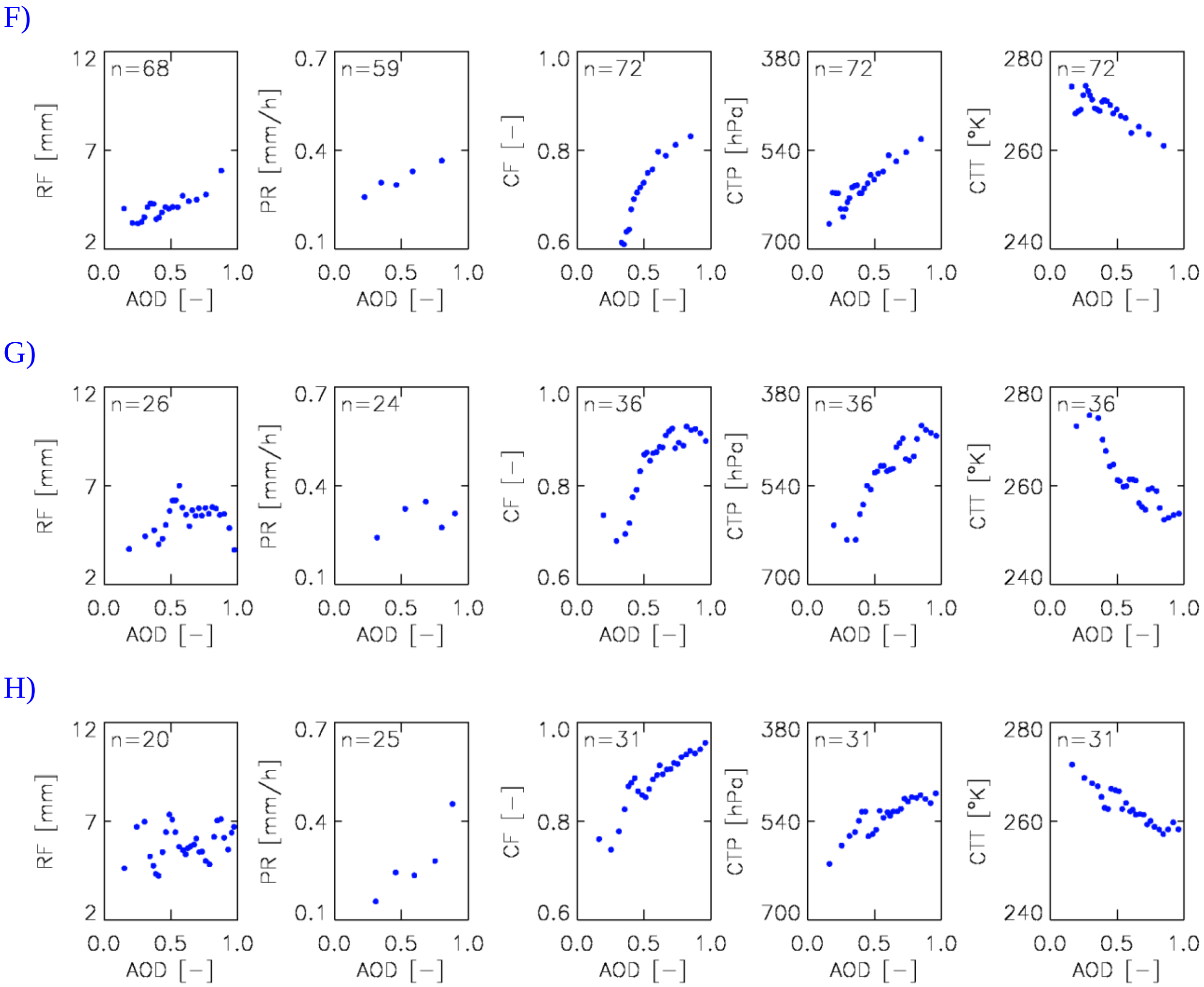


Figure A: Associations of accumulated daily rainfall, precipitation rate, cloud fraction, cloud top pressure and cloud top temperature with AOD for meteorology regime **A) R1, B) R2, C) R3, D) R4, E) R5, F) R6, G) R7, H) R8.** The daily collocated measurements of these variables (except PR) with AOD from all the grids within ISMR during JJAS, 2002-2013 are sorted as a function of collocated AOD values (each variable separately), divided into 25 bins of 4 percentile each and averaged. In case of PR-AOD association, the number of sample points were greatly reduced within each regime so the dataset was divided into 5 equal bins of 20 percentile each and samples averaged. The number of samples (n) corresponding to each scatter point are indicated on the plot. The total number of samples used in these separate associations are equal to n times 50.

Page 31 Line 2: Could you describe the method used in Bar-Or et al. (2012)?

Response: We have described the methodology of Bar-Or et al. (2012) in detail in Methodology section Page 15 Line 5.

Page 31 Line 16: This conclusion needs more cautiousness. The analysis using all-sky and clear-sky of CERES radiative fluxes may not represent aerosol direct and indirect effects. At least, add region here.

Response: We have removed the statement in the revised manuscript.

Technical corrections:

Table 1: change 2002–13 to 2002–2013

Response: We have modified the caption abbreviation as suggested.

Page 7 Line 8: I suggest changing abbreviation of rainfall. DRF is often used to represent direct radiative forcing.

Response: We have replaced DRF with RF in the manuscript and figures.

Figure 2: What are these colored lines? Please add more information in figure caption.

Response: We have modified the caption of Figure 2 with detailed information.

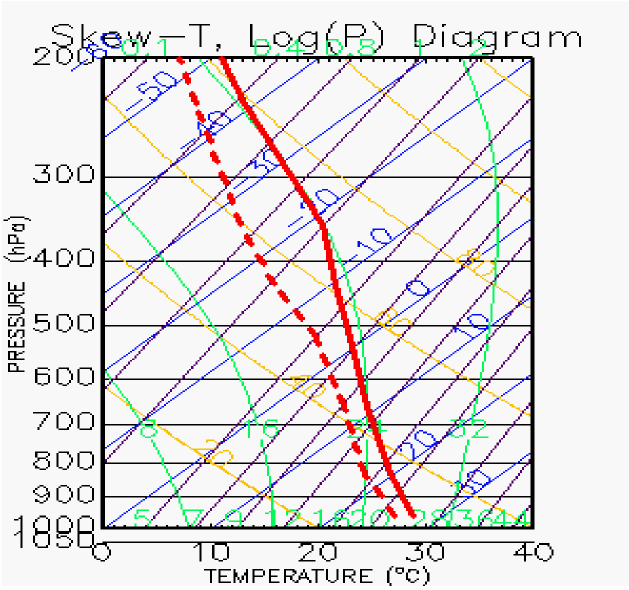


Figure 2.Skew-T - log-P diagram illustrating the initial conditions of dew point temperature (red hashed line) and atmospheric temperature (red solid line) used in all the three WRF-SBM idealized simulations. Blue, yellow, green, black and purple lines indicate lines of constant temperature (isotherm), potential temperature and equivalent potential temperature, pressure (isobar), and saturation mixing ratio, respectively.

There are too many abbreviations in this study.

We have tried to keep them to minimum.