Atmos. Chem. Phys. Discuss.,
https://doi.org/10.5194/acp-2019-1-AC2, 2019

Atmospheric Chemistry and Physics
Discussions

Interactive comment on "Growth in mid-monsoon dry phases over Indian region: Prevailing influence of anthropogenic aerosols" *by* Rohit Chakraborty et al.

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Received and published: 26 April 2019

First of all we wish to thank the reviewer for appreciating actual content of the work and providing constructive comments/suggestions which significantly improved the content of the manuscript. We have addressed all the comments raised by the reviewer and incorporated in the revised manuscript.

1. The essential problem is that when there is no rain the aerosol loading will increase due to the absence of washout. May be this is bit debatable when there is a non-hydrophylic BC is present, but when using AOD as an indicator washout is a fact. Essentially, most of the India with anthropogenic aerosol pollutants that AOD can be

expected to recover quickly after a rainfall (washout) event. This implies that the dry days will have more aerosols (AOD) in the atmosphere and there will be a pretty good correlation between dry days and AOD over much of India during monsoon in places with significant anthropogenic pollution. Then to argue that more AOD leads to more dry days, we will need a testable hypothesis. I didn't see any such hypothesis in this manuscript or I might have completely missed it. For example, separating the data into high AOD days of few days and the next rain event, holding all other factors constant, to days with low AOD days with similar set of meteorological conditions and show that the next rainy day is extended by x number of days may prove the authors point. As the manuscript stands now, it doesn't. Reply: Thanks for nice suggestion. Keeping the reviewer's comment in mind, we tried to investigate the interrelationship between atmospheric aerosols and rainfall distribution for this study region. We already discussed that in the main region of interest (Region 1a and Lucknow), the dry day frequencies are progressively increasing in number during late July- mid September. For instance, we here concentrate on Lucknow which is an urbanized location in Region 1. Next, we show the average meteorological conditions of surface temperature, pressure, winds, moisture content and rainfall accumulation over 16-30 July during 1980-2015 in Figure 1. The long term mean and 2 sigma standard deviations are also shown in the figures to exclude the years having abnormal weather conditions. The diagram shown below suggests that for three years namely: 1980, 1987 and 2002, few met parameters have shown values beyond the general range, hence they are obliterated. In the next attempt, it was required to see the effect of low rainfall periods and AOD on impending DDF for the next few days during these years. Hence a set of years having comparatively lower rainfall accumulation during 16-31 July were identified. A total of 16 years were recorded which had rainfall values between the 50th and 25th percentile of the population. It may be noted that certain years experienced rainfall below the 1st quartile and hence they were neglected to preserve the data uniformity. Next the average AOD values were accumulated for those years and interestingly, two well separated clusters having a set of non-adjacent 8 years in each were observed: one with AOD below 0.3 and other above 0.4. Now to study the effect of these two AOD clusters on rainfall, their corresponding DDF values are observed for the next 15 days (1-15 August). This time shift was employed in order to investigate the net effect changing AOD on impending rainfall distributions. It was observed that DDF values are distinctly higher for high AOD compared to the lower AOD case. Hence this supports that higher AOD necessarily leads to more DDF in next few days. We have included this new analysis along with discussion in the revised manuscript.

2. A second issue I have is the definition of DDF, it described as a frequency. The way it is computed seems like it is simply a daily count of number of days with less than 1mm/day rainfall. When these types of duration statistic is used in hydrology or climate statistics the frequency is given a period 3 day or 5 day (example a heat wave is a 3 day event with greater than 95F maximum temperature in the USA). One day of less than 1mm rainfall does not lead to drought, there has to be a sequence of such days to create this event and this statistic should be modified to prescribe a consecutive number of days over which this is calculated. Reply: First of all we wish to inform that it is not our intention to indicate that single day instances of rainfall less than 1 mm may lead to a potential drought situation. Instead, we investigate a change in daily rainfall distribution over the mid-monsoon period by studying the total number of dry days over a 15 and 30 day span. Secondly, the month of August experiences very heavy rainfall ($\sim$300 mm) over region 1; hence the number of dry days is expected to be very low (<10) there. However, we have observed that the DDF has become very high in recent years (>20). As a result, it is now possible to create a near-drought situation without the presence of any extended dry phases (3-5 days).This argument is further supported by the presence of a prominent relationship between DDF and drought intensity over the same region. .Nevertheless, to verify the feasibility of the reviewer's comment, we have calculated the length of all continuous dry spells in the month of August which experienced rainfall less than 1 mm. Consequently, the frequency distribution analysis of these continuous dry spell lengths in Figure 2 depicted a very negligible number of cases having length greater than 2 days (as shown in the figure). Now since this data

volume is found to be extremely less for performing further statistical analysis we have continued with the same definition of DDF as used previously in this study.

3. Third issue is that the DDF and DI as described here are essentially precipitation derived and not independent. It just happens that DDF is high frequency description of DI and one would expect them to be correlated when the precipitation is in the same direction as DDF(low). I don't see the value of correlating DDF to DI in this context. Again, I may be missing something. Reply: We wish to clarify that DDF and DI are not controlled by precipitation in similar manner due to a number of reasons. First, DI is dependent on the monthly accumulated difference between precipitations and PET while DDF depends upon the behaviour of daily rainfall accumulation. As the distribution of daily rainfall is not generally symmetric, hence there cannot be any agreement between the day-wise and monthly aggregate data. The second reason in support of the DDF, DI independence is the presence of a third factor called PET which it depends upon a set of fixed (geographical location, season, vegetation and soil type) as well as variable components (temperature (max, min and daily mean), moisture content, wind speed, surface pressure and net radiation flux (which again depends on many other variable components)) but it does not depend on rainfall. As a result of these arguments the correlation analysis between DDF and DI are found significant only in few months and regions and not in all cases as doubted by the reviewer. We have included this analysis along with discussion in the revised manuscript.

4. Fourth big issue is the cloud analysis. It seems like the cloud analysis is used to suggest that there is a decrease in drop size an increase cloud lifetime (more cloudiness) and a decrease in rainfall (drizzle suppression) all lending credence to aerosol second effect. I think this is an interesting insight coming from the data. However, I couldn't figure out where all this data is coming from (MERRA2?). This needs more supporting data than presented here, I am not even sure what to make of figure 7, so the cloud droplet radius (I am assuming that is what this is? It cloud particle radius for low level clouds?) has decreased by >11% over Lucknow over the past 10 years in

MERRA data. Can you also discuss what uncertainties are there is MERRA data estimates of cloud droplet size? This requires a separate paper and much more detailed analysis and support than presented here. Reply: We would like to clarify that cloud lifetime information was derived from cloud cover data as given by the ERA-Interim Reanalysis database while the Cloud Particle Radius was utilized from NASA. Further, we would like to add that the long term trends of cloud particle radius are not found to be statistical significant which actually goes with the question raised by the reviewer (regarding CPR uncertainty). On the other hand, we have shown the evidence of increasing of dry day frequency even in the presence of increased low cloud cover; thus indicating towards the development of second radiative effect of aerosols and this argument negates the necessity of showing CER trends. In this case, cloud radius analysis portion has been removed from the revised version of the manuscript.

5. Fifth, why sunspots? Is there a physical reason why sunspot activity effects precipitation over India? Reply: There have been several scientific mentions underlying the effect of solar intensity on tropical rain and monsoon strengths both over India and abroad in the last few decades. A few references are added according to the reviewer's query namely: Neff, U., Burns, S.J., Mangini, A., Mudelsee, M, Fleitmann, D., and Matter, A., Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago, Nature 411 (2001) 290 – 293. Agnihotri, R., Dutta, K., Bhushan, R. and Somayajulu, B. L. K., Evidence for solar forcing on the Indian monsoon during the last millennium, Earth and Planetary Science Letters 198 (2002) 521 – 527. We have included these references along with discussion in the revised manuscript.

6. Last but not least dust transport analysis seems irrelevant and adds no information to paper. Reply: Thanks for suggestion. After going through the comment, we realize that the transport analysis is only speaking about additional possibilities which have not been supported in any solid form in the paper. Hence for simplicity, the transport analysis part has also been removed in the revised manuscript.

7. Also, let us not forget population density thrown into the mix, how does that ef-

fect precipitation and dry days and through which physical mechanism? Reply: We acknowledge that the correlation between population growth and urbanization (which leads to more BC emission and hence higher DDF) varies depending on several other factors. It may be noted that over India, population rise and over-crowding of cities is a big issue and owing to the dearth of suitable pollution mitigation strategies, the impact of population density is expected to be more dominant over BC emission compared to the other contributing factors such as industrialization and vehicular emissions. To prove this hypothesis, the population density and BC AOT extinction datasets are taken over Region 1, 1a, Lucknow and 3 separately and the variation is shown in Figure 3 shown below. It may be noted that here, the BC AOT values have been averaged during the month of August over a moving window of 5 years to be synchronous with the population density measurements. The figure suggests that population density and anthropogenic aerosols show similar long term variations with the highest values being in Lucknow and lowest in Region3 in both cases. Hence this explains the choice of using population as a proxy of urbanization intensity in this study. We have included the references along with discussion in the revised manuscript. We thank the reviewer once again the reviewer for providing constructive comments/suggestions which made us to improve the manuscript content further.

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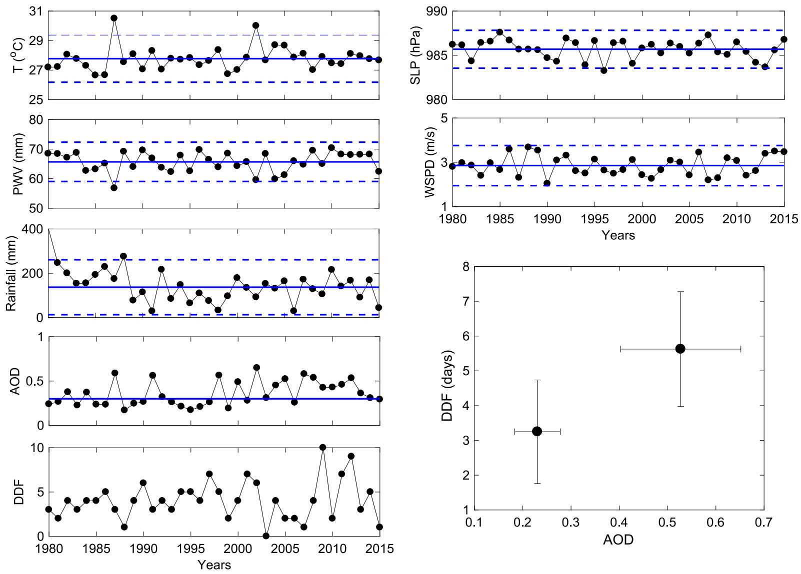

Fig 1: Effect of various meteorological parameters such as surface temperature, pressure, PWV, winds and rainfall along with average AOD during 16-31 July with DDF during 1-15 August.

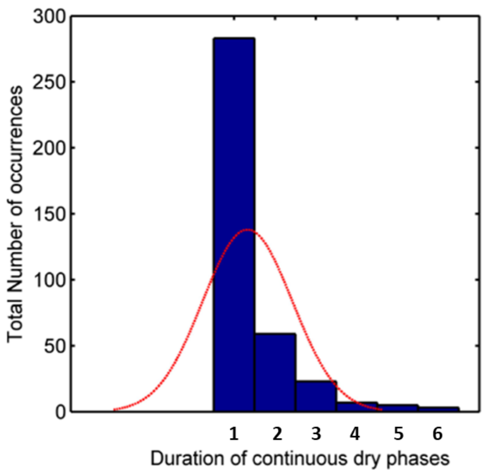

Fig 2: Distribution of extended dry phases

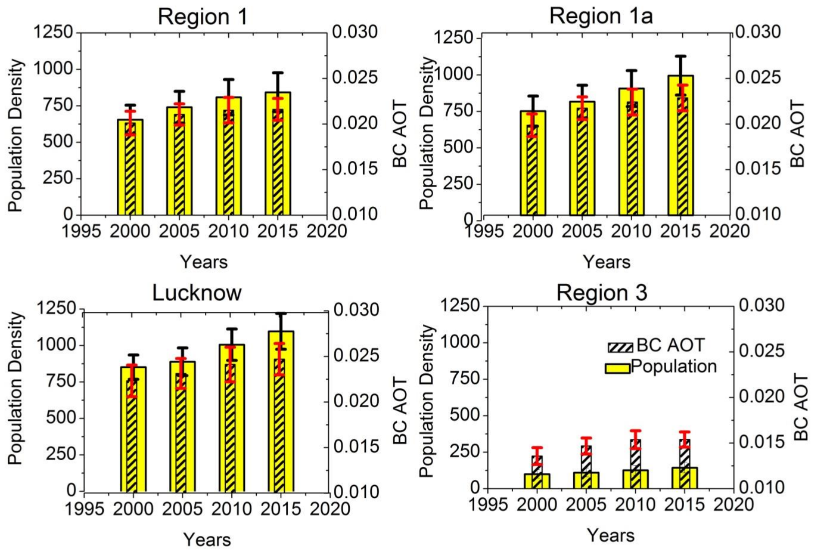

Fig 3: Region-wise population densities and BC AOT values (during August) for Region 1, 1a, Lucknow and Region 3 during 2000-2015, vertical bars represent the corresponding 1 sigma standard deviations values