

## **Replies to Referee #1 Comments/suggestions**

First of all we wish to thank the reviewer for his comments/suggestions which significantly improved the content of the manuscript. The authors have addressed all the comments raised by the reviewer and incorporated in the revised manuscript.

### **Major comments -**

**1.** Data - monthly averaged data of CER have several issues as has been studied by several researchers.

**Reply:** We admit that the monthly averaged variation of CER does not provide any statistically significant trends. This may be attributed to certain factors namely: insufficient time frame (<20 years) for studying the long term variation as well as other reliability issues with the data. On the other hand, we have shown the evidence of increasing number of dry days even in the presence of increased low cloud cover. Hence this phenomenon indicates the development of second radiative effect of aerosols without the necessity of showing CER trends. However, to improve the contention of this paper, we have removed the CER portion in the manuscript to avoid further ambiguity.

**2.** MERRA-2 simulations of aerosol properties over India have not been validated, and they have several issues. These simulations cannot be taken to represent the aerosol characteristics, which is a major input on which the paper relies upon. Also, as mentioned above while the current aerosol simulations are not validated, how these simulations can be taken to represent the past and future?

**Reply:** First, we wish to inform that the BC AOT dataset from MERRA 2 is validated against in-situ surface BC concentration measurements over Kolkata, a metropolitan city in Figure S1. Second, there also have been many recent attempts such as Pandey et al. (2017), Randles et al. (2017) and Buchard et al. (2017) which supported the validity of using MERRA datasets for similar climate studies both globally as well as over the Indian region. Finally, we have always used frequency distribution analysis in this paper to show the qualitative relation between aerosols and rainfall. Consequently, we have not focussed on the future trends of aerosols; rather we have exploited their interrelationship with cloud properties to arrive at a possible future trend of rain events.

**We have included following references along with discussion in the revised manuscript to support our observations.**

Pandey, S.K., Vinoj, V., Landu, K. and Suresh Babu, S., Declining pre-monsoon dust loading over South Asia: Signature of a changing regional climate Scientific Reports, 7: 16062, 2017, DOI:10.1038/s41598-017-16338-w.

Randles, C.A., Da Silva, A.M., Buchard, V., Colarco, P.R., Darmenov, A., Govindaraju, R., Smirnov, A., Holben, B., Ferrare, R., Hair, J. and Shinozuka, Y., 2017. The MERRA-2 aerosol reanalysis, 1980 onward. Part I: System description and data assimilation evaluation. Journal of climate, 30(17), 6823-6850, 2017, DOI:10.1175/JCLI-D-16-0609.1

Buchard, V., Randles, C.A., Da Silva, A.M., Darmenov, A., Colarco, P.R., Govindaraju, R., Ferrare, R., Hair, J., Beyersdorf, A.J., Ziemba, L.D. and Yu, H., 2017. The MERRA-2 aerosol reanalysis, 1980 onward. Part II: Evaluation and case studies. Journal of Climate, 30(17), 6851-6872, 2017, DOI:10.1175/JCLI-D-16-0613.1

**3.** Monsoon breaks in Indian monsoon is an important phenomena that contributes to aerosol increase or decrease and contributes to dry days.

**Reply:** Monsoon break phase occurrences may additionally contribute to the increase of dust type aerosols to some extent. However, this investigation is beyond the contention of the present analysis as here we indicate the dominance of anthropogenic aerosols over other natural factors such as ENSO and solar effect in changing the DDF over Indian region.

4. The changes in CER are almost NIL and statistically insignificant, be it in region 3 or region 1. Also, a few changes are quite abrupt.

Reply: We have already addressed this issue by keeping away the CER portion in the revised manuscript.

5. Datasets used have different resolution; this is another major issue, because the components exhibit large spatial variations within even 10 km.

Reply: It may be noted that we have focussed on three broad study areas each of whom had a minimum aerial coverage of 3x5 Degrees (~300 – 500 Km on both dimensions) as we want to study the redistribution of monsoon rainfall which is not a local phenomenon. Hence to investigate this qualitative relationship we have used several controlling factors from ERA and MERRA with a resolution of 0.5-0.75 degrees (~50-80 km). It may be noted that to understand the variability in this meso to synoptic scale aberration of rainfall diversity, a spatial averaging of various factors are computed. Hence, in no possible case, these relationships will change drastically due to mismatched grid resolutions of by 10-20 km.

6. Figure 4 - the number of dry days do not show any significant difference between the first and last 60 years except for region 1a.

Reply: We accept that from Figure 4, the number of dry days does not show any significant difference between the first and last 60 years except for region 1a which has led the full focus of the present study to go towards region 1a. Since region 1b also falls in almost the same zone of upper Indo-Gangetic Plane, hence some changes were also expected there; however such variations are not reflected in Fig 4a. But interestingly, further investigations also showed that the 15 day trend values are notably higher in Region 1a compared to 1b. This is again proved, in later sections where it has been indicated that anthropogenic BC has stronger dominance over DDF in region 1a than in overall region 1. Hence, we have to accept the fact that due to combined effect of all natural and anthropogenic factors, the distribution of dry days did not show that much prominent shift in last 60 years over region 1b as it happened over 1a.

We once again thank the reviewer for providing potential suggestions throughout the paper. This review experience was indispensable in pushing us forward to improve our work.

### **Replies to Referee #2 Comments/suggestions**

The manuscript describes possible correlations between absorbing aerosols and drought over parts of India and Lucknow in particular to increase in aerosol concentrations over the past sixty years and more appropriately for the past 30 years when satellite datasets of aerosol loadings are available. There is a lot of hard work and analysis that went into the study and appreciate the effort put in by the authors. Unfortunately, they are challenged by the lack of specific data sets that will help tease out any such effect and the possibility that this may not be an easy trend to distinguish with the current available data. In the end this manuscript goes in so many directions that it is hard to follow and some of the relationships discussed are thinly supported and probably contradictory.

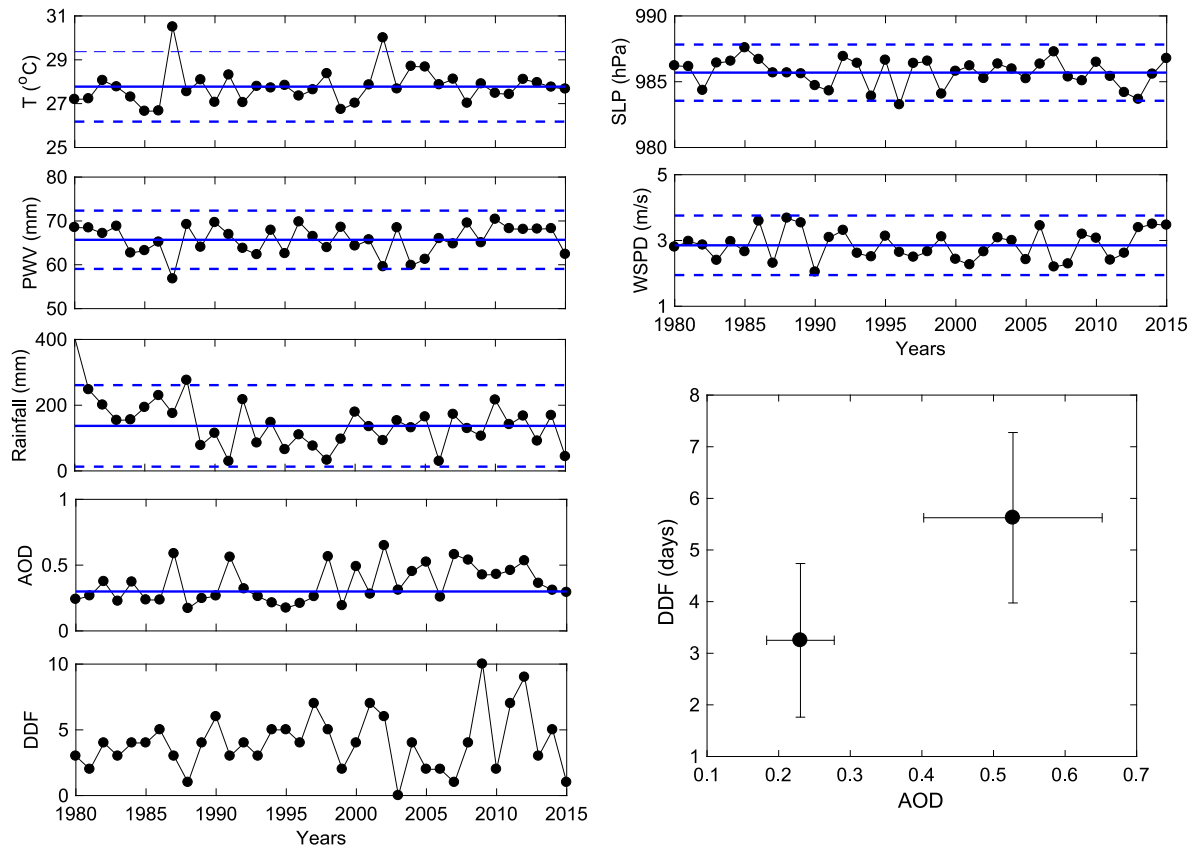
First of all we wish to thank the reviewer for appreciating actual content of the work and providing constructive comments/suggestions which significantly improved the content of the manuscript. We have addressed all the comments raised by the reviewer and incorporated in the revised manuscript.

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.

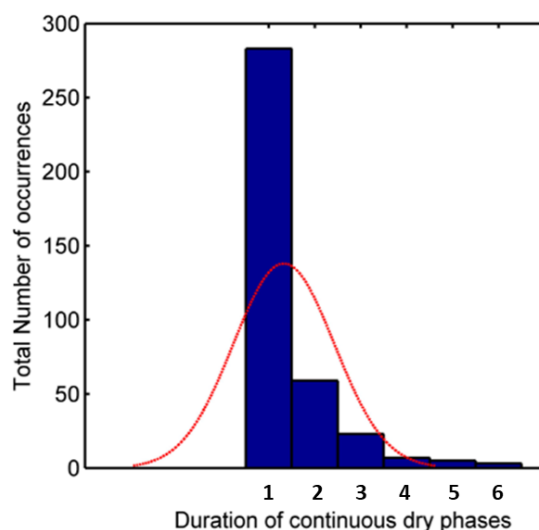
**Reply:** Thanks for nice suggestion. Keeping the reviewer's comment in mind, we tried to investigate the interrelationship between atmospheric aerosols and rainfall distribution for this study region. We already discussed that in the main region of interest (Region 1a and Lucknow), the dry day frequencies 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. 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 (~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 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.*

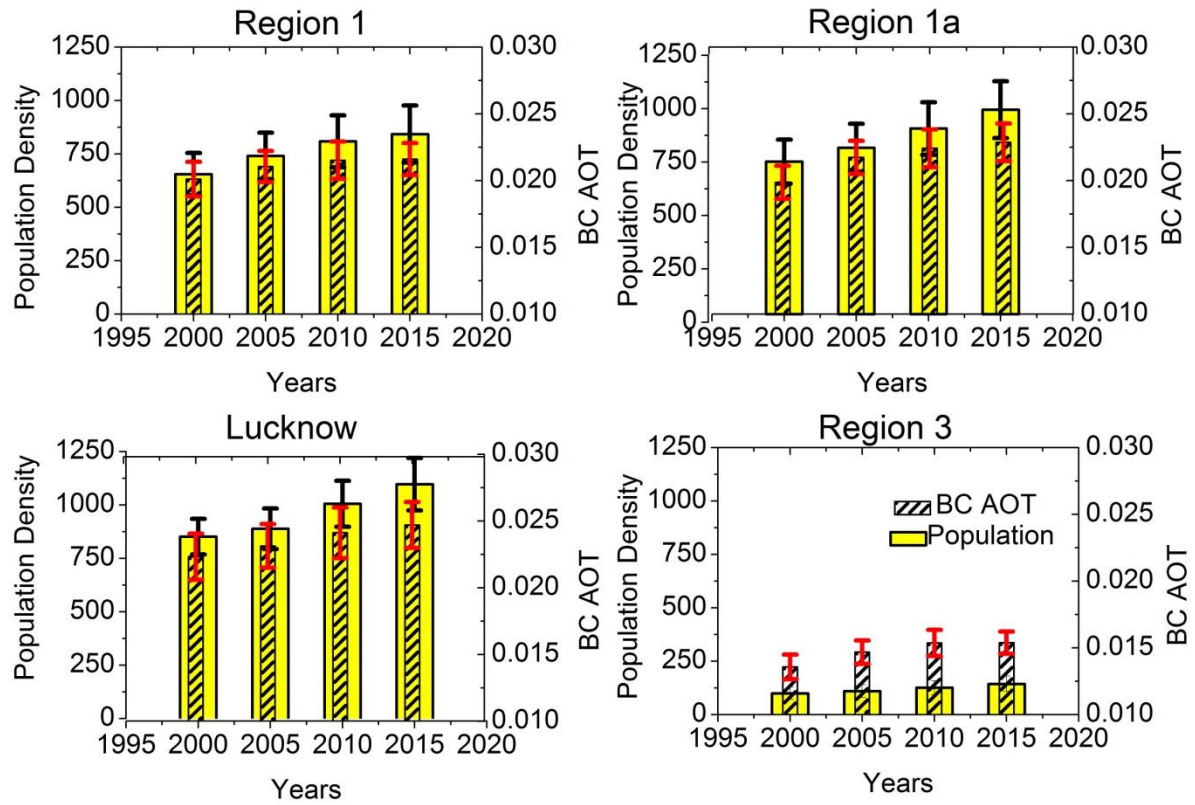
We have included these references along with discussion in the revised manuscript.

**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 effect 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 the figure 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.



# Growth in mid-monsoon dry phases over Indian region: Prevailing influence of anthropogenic aerosols

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## Abstract

A detailed investigation on the potentially drought prone regions over India has been presented in this study based on the balance between precipitation and potential evapotranspiration (PET) during the South West Asian mid-monsoon season. We methodically introduce a parameter named dry day frequency (DDF) which is found suitable to present the drought index (DI) in mid-monsoon season hence strongly associated with the possibility of drought occurrences. The present study investigates the probable aspects which influence the DDF over these regions revealing that the abundance of anthropogenic aerosols especially over urbanized location have prevailing role on the growth of DDF during last few decades. The prominent increasing trend in DDF over Lucknow (26.84° N, 80.94° E ), a densely populated urban location situated in the Indo-Gangetic plain, strongly reflects the dominant association of anthropogenic aerosols with the increasing dry phase occurrences. Increase in DDF (~90%) during the last 60 years is observed over this urban area compared to a broader region in its surroundings. In addition, periodic impacts of large scale phenomena like ENSO (El Niño–Southern Oscillation) or SSN (Sun spot number) become weaker when the study location is downscaled towards an urbanized region. Finally, when long term projections of DDF are drawn using the high urbanization scenario of RCP 8.5 a huge rise in dry days are seen during mid-July to mid-September (reaching up to 50 dry days by the year 2100 over Lucknow) which will be a crucial concern for policy makers in future.

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## 1. Introduction

Drought is a natural and recurrent phenomenon which occurs in all forms of climate. Although similar to aridity in many ways, droughts are mainly temporary in nature thus it should not be confused with the water scarcity due to excess of water demand over available supply. On the other hand these weather extremes are more reasonably linked with the distribution and frequency of rainfall over any region. Although, there are no generally accepted definitions for drought, the American Meteorological Society has categorized it into four types namely: meteorological or climatological, agricultural, hydrological and socioeconomic (Heim, 2002). A prolonged drought lasts several months or even years while the absence or reduction of precipitation creates meteorological droughts. On the other hand, short-term (few weeks) dryness in surface layer could results an agricultural drought (Heim, 2002). However, when prolonged meteorological droughts reduce the ground water level severely then hydrological droughts occur. Finally, all first three droughts with a deficit in water availability are named as socioeconomic drought. Among these four, the agricultural drought might be a serious issue when the farming or crop producing in humid or sub humid zones are concerned. The situation has however become more serious in the present due to rapid population growth across all continents, thereby also producing a hike in their global demand (Sivakumar, 2011).

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India is a country where agriculture and its allied activities act as major source of livelihood and hence it is expected to be deeply affected by drought occurrences especially if it occurs in the mid-monsoon period (as it experiences ~80% of the annual rainfall due to the southwest monsoon). Generally drought events originate from the deficiency in precipitation, and water shortage over a particular region and time. As rainfall observation data is available from past two centuries, mostly all the calculations of drought indices includes this variable either single headedly or in combination with other meteorological parameters (WMO, 1975). Some early drought index were simply represented the drought duration or intensity upon satisfying the drought defining criteria, e.g. Munger (1916) defined the drought index as the length of period without 24 hours precipitation with a minimum of 1.27 mm. Marcovitch (1930) used temperature data along with the precipitation while Benton (1942) used the length of drought in days, where the count was terminated upon occurrence of 2.54 mm of rainfall over a span of 48 hours. Likewise, many other drought index can be found in the past literature where precipitation has been used as a primary factor (Palmer, 1965; Lloyd-Hughes and Saunders, 2002). Recently, the multi-scaler drought index like Standardized Precipitation Index

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(McKee et al., 1993) is widely used by several researchers in analysing the drought characteristics. However, no single index has the ability to precisely represent the drought duration and intensity and its possible impacts (Wilhite and Glantz, 1985). Again, apart from the rainfall, there are also some other parameters that affects the drought severity, e.g. potential evapotranspiration (PET) and soil water holding capacity (Dai et al., 2004). The Palmer Drought Severity Index (Palmer, 1965) is an effective parameter which uses all these three parameters; however, it has some limitations when applying over climatic zones like India (Kumar et al., 2013). In addition, gathering all these parameters in gridded form and then quantifying the drought index will be very difficult over the Indian region. On the other hand, the standardized precipitation–evapotranspiration index (SPEI) uses only precipitation and temperature, and is considered to be better for analysing drought occurrence (Begueria et al., 2010).

India happens to be one of the most vulnerable drought-prone countries, as severe droughts occur at least once in a three year time span since the past few decades. In addition, there are numerous instances of severe drought conditions during Monsoon as reported in recent past (Pai et al., 2011). Consequently, several studies have been carried out in the recent years in order to understand the drought occurrences during the Indian summer monsoon period (Gore and Sinha Ray, 2002). Bhalme and Mooley (1980) defined the Drought Area Index for drought intensity assessment using monthly rainfall distribution. Raman and Rao (1981) suggested a possible relation between summer droughts and prolonged brake phase of southwest monsoon over the Indian sub-continent. Parthasarathy et al. (1987) identified the extreme drought years by analysing the decade long anomalies in the Indian summer monsoon rainfall. Tyalagadi et al. (2015) analysed more than 100 years of rainfall and identified 21 drought years, half of which were associated with El Niño. Gadgil et al. (2003) explained the excess rainfall or drought in terms of Equatorial Indian Ocean Oscillation (EQUINOO) during 1972 – 2002, especially during monsoon season. Francis and Gadgil (2010) also suggested the role of El Niño Southern Oscillation (ENSO) and EQUINOO behind the 48% deficit of June rainfall over India., Apart from these oscillations like ENSO or IOD (Indian Ocean Dipole) there are also lots of other parameters which may have prominent influences on drought occurrence, e.g. Himalayan ice cover, Eurasian snow cover, the passage of intra-seasonal waves, effects of accumulated pollution etc., e.g. Krishnamurti et al. (2010) reported the intrusion of desert air mass to be responsible towards the drought occurrences over the central Indian region.

109 In general, most of the previous studies on monsoon droughts are discussed on the basis of  
 110 rainfall accumulation, and there are very few, which quantify its relation with the direct or  
 111 indirect radiative effects of aerosols (Twomey, 1977) while considering both rainfall and PET.  
 112 Absorbing aerosols such as black carbon (BC) or dust have the capabilities of atmospheric  
 113 heating by absorbing solar radiation, while non-absorbing aerosols (e.g. sulphates) scatter the  
 114 solar radiation have less effect over the same (Lau and Kim, 2006). Additionally, they have the  
 115 capability of modulating the cloud characteristics by altering cloud radiative properties  
 116 (Wencai et al., 2015). Previous studies have shown the presence of the aerosols (mainly dust  
 117 and BC), and their ability to impact the rainfall (depending upon their sizes) during Indian  
 118 summer monsoon as described by elevated heat pump hypothesis (Solmon et al., 2015). During  
 119 late pre-monsoon or early monsoon season, the aerosol loading over India is nearly three times  
 120 higher than the average due to the dust abundance, which is partly dependent upon the winds,  
 121 precipitation and surface temperature (Dey, 2004). However, the vice versa can also be true  
 122 (e.g. Moorthy et al., 2007). Very recently some new attempts were also undertaken to study the  
 123 long and short term implications of both natural and anthropogenic components in producing  
 124 ~~several atmospheric processes in the boundary layer which thereby produces~~ hindrance to  
 125 convective rainfall especially over urbanized coastal locations which may also lead to  
 126 subsequent drought occurrences (Chakraborty et al., 2017 and Talukdar et al., 2017). Keeping  
 127 all these assertions in mind, the present study has put an effort in establishing a possible  
 128 relationship between aerosol loading and summer monsoon rainfall, consequently, over  
 129 drought occurrences during this period in past few decades.

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130 Hence a detailed investigation is presented ~~on~~ the evolution of dry phase leading to  
 131 drought conditions during mid-monsoon over three Indian regions based on the balance  
 132 between precipitation and PET during the monsoon season. Next, a new parameter called dry  
 133 day frequency is used to understand the trends of drought potential over the mentioned Indian  
 134 regions. This is followed by a three pronged investigation to identify the most dominant factor  
 135 behind these trends after which future projections of DDF is observed and explained for these  
 136 locations during the mid-monsoon period.

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## 137 2. Dataset and methodology

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138 Most of the research attempts in recent past have employed SPEI as an indicator of drought  
 139 occurrence over the Indian region (Beguería et al., 2010). SPEI which is precipitation minus  
 140 PET mainly represents the climatic monthly water budget. Interestingly, this parameter is  
 141 found to be the most reliable identifier of drought occurrences as it can be expressed in terms

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of standardized Gaussian variance with zero mean and one standard deviation. Another advantage of using SPEI over any other multi-scalar drought indicators (e.g. SPI) is that it not only includes the effect of the evaporative demand in its calculation, but also can be calculated for different time scales (Beguería et al., 2010), unlike the PDSI which rely on a water balance of a particular system. In this study the SPEI is calculated using monthly precipitation and PET from the CRU TS3 dataset (<http://badc.erc.ac.uk/data/cru/>), where the PET is calculated considering the monthly mean temperature and the geographical location of the concerned region as per the method suggested by Thornthwaite (1948). Hence, it provides long-term information about the drought conditions over any location with a high spatial resolution of  $0.5^\circ \times 0.5^\circ$  on monthly basis. However, the available precipitation ( $P$ ) data is provided in the form of monthly accumulated value, whereas, the  $PET$  represents the monthly mean. Therefore, the difference ( $D$ ) or SPEI is calculated for each month as follows:

$$D = P - (PET \times \text{number of days in a month}) \quad (1)$$

It may be noted that for this analysis, the value of  $D$  is normalized with respect to the climatic mean and 1 sigma standard deviation to obtain comparable values for all regions of the country. These normalized values of  $D$  are hereafter referred to as DI. This study considered the length of the dry phase as an indicator of drought occurrence and severity, which is calculated from  $0.25^\circ \times 0.25^\circ$  daily gridded rainfall datasets as in the National Data Center, India Meteorological Department (IMD) (Guhathakurta and Rajeevan 2008) during the period of 1901-2015. Owing to its better temporal and spatial resolution, the IMD rainfall dataset has been used in several research attempts in the recent past for analysing the morphology of drought occurrences over India (e.g. Gore and Sinha Ray, 2002). In previous literatures there have been various mentions for identifying certain days as dry, based on some predefined daily rainfall accumulation thresholds. Singh et al. (2010) has mentioned that days having rainfall less than 5mm/day can be considered as dry. But this criterion is only valid for ecological droughts and hence it will not be a suitable threshold for many Indian regions experiencing very low rainfall. Recently, another classification scheme has also been attempted by Sushama et al., (2014) where rainfall accumulation lower than 1 or 3 mm/day is considered as a dry day. So, to further check which threshold provides best results, the correlation coefficient of DI verses DDF are plotted in **Table S2**. The correlation coefficients follow some spatial diversity but interestingly, they do not exhibit much change with respect to the rainfall threshold. Hence, to understand its implication, the number of days having rainfall accumulation above 1 and 3 mm (during JJAS) is expressed in the form of ratio in **Figure S1**. The ratio indicates that for

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all the months and regions, days having rainfall accumulation above 1 mm/day are more in number compared to the days having rainfall accumulation above 3 mm/day. This makes it reasonable to put 1 mm/day as threshold rainfall accumulation for DDF consideration as it will filter out only the intensely dry conditions which will make the drought identification more reliable. Hence, this study is progressed using 1mm/day as the dry day identification threshold. Further, the DI values obtained are normalized with respect to mean and standard deviation for simplicity. Data sets of number of dry days and drought index are passed into three dependence tests: first, using three equal sized grouped box whisker distributions; second by principle component analysis of variances of two main contributors. The third and final approach involves a multi-linear regression in order to see the net contribution of the various components on dry or wet condition,

Datasets of sunspot numbers are considered here as a reliable representative of solar activity, which in turn may modulate the earth's hydrological balance. There have been several scientific mentions in the past underlying the effect of solar intensity on tropical rain and monsoon strengths both over India and abroad (Agnihotri et al., 2001). Monthly averaged sun spot numbers are obtained from the Solar Influences Data analysis Center (SIDC) in the Royal Observatory of Belgium from the year 1749 till present (Cliver et al., 2013). This study also considered ENSO index, obtained from the Oceanic Niño Index (ONI), which is calculated using 3 month running mean of Extended Reconstructed Sea Surface Temperature, Version 5 (ERSST.v5) SST anomalies in Niño 3.4 region (5°N – 5°S, 120° – 170°W) with a 30-year base period (Huang et al., 2017). Conditions resulting in values beyond the threshold of  $\pm 0.5^{\circ}\text{C}$  are considered to be either an El Niño or La Niña. These datasets are obtained from 1950 to present. Present study also uses  $0.5^{\circ} \times 0.625^{\circ}$  gridded datasets of AOT at 550 nm, Black Carbon (BC), dust (pm2.5 only), Organic Carbon (OC), sea salt and sulphate obtained from MERRA-2 (Modern-Era Retrospective analysis for Research and Applications version 2) provided by NASA. MERRA-2 provides global reanalysis product since 1980 to present (<https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/>). The reliability of the aerosol products from MERRA-2, have already been authenticated in studies like Buchard et al. (2017) and in recent years, these datasets have also been utilized for similar climatic investigations over the Indian region (Pandey et al., 2017). Moreover, in this study an additional validation of the aerosol components from MERRA2 have been validated against in-situ datasets from Aethelometer measurements over Kolkata. However, to preserve the parity with monthly averaged Black Carbon Extinction as in MERRA2, the observation datasets are also monthly

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227 averaged for a net period of 36 months during 2013, 2015 and 2017. Consequently, a well  
228 matching is observed between the two sources as shown in **Figure S2**. To double check, the  
229 datasets of BC AOT and concentrations are both normalized and then their probability  
230 distributions are plotted. The distributions fitted with Gaussian curves shows almost similar  
231 behaviour in both the cases, which shows the suitability of this datasets in subsequent sections.

232 In addition, the ERA Interim reanalysis cloud cover data is utilized  
233 (<http://www.ecmwf.int/>) at  $0.75^{\circ} \times 0.75^{\circ}$  default resolution (Beriford et al., 2011). As DDF is  
234 being observed mostly over the month of August, hence monthly averaged data of total, high,  
235 medium and low cloud covers are extracted over the required regions and are plotted for the  
236 same time period (as in for aerosol parameters) during 1980-2015. The idea behind using this  
237 dataset was to identify the association between increased cloudiness and reduced rain  
238 accumulation during the mid-monsoon months. Additionally, in order to show its relation with  
239 cloud microphysics, dataset of cloud particle radius are utilized, and is obtained from NASA  
240 Earth Observation (NEO) portal  
241 ([https://neo.sci.gsfc.nasa.gov/view.php?datasetId=MODAL2\\_M\\_CLD\\_RD](https://neo.sci.gsfc.nasa.gov/view.php?datasetId=MODAL2_M_CLD_RD)). The dataset  
242 provided by Terra/ Aqua Satellite of MODIS on daily, weekly or monthly basis with a good  
243 spatial resolution of  $1^{\circ} \times 1^{\circ}$ , and is available only over a relatively shorter span of 2000 – 2018.  
244 The monthly averaged values of CER have been utilized during the month of July and August  
245 for the present study.

246 This study uses gridded population density (as a proxy of urbanization), obtained from  
247 Gridded Population of the World (GPWv4), and provided by the CIESIN-SEDAC database  
248 from Columbia University for the year 2000, 2005, 2010 and 2015. This data set is constructed  
249 by extrapolating the population data from national or sub-national administrative units all  
250 around the world. The resolution of the product is 30 arc-seconds, or approximately 1 km at the  
251 equator, further details about the data can be obtained from  
252 <http://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-count-rev10>.

253

### 254 3. Results and Discussion

#### 255 3.1. Identification of potentially drought prone regions over India

256 Considerable conditions for drought occurrences are identified on the basis of the  
257 balance between monthly PET and rainfall accumulation during June-September as depicted in  
258 **Figure 1**. It is seen that due to arid climates, north western India experiences higher values of  
259 PET particularly up to July which may happen due to late arrival of monsoons at that location

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and hence this region may be considered for the analysis. On the other hand the south eastern peninsula of India experiences higher PET values, hence it has been considered for further analysis. However, the rest of the country experiences much lesser values of PET. In contrast, precipitation values are consistently lesser both in the north western India as well as the south eastern peninsula, so both these regions may face more probability to experience negative DI, hence are selected for analysis. Another highlight from the figure is that, the mid-section of IGP depicts a sharp gradient of precipitation. This diversity becomes more prominent during the months of July-August as during this period, the entire IGP experiences very heavy rain accumulation (>300 mm on average) but the mid-IGP experiences much lesser rainfall ~200 mm. Consequently, this mid IGP region is also selected for analysis. Accordingly, the grid points with 0.5 degree resolution in these three regions are identified and accumulated to form three main study regions which are numbered 1, 2 and 3 corresponding to IGP, South Eastern peninsula and North West India, respectively as shown in **Figure S3**.

### **3.2. Importance of dry day frequency (DDF) in analysing the drought conditions**

After the identification of the drought prone regions, the main objective is to determine a suitable parameter which best represents the probability of droughts and which also can be related to other natural and anthropogenic factors in all regions. Hence an assumption is taken, that if the temporal distribution of rainfall is considered constant month wide, then a drought is only possible when both PET is high and precipitation is low. Now low precipitation and high PET mainly arises from multiple dry day occurrences in a month leading to droughts. So, for simplicity, during each of four months in three seasons, the difference between precipitation and PET is calculated over 115 years and the obtained data is normalized with respect to mean and 1 sigma std for simplicity, Next, the DDF time series is calculated from daily precipitation values as already described previously after which the correlation coefficients between drought index DI and this dry days frequency are calculated and shown in **Figure 2(a)**. The correlation analysis is done for two overlapping periods of 115 and 60 years namely: 1901-2015 and 1956-2015. The reason for this two part analysis is that during the second part, more technological advancement may lead to more reliable daily rainfall data, this is because during recent years the advent of more accurate rain gauges have led more reliability in deciding whether daily accumulation < 1mm and thus more reliable dry day frequencies are calculated. Another reason is that, second part witnessed more station and satellite data sources, so possibility of relationship is expected to be stronger in last 60 years. However, to bear better evidence to the



294 above stated hypothesis **Figure S4** shows scatter plots of DI and dry day frequencies for all  
295 regions and months.

296 The correlation analysis depicts a set of reasonable correlation coefficients in both  
297 regions 1 and 3 over 115 years. Importantly, better correlation values are observed typically  
298 over July in region 3 and August in region 1 while it is lesser in all other cases. It may be noted  
299 that regions situated in the western and north western parts of the country experiences delayed  
300 monsoon (supported from many independent sources) which have led to high correlation  
301 values during June and July over region 3. However, region 1 specially shows good correlation  
302 in August which is mid monsoon month which need more attention in coming sections. Here, it  
303 may be noted from Figure S4 that the agreement between DDF and DI is not strong in most of  
304 the cases other than 3-4 instances only. The reason is that firstly, DI is dependent on the  
305 monthly accumulated difference between precipitations and PET while DDF depends upon the  
306 erratic distribution of daily rainfall accumulation, hence the temporal scales of these two  
307 parameters are different from each other. The second reason is the presence of an independent  
308 factor called PET which depends upon a set of various components (location, season,  
309 vegetation and soil type, temperature, moisture content, wind speed, surface pressure and net  
310 radiation flux) but not on precipitation. Hence this explains the disagreement between the two  
311 parameters on a climatic scale.

312 Considering the last 60 years, correlation coefficients are improved in all regions and  
313 months as expected. Region 3 shows high correlations in July followed by August, while  
314 region 1 depicts comparatively much higher values during July and August. Thus the  
315 consideration of delayed monsoon onset may bring out more dry days in region 1 and 3. But on  
316 the other hand region 1 shows a high association between DI and dry days in August which  
317 needs to be studied. Region 2 is mainly influenced by precipitation occurring during the late  
318 monsoon months i.e. September and not by the mature monsoon stage which is evident from  
319 the higher correlation values at that time. Hence this region may not fit with the scope of the  
320 present study. Additionally, as more significant correlation values are obtained during 60 years  
321 span compared to 115 year scale, hence DDF trends will be studied over the last 60 years span  
322 in the coming sections.

### 323 3.3 Determining the time spans for the analysis of DDF trend over mentioned regions

#### 324 3.3.1. The importance of partitioning Region 1 for further analysis

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339 It can be seen from the preceding sections that the correlation between DI and dry days  
 340 for region 1 is noticeable but it is not highly prominent due to the presence of many outliers in  
 341 the scatter plots (Figure S4). This is because region 1 encompasses a total spatial coverage of  
 342  $5^{\circ}\times 8^{\circ}$  which has a lot of topographical and climatic diversities between them. A better example  
 343 of this has already been depicted from the precipitation diversity in Figure 1 where the  
 344 precipitation gradient was found to change abruptly even within region 1. So these spatial  
 345 diversities can interrupt the association between droughts and dry days. Hence to have more  
 346 realistic investigation, the region is now partitioned horizontally along  $81.25^{\circ}\text{E}$  which lies in  
 347 the middle of IGP. This gives rise to two different regions in the east and west of region 1  
 348 which will hereafter be referred as region 1a and 1b, respectively. Next the total distribution of  
 349 data of DDF for 1a, 1b, 2 and 3 are again investigated for two overlapping periods 1901-1960  
 350 and 1956-2015 for parity in **Figure 2(b)**. Region 2 and 3 show almost no change in the  
 351 distribution before or after 1955, hence it is not given importance. Region 1b shows slight  
 352 increase in mean and median but with no prominent change in the distribution while the same  
 353 thing is very prominent over region 1a. In this case, since last 60 years the mean and median  
 354 values changed by more than 4 days which is a very alarming fact. Most importantly, the upper  
 355 quartiles and whisker have ascended to a maximum value of 30 days, which indicates severe  
 356 drought occurrences. Thus it can be inferred that region 1a emerges as a prominent drought  
 357 prone region showing an abrupt rise in DDF especially over the month of August and hence it  
 358 will be investigated in detail in the coming sections.

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### 359 3.3.2. Analysing the climatic trends of DDF using a 15 day window

360 It has already been discussed that the drought intensity has significant correlation with  
 361 DDF on a monthly basis. However, it is also necessary to investigate whether the intra-monthly  
 362 distribution of rainfall may also have its own impact in modulating the dry day frequencies  
 363 especially during the mid-monsoon months which experience maximum precipitation  
 364 variability. Hence, the monsoon months (JJAS) are now divided into 8 equal slots of 15 days  
 365 each and the 60 year time series for all these regions are obtained. Next the robust-fit trend  
 366 analysis at 95% confidence level is done to find the mean yearly trends, which is multiplied by  
 367 60 years and then normalized, respect to mean to generate a percentage wise change in DDF.

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368 The percentage changes are shown in **Figure 2(c)** which depicts an overall increase of  
 369 DDF for all regions with a few exceptions. Region 2 shows very weak trends ( $< 5\%$ ) all  
 370 throughout monsoon, however, by the end of September, a reasonable trend of  $\sim 20\%$  is seen

374 which may link to dry phase developments in the later months. However, this period falls at  
375 the declining phase of monsoon which is beyond main scope of this study; hence neglected.

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376 Region 3 shows quite weak but alternating dry day trends over June followed by the  
377 month-long increase in July. This indicates a probable change in the timing of monsoon rainfall  
378 over region 3. However, this cannot be firmly confirmed as there is no particular time slot  
379 having a prominent trend value (all cases showing trends < 5%). Rainfall in June and early  
380 August lead to dry region conditions over July, but the cumulative monthly growth in July is  
381 ~10% which is not very strong enough and hence it will be discussed later in the study.

382 Finally, Region 1 shows very strong increasing trends in dry day frequencies with  
383 similar pattern over 1a and 1b. Both these sub-regions experience relative wetting at late June,  
384 followed by a prolonged dry phase up to September. But the main difference between the two  
385 sub-regions is that the trends are consistently high all throughout in 1a with as much as 60%  
386 and 20% increase over August which also continues onto September; while in region 1b the  
387 trend values are comparatively lesser (40% and 5%) during August. Thus, it can be inferred  
388 that though a clear increase in DDF is obtained all throughout region 1 during July-September,  
389 yet the trends are relatively stronger in region 1a especially during August which demand  
390 primary importance throughout the study.

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### 391 3.4 Investigating the probable influence of natural and anthropogenic components on 392 DDF for region 1a

393 In light of the previous sections, the probable influences behind the increasing trends in  
394 dry day occurrences are investigated over region 1. Number of natural or anthropogenic factors  
395 may be responsible for this phenomenon. While natural factors mainly include the effect of  
396 solar activity, ENSO variability or moisture tendencies, the anthropogenic constituents mainly  
397 include aerosols which again encompass a lot of organic and inorganic pollutants. Now, to  
398 quantify the effect of aerosols, the aerosol extinction coefficient values can be utilized from  
399 either satellite observations (MISR) or from dedicated model simulations (MERRA2). Since  
400 observational datasets from MISR satellites are very sparse during monsoon season and also  
401 the total measurement period is only 16 years, hence MERRA 2 datasets are used for further  
402 analysis. Keeping the availability of AOD datasets in mind further analysis has to be  
403 concentrated on 36 years span between 1980 and 2015. Owing to the prominence of DDF  
404 trends during the month of August, further studies are concentrated on this period only. As  
405 already mentioned, natural factors like solar activity and ENSO oscillations (hereafter referred

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as SSN and ENSO) may have some impact on precipitation variability which is also supported from previous attempts taken, hence they are considered. Additionally, moisture content also directly controls precipitation and so their monthly means at 850 hpa (corresponding to maximum moisture content during monsoon) are also utilized from MERRA 2 reanalysis database. To understand the dependence of these factors on DDF, first, the monthly DDF values during August 1980-2015 are arranged in descending order and then the sorted dataset is divided into three equal groups as Short Dry Phase (SDP) corresponding to normal conditions (8-10 days with average of 9), then Medium Dry Phase (MDP) signifying near drought (10-14 days, with average of 12.5 days) and Long Drought Period (LDP) which represents a full drought conditions (14-18 days, average ~ 16) as depicted in **Table 1** and they are also hereafter mentioned as SDP, MDP and LDP. Next, for all these three groups, the distribution of total aerosol extinction (AOT), SSN, ENSO index and SHUM at 850 hpa are shown in the form of box plots in **Figure 3**. It is seen that as DDF increases, the distribution of total aerosols start increasing, as evident from the rise in median and upper whisker values. The variation of SSN is almost random in all cases hence neglected. Additionally, ENSO intensity changes fairly with droughts. The upper whiskers and median rises slightly, but its effect is doused due to a dominant overlapping between the groups which fails to indicate a clear relationship. Specific humidity shows a minor decrease in all groups, though the median and quartiles do not show any prominent change (from 15 to 13 g/kg). Hence the importance of this factor cannot be ascertained.

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As the dry phase length distribution fails to identify the dominant factor behind the rise of dry days in region 1a, hence all these four factors are passed through principal component analysis test (PCA) and the results are shown in **Figure S5(a)**. The analysis produced a set of three orthogonal components out of which pc1 and pc2 account for 50 and 25% of variances so we can neglect the contribution of the 3<sup>rd</sup> component. Next, the corresponding variance scores of these components are plotted in Figure S5 which shows that SSN and humidity have very less variance according to the pc1 axis hence considered as less important, but aerosols and ENSO have comparatively higher values so they are considered important for further analysis.

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Further, multi linear regression analysis is done to see the independent contribution of these four parameters to DDF. All datasets are normalized so as to get uniform variability to enable easy identification of the dominating factors. The MLR concludes that the coefficients for aerosol, SSN, ENSO and SHUM are 0.393, 0.008, 0.161 and -0.207 as shown in **Table 2**, SSN does not show any effect hence finally rejected. ENSO and specific humidity have

448 significant contributions but in opposite manner and also their distribution analysis showed  
449 significant overlapping; hence they should not be considered in order to remove ambiguity.  
450 Finally aerosols have a coefficient of 0.393 which is much higher than the others as also  
451 observed in the PCA test and distribution analysis. Hence one has to consider aerosols as more  
452 dominating factor compared to other natural components in modulating dry day occurrences.

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453 In view of the dominance of total aerosol AOT over DDF, now the analysis is  
454 concentrated on the datasets of various aerosols components over region 1a. Total columnar  
455 extinction values of 5 aerosol components namely: black carbon (BC), Dust PM2.5, organic  
456 carbon (OC), Sea Salt and Sulphates are obtained from MERRA 2. BC and OC mostly comes  
457 from anthropogenic sources and significantly contribute in warming up the atmosphere. It has  
458 been reported in earlier studies that the presence of BC aerosol in rain cloud may have “burn  
459 off” effect on the cloud due to heating [Ackerman et al, 2000]. On the other hand aerosols like  
460 PM2.5 which may have both natural and anthropogenic sources can also influence the cloud life  
461 time by increasing cloud droplet number (Sato et al, 2018). Thus, the cloud cover is modulated  
462 and precipitation process is affected. Now the change in concentration of these parameters  
463 during last 36 years over region 1a has been discussed in the next section.

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464 Though it has been discussed in the previous sections that aerosols have a dominating  
465 influence over dry day occurrences, however, it is yet to be specified which type of aerosols  
466 (natural or anthropogenic, organic or inorganic) are becoming major influencing factor for this  
467 phenomenon over region 1a. Hence time series datasets of these five components are again  
468 taken for 36 years and are grouped with respect to the corresponding dry day ranges as already  
469 explained in previous section. After that the corresponding distributions are plotted in box plots  
470 in **Figure 3**. The distribution analysis depicts that the sea salts show some overlapping which  
471 reduces the impact on DDF. Sulphates have quite high values all throughout but their medians  
472 or distribution does not exhibit any deterministic sequence (first decrease then increase); so  
473 they also cannot be used here. Dust AOT values are less but its median shows weak  
474 contribution towards drying, but the overlapping in distribution makes the overlap association  
475 very weak. But compared to the others BC and OC have shown a better association with DDF  
476 along with reasonably increasing tendencies in medians and quartiles. But this phenomenon  
477 also hints towards a dominant component of pollution coming from certain highly urbanized  
478 sectors of region 1a such as Lucknow, Allahabad (25.43° N, 81.84° E) and Varanasi (25.31° N,  
479 82.97° E). Again out of these two, BC has relatively better variation as it has the least

487 overlapping nature so it may be considered the most dominant factor. But still to have better  
488 evidence, the PCA and regression analysis are attempted.

489 The PCA analysis results are depicted in **Figure S5(b)** which shows the contribution of  
490 pc1 alone is 60% followed by pc2 of 25% to be more prominent hence there may not be a need  
491 to study pc3 here. From the scores it is found that sulphate and dust behave similarly in their  
492 variances with high pc1 and low pc 2 values, but OC and BC have both high pc1 and pc2  
493 components, so they may be found responsible for the variability in dry day changes. However,  
494 sea salt also may have some influence but it is not much clearly understood from the figure.

495 To clarify any remaining misconceptions, the MLR coefficients are computed which  
496 gives the values as 0.542, 0.129, 0.263, 0.326 and 0.124 (shown in **Table 3**). It is expectedly  
497 obtained that the dust and sulphate have very less contributions so should be neglected. BC,  
498 OC and sea salt have higher values, of which OC and sea salt have comparable magnitudes,  
499 but, sea salt has much less AOT values with lesser pc1 variance score and also reasonable  
500 distribution overlapping, so the effect of OC may be considered better. BC has very high MLR  
501 coefficient with high pc1 score and also a clear variability of distributions. Hence, it may be  
502 concluded that owing to urbanization, the effect of BC followed by OC has much stronger  
503 association with drought intensity and dry day occurrence.

### 504 **3.5. Investigating the probable influence of natural and anthropogenic components on** 505 **DDF over Lucknow**

506 From the previous section, it has surfaced that anthropogenic emissions (of BC and OC)  
507 as a result of urbanization may have a dominant association with the increase in DDF during  
508 August. To be definite about this, a re-investigation has been done over Lucknow (26.8°N,  
509 80.9°E) which is the state capital of the state Uttar Pradesh, and is a more urbanized point  
510 location belongs to region 1a. However the relationship of DDF with SSN, ENSO and SHUM  
511 is not shown as Lucknow already falls in region 1a whose synoptic effect would not change  
512 within the region. Here, the effect of individual aerosol components is also depicted in the  
513 distribution analysis as shown in Figure 4. Now, in case of Lucknow the variability in dry day  
514 values are much stronger as shown by SDP (4-12 dry days average 9.5) MDP (13-17 days with  
515 average 15) and LDP (18-30 days with average at 22 days) mentioned in Table 1. The  
516 distribution analysis on total aerosol AOT shows much larger values over Lucknow than in  
517 region 1a and also the variability of the median values with the quartiles and whiskers are also  
518 far more deterministic here which may have influenced the entire distribution towards more

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dry conditions. Next, coming to sea salts and sulphates, they have much less values than in region 1a due to its significant distance from the seas. Sulphates show no meaningful variation, hence are rejected straightaway, sea salt values are less but the variation of median and upper whisker shows a prominent increase which may be important. However, the lower quartile is very small and overlapping in all three cases which serve as a setback to its variability. However, Dust does not such variations due a considerable overlapping in it. On the other hand, BC and OC do not have much overlapping and they also have clear increase in medians and both quartiles thus supporting the more sensitivity of this region towards dry days.

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Figure S6 shows the distribution analysis of these components with PCA tests. The analysis reveals the presence of three strong principal components where pc1 is 60% and pc2 of 30%; hence pc3 is not considered further. Next, when the variance scores for these parameters are plotted, then all factors show almost similar values of pc1 score, so pc2 becomes important. While judging the pc2 scores, we see that BC followed by OC has the best variability in this set hence they may be considered for the dry day variation. To confirm this, multi linear regression is done on the components and the results yield values of 0.864, 0.218, 0.556, 0.0106 and 0.155 (Table 3). According to previous results, the contribution of BC and OC is much higher than the others, with BC shows a higher correlation in all cases compared to OC, hence the dependence of dry days can be primarily associated with urbanization. Dust follows this parameters but its dependence is comparatively much smaller than both BC and OC which further supports these findings.

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In the previous sub-section, the effect of aerosols with BC in particular is found to be strongly associated with low rainfall occurrence. However, the effect of all meteorological parameters was not isolated in the previous analysis. Also a time series analysis showing the impact of present AOD on impending rainfall accumulation was not demonstrated earlier. Hence, an attempt has been progressed over Lucknow as it is an urbanized location in Region 1a. Now, to isolate the effect of various meteorological parameters such as temperature, pressure, winds, moisture content and rainfall accumulation, these datasets have been collected and then plotted in Figure S7 for 16-30 July of 1980-2015. The long term mean and 2 sigma standard deviations are also shown to exclude years having abnormal weather conditions. The screening process revealed that three years: 1980, 1987 and 2002, have exhibited meteorological variations beyond the general range, hence they are obliterated.

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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 on these years. Hence a set of years having

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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. 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.

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### 3.6. Comparative analysis on the DDF trend of last 60 years and cloud properties among Region 1, 1a and Lucknow

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The preceding sections have given an idea of how urbanization is influencing the evolution of dry day occurrences. But to understand quantitatively its climatic impact now the averaged DDF of last 60 years are plotted for regions 1, 1a, Lucknow. In order to examine the change in DDF patterns as one downscales from a broad synoptic scale (IGP) to a small localised urban location. **Figure 5** reveals that region 1 has a weak but discernible increase from 5 to 15 days in last 60 years. When robust-fit analysis was performed, it was inferred that the net change in dry day frequencies over region 1 is ~35% with respect to the 60 year average. However, the existence of some periodicities in the data was observed while no evident extremes were observed in the time frame. The value of the slope is found to be less (0.074) which leads to a poor r of 0.384. For region 1a the total variability is from 5 to 18 days; so the slope is expected to improve a bit (with a robust-fit net trend of ~44% with respect to the average) while the periodicity seems to be apparently disturbed due to presence of more data extremes. Finally, in case of Lucknow, huge change is observed from 4 to 25 days which indicates a complete shift in rain climatology with trend values as high as 61% with respect to 60 year average during August when normally, the maximum rainfall occurs over India. Huge number of outliers and extremes are seen some of which are close to 30 days (indicating no rain over August at all). The periodicity also seems to be disturbed due to outliers resulting in a very sharp slope of 0.139 per year. Thus, the severity in drought climatology is well explained with respect to urbanization as already hypothesized earlier. But it may be noted that the increasing trends and correlations are mainly caused by more occurrence of high dry days in

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597 present rather than a gradual rise in the mean values; additionally there are also some  
598 periodicities in the signal which results in the correlation being less than 0.5.

599 It is reported earlier that increase in anthropogenic aerosols may lead to more number  
600 of CCN causing reduction in cloud particle radius, which may result into less-occurrence of rain  
601 in spite of the increase in cloud cover. From previous section it is clear that dry day frequency  
602 exhibits a definite increase in magnitude over region 1a and Lucknow. Since anthropogenic  
603 components have shown highest possible dominance on dry day occurrences, so an attempt is  
604 made to identify how cloud parameters has changed with time over region 1, 1a and Lucknow  
605 having different urbanization growth and so on the anthropogenic components. Region 1 which  
606 is covering a broad area does not show prominent change in DDF and it is also observed that  
607 that the change in cloud cover over region 1 (~ 2%) and reduction in cloud particle size are  
608 very feeble. But interestingly as the region of concern is downscaled to Region 1a followed by  
609 a further downscaling to a region the urbanization impact becomes prominent and that is also  
610 reflected in the observed cloud parameters. A significant increase in cloud lifetime is observed  
611 which has resulted in a more definite growth of mid and low level clouds. The situation  
612 however, becomes more prominently worse in case of Lucknow where the cloud cover  
613 increased consistently (~18%) reflecting the impact of urbanisation. As a consequence, the dry  
614 day frequency ascends at a rapid rate over Lucknow in spite of increasing cloud cover which  
615 definitely needs to be studied in more detail in future approaches.

616 The long term trends of dry day occurrences have exhibited a prominent growth in dry  
617 days but the effect of this trends were found to be subdued to some extent by several  
618 periodicities over the last 60 years in both region 1 and 1a. To understand their role to a  
619 quantitative scale, periodicity analysis is done on last 60 years using autocorrelation functions  
620 and the results are depicted in **Figure S8**. The ACF values show highest value of 1 for a time  
621 lag 0, hence it is removed. Also there is no use in understanding periodicities greater than half  
622 of the period hence the maximum period is fixed to 30 years. 1 sigma bars are provided to  
623 understand which periodicity may be significant enough to impact the long term trends. Figure  
624 shows that the ACFs are reducing with time for all regions just as expected. However, only two  
625 points are found considerable, one is at the local maxima of 4 years corresponding to ENSO,  
626 where as expected the synoptic influences will be stronger in larger spatial scales. Another  
627 periodicity is expected to lie at ~1-2 years which represents the year-year varying component  
628 of urbanization. However, this effect is found to be much lesser in region 1 as it has a much  
629 higher spatial scale. But in case of region 1a the 1 year periodicity is expected to more

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prominent than in region 1 which is also supported with the comparatively lesser contribution of ENSO in region 1a as also shown. Again, because of the same reason, the year to year variability (shown by periodicity 1) should be most dominant in Lucknow followed by 1a and then 1. Same thing follows in the figure and interestingly, the effect of urbanization overshadows the other factors like ENSO in the periodicity analysis for Lucknow (due to presence of many outliers) as shown previously. The contribution of both outliers extremes with periodicities are seen almost comparable in region 1a. But in region 1 the effect of periodicities is more than the outliers as clearly seen with higher ACF in ENSO for region 1 compared to 1 year periodicity case. This clearly infers about the effect of urbanization which suppresses the effect of ENSO periodicity and thereby results in the drastic increase in DDF over Lucknow.

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### 3.7. Probable influence of natural and anthropogenic components on DDF for region 3

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In most of the preceding sections, the variability of DDF has been studied over Region 1 falling in the IGP. However, the north-western part of the country also comes under high drought severity zone as already discussed; hence this region is studied in detail now. Figure 2 has showed that the DDF trend is comparatively higher during the month of July; hence DDF during that month will be considered hereafter for further analysis over region 3. But it may be noted that the change is not so much prominent here as in region 1 (with a cumulative average of ~8% rise) and also the yearly fluctuations are too large which has subdued the trends resulting in a feeble rise of two days in the last 60 years (23-25 days) over this region shown in Figure 6. To start with the distribution analysis, three classes are made as SDP (14-20 dry days average 19) MDP (21-24 dry days average 22.6) and LDP (24.5-27.5 days with average 26 days) as depicted in Table 1. It may be noted that the values themselves have high magnitudes for all classes and the variability is also quite less (19-26 days) here compared to 9-22 in Lucknow; so the observed variation also should not be much prominent which is also evident from Figure 6. Further, as this region generally experiences arid climate, hence specific humidity can be an important factor here. Accordingly a decreasing trend is seen as supported by the median and lower bounds. But there is more overlapping among the classes and the total variance of humidity at 850 hpa is only between 12-10 which may not be strong enough to modulate drought intensities all by itself. SSN shows no definite variation hence not considered further. Aerosols and ENSO seem to have a weak increasing trend in their medians which again is diffused by more overlapping in these distributions. So this weaker variability is in

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683 good agreement with the feeble trend in dry days, but simultaneously makes it difficult to  
684 determine the potential driving factor behind the increasing DDF in region 3.

685 A better insight into the inter-dependence of all these components are investigated by  
686 the PCA test in **Figure S9 (a)**. The analysis reveals four PCA components out of which three  
687 PCs are considered to explain the complete range of variances in dry days. The scores signify  
688 no definite pattern with the total aerosol AOT assuming high pc1 and low pc2 pc3 while ENSO  
689 has high pc2 and pc3 with lesser pc1 and SHUM falls in completely different quadrant. Now  
690 since aerosols have higher pc1 component which is comparatively stronger than other pcs so it  
691 may be a deciding factor. To clarify this confusion, MLR coefficients are calculated which  
692 come around 0.107, 0.078, 0.056 and -0.267 also shown in Table 2. It is clear from the MLR  
693 outputs that specific humidity has a strong negative influence on dry days so it will have good  
694 effect on drought occurrences. But apart from this, the second dominant factor behind droughts  
695 is still found to be the aerosols. However, this fact needs to be supported with more detailed  
696 analysis as shown in the later sections.

697 In view of the previous sub-section, now the analysis is concentrated on the aerosols  
698 components over region 3. The distribution analysis of aerosol components are now shown in  
699 **Figure 6**, which depicts that as usual, sea salt aerosols and sulphates have no role in  
700 modulating the DDF. But it may be noted that here the magnitude of sea salts and sulphates are  
701 higher than in region 1 or 1a may be due to its transport from the nearby seas which has not  
702 been washed away by rain in its path owing to the arid climate. However, experience a very  
703 prominent overlapping between the components which reduces the overall trend. The variation  
704 of OC is not clear and hence is obliterated. BC as usual has a deterministic variance with some  
705 overlapping; but still the whiskers and median values indicate its impact on dry days. Another  
706 important aspect here is that, the range of values for these parameters are much lesser here due  
707 to lesser urbanization which still affects the DDF. But the contribution of dust aerosols  
708 emerges as the dominant component here as it not only shows higher values compared to all  
709 other regions but it also signifies a clear trend in the medians and distribution values. Thus it  
710 can be inferred that both dust and BC may contributed to this phenomena.

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711 To investigate which parameter has more dominance in dry day formation, PCA  
712 analysis is done on the individual components and the results are depicted in **Figure S9(b)**.  
713 Here four PCAs are obtained, but the first two PCAs contribute 80% of variability so the 2D  
714 variance is seen. Also the contribution of pc1 is comparable to pc2 so here both will be  
715 important. While analysing the scores it is observed that only dust and BC have both high pc1

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and pc2 so should be considered while most of the others have lower pc2 scores so they can be neglected. Further investigation is done on MLR analysis towards the trend contribution which also gives similar outputs as 0.464, 0.431, 0.120, 0.182, and 0.033 (Table 3). Again here both BC and dust emerge potentially significant for the region 3 to be considered in association, with the slant rise in dry days. Both of these two components may have local sources but owing to its location, there are possibilities of having added amount of dust aerosols being transported from adjoining deserts or from dust storms and fumigation of dust from the ground during intense dryness which are not found prominent over the region 1a (where BC and OC was high due to high urbanization). Further for more meticulous observation, cloud cover values have also been checked (Figure 7) which shows that all the types of cloud cover have remained almost unchanged over the years, unlike region 1a and Lucknow. This is again in good agreement with less prominent increase of anthropogenic emissions or in short less increase in urbanization over region 3 compared to region 1a or Lucknow. This is further discussed in coming sections. But few things are important to mention here: the trend of dry days in region 3 though it is weaker compared to region 1a may have serious impact in future as the region already experiences high number of dry days itself so a slight increasing trend is also alarming. Thus the effect of urbanization will be still an important parameter contributing towards the hike of BC and (some of) dust aerosols growth and in turn leading to more strong trends in DDF over this region.

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### 3.8. Impact of urbanization on DDF trends

From the previous section, a strong association has been observed between dry day frequency and anthropogenic emissions such as BC and OC which in turn is closely related with the urbanization growth. On the other hand, high population density is also generally associated with the growth of urbanization and hence it may be taken as a suitable proxy for the latter in this study. The population density values have been taken from the gridded 1° population densities during 2000 -2015 (from SEDAC website) while the BC AOT extinction datasets are utilized from MERRA-2. The BC AOT values have been averaged during the month of August over a moving window of 5 years for Region 1, 1a Lucknow and Region 3 to be synchronous with the population density measurements and their variations are shown in Figure 8. The figure suggests that both population and BC AOT show a similar increasing trend and this supports the utility of using the population data for further analysis.

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The primary distribution of population for year 2000 is shown in Figure S10 which depicts, more values at region 1a compared to region 1b, and another thing is that, Lucknow is

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776 still found as a patch of very high population even at 2000. On the other hand, region 3 had  
 777 much lesser populations at the same time. Next, the long term variation of population density  
 778 are again observed over region 1, 1a and Lucknow from Figure 8. It may be noted from the  
 779 figure that all throughout region 1, population density rises from 650 to 800 persons per sq  
 780 kilometre which is quite a high value. Next, region 1a shows even higher values than region 1  
 781 with a steep rise from 760 to 1000 persons per square km. Thus it follows that region 1a has  
 782 consistently higher population average and trends leading to higher OC and BC. However, the  
 783 situation worsens in Lucknow where population density changes drastically from 850 to 1100  
 784 persons with most of the change happening in last 10 years; hence this phenomenon strongly  
 785 supports the amplified DDF trend over Lucknow compared to 1a. But region 3 shows very less  
 786 variations in last few years (100 to 140) leading to comparatively lesser BC and OC emissions.  
 787 However, it may also be noted that the relative change over region 3 is higher (40%) compared  
 788 to Lucknow (30%). Hence in future, if urbanization and population persists to grow at the same  
 789 rate over region 3, then BC, OC and dust will also expectedly grow to alarming limits which  
 790 can cause a drastic change in DDF over North-Western Indian regions.

### 791 3.9. Future trends of DDF over Region 1 and 3 using RCP 8.5 scenario

792 The next concern of this study is to investigate the projected change of dry phase  
 793 lengths over the foreseeable future. Many attempts in the recent years have employed CMIP5  
 794 GCM simulations to provide future projections for any urbanization scenario. In accordance  
 795 with the present study, RCP 8.5 projections of rainfall (and DDF) corresponding to maximum  
 796 urbanization levels has been considered over the mentioned regions. It may be noted that in the  
 797 last sixty years itself, DDF values have reached ~ 30 days in August, hence it is useful to study  
 798 DDF in a two months span of mid-July to mid-September (having a reasonable increasing trend  
 799 in dry days). The future projections of DDF over this time span is now obtained from 1950-  
 800 2100. But the reliability and accuracy of these datasets first need to be validated from in-situ  
 801 measurements. Hence, historical daily precipitation datasets of r1i1p1 realization from 11 well  
 802 known GCM simulations are taken during 1955-2005 for all grid points in region 1 and 3 after  
 803 which the DDF is calculated and recorded. Finally the averaged DDFs from each model was  
 804 compared with the IMD data and the correlation coefficient with the normalized standard  
 805 deviation values in **Table S3** indicate that three models namely: CAN ESM2, CNRM CM5,  
 806 NORESM 1M show better agreement; hence they can be utilized to generate future projections  
 807 for region 1 and 3 up to year 2100. For simplicity the yearly means of DDF historical data from

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From the previous section, it follows that urbanization has considerable impact in increasing the dry phases over region 1a during the mature monsoon phase. But in region 3, relatively the effect of urbanization is feeble as has been reflected through the less population density and BC, OC concentrations. However, the observed increasing trend of dry days in association with the increase in dust aerosols over this region may be partially attributed by the loading of dusts aerosols from local sources and partially transport from the adjoining deserts. To investigate the transport issues the back trajectory analysis has been carried out during second week of July (shows highest trend in dry days over region 3) using HYSPLIT. The frequency of all possible trajectories are drawn in 12 hour steps for the preceding 10 days at 1 degree resolution of GDAS data at 2000 m to understand the probable transport of dust aerosols. The endpoint of the trajectories has been taken fixed at 27.5°N 72°E (pointing to the centre of region 3). Primarily, trajectories are drawn for all available years from 2005 – 2018 but observation does not lead to any significant inferences because the trajectories show ...



955 the models are also shown in **Figure S11** which again are found to follow the expected trends  
956 of DDF in all three regions

957         Next the total variation in dry days are investigated over region 1 and 3 including both  
958 historical and CMIP5 RCP 8.5 projections data to get a 150 year trend of dry day frequencies  
959 in **Figure 9(a)**. The DDF for all 29 grid points in region 1 and 20 grid points over region 3 are  
960 averaged yearly and then depicted in Figure 5 and 7. The multi model mean data shows that  
961 even when averaged spatially, dry days show clear increase from ~ 8 days in 1950 to ~40 days  
962 near 2100. Thus, Region 1 will experience a rise in DDF from 10% to 70% during mid  
963 monsoon phase which is highly alarming and is attributed to the rapid pace of urbanization  
964 over those regions in the future. Again, this trend looks less discretely increasing compared to  
965 the historical trends over Lucknow. Again, in certain cases the projected DDF is expected to  
966 increase up to ~50 days (80%) during the 2100 monsoon which should lead to severe drought  
967 conditions. Again, the trends look comparatively weaker in first fifty years (8-12), then it gets  
968 stronger (12-24) and finally shoots up to very high values (24-42 days) after 2050 which is  
969 primarily caused due to high urbanization rate over this region in the future. However, when  
970 the same analysis was done for region 3 DDF was found to increase steadily from 20 to 40  
971 days over 150 years. The trends of DDF are clearly much weaker in region 3 compared to  
972 region 1 while the standard error bars are also less here. Both of this factors can be attributed to  
973 the fact that region 3 has much less urbanization components than region 1. But it may be  
974 noted that if region 3 continues to face urbanization at the present rate, then in future it will  
975 experience more number of dry days. Additionally, it has been observed that, the trends have  
976 increased almost steadily in region 3 with no abrupt change in DDF in the last 50 years like  
977 region 1. This is attributed to the low urbanization levels at region 3 at present.

978         Hence region 1 creates a more alarming situation with dry days increasing by around 5  
979 times compared to the other regions. So to further investigate this abrupt change spatially, the  
980 model averaged data of DDF for 50 years span are shown for region 1 in the bottom panel of  
981 **Figure 9(b)**. The figure shows an expected high value around Lucknow for the 50 year  
982 periods; but its effect diffuses as one goes towards the outskirts of Lucknow facing lesser  
983 urbanization. Another thing is that the places adjoining Lucknow show a very drastic change  
984 only after 2010. Thus, most of the places adjoining Lucknow shows very high number of dry  
985 days (>45 days) near the end of this century which will grossly affect the monsoonal rainfall  
986 leading to severe droughts and so it needs to be addressed by policy makers.

#### 987 **4. Conclusions**

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989 It is an essential aspect to study the probability of drought occurrences over India during  
 990 monsoon as agricultural and economical issues are directly related with it. Here, a detailed  
 991 study on the occurrence of dry days during monsoon over the Indian region is presented. The  
 992 study investigates three potentially drought prone regions in India based on the dearth of  
 993 precipitation and abundance of PET. Region 1 mostly belongs to the State of Uttar Pradesh  
 994 (UP), Region 2 covers major parts of the states of Andhra Pradesh and Tamil Nadu and small  
 995 portion of Karnataka while Region 3 encompass the arid part of Rajasthan. A series of  
 996 investigations are progressed which infer that over the eastern part of region 1 which is referred  
 997 as region 1a urbanization plays significant role in increasing DDF. Prevailing impact of  
 998 anthropogenic emission like BC or OC aerosols becomes more prominent as the study goes in  
 999 depth with a downscaling approach from a broad region 1 to a specific urbanized location like  
 1000 Lucknow which is one of the urbanized sectors of IGP. The increase in cloud cover and non-  
 1001 occurrence of rain events indicate rain suppression phenomena over region 1 which is yet to be  
 1002 investigated in detail. This also indicates the scope of the study over several other point  
 1003 locations having drought occurrence record but could not be included in the present study  
 1004 approach. Finally, the long term projections of DDF are drawn over region 1a and 3 using  
 1005 intense urbanization scenario of RCP 8.5 and an average of 70% rise in dry days are seen  
 1006 which may be a very crucial concern by the year 2100 and hence it needs to be considered by  
 1007 policy makers in future aspects. However, this study is mainly done from modelled  
 1008 components of aerosols, so a far more accurate analysis can later be done over IGP subject to  
 1009 more availability of aerosol in-situ data in the other major urban locations over India. The main  
 1010 findings of the study are shown in a schematic presentation in **Figure S12** and are highlighted  
 1011 as follows:

- 1012 ➤ The DDF (based on the frequency of days having local precipitation accumulation less  
 1013 than 1mm) has a significant level of correlation with the universally accepted monthly  
 1014 SPEI Drought Index (DI) especially in the last sixty years. Further, the correlation levels  
 1015 between DI and DDF are more prominent during August in Region 1a and during July in  
 1016 region 3.
- 1017 ➤ The trends of DDF (within 15 days window) are more prominent during August for  
 1018 region 1a. However, region 3 shows a descent trend during July while region 2 shows the  
 1019 same during late September, (corresponding to the monsoon retreating phase) hence it has  
 1020 been neglected as it may not completely reflect a monsoonal drought.

**Deleted:** In association with the increase in aerosols a reduction in cloud particle radius has been observed in our investigation which indicates a reasonable cause of reduced rainfall occurrences and increase in DDF

- Results from region 1a indicate prevailing contribution of aerosols compared to ENSO, Humidity or SSN. Further studies show that BC and OC aerosols over urbanized region are more active in increasing the DDF, which is also supported from distribution, PCA and MLR analysis
- The trend analysis on DDF reveals that the increasing trends become stronger as the spatial coverage is downscaled from region1 to 1a and followed by a local urbanized location of Lucknow. About 50% increase in DDF is found in Lucknow compared to 17% all through region 1. Further, a periodicity of 4 and 8 years is found stronger in region 1 which gets overpowered by the randomly varying urbanization component over Lucknow.
- Population density maps have been taken as a proxy of the urbanization component owing to its significant agreement with anthropogenic carbonaceous emissions (BC). A higher population density is observed over Lucknow (average of 850 persons/km<sup>2</sup> and trends of ~35%) compared to the rest of region 1 and 1a. Further the population density values are very less in region 3 (100 persons/km<sup>2</sup>) which is in good agreement with lesser impact of urbanization on DDF over this region.
- In depth investigation revealed that the increase of urbanization components like BC or OC exhibits a significant association with increased cloud lifetime (~ 18% rise in LCC) over Lucknow which results in a stronger gradient of dry day occurrences (from 9 days in 1956 to ~17 days at present).
- Though in region 3 aridity plays a major role to experience a high number of dry days (~23) still dust aerosols show an increasing trend and hence it probably influences a further increase in DDF (an increase from 23 days in 1956 to 25 days at present) which is alarming for region 3.
- The climatic projections of dry day frequency from CMIP5 simulations of 3 GCM model (CNRM CM5, CAN ESM and NOR ESM 1M) show a sharp increase in dry days during July 15 to September 15 with DDF reaching up to 50 dry days over region 1 and 45 days over region 3 by 2100.

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#### Author contributions.

RC performed the main analysis, ST and MVR provided the initial concept, main guidance, writing and editing of the manuscript, BKG and AM provided the needed data and contributed to the analysis, discussion, and editing.

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## Tables

**Table 1.** Classification of dry day phase according its length.

Region	Case 1(SDP)		Case 2(MDP)		Case 3(LDP)	
	Range	Average	Range	Average	Range	Average
Region 1a	8-10	9	10-14	12.5	14-18	16
Lucknow	4-12	9.5	13-17	15	18-30	22
Region 3	14-20	19	21-24	22.6	24.5-27.5	26

**Table 2.** MLR coefficients for all general factors.

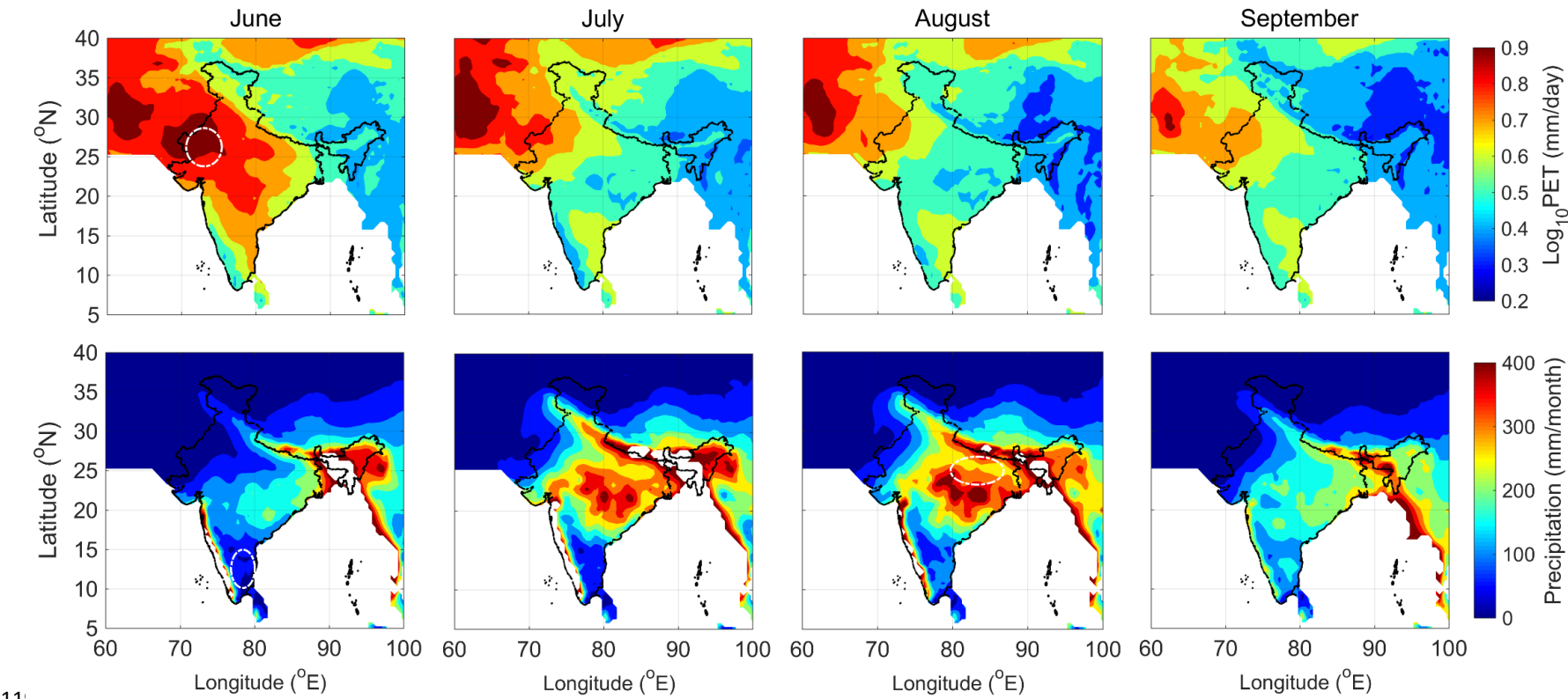
Region	Components			
	Aerosol	SSN	ENSO	SHUM
Region 1a	0.393	0.008,	0.161	-0.207
Region 3	0.107	0.078	0.056	-0.267

**Table 3.** MLR coefficients for aerosol components.

Region	Components				
	BC	Dust	OC	Sea Salt	Sulphate
Region 1a	0.542	0.129	0.263	0.326	0.124
Lucknow	0.864	0.218	0.556	0.011	0.155
Region 3	0.464	0.431	0.120	0.182	0.033

1191 **Figures**

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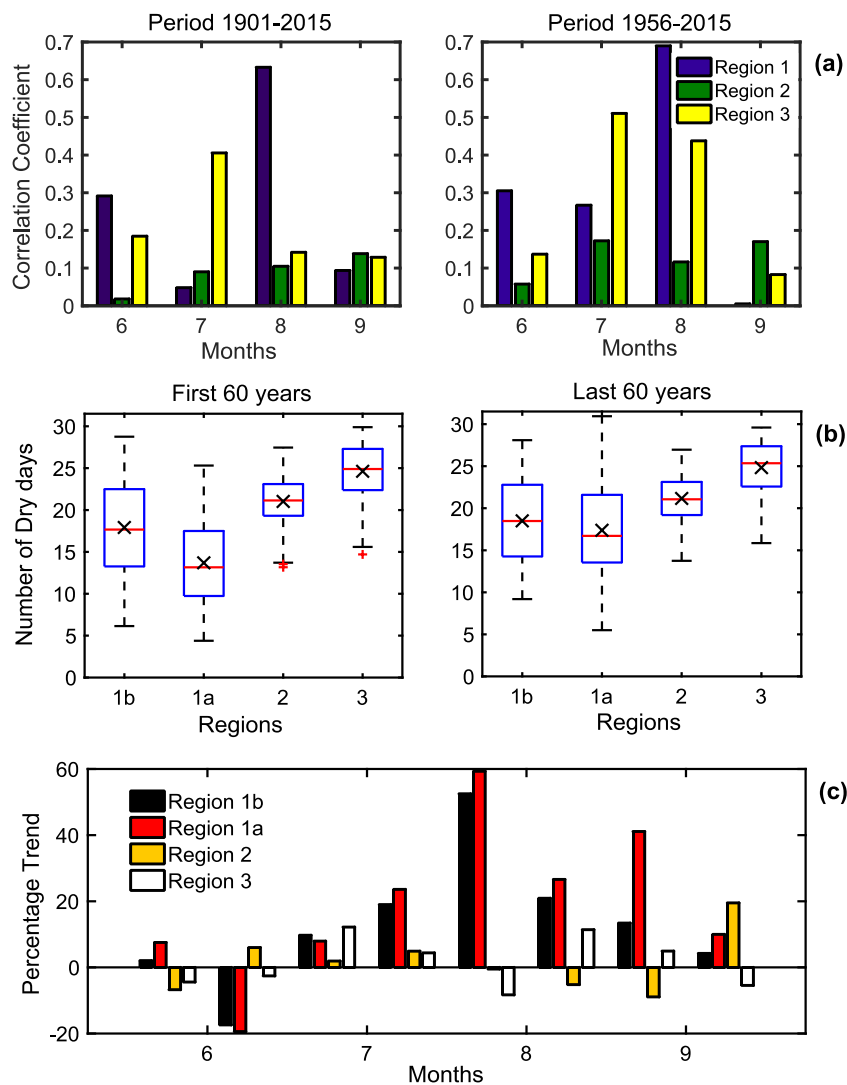
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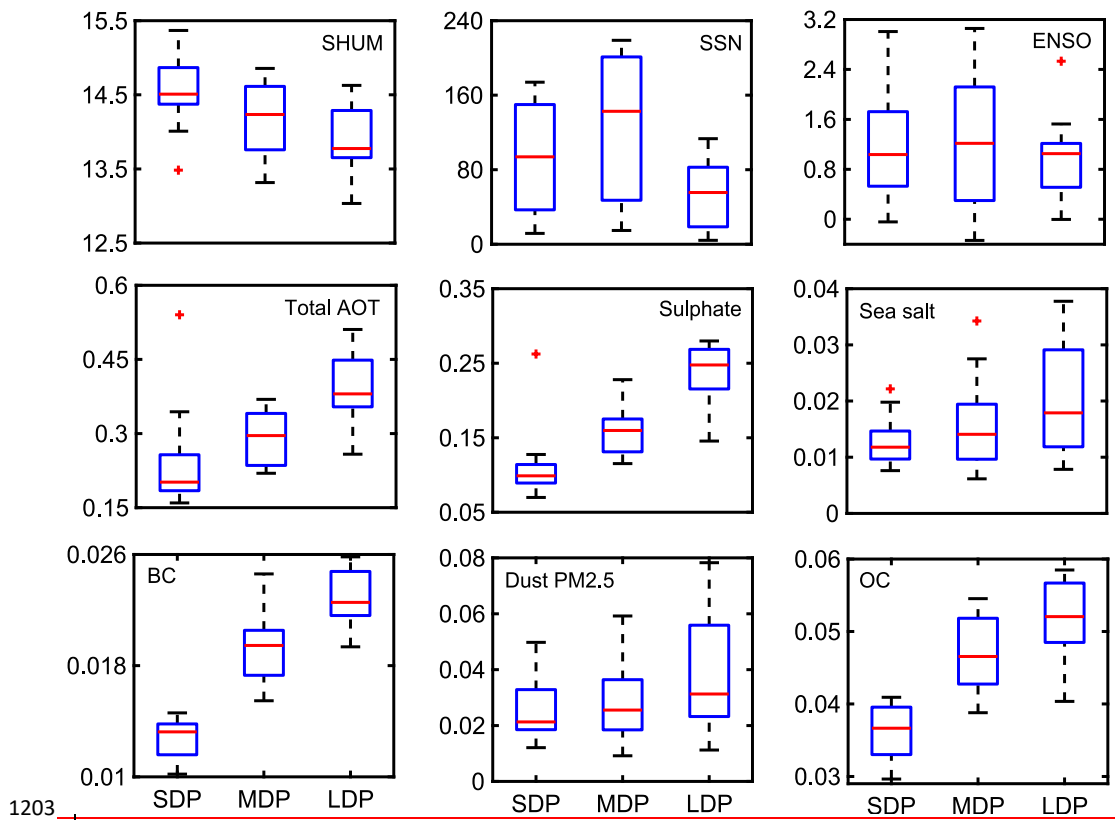
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**Figure 1.** Monthly averaged maps of potential evapo-transpiration rate and precipitation during June-September.

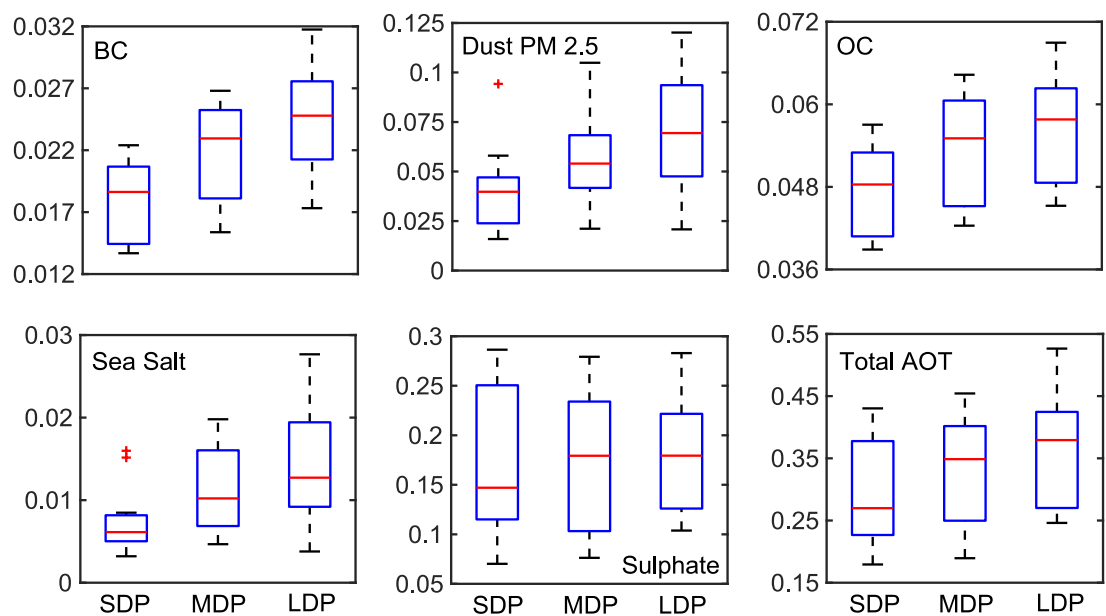




**Figure 2(a).** Correlation coefficients between DI and DDF values for all monsoon months for two different climatic periods 1901-2015 and 1956-2015, (b) Monthly mean values of DDF for regions 1a, 1b, 2 and 3 during 1901-1960 and 1956-2015, (c) 15 day trends of DDF trends during 1956-2015.



**Figure 3.** Frequency distribution analysis results of various controlling factors behind DDF evolution for various types of dry phase lengths over region 1a, namely: Humidity, SSN, ENSO Total aerosols, Sulphates, Sea Salt, BC, Dust PM 2.5 and OC.



1211  
1212 | **Figure 4.** Frequency distribution analysis results of various controlling factors behind DDF evolution  
1213 for various types of dry phase lengths over Lucknow corresponding to 5 aerosol components such as  
1214 BC, Dust PM 2.5, OC, Sea Salt and Sulphates.

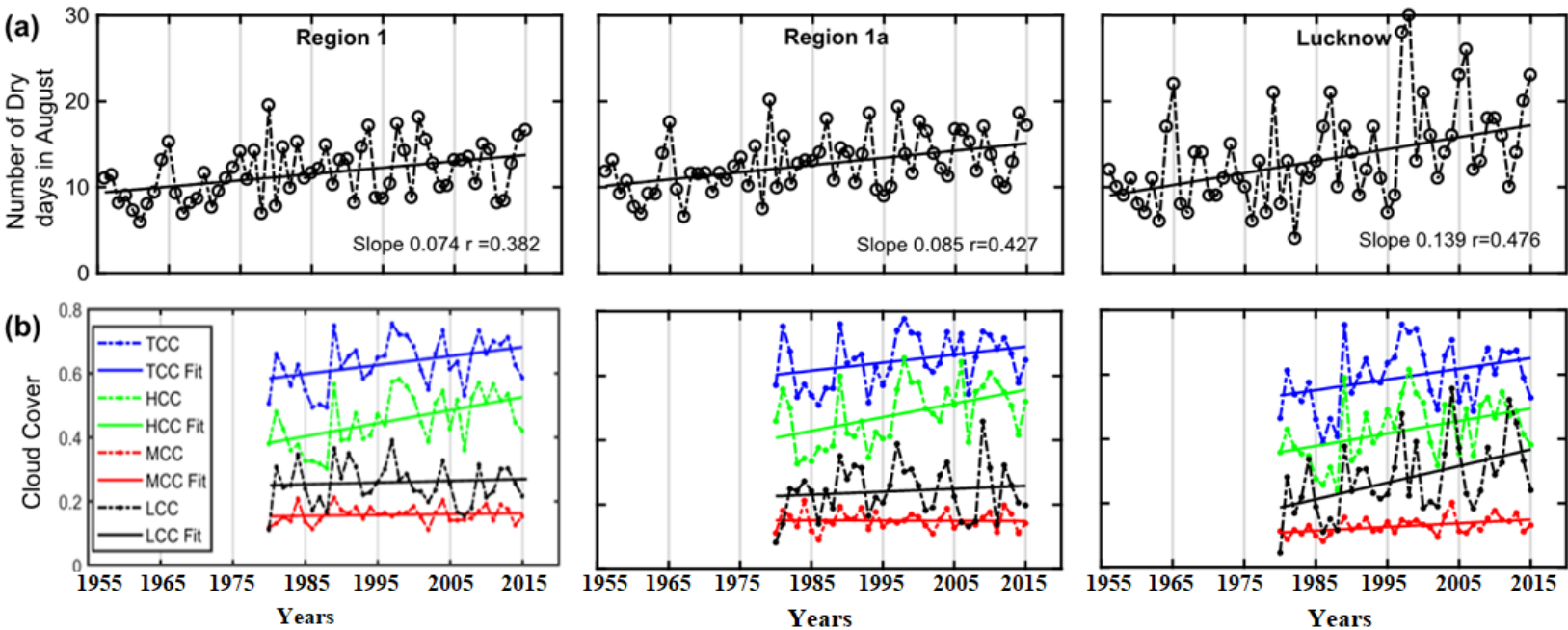
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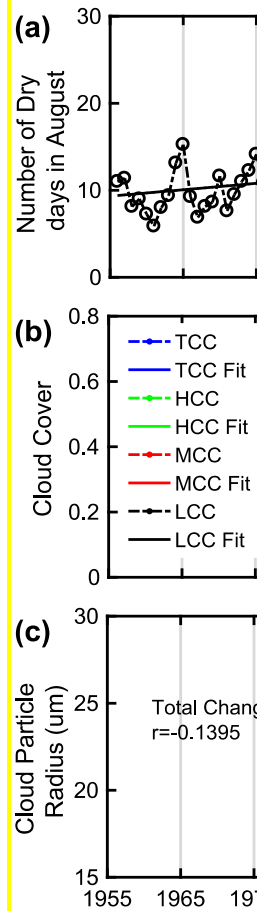
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1220

1221 **Figure 5.** Statistical comparison of the climatology of all parameters during August for region 1, region 1a, Lucknow during various time spans  
1222 (a) Dry Day Frequency values between 1956-2015 and (b) Cloud cover parameters (TCC,HCC,MCC,LCC) during 1980-2015

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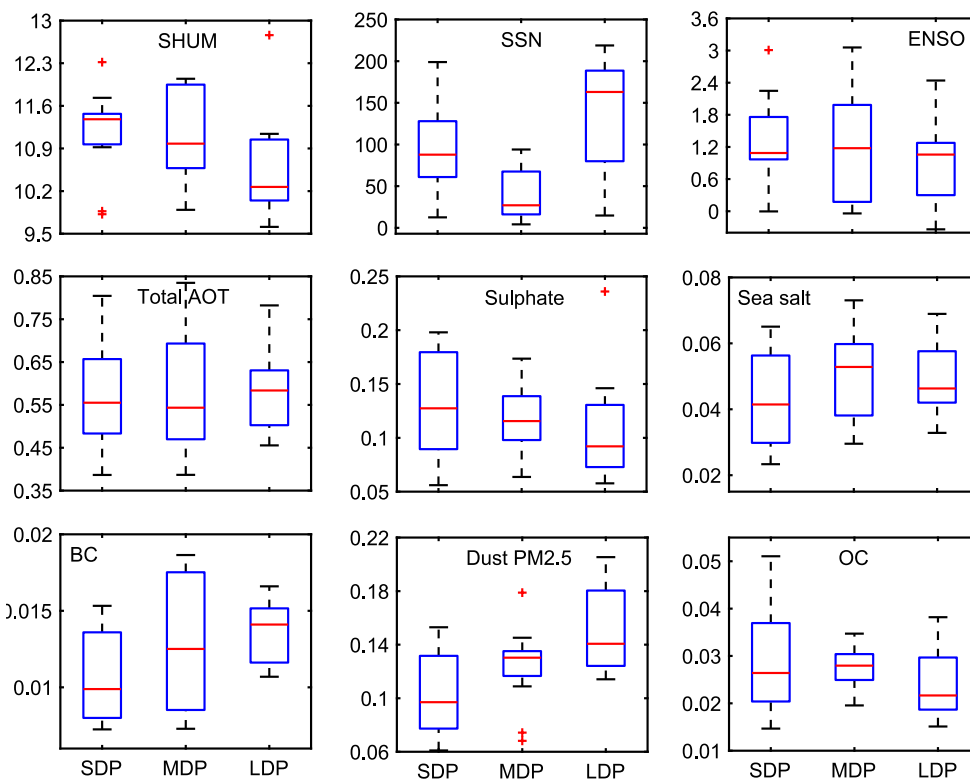
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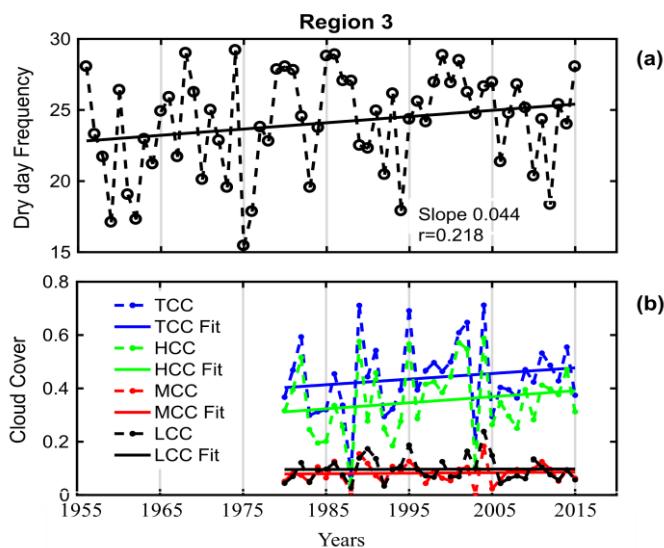
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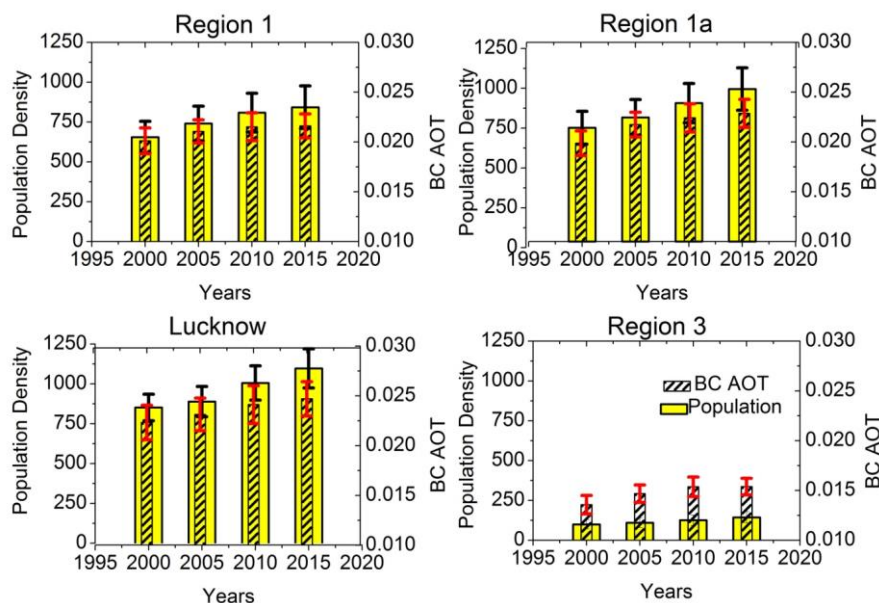
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1234 **Figure 6.** Frequency distribution analysis results of various controlling factors behind DDF evolution  
 1235 for various types of dry phase lengths over region 3, namely: Humidity, SSN, ENSO, Total aerosols,  
 1236 Sulphates, Sea Salt, BC, Dust PM 2.5 and OC.

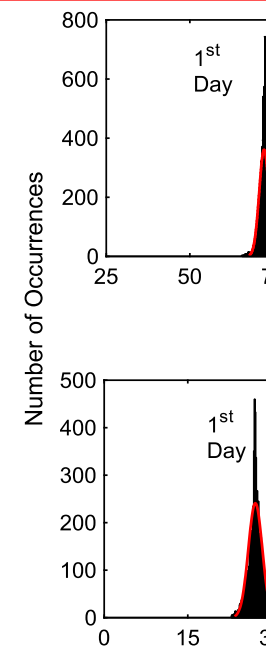
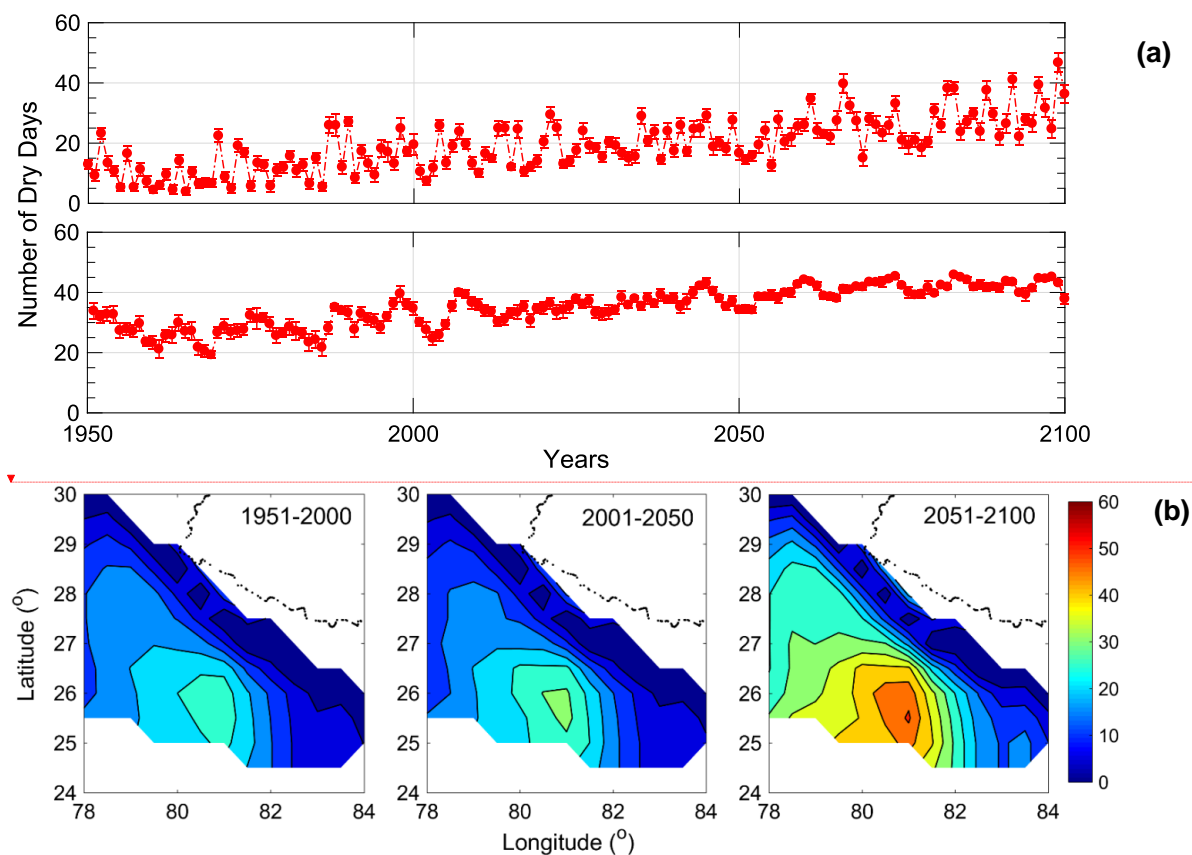
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**Figure 7.** Statistical comparison of the climatology of all parameters during July for region 3 during various time spans (a) Dry Day Frequency values between 1956-2015 and (b) Cloud cover parameters (TCC,HCC,MCC,LCC) during 1980-2015.



**Figure 8.** 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.



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**Figure 11.** Statistical representation of all back trajectory endpoints with respect to latitude and longitude starting from the central grid point (27 N, 72.5 E) of Region 3.¶

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