Aerosol-Cloud-Interaction Variability Induced by Atmospheric Brown Clouds during the 2009 Indian Summer Monsoon Drought

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ABSTRACT

Contrasting monsoons of 2008 and 2009 provided a test bed to enhance the understanding of the aerosol variability and aerosol-cloud interaction. Vertical aerosol profiles derived from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) are used to delineate the aerosol properties during the two contrasting Indian summer monsoons. We observed a 30–40% increase in the aerosol occurrence frequency (AOF) in lower altitudes (below 6 km) in 2009 and a 5–8% enhancement in AOF at higher altitudes in 2008. The cloud occurrence frequency also showed more deep convective clouds in 2008 (13–15%) than in 2009. Cloud Fraction, Aerosol Optical Depth and TRMM precipitation data sets have been also used to investigate the aerosol-cloud interaction. We define the microphysical effect as the increase in cloud fraction with increase in aerosols (CCN) and the radiative effect as the decrease of cloud fraction with increase in aerosol loading. We observe a stronger microphysical effect than the radiative effect in 2008 as compared to 2009. In 2009, atmospheric brown clouds were observed from March to September, which slowed down the microphysical effect and enhanced the radiative effect. This resulted in a 30% reduction in the total cloud fraction that may have reduced precipitation, and invigorated the drought conditions during 2009.

Keyword: Atmospheric aerosols; Aerosol optical depth; Atmospheric chemistry; Air pollution; Cloud aerosol interactions; Remote sensing.

INTRODUCTION

Changes in precipitation intensity, pattern or cycle over the Indian region during monsoon season have a large-scale impact on the life, agriculture or economy of India. The severe droughts of 2002 and 2004 resulted in economic losses of billions of dollars and the lowest rainfall in the historical records during the last 130 years (Mujumdar *et al.*, 2006). A similar situation occurred during the summer monsoon (June–September) 2009, with a deficit in the all-India rainfall of 54% of the long-term average for this period (Francis and Gadgil, 2009).

Several satellite datasets have been used for studying aerosol-cloud interactions (Bréon *et al.*, 2002) to observe the first indirect effect (Twomey, 1977), the second indirect effect (Albrecht, 1989), effect of biomass burning (Andreae *et al.*, 2004), urban and industrial air pollution (Rosenfeld, 2000), and desert dust (Rosenfeld *et al.*, 2001). More recently, satellite data analyses have revealed a persistent correlation between cloud fraction and aerosol optical depth in regions influenced by marine aerosol, smoke, dust, and industrial air pollution (Kaufman *et al.*, 2005). There has been a study by Koren *et al.* (2008), over the biomass-burning region of Brazil, South America showing a smooth transition between microphysical and radiative effects of aerosols on clouds. There are only few studies of aerosol-cloud over the complex Indian monsoon system, most of them over oceans (Jayaram *et al.*, 2001; Rahul *et al.*, 2008). Many large-scale satellite surveys provide a detailed view of the aerosol-cloud-precipitation system, particularly with the emergence of a new generation of active remote sensors. Most importantly, the vertical resolution is necessary to assess whether or not cloud and aerosol layers are intermingled (Avey *et al.*, 2007). These detailed profiles of aerosol and clouds are needed to quantify the effects of aerosols on clouds and how these in turn influence climate and the hydrological cycle (Kaufman *et al.*, 1997). Vertical profile data are now available through the Cloud Aerosol Lidar and Infrared Pathfinder Satellite (CALIPSO) (Winker *et al.*, 2007), launched in April 2006. The primary payload on the CALIPSO satellite is a two-wavelength, polarization-sensitive backscatter lidar known as the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP). CALIOP is

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unique in its ability to measure high-resolution vertical profiles of both clouds and aerosols within the Earth's atmosphere all over the world (Winker *et al.*, 2003). Kim *et al.* (2008) also confirmed that the CALIPSO algorithms discriminate clouds and aerosols and detect the layer top and base altitudes reliably by comparing CALIOP and ground-based lidar data at a site far from the dust source, in Seoul, Korea.

EXPERIMENTAL SECTION

Here, we use level 2 version 3.01 CALIPSO aerosol profile (APro) and cloud profile (CPro) data. Aqua MODIS daily level 3 data for aerosol optical depth (AOD) and cloud fraction (CF) are used to differentiate the aerosol-cloud relationship. Daily precipitation during the monsoon months is derived from the Tropical Rainfall Measuring Mission (TRMM). CALIPSO and Aqua MODIS both fly in the A-Train constellation (L'Ecuyer and Jiang, 2010). Aqua leads the constellation followed by CALIPSO by about 2 minutes and cross the equator at approximately 1:30 local time. There are three terms used in the present study; Aerosol occurrence frequency (AOF), Cloud occurrence frequency (COF) and AOD. The AOF calculated from CALIPSO are during the presence of aerosols and/or thin clouds as observed by lidar. AOF is derived from the observed aerosol extinction profiles and defined as the frequency of occurrence of aerosol pixels divided by the total number of aerosols and clear sky pixels at a particular level. Similarly, COF derived from the observed cloud extinction profiles is defined as the frequency of occurrence of cloudy pixels divided by the total number of cloudy and clear sky pixels at a particular level. AOD is the integration of extinction due to aerosols in a column of atmosphere. The AOD, which is a unitless quantity, is obtained from Aqua MODIS (MYD08_D3) daily level 3 data. The AOF,

COF, AOD, CF, and precipitation considered in this study are during the June-September months of 2008 and 2009, which is the period of Southwest monsoon season over India. We considered two regions; the whole Indian region (8°N to 35°N and 65°E to 95°E) and a subset which focuses on the severely drought affected region in 2009 called as the core region (18°N to 28°N and 65°E to 88°E). Core region is the region of central India (not including the foothills of Himalayas) where the tropical convergence zone, responsible for the large scale rainfall during the summer monsoon gets established at the peak, of the peak, of the onset phase of monsoon (Rajeevan *et al.*, *2010*). Thus significant rainfall fluctuations over this core region serve as criteria for active or weak phases of monsoon. In this paper we look into the spatial and vertical aerosol distributions, especially over the core region during a normal Indian monsoon year 2008 and an acute drought year 2009. We also analyze the variability in the microphysical and radiative properties during these two years for which the CF and AOD data are taken from MODIS, while precipitation data is obtained from the TRMM satellite.

RESULTS

Precipitation Variability

Figs. 1(a) and 1(b) represents the daily mean precipitation in mm from June–September for 2008 and 2009, over the core region. Also, the seasonal cumulative monsoon rainfall pattern based on the real time reports from about 200 stations well spread over India, as published in the Daily Weather summaries issued by India Meteorological Department show the same variation as in Figs. 1(a) and 1(b) [source; *Monsoon Online*] (figure not shown). To arrive at clear and contrasting comparative differences of aerosol variability, we have included the analysis during a normal Indian monsoon year of 2008 along with the extreme
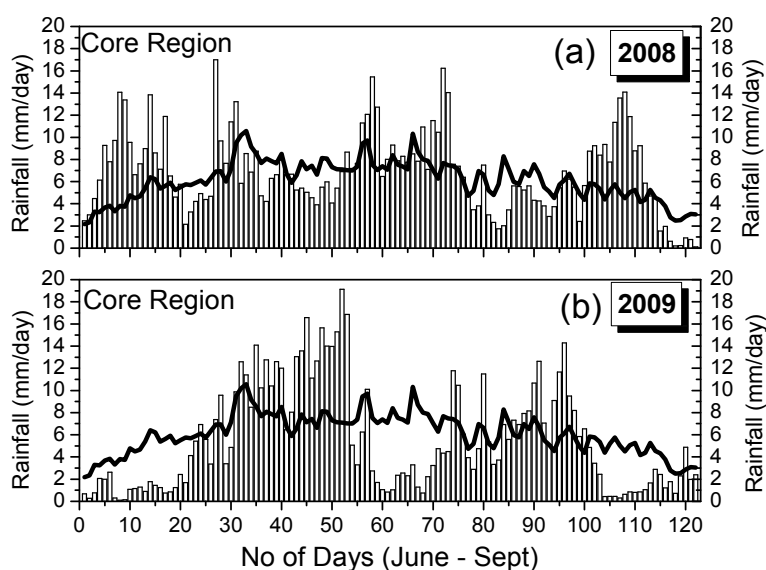

Fig. 1. (a) and (b) represents daily rainfall in mm from TRMM over the core region considered in study. The solid black line represents the climatological rainfall in the core region while the bars indicate daily rainfall during the south-west monsoon season (June–September).

drought year of 2009. In both the panels solid black line indicates the climatological precipitation (using TRMM data for 1998–2010) while the bars denote daily precipitation over the core region. From Fig. 1 it is distinctively clear that during the monsoon of 2009 the precipitation was alarmingly low as compared in 2008 in the core region. We observe very little precipitation during 2009 for the month of June, first 2 weeks of August and almost all September, while in 2008 (normal monsoon year) we find the rainfall values greater than or equal to the climatological values. The deficit in the all-India rainfall for the month of June in 2009 (48%) was close to the lowest recorded rainfall (50% in June 1926) since 1871 and the deficit in the all-India summer monsoon (June–September) rainfall was 23% (*India Meteorological Department*, India: as also seen in Fig. 1(b), which is comparable to the most severe droughts in the last 100 years (24% in 1972, 22% in 2002 and 15% in 2004).

Figs. 2(a)–2(d) represent the daily rainfall evolution and also the cumulative rainfall during the monsoon season (starting from June 1st–September 30th) of 2008 and 2009 respectively. From the plots it is distinctively clear that the year 2009 was marked with deficient rainfall in comparison with the rainfall pattern during 2008. Such marked variation, infact had made 2009 an acute drought year. Fig. 2(d) clearly shows below normal rainfall as compared to the normal year 2008. Also, the spatial distribution of rainfall obtained over 36 meteorological sub-divisions of India, which were computed from the real-time reports and published in the Weakly Weather Reports of India Meteorological Department (IMD) [*Monsoon online*] showed 30% departure in rainfall during 2009 as compared to 2008 (Figure not added).

Spatial Variability of AOD

The spatial distribution of aerosol optical depth derived from CALIPSO during the monsoon season of 2008 and 2009 is shown in Figs. 3(a) and 3(b). The aerosol plume is present in both years; with a significant increase, encompassing the entire Indian domain, during the year 2009. In 2008, AOD values of 0.3–0.6 are predominantly persistent along the
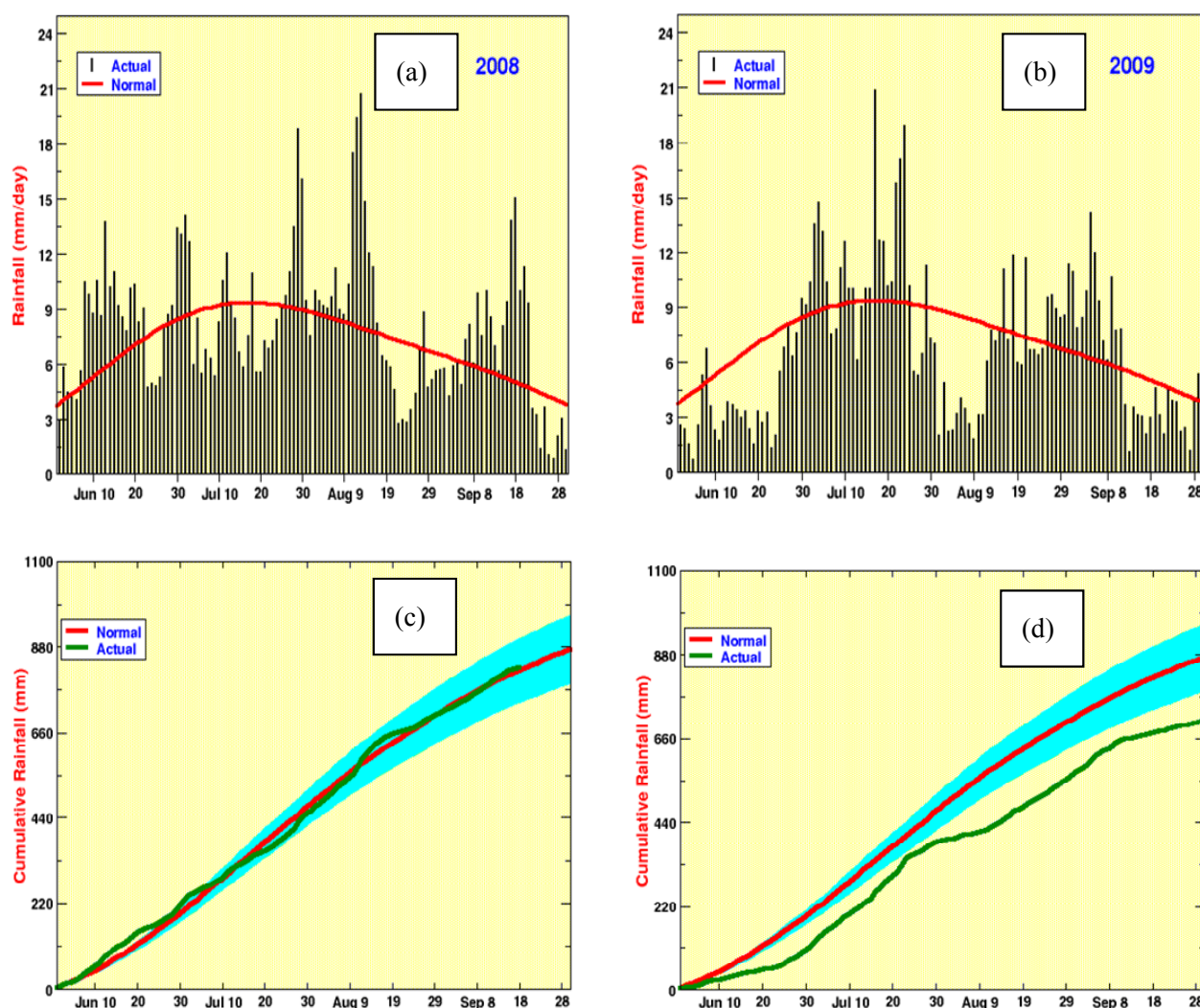

Fig. 2. (a) and (b) represent daily rainfall (derived from 200 real time observations spread over the entire Indian domain) evolution from June-September during 2008 and 2009, respectively; while (c) and (d) represents cumulative rainfall for 2008 and 2009. (Source: http://www.tropmet.res.in/~kolli/MOL/Monsoon/frameindex.html).
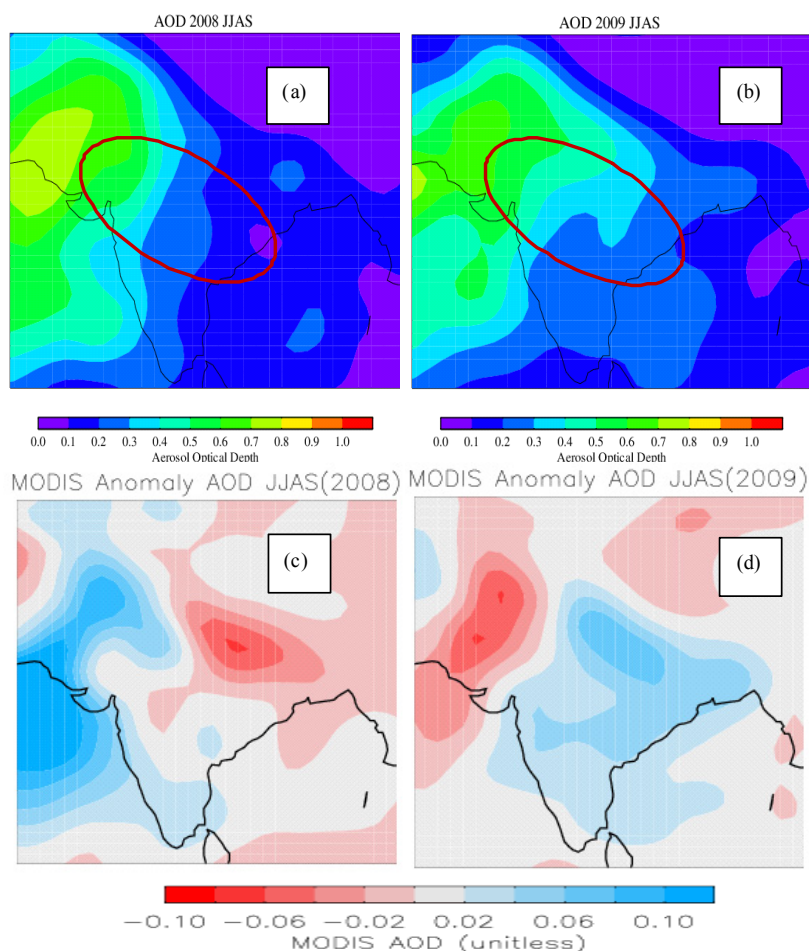
Fig. 3. (a) and (b) represents the spatial map of aerosol optical depth derived from CALIPSO while (c) and (d) MODIS AOD anomaly during the South-west monsoon season June to September for 2008 and 2009. The red circle indicates the core region considered in our study.

western India and the western Arabian Sea (along the west coast of India-which is mostly dust aerosols (Badarinath *et al.*, 2010)). During 2009 the spatial aerosol loading has extended to the whole of India with a minimum value of 0.3. In 2009 AOD increases to 0.6 over western India and to about 0.3 across the entire region of India - with mostly dust over the western region and Atmospheric Brown Clouds (ABC) over the central part of India (Rahul *et al.*, 2011). In 2008 over central India the AOD is less than 0.2. The circled region indicates the core region of our study. Also, plotted in Figs. 3(c) and 3(d) is seen the MODIS aerosol anomaly for June–September (JJAS) of 2008 and 2009. It shows persistent positive aerosol anomaly encompassing the central, southern and eastern Indian regions in 2009 while, 2008 shows negative anomaly over the same region.

Vertical Distribution of AOF and COF

Fig. 4(a) shows the monthly vertical distribution of AOF, derived from the CALIPSO data over the Indian region, during the monsoon season (June–September) for 2008 (dashed lines) and 2009 (solid lines). As the altitude increases the AOF decreases as observed in both 2008 and 2009. In 2009, during the monsoon period we observe that the

frequency of occurrence of aerosols at lower levels, i.e., up to 4 km, is 5–10% higher when compared to the occurrence distribution in 2008. As altitude increases, the pattern reverses, i.e., the occurrence frequency is 2–5% higher in 2008 as compared to 2009, this mode continues even above 10 km. The COF shown in Fig. 4(b) during the same time period shows a similar variability as observed in AOF, i.e., at higher altitudes the COF is 5–13% higher during 2008, which indicates presence of more deep convective clouds in 2008 than in 2009. Observations of cloud occurrence below 4km might be underestimated as they are affected by the presence of thick clouds in upper levels; hence only high level clouds are discussed here.

Along the core region shown in Fig. 4(c), the AOF shows dramatic signatures of the occurrence frequencies, below 6 km. The AOF is 65%, 55%, 42% and 70% during June, July, August and September 2009, respectively; while during 2008 the AOF is 42%, 41%, 35% and 30% during June, July, August and September 2008. Hence, the percentage increase in AOF during 2009 in comparison with AOF in 2008 is 23% for June, 14% for July, 7% for August and 40% for September. The cumulative increase in the AOF during 2009 was 84% higher than in 2008 (below 6 km). It
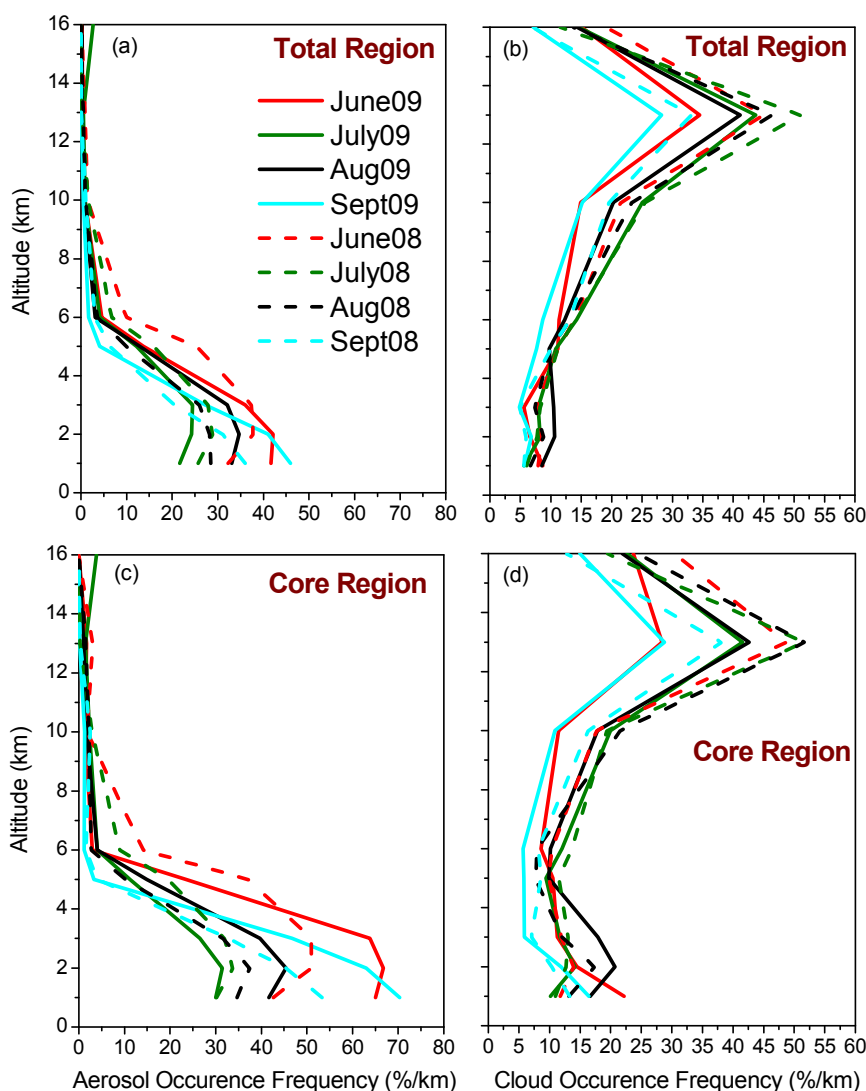
Fig. 4. (a) and (c) represents the vertical distribution of aerosol occurrence frequency over the total region and core region respectively while (b) and (d) represents the vertical distribution of cloud occurrence frequency over the total and core region respectively. Each line in the figures represents monthly profile over the regions considered.

is interesting to note that the AOF above 6 km showed an enhancement during 2008 than in 2009. The COF's show clear variability at higher altitudes (10–16 km), i.e., the COF is observed to be higher in 2008 than in 2009 during monsoon months as seen in Fig. 4(b) and d. It is inferred from the vertical distribution of aerosols and clouds that with increased convection more aerosols are advected to higher levels (Jiang *et al.*, 2007, 2011). Thus, high AOF's were persistent in 2008 than in 2009 at higher levels, suggesting that increased convection vertically transported more aerosols in 2008. While in 2009 less AOF's in upper levels indicates less convection and hence more aerosol loading in the lower levels. Hence, due to more COF's in 2008 in higher levels; less aerosols were observed from CALIPSO while, less convective clouds in 2009 observed more aerosols in lower levels.

AOD-CF-Precipitation Relation
    Using a conceptual model, Koren *et al.* (2008) proposed

that the microphysical and radiative properties could be coupled to subsequently understand the role of aerosols in controlling the precipitative nature of clouds. The microphysical effect is defined as the increase in cloud fraction with increase in aerosols (CCN). The radiative effect is defined as the absorption of solar radiation by aerosol layers and cooling the surface below. This may stabilize shallow layers and reduce their relative humidity, suppress moisture and heat fluxes from the surface and reduces cloudiness (Koren *et al.*, 2005; Feingold *et al.*, 2005) thus, affecting cloud fraction. Figs. 5(a) and 5(b) show the AOD-CF-Precipitation relationship for the years 2008 and 2009 in the core region of study. The contour plot indicates the combined microphysical and radiative effect during both the years. These separate processes and the superposition of the effects are stated in Koren *et al.* (2008). It is interesting to find the different microphysical and radiative response during the normal (2008) and drought (2009) years.
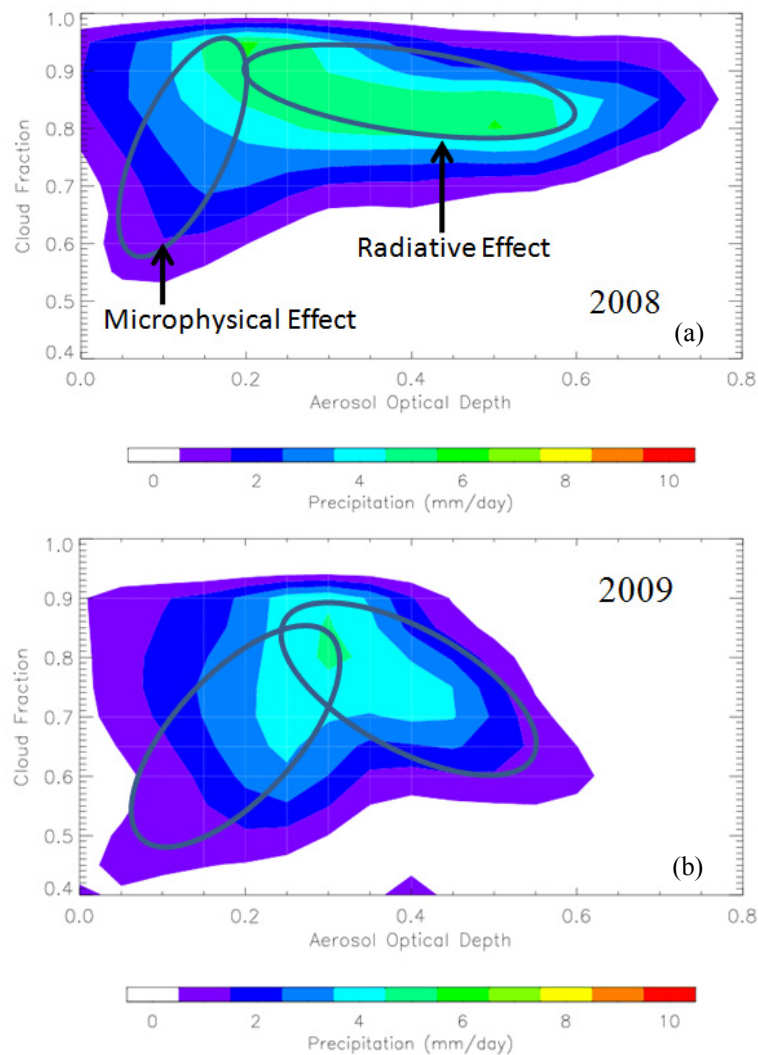
Fig. 5. (a) and (b) represents the 3-d plot of cloud fraction-aerosol optical depth and precipitation for 2008 and 2009 in the core region.

As the AOD increases we see increase in CF in 2008, quickly reaching the saturation CF at about optical depth 0.2, while in 2009 we find this microphysical effect slows and reaches its saturation CF at higher AOD of 0.3. Also, the saturation CF is higher of about 0.95 in 2008 as compared to 0.8 in 2009. Once CF reaches its saturation point the radiative effect starts dominating. We find the radiative effect in 2008 reduces cloud fraction by < 10% at a slow pace. In 2009 we observe that, the radiative effect has a strong dominance once the CF reaches its saturation point. In our recent paper, Rahul *et al.* (2011), we found that during the year 2009, summer monsoon was dominated by the presence of the ABCs. It is crucial to note that the Indian domain was loaded with the abnormally intense ABCs during both the pre-monsoon and monsoon period (for over 7 months, March–September 2009). From this study, it is definitive that the persistent ABC plumes were responsible for generating a strong radiative forcing. Also, further evidence is provided by the observed excessive loading of smoke aerosols during 2009 compared to 2008 (not shown). In 2009 the smoke aerosol loading was higher by almost 60–

100% than in 2008, especially during the monsoon months.

Since, water vapor also influences the role of aerosols in precipitation (Ranjan *et al.*, 2007), we have also analyzed the water vapor variability over the region of study during 2008 and 2009. During June 2009 less water vapor, high aerosol loading of ABC's below about 6 km in core region give rise to smaller cloud droplets and reduced cloud fraction and in turn precipitation thus, invigorating the drought situation. Thus, we hypothesize that the differences aerosol type (size distribution and chemistry), clouds have a logarithmic sensitivity to the amount of potential CCN (Feingold *et al.*, 2001, Kaufman *et al.*, 2005, Koren *et al.*, 2005). Small changes in the amount of cloud coverage (Cloud Fraction) can produce a climate forcing equivalent in magnitude and opposite in sign, to that, caused by anthropogenic greenhouse gases, and changes in cloud height can shift the effect of clouds from cooling to warming (Koren *et al.*, 2008). Hence, the CF in 2009 which was reduced by almost 30%, (due to radiative effect) might have contributed to suppression of precipitation drastically due to less cloud, producing the deficient rainfall pattern.

DISCUSSION

The years 2008 and 2009 present contrasting behavior in terms of precipitation, the former being a normal Indian summer monsoon while the later, a case of acute drought. The contrasts also manifest in the aerosol loading and their interactions with the cloud parameters (cloud fraction). Previous studies (Kaufman and Koren, 2006; Koren *et al.*, 2008) showed a similar relationship of increase in cloud fraction with the aerosol variability over the Atlantic Ocean and the South American biomass-burning region. Also, the impact of ABCs in suppressing rainfall over China has been reported (Xu, 2001) and modeling studies have had predicted a possible similar impact (reduction in precipitation) of ABCs over India (Andreae *et al.*, 2004; Ramanathan *et al.*, 2005). However, such an aerosol-controlled convection modulation especially, with respect to the type of aerosol loading (ABCs etc.) have not been earlier studied and the contrasting years of 2008 and 2009 provided us an opportunity to observationally prove that the ABCs can intensify the droughts via the aerosol effects on convection regimes (enhanced radiative effect during the drought year 2009) over India, too. Our speculation is that the type of aerosols and aerosol loading in 2009 as compared to 2008 also played an important role, affecting cloud formation and in turn suppressing precipitation. There is a strong debate that, aerosols cannot play the role of initiators that could trigger long breaks (which accumulate to drought like situation), and that the aerosols and their variability is only an after-effect of the monsoon (aerosol wash out or persistence of aerosol plumes in the absence of precipitation) (Kiran *et al.*, 2009). Though it is true that the drought like conditions cause the observed aerosol variability, it is subject to the time period of study, i.e., if the aerosol variability is investigated after the onset of the monsoon, this assumption is applicable. Over the Indian region we observe a seasonal cycle of aerosols, that is more absorbing aerosols during pre-monsoon, less during winter and washout due to rain in monsoons or acting as CCN during monsoons. We also find that the absorbing aerosol cycle extends to double its time period in drought years (Bhawar *et al.*, 2010) as compared to normal monsoon conditions. Thus, during the pre-monsoon months, if the aerosol loading shows an increase, the question arises; what happens to these aerosols before the first rain shower occurs (onset of the monsoon)? It is proposed that such aerosol plumes must react/interact with the clouds to either reduce/enhance precipitation process (depending on the nature/type of aerosols). Hence, our study adds a new dimension, i.e., if there is profuse loading of the ABCs, reflected with an increase in the AOF (~84% in the present case) then, such a lethal combination could act as a trigger point to simulate long break conditions (by enhancing the radiative effect and reducing the total cloud fraction).

We hypothesize that these aerosols affect the cloud formation by affecting the cloud properties (initial cloud formation) by either dissipating or increasing the lifetime of clouds and hence cause unorganized rains. Once, the first pattern is affected (even at a smaller scale) its after-effect might help in intensifying the extreme drought scenario as in 2009. Thus, less rain helps increase break events and hence enhances the drought like condition. So the first effect (to cause an increase in cloud dissipation or its life time, based on the rate of microphysical/radiative forcing) of the aerosol variability on the clouds, could act a trigger to the impeding drought and hence should be considered seriously.

CONCLUSION

We present a detailed analysis, providing an insight as to how the polluted brown clouds suppressed precipitation and enhanced the drought conditions during the acute 2009-drought year. We observe 84% cumulative increase in aerosol occurrence frequency in 2009 compared to 2008 in the altitude below 6 km. ABC's slowed down the microphysical effect and enhanced the radiative effect, which eventually resulted in a 30% decay in the total cloud fraction leading to reduced precipitation in 2009. Further, more work needs to be done in understanding to what % pre-monsoon and monsoon aerosols give rise to breaks which could be taken into account in models to better understand the role of aerosols in summer monsoon if any.

ACKNOWLEDGMENTS

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