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Cloud Aerosol Interactions and its influence on Cloud Microphysical parameters during Dry and Wet spells of Indian Summer Monsoon using CAIPEEX data

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ABSTRACT

The variations of cloud condensation nuclei (CCN), aerosol and cloud particle concentration (PCASP), cloud droplet effective radius ($CDPR_e$), and Liquid water content (LWC) have been measured using instrumented aircraft over Hyderabad, Bengaluru and Bareilly in India during Cloud Aerosol Interactions and Precipitation Enhancement Experiment (CAIPEEX-2009). Three intensive observation periods (IOPs) i.e. 17-22 June and 13 July representing the dry spells, and the IOP during 16-25 August, representing wet spells of Indian summer monsoon were analyzed. Cloud droplet size is highly sensitive to liquid water content and temperature in the cloud environment. The CDPRe and LWC show strong linear correlation during both dry spells and wet spells of ISMR. The mid level clouds C_M ~ 2000 meters are more favorable for coalescence of cloud droplets leading to growth of CDPRe > 14 μm required for warm rain formation.

Key words : Cloud condensation nuclei (CCN), Aerosol and cloud particle concentration (PCASP), Cloud droplet effective radius ($CDPR_e$), Liquid water content (LWC) and Indian Summer Monsoon.

INTRODUCTION

The Indian Summer Monsoon Rainfall (ISMR) during a four-month period (June-September) shows large variations in the interannual and intraseasonal time scale due to embedded dry and wet spells. Droughts over India impact the economy of the country leading to major loss of agricultural productivity and livelihood of a large population (Swaminathan, 1987). Following Deka et al., (2010) the definition of spell is based on the duration of consecutive wet and dry days. A wet spell is a sequence of wet days and it begins and ends the day after and the day before a dry day. In this study a wet day (W) is considered as one where the precipitation is ≥1 mm and above. Obviously, dry day (D) is the one where there is no precipitation or is < 1 mm. The important aspect of dry spells of the Indian summer monsoon have been reported by Krishnamurti et al., (2010) regarding the formation of a blocking high around Arabian Peninsula located at 3-9 km above sea level. Studies on the aerosol-cloud interaction over Indian summer monsoon zone and associated dry and wet spells have not received adequate attention due to lack of extensive in-situ field observations. It is in this context CAIPEEX-2009 (Cloud Aerosol Interaction and Precipitation Enhancement Experiment -2009) was taken up with the main objectives as: (i) to simultaneously measure microphysics of aerosols, CCN, cloud parameters (number concentration, liquid water content, particle size, etc.) and large-scale meteorological conditions to document and (ii) to analyse the data towards understanding the pathways through which aerosols interact with clouds and influence precipitation over the continental Indian monsoon region.

Aerosols cloud interactions and warm rain formation

Aerosols modulate the weather and climate by perturbing the radiative budget through direct absorption and scattering of solar radiation (the direct effect) and altering the cloud microphysical properties by acting as cloud condensation nuclei (the indirect effect) (Jayaraman, 2001; Kaufman and Koren, 2006; Devara et al., 2009; Manoj et al., 2012). Sarkar and Kumar (2007) reported rain-bearing cloud height along the east and west coasts and peninsular India to be 3-6 km. Leiming et al., (2006) reported that usually marine and continental clouds show different precipitation efficiencies. The different cloud condensation nuclei (CCN) size distributions and composition play a major role in precipitation development particularly in warm clouds. Warner and Twomey (1967) concluded that droplet concentration in clouds forming in air contaminated by smoke from cane fires is greatly increased leading to much retarded coalescence process causing less rain. Enhanced aerosol concentrations also suppress warm rain processes by producing a narrow droplet spectrum which inhibits collision and coalescence processes (Squires and Twomey, 1960, Warner, 1968, Rosenfeld, 1999). Elevated concentrations of CCN contains higher concentrations of smaller cloud droplets; which slows their coalescence into raindrops (Squires, 1958). This can lead to suppression of precipitation in shallow and short-lived clouds (Warner, 1968). The CCN fraction at a given super saturation (CCNS) is the subset of the overall aerosol population, which can be activated to cloud droplets at a higher super saturation. The CCN and condensation nuclei (CN) indicate strong dependence of (CCN/CN) on particle size. For this reason, they play a significant role in the CCN budget and in the cloud-mediated effects of aerosols on climate (Adams and Seinfeld, 2003; Pierce et al., 2007).

METHODOLOGY

Description of CAIPEEX aircraft and its instrumentation

The PA-31T instrumented aircraft was used during the CAIPEEX programme. The instruments include (i) Passive Cavity Aerosol Spectro Photometer (PCASP: DMT -100X) for aerosol particle measurements inside the clouds in the range of 0.1-3.0 μm (ii) An aerosol counter (DMT-100) to measure cloud condensation nuclei (CCN) which form at different super-saturations in the range of 0.1 - 1.2 %. (iii) The cloud droplet probe (CDP), which measures the concentration and size distribution of cloud droplets in the size range from 2-50 μm. [The effective radius (Reff) is measured using the CDP probe which is referred as (CDPRe) the cloud droplet size distribution in the range 3-50 μm.] (iv) DMT LWC-100 to measure liquid water content (LWC) in the range of 0-3 gm^{-3}. Details of the cloud-aerosol instrumentation and CAIPEEX experiment are described by Kulkarni et al., (2012).

Data and synoptic weather conditions

Data used are daily aircraft observations viz., (a) CCN (b) aerosol concentrations (c) CDPR$_e$ (d) LWC (e) Flight track data (f) radiosonde data (g) Composite daily wind field at 700 hPa from NCEP/NCAR- Reanalysis and (h) Meteosat-7 visible satellite imagery.

Intensive observation periods

During June 8-20, 2009 there was a prolonged hiatus in the further advance of the monsoon. A Depression was formed over the Arabian Sea during June 23-24, 2009 and the monsoon revived and further advanced as reported by IMD (2009). Thus 17-22 June and 13 July, 2009 were identified as dry and 16-25 August as wet spells of monsoon. Daily flight routes were accordingly planned based on the prevailing weather conditions. The aircraft base stations in India are shown in Figure 1 and the flight tracks for dry and wet spells are illustrated in Figure 2a-b. The aircraft data measured over Hyderabad, Benguluru and Bareilly are utilized in this study.

The daily flight routes

During the experiment, aircraft measurements were conducted near Hyderabad (17.38°N, 78.48°E) during the dry spell. While in the wet spell, the aircraft observations were continued near Benguluru (12.97 °N, 77.59°E) and Bareilly (28.35°N, 79.41°E). Figure 2a shows the aircraft route map for 17 June, 2009 over Hyderabad. The aircraft flight track extending up to about 7 km with low cloud depth reveals a weak convective activity and the same is evident from the satellite imagery for this day. Figure 2b shows aircraft flight tracks on July 13, 2009. On this day the well developed clouds attained high vertical depths, height extending above 7 km, which caused intense convective activity. Figure 2c shows the 17 June, 2009 Meteosat-7 0600 UTC visible satellite imagery representing the Indian sub-continent and adjoining ocean areas such as Indian Ocean, Arabian Sea and Bay of Bengal. Satellite imagery clearly depicts few isolated shallow clouds over Hyderabad, which indicates subdued convective activity and dry weather. Similarly Figure 2d depicts the 13 July, 2009 Meteosat-7 0600 UTC visible satellite imagery showing the prevalence of dense thick convective rain bearing clouds over Bengaluru and major parts of Indian land mass representing wet monsoon conditions.

Daily mean values of air-borne measurements were calculated from instantaneous values for respective dates of observations over the study region and discussed. Warm clouds form when a large number of water droplets having a wide range of radius, collide with each other and interact with suspended aerosol particles present in atmosphere which act as a seed for the development of cloud. When the effective radius (Reff) of the droplet, under conditions, is < 14 μm the rain rate is limited by the rate of coalescence of cloud drops (Rosenfeld et al., 2012).

RESULTS AND DISCUSSIONS

Cloud base characteristics during dry and wet spells

The cloud base heights, referred as lifting condensational level (LCL) for air parcel and air temperature during dry spell derived from radiosonde data, are shown in table-1. The cloud base temperature during the dry spell varies between 11.5 to 16.5 °C, with a mean of 13.8 °C. Cloud base height varies between 2060 and 3044 meters and the mean height is ~ 2742 meters. The cloud temperature is one of the responsible parameters which might enhance or suppress the growth of CDPRe. Cloud base height and temperature during wet spell are shown in table-2. While the cloud base temperature during the wet spell varies between 16.0 to 23.7°C with a mean of 20.8 °C, the cloud base height varies between 1299 and 1828 meters and the

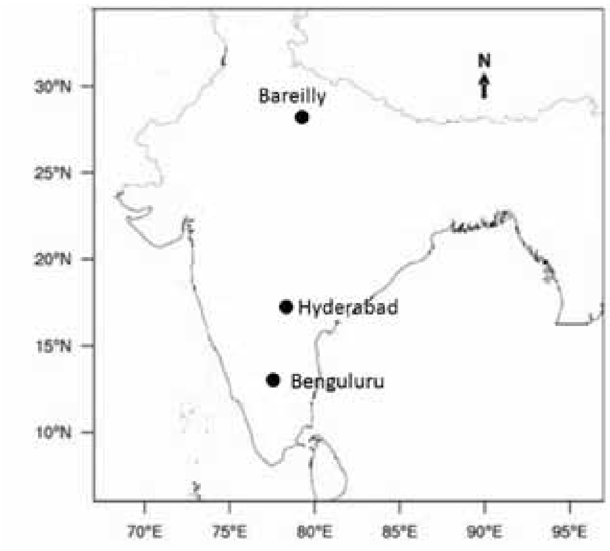

Figure 1. Map showing IOP base stations of Hyderabad, Bengaluru and Barelliey.

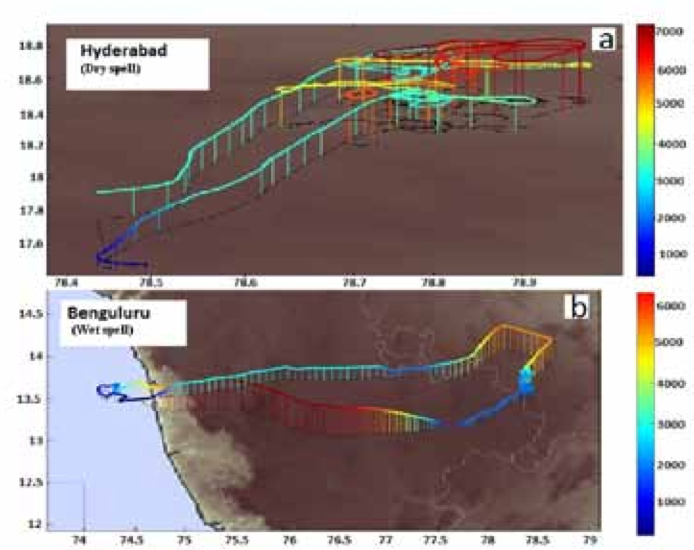

Figure 2a. Flight tracks over Hyderabad during dry phase on 17 June, 2009.
Figure 2b. Flight tracks over Bengaluru during wet phase on 13 July, 2009.

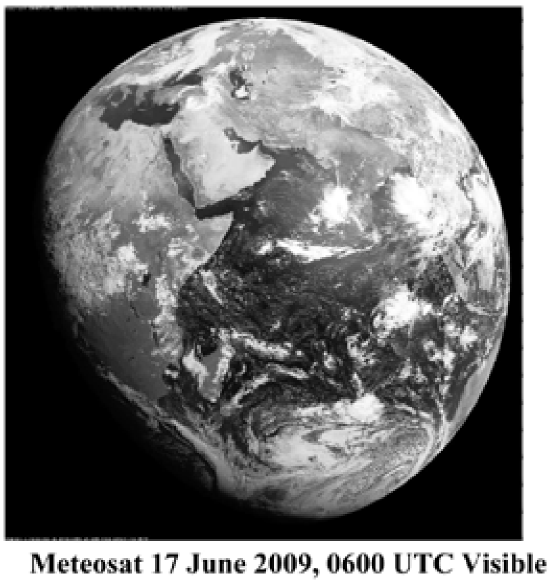

Figure 2c. The Meteosat-7 visible imagery for 17 June 0600 UTC, 2009 in dry phase.

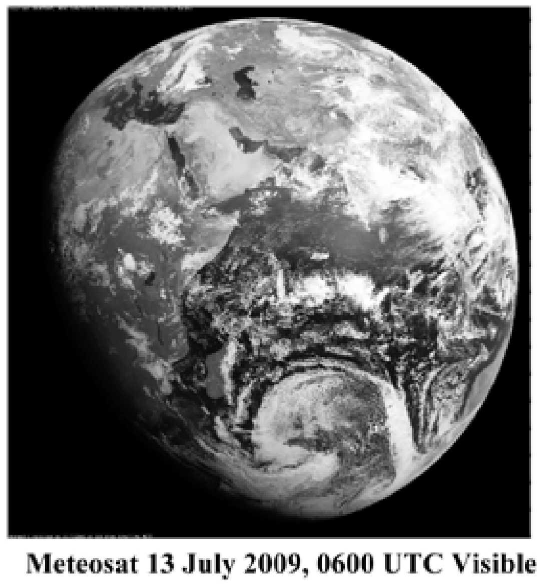

Figure 2d. The Meteosat-7 visible imagery for 13 July 0600 UTC, 2009 in wet phase.

mean height is ~ 1556 meters. It may be observed that the cloud base height is comparatively lower during the wet spell than in dry spell.

Most cloud drops in convective clouds nucleate at the cloud base and grow with height since more vapour condenses on the nucleated drops as the rising air cools. The modal size and width of the cloud drop increases with the vertical distance above cloud base (D) (Rogers and Yau, 1989; Rosenfeld and Givati, 2006; Freud and Rosenfeld, 2012). The cloud drop coalescence becomes more efficient with increasing D. The raindrops in convective clouds cannot form by diffusional growth alone; also efficient drop coalescence is required for warm rain to form. Mixing of the cloud with ambient dry air evaporates some of the cloud drops and dilutes the rest of them; this would decrease the ability of the cloud to form warm rain.

Table 1. Cloud base height estimated by LCL height and temperature during dry spell, 17-22 June, 2009.

Date	Temperature (°C)	LCL (m)
17/6/2009	13.5	3203
18/6/2009	11.5	3024
19/6/2009	12.2	3044
20/6/2009	13.9	2730
21/6/2009	16.5	2060
22/6/2009	15.3	2395

Table 2. Cloud base height estimated by LCL height and temperature during wet spell, 13 July 16-25 August, 2009.

Date	Temperature (°C)	LCL (m)
13/7/2009	16.0	1828
16/8/2009	23.0	1524
23/8/2009	21.8	1456
24/8/2009	23.7	1299
25/8/2009	19.9	1677

Table 3. Cloud microphysics data during dry spell monsoon period 2009.

Dates	Cloud level	CCN (cm^{-3})	CDPRe (μm)	PCASP(cm^{-3})	LWC(g/m^3)
17/6/2009	C_L	$10 x10^3$	4.5	$5 x10^3$	0.57
	C_M	$30 x10^3$	11	$20 x10^3$	2.5
18/6/2009	C_L	$2 x10^3$	4.25	$5 x10^3$	1.0
	C_M	$8 x10^3$	12	$20 x10^3$	2.9
19/6/2009	C_L	$5.5 x10^3$	4.2	$13 x10^3$	0.16
	C_M	$9 x10^3$	6.4	$20 x10^3$	0.28
20/6/2009	C_L	$5 x10^3$	5.4	$2.25 x10^3$	1.2
	C_M	$15 x10^3$	12	$8 x10^3$	2.5
21/6/2009	C_L	$20 x10^3$	4.9	$4 x10^3$	1.0
	C_M	$79 x10^3$	12	$11.5 x10^3$	3
22/6/2009	C_L	$1 x10^3$	5.2	$4 x10^3$	0.9
	C_M	$3.5 x10^3$	15.2	$15 x10^3$	3.1

* Column PCASP refers to aerosol number concentration (cm^{-3})

Cloud aerosol interactions during dry spell

The cloud microphysical characteristics during the dry spell are shown in table-3. The daily mean values of aerosol number concentration (cm^{-3}) and cloud droplets sizes (CDPRe) at two cloud levels are designated as C_L - cloud at low level (surface to 2000 meters), and C_M -cloud at medium level (2000 to 8000 meters). These two levels, in fact correspond to a single cloud.

Cloud aerosol interactions during dry spell are presently discussed with respect to cloud microphysics data (Table 3). The aerosol number concentration (cm^{-3}) is observed to vary in the range from 2.25 x 10^3 to 13.0 x 10^3 cm^{-3} for low level clouds, C_L with the mean value of aerosol as 15.75 x 10^3 cm^{-3}. Similarly Table 3 also shows the variability of CCNs from C_L to C_M level, with the minimum and maximum as 8.0 x10^3 and 20.0 x 10^3 cm^{-3} respectively and mean value prevailing at C_M as 24.083 x 10^3 cm^{-3}. From Table 3 the mean value of LWC at C_L is of the order of 0.80 gm^{-3} and the corresponding mean of LWC at C_M is 2.38 gm^{-3}. It indicates that the low LWC at C_L does not favor faster conversion to a larger drop size due to availability of less water. In comparison, the mean LWC at C_M is higher than at C_L, which indicates that as LWC increases the CDPRe size also increases. The CDPRe shows variations between 4.2-12 μm except for the case of 22 June when the CDPRe exceeded the threshold and on other days it was lower. The CCN was observed to increase up to 79 x 10^3 cm^{-3} in dry spell. The high concentration of CCN leads to suppression of coalescence. Also if the

Table 4. Cloud microphysics data during wet spell monsoon period, 2009.

Dates	Cloud Level	CCN (cm^{-3})	CDPRe(μm)	PCASP(cm^{-3})	LWC(g/m^3)
13/7/2009	C_L	$5x10^3$	5.2	$4.5 x10^3$	0.5
	C_M	$12 x10^3$	19	$12 x10^3$	1.8
16/8/2009	C_L	$14 x10^3$	2.8	$0.4 x10^3$	0.6
	C_M	$52 x10^3$	15.4	$4.5 x10^3$	6.5
23/8/2009	C_L	$20 x10^3$	4.2	$1.725 x10^3$	1.2
	C_M	$58 x10^3$	14.5	$6.5 x10^3$	3.9
24/8/2009	C_L	$1 x10^3$	1.8	$9 x10^3$	1.0
	C_M	$10 x10^3$	15.2	$35.8 x10^3$	4.4
25/8/2009	C_L	$4 x10^3$	2	$2 x10^3$	0.9
	C_M	$25 x10^3$	19	$18 x10^3$	5.4

* Column PCASP refers to aerosol number concentration (cm^{-3})

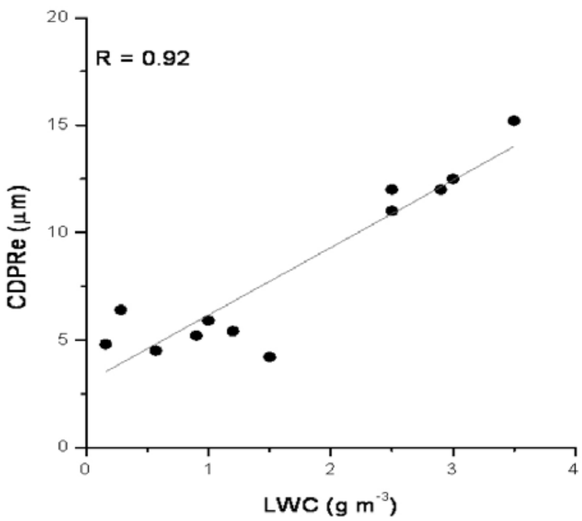

Figure 3. Relationship between CDPRe and LWC for dry monsoon days, 17-22 June, 2009.

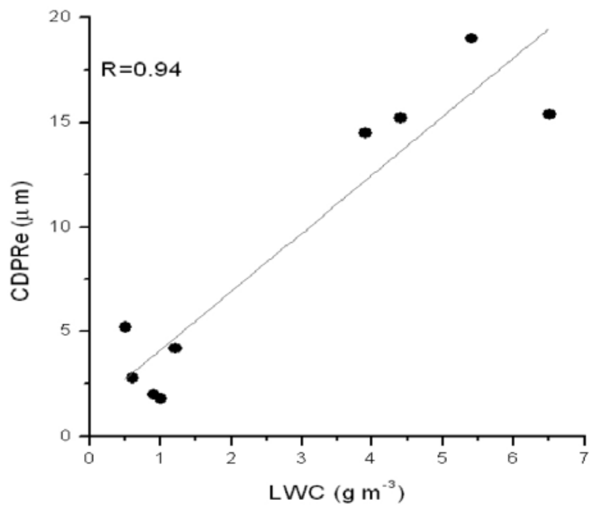

Figure 4. Relationship between CDPRe and LWC for wet monsoon days, 13 July and 16-25 August, 2009.

clouds evaporate before acquiring a sufficient depth for considerable droplet growth by coalescence they may not precipitate and may lead to reduced rainfall activity causing dry monsoon conditions.

Cloud aerosol interactions during wet spells

The cloud aerosol interactions in the cloud environment during wet spells are discussed with reference to Table-4. The mean aerosol number concentration is 3.525 x 10^3 cm^{-3}. The aerosol number concentration at C_L varies in the range of 0.4 x 10^3 to 9.0 x $10^3 cm^{-3}$. Aerosol (CCN) at cloud level C_M varies in the range of 10.0 x 10^3 to 58.0 x 10 $^3cm^{-3}$. The LWC is significantly low at C_L and increases sharply at C_M. LWC plays a significant role in faster conversion to a larger droplet. On all days of study period during wet spells the CDPRe had crossed the threshold limit of warm rain formation. CDPRe was a maximum of 19 μm on 13 July and 25 August, 2009. Aerosol at C_L are less in number as compared to C_M which indicates that sufficient number of hygroscopic aerosols was available at C_M. This is also supported by the increase in LWC at C_M levels. The condensation and coalescence process depends on the cloud environment temperature during the formation and growth of clouds which is discussed in the later part of the paper. The ratio of increase in (CDPRe) size at C_L to C_M is nearly 1:3 indicating the growth of cloud droplets as more effective at C_M level during both the phases. CCN was observed to attain a value of 58 x10^3 cm^{-3} during wet spell. The lower number of CCN is favorable for efficient coalescence processes which shows the significance of cloud condensation nuclei during wet monsoon spells.

The threshold values for onset of rain were also observed in deeper convective clouds. Rosenfeld and Gutman (1994) showed a threshold of 12-14 μm when comparing Reff with ground based radars.

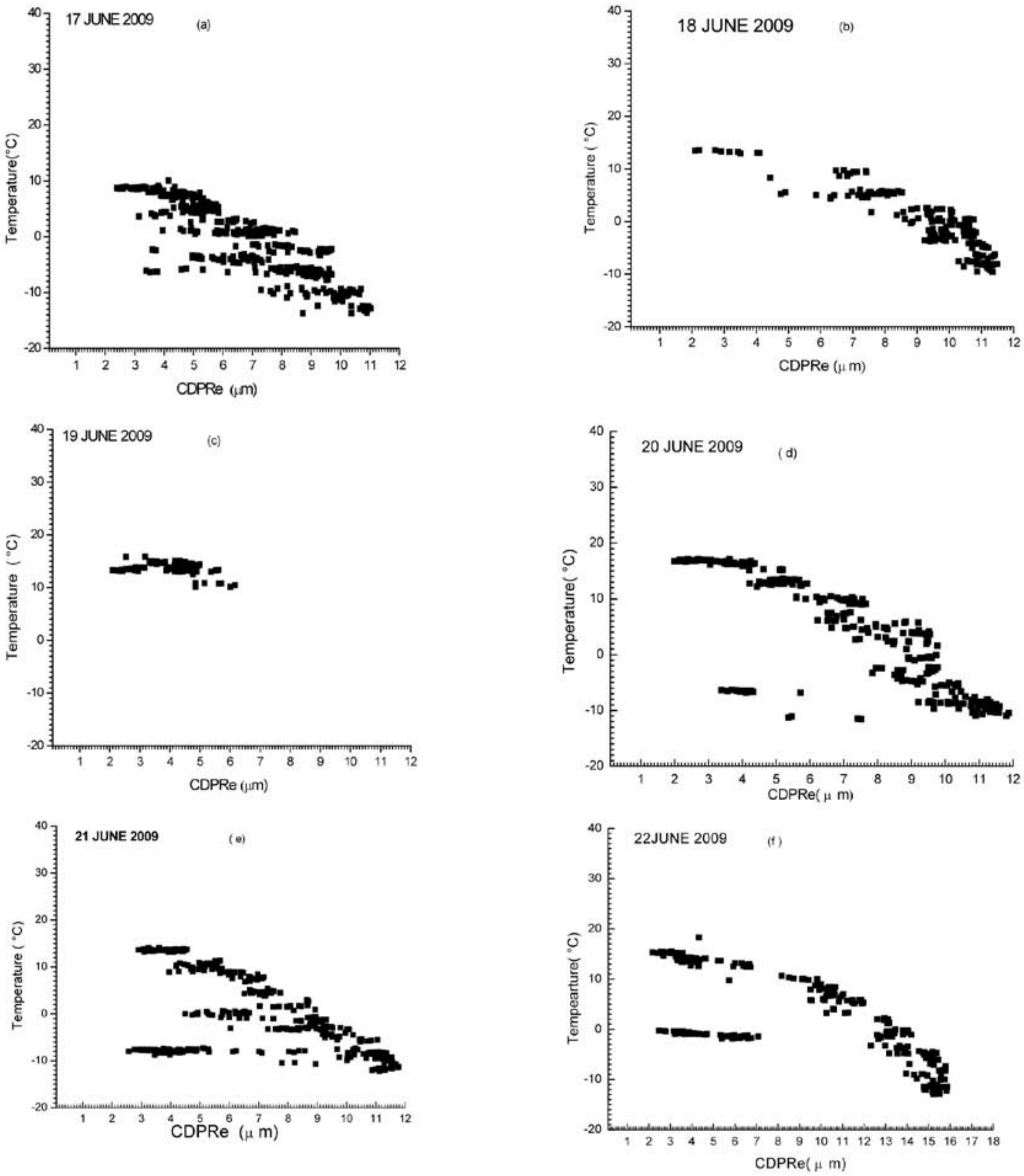

Figure 5. (a-f) Scatter plot of Temperature and CDPRe during 17-22 June, 2009.

According to Gerber (1996) significant coalescence starts when the main body of the cloud drop size distribution exceeds ($Reff_c$) effective radius for efficient coalescence, which is 15 μm, as opposed to the situation in which the largest drops from the tail of the distribution grow to isolated drizzle. It must be emphasized that most cloud drops in convective clouds nucleate at the cloud base and grow with height as more vapor condenses on the nucleated drops as the rising air cools. This trend was also observed during almost all days of dry and wet spells.

Figure 3 shows a positive linear correlation coefficient of 0.92 between CDPRe and LWC during dry phase of monsoon for the period 17-22 June, 2009. CDPRe increase with rise in LWC suggests that both the parameters are highly sensitive and play a significant role in cloud formation and precipitation. It can be seen that the cloud formation is initiated within the C_L level and growth of cloud is enhanced at the C_M level; at both these levels the CDPRe and LWC increase linearly. The threshold value of 14 μm for CDPRe required for warm rain initiation during the dry spells was limited due to low values of LWC. Also, in case of non precipitating clouds, high concentration of CCN may cause the cloud to lose condensed water due to increased evaporation of smaller droplets that increases mixing of the cloud with ambient air (Wang et al., 2003; Xue et al., 2008).

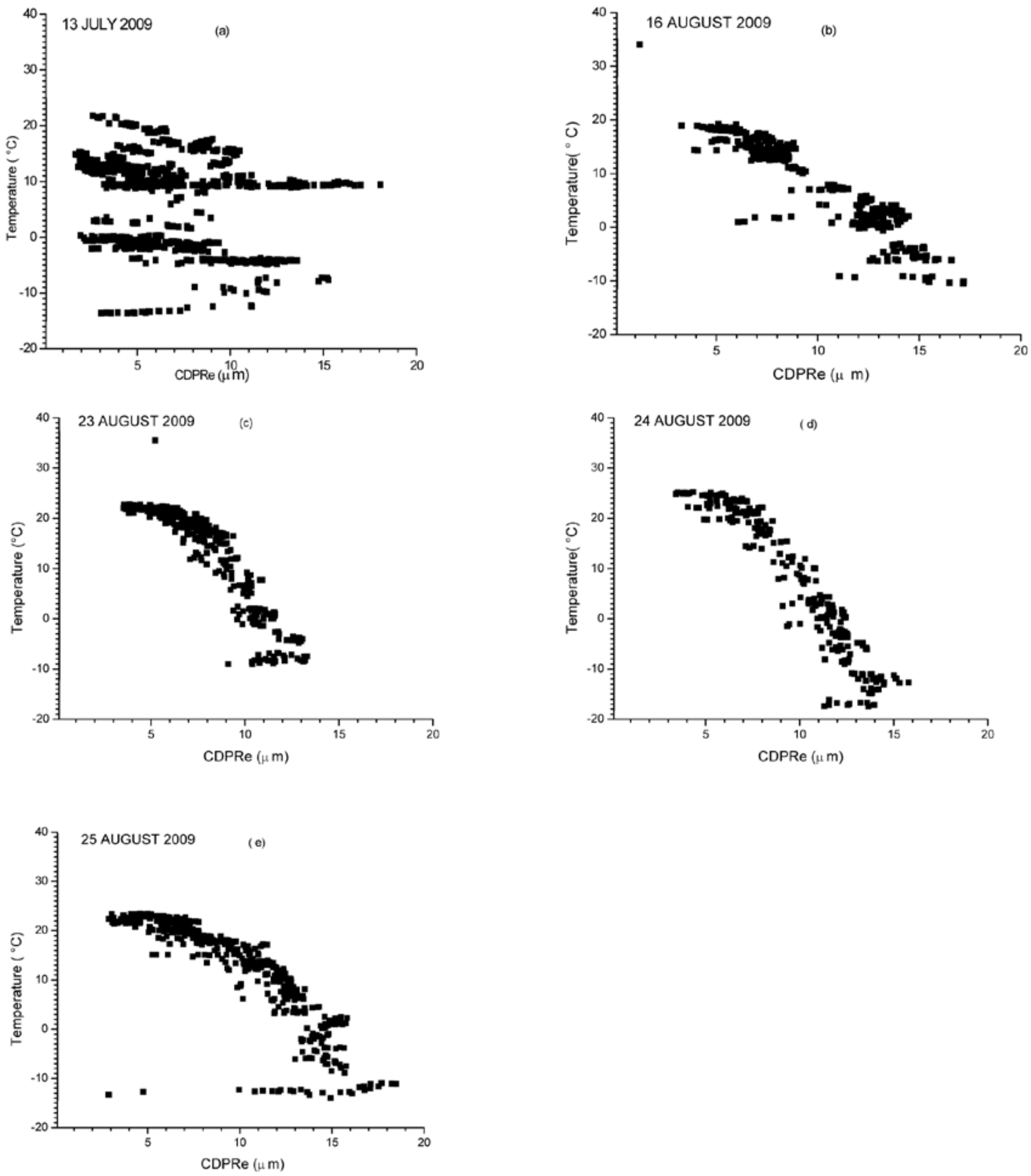

Figure 6. (a-e) Scatter plot of Temperature and CDPRe during13 July and 16-25 August, 2009.

Figure 4 show strong positive linear correlation (coefficient 0.94) between CDPRe and LWC during the wet spells. The CDPRe tends to rise sharply with rise in LWC. It can be seen that during the wet spells, the CDPRe had crossed the threshold limit of 14 μm on almost all days. The reason for the significant growth in the size of CDPRe during wet spell may be increase in the availability of highly hygroscopic sea salt aerosol. From correlation analysis of CDPRe and LWC during dry and wet spells it is observed that these parameters show similar trend. However during the wet spells, the convective activity increases due to hygroscopic aerosol and incursion of significant moisture from marine environment. The fundamental causes for the existence of this threshold are provided in Freud and Rosenfeld (2012).

Temperature and CDPRe variations during dry spells

Figure 5a-f shows scatter plots of cloud temperature (varying in the ranges of -15 to 10^{0}C and -15 to 20^{0}C) and CDPRe during the dry spells. Variations in CDPRe and temperature indicate the nature of coalescence occurring in the cloud environment. At higher temperature the CDPRe grows slowly. As the cloud temperature falls with increase in cloud altitude, CDPRe increase in size at various

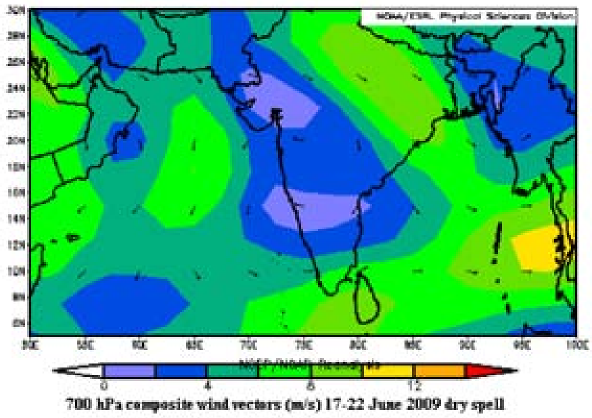

Figure 7a. Composite wind vectors (m s^{-1}) at 700 hPa level during 17-22 June, 2009 for dry period.

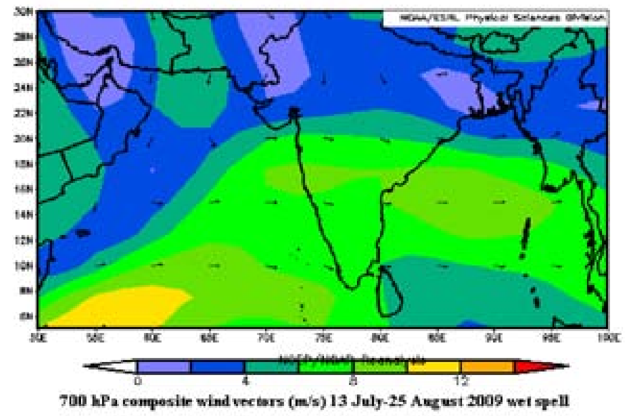

Figure 7b. Composite wind vectors (m s^{-1}) at 700 hPa level during July 13- 25 August, 2009 for wet period.

temperature intervals. At higher temperature the cloud droplets undergo slow coalescence. As temperature falls with altitude, the process of coalescence becomes faster and the resultant droplet grows larger to a maximum size of 11 μm at altitude C_M and a minimum of 4.2 μm at C_L. This trend was noticed on all days of the observation during the dry spells. Figure 5c shows certain deviations with respect to other days of the observation. It can be clearly seen that the temperature varies in the range of 10-16°C, which implies the cloud had dissipated partially due to rainfall or evaporation at the C_L level. The CDPRe shows 4.2 μm at C_L while it is 6.4 μm at C_M. This marginal rise in CDPRe indicates the prevalence of very low cloud depth and hence the coalescence process is rather inefficient in such environment.

Figure 6a-e depicts scatter plots of cloud temperature and CDPRe during the wet spells. Cloud temperature varies between -15 to 25 °C. The temperature and CDPRe variation shows similar trend as observed during the dry spell. As temperature falls at higher altitude, growth of CDPRe increases to a maximum of 19 μm at C_M and a minimum of 5 μm at C_L. Fluctuation in CDPRe shows cloud droplets attaining maximum size at lower temperature and minimum at higher temperature. These fluctuations can be attributed to the dissipation of cloud due to rainfall or evaporation in the cloud environment or phase transformation from water to ice and vice-versa.

Variations of wind field during dry and wet spells

The wind data used in our analysis are obtained from the NCEP/NCAR Reanalysis data sets for the period from 1948 to present. These data are made available for purpose of research using state-of-the-art analysis/forecast system. A large subset of this data is available from PSD in its original 4 times daily format and as daily averages. The 4x daily data is considered for local ingestion process such as 0Z, 6Z, 12Z, and 18Z forecasted values, and only those were used to make the daily time series data sets. The daily NCEP/NCAR 700 hPa wind field (ms^{-1}) during dry and wet spells was analyzed to supplement the inferences drawn from air-borne measurements.

Figure 7a shows the composite analysis of 700 hPa wind field during dry spell, indicating the winds as blowing from northwesterly direction from the adjoining desert region. The transport of non hygroscopic aerosols from the desert regions of Saudi Arabia and Thar desert of Rajasthan might lead to the inhibition of CDPRe during the dry spell. The predominant northwesterly flow devoid of moisture and loaded with mineral dust from the adjoining desert region of Saudi Arabia during the dry spell corroborates the findings of Krishnamurti et al., (2010). In the drought (normal) year, during the pre-monsoon (March-May) season the higher aerosol loading and higher optical depth were associated with weak (strong) winds over India (Bhawar and Devara, 2010).

During dry spells, although the winds from Arabian Sea are southwesterly, they are not strong and confine to the ocean areas. They do not reach the west coast of India resulting in suppressed rainfall activity. During the wet spells (Figure 7b) the wind speeds gained significant momentum and increased drastically to 10-12 ms^{-1} blowing in the southwesterly direction, from Arabian Sea reaching up to central India. Strong south westerlies carrying abundant moisture loaded with highly hygroscopic sea salt aerosols favor strong convective activity, and thus helped in the revival of monsoon. Sateesh (2012) reported that when there was very strong wind (> 10 ms^{-1}) direct sea-spray production takes place by breaking of wave crests. Also Feingold et al., (1999) reported that sea salt particles are very efficient CCN due to its hygroscopic property. This suggests that the large scale wind forcing across the sea has a considerable influence on regional weather over interior Indian land mass and associated cloud microphysical parameters.

CONCLUSIONS

Analysis of aircraft measured data during CAIPEEX-2009 reveals the following significant characteristics of aerosol cloud interactions and cloud microphysical parameters.

i) There is a linear relationship between cloud droplet effective radius and liquid water content.

ii) During dry spell CDPRe was < 14 μm on all the days of aircraft observation at C_L and CDPRe in the medium cloud level $C_{M,}$ exceeds the threshold value of > 14 μm required for warm rain initiation during wet spells which implies that the collision and coalescence process is more efficient at cloud levels above 2000 meters during the wet spells.

(iii) The LWC and CDPRe are highly sensitive to cloud environmental temperature due to processes such as cloud water evaporation and phase transformation from ice to water.

(iv) During dry spells the flow of North westerly winds, which carry mineral dust aerosols from adjoining desert regions of Saudi Arabia and Thar desert of Rajasthan, appears to be one of the reasons for the low amount of LWC in cloud environment thus acting as limiting factor for the enhancement of CDPRe.

(v) The winds during wet spells at 700 hPa were significantly stronger and predominantly southwesterly with ~10-12 ms^{-1} velocity. They carry highly hygroscopic sea salt aerosols from the Arabian sea. Hence wind force plays major role during wet spells of Indian summer monsoon influencing the cloud microphysics.

(vi) The cloud seeding operations for rainfall enhancement is more likely to be successful during the prevalence of strong southwesterly wind flow from Arabian sea (velocity> 10-12 m/s.)

(vii) For better understanding of cloud microphysics this study recommends more aircraft observations over rain shadow regions of India during monsoon for generating longer multiyear data sets.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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