Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX) : Recent Findings

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ABSTRACT

Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX), an Indian National Experiment was carried out during 2009-2015 in three phases with a focus on the aerosol-cloud-precipitation interactions in the premonsoon and monsoon environment and to derive useful guidelines for cloud seeding purpose. In situ observations of aerosol, cloud microphysics and associated thermodynamics and dynamics were carried out with this campaign. There have been several research papers in refereed journals and data that was collected during the campaign has contributed significantly to the understanding of cloud microphysics in different environments over the Indian region. These observations are used at process level understanding and development of process parameterization. Vertical profiling of aerosol and cloud microphysical properties was carried out for the first time over India during CAIPEEX and revealed insightful understanding on the warm rain process and its link with subcloud aerosols, rain drop formation, ice nucleation, etc.

Keywords : *Aerosols, cloud microphysics, rain drop formation, ice nucleation.*

1. Introduction

Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX) is an Indian national experiment with a focus on the research and application aspects of processes in the premonsoon and monsoon clouds. The two main objectives of the CAIPEEX program were a) to address the physics and dynamics of aerosol-cloud-precipitation interactions and b) to formulate a scientific basis for rain formation and rain enhancement using the recent cloud seeding technologies. Indian Institute of Tropical Meteorology conducted a cloud seeding experiment in the 70's during which no definite conclusions could be made on the efficacy of seeding. CAIPEEX was formulated with the understanding that monsoon rainfall is heterogeneous in space and time and in spite of existing rain bearing clouds, several locations in India experience drought conditions during the monsoon season. The CAIPEEX program benefitted from the recent technological advances of in situ observational capabilities to measure cloud and aerosol microphysics. The main research emphasis on aerosols in India has been on its direct effect and CAIPEEX is first experiment to investigate the indirect effect of aerosols in monsoon clouds. The basis for cloud droplet and rain drop formation in monsoon clouds and how aerosol pollution influences these processes has been addressed in CAIPEEX.

2. Observations

Airborne observations of cloud microphysical parameters, aerosol size distribution, cloud condensation nuclei (CCN) concentrations and environmental parameters such as temperature, humidity and winds were carried out with the help of a twin engine Piper Cheyene pressurized aircraft in 2009, which was exploratory experiment for two reasons. This was to survey the aerosol, CCN and cloud droplet characteristics over different parts of India and to identify a suitable location to conduct cloud seeding experiment (Kulkarni et al., 2012 for details). During the Phase II of CAIPEEX (during 2010-2011), airborne observations were conducted with Hyderabad as the base station and generally continental clouds were observed. Total of 670 hours of observations were carried out under varying aerosol pollution conditions over these two phases of the experiment (Phase I in 2009 and Phase II in 2010-2011). CAIPEEX 2011 also included an Integrated Ground Observational Campaign (IGOC), which has made ground to cloud layer observations possible in an integrated way, addressing the thermodynamical and microphysical aspects of convection over the lee side of Western Ghat. The information on CAIPEEX and data and availability is at the website http://www.tropmet.res.in/~caipeex/

The main focus of CAIPEEX so far was on the scientific aspects of cloud-aerosol-precipitation interactions and the objective with the cloud seeding could be addressed only with the help of collocated C-band radar. We have collected a few observations which have already been discussed in the report provided at the website http:// www.tropmet.res.in/~lip/Publication/Scientific-Reports/SR-15.pdf . Formulation of guidelines will require more number of observations with aircraft and collocated C-band radar.

The understanding of cloud and precipitation formation is essential for accurate weather and climate modeling, where representation of clouds introduce one of the biggest uncertainties. Recent IPCC AR5 report states that "Cloud and aerosol properties vary at scales significantly smaller than those resolved in climate models, and cloud-scale processes respond to aerosol in nuanced ways at these scales. Until ***subgrid-scale parameterisations of clouds and aerosol-cloud interactions are able to address these issues, model estimates of aerosol-cloud interactions*** and their radiative effects will carry large uncertainties". Data collected in CAIPEEX field campaign address these aspects.

3. Aircraft and Instruments

Details of the aircraft and instruments used in Phase I of CAIPEEX have already been described in **Kulkarni et al., (2012, CS).** The Aero Commander 690A (South African Weather Service SAWS) was used as the CAIPEEX-II research aircraft in 2010 and 2011. The instruments were chosen (Fig.1) to have most accurate measurements of cloud particles that have a range of sizes, shapes, and concentrations. It was noted that water and ice coexisted in several of the observations made in deep cumulus clouds and more instruments were added in 2011 campaign to have detailed and reproducible observations. Cloud hydrometeors of different size and shapes were measured in situ by aircraft is invaluable for cloud microphysics studies.

Cloud droplets (<50 μm) were measured with a forward scattering probe (FSSP was used in Phase II and CDP in Phase I and III). Optical array probes are used for larger particle sizes which provides images for size and shape, which need to be processed later to derive various parameters of interest. These are CIP, PIP and 2D-C probes having different resolution and ranges as illustrated in the Figure. PMS Forward Scatter Spectrometer Probe (FSSP-100; 3-47 μm), Cloud Aerosol Spectrometer (CAS; 0.5-50 μm), the Cloud Imaging Probe (CIP; 25-1550 μm), Precipitation Imaging Probe (PIP), Liquid Water Content (LWC) hot-wire probe, the King LWC hot-wire probe, two dimensional stereo probe (2D-S; 10-1280 μm) were used in the campaign. Passive Cavity Aerosol Spectrometer Probe (PCASP; 0.1-3 μm) and CCN counter was used to characterize the subcloud aerosol size distribution and CCN concentration. The nucleation mode aerosol size and concentration were measured by a high flow differential mobility analyzer (DMA; 0.02 to 0.47 μm) in 2011 campaign.

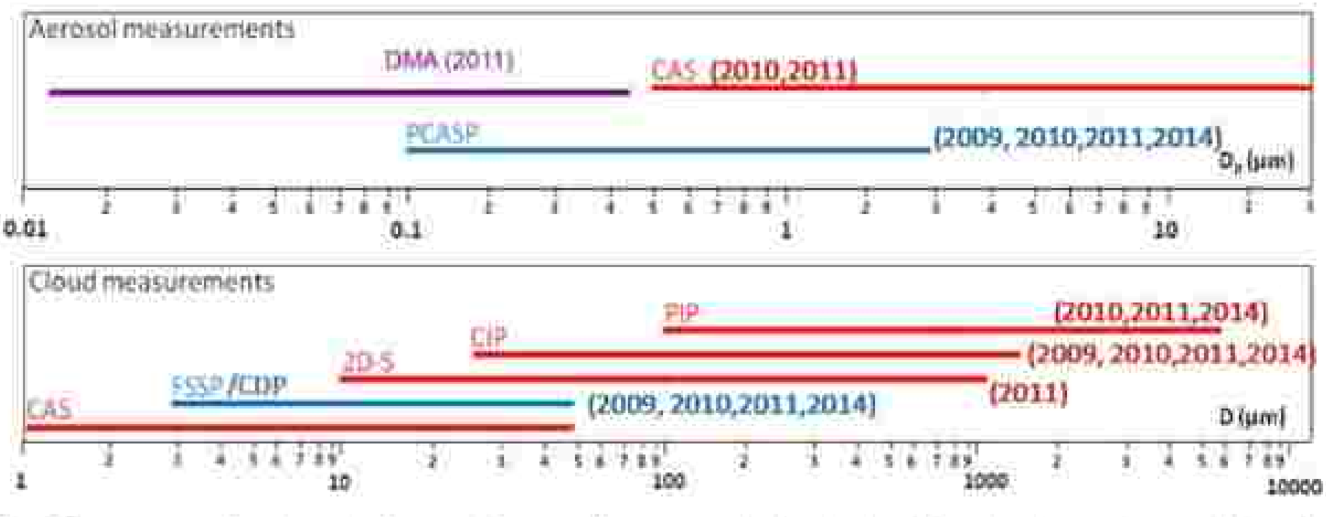

Fig.1 Summary of various instruments used for aerosol, cloud droplet, rain drops, ice particle size distributions (DMA: Differential Mobility analyser ,PCASP: Passive Cavity Aerosol Spectrometer Probe , FSSP: Forward scattering spectrometer probe, CAS: Cloud Aerosol spectrometer, CDP: Cloud Droplet Probe, CIP: Cloud Imaging Probe, 2D-S: 2D stereo cloud probe, PIP: Precipitation Imaging Probe) from 4 phases of CAIPEEX.

The single engine Ayres Turbo Thrush aircraft was used as a seeder aircraft. It could disperse salt micropowder and had flare racks that carry 20 hygroscopic or glaciogenic flares. The aircraft was also instrumented with a PCASP, FSSP, CCN, CPC, LWC and AIMMS probe during 2011 CAIPEEX.

Beechcraft King Air B-200 aircraft was hired in the Phase III with the cloud physics and aerosol instrumentation as illustrated in Figure 1. In addition to the LTC, Total Water content probe (TWC), AIMMS and several instruments such as Cloud Combination Probe (CCP), Chemistry of aerosol and precipitation particles, CRDS gas analysers were installed by IITM.

4. Droplet Size Distribution in Premonsoon and Monsoon Clouds

Fig.2 gives an example of aerosol and cloud droplet size distribution observation during CAIPEEX. It may be noted that the observations in the size ranges from 0.01 to 10000 µm requires different instruments as illustrated earlier. The size distribution from various instruments also has an overlap, which indeed demonstrates the quality and reliability of these observations.

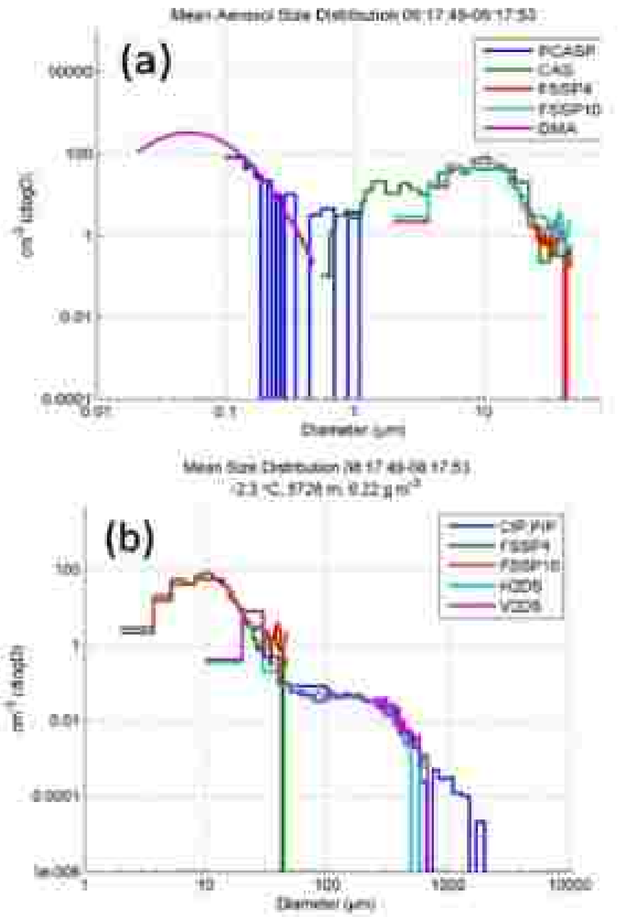

Fig.2 Aerosol size distribution (a) outside cloud and cloud droplet - precipitation and ice particle size distribution (b) measured in a congestus cloud. The combined size distribution is from various probes. There is very good agreement between the different probes.

The indirect effect of aerosols was not addressed in any of the observational campaigns prior to CAIPEEX. In polluted conditions, with more aerosol particles, droplet size is much smaller and spectrum is narrower as collision-coalescence is suppressed as compared to the cleaner conditions.

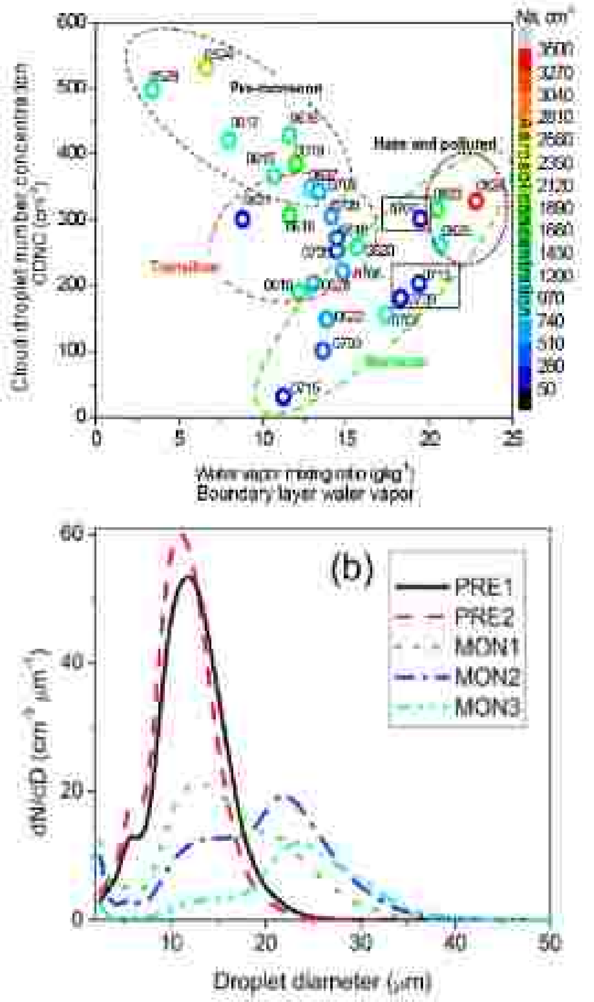

Fig.3 The variation of cloud droplet number concentration in the premonsoon, transition and monsoon periods (indicated with boundary layer water vapor). The observations corresponding to hazy conditions are indicated in the figure. The droplet size distribution in the premonsoon (PRE1, PRE2) and monsoon cloud (MON1, MON2, MON3) showed gradual change from the single mode to multiple modes in the conditions during the monsoon (MON2, MON1) with high aerosol. (from Prabha et al., 2012 JGR).

Droplet size distributions (DSDs) in highly polluted premonsoon clouds are substantially narrower than DSDs (Fig.3) in less polluted monsoon clouds. High DSD dispersion is attributed to the existence of small cloud droplets with diameters less than 10 µm, found at all levels. The presence of small droplets lead to the bimodal spectra (Fig.4), which was more pronounced with the polluted monsoon clouds. Observational evidence for incloud activation was presented. It was found that such multiple modes are attributed to incloud activation/evaporation of particles/cloud droplets (Prabha et al., 2011, JAS). The secondary modes in the droplet size distribution as illustrated in the Figure 5. Incloud activation may be the presence of interstitial aerosol particles in cloud updrafts and there is high liquid water in the polluted clouds close to its top. This study emphasized the need to include aerosol processing in cloud models, where aerosol activation is designed only at cloud base.

Morwal et al (2012; JASTP) illustrated the cloud droplet size distribution effective radius over geographically different locations in India. The drop size distribution was wider at elevated layers and the effective radius increased with height. Nair et al., (2012, AR) illustrated various cloud microphysical parameters in the premonsoon, transition to monsoon and active monsoon conditions.

Padmakumari et al., (2012, IJRS) compared the space-borne lidar (CALIPSO) and radar (CloudSat) together with the aircraft observations (Fig.5). Similar features of aerosol layering and cloud parameters are observed by both aircraft and CALIPSO. The CloudSat

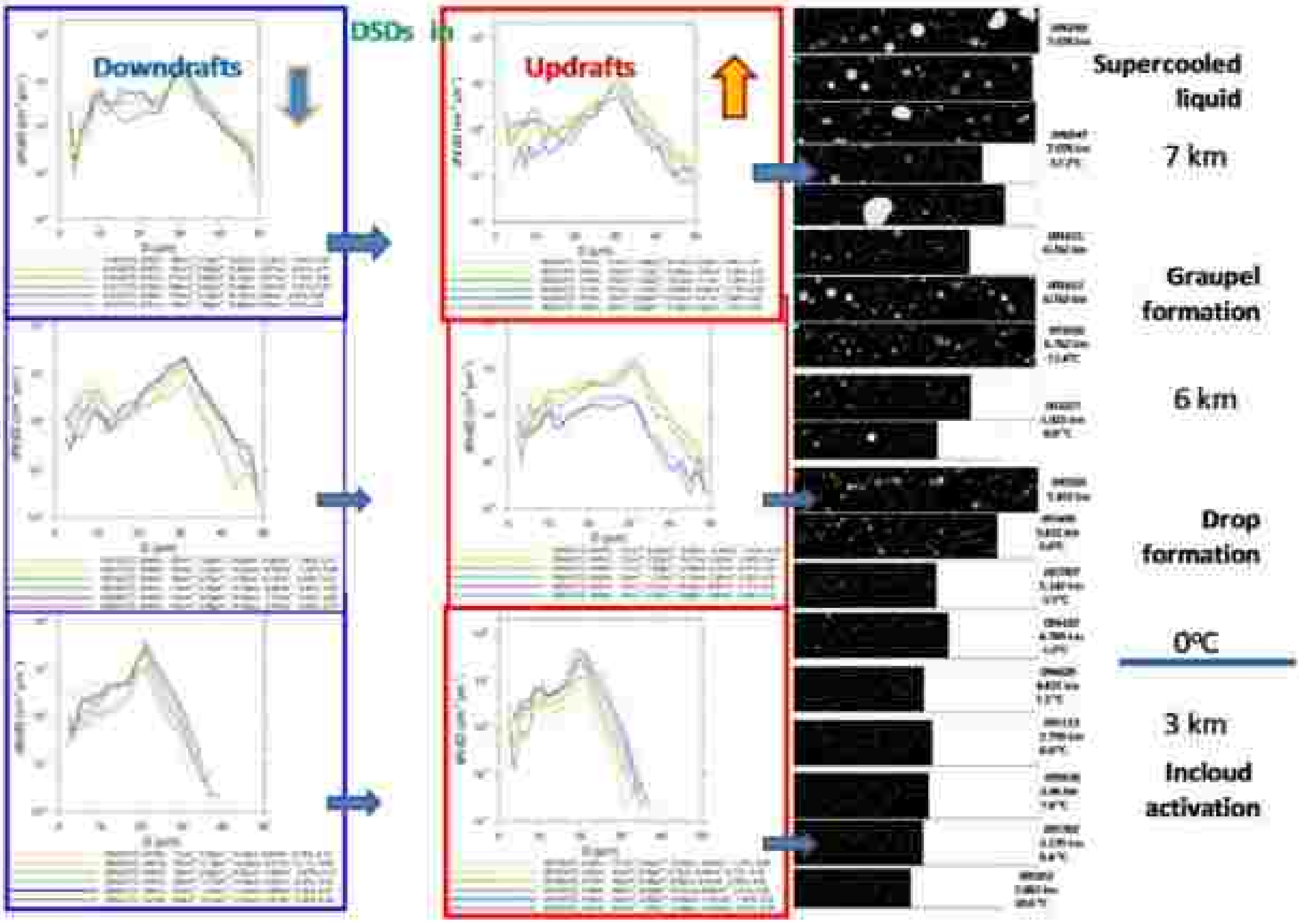

Fig.4 Variation of droplet size distribution in the downdrafts (left) and updrafts (right) from Cloud Droplet Probe (CDP) and the Cloud Imaging Probe images of cloud droplets, graupel and supercooled drops in the monsoon cloud. The legend is labeled with Time, Height, droplet number concentration, liquid water content, effective radius, vertical velocity, quasistationary supersaturation and adiabatic fraction. The mixed phase nature of these clouds was illustrated for the first time with in situ observations. (derived Prabha et al., 2011, JAS)

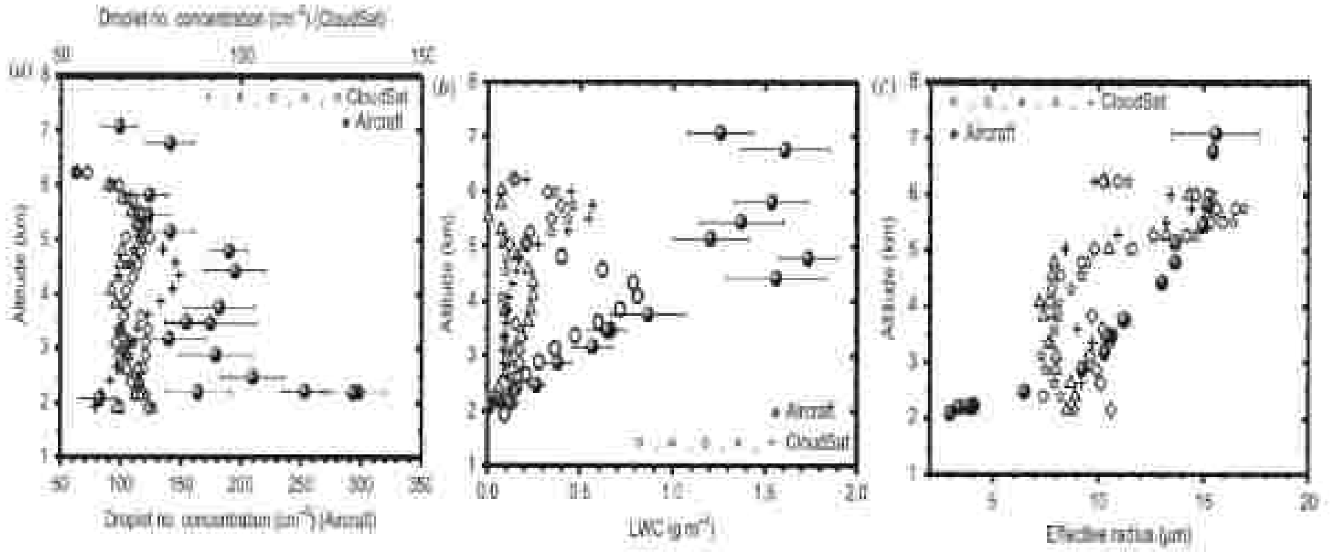

Fig.5 CloudSat-and aircraft-derived cloud microphysical parameters such as (a) droplet number concentration, (b) liquid water content, and (c) droplet effective radii. (The bars represent spatial variation along specific level. Different symbols are given for CloudSat, each symbol representing retrievals at different neighbouring lat-long coordinates close to the aircraft profiled area along the satellite track.) (Derived from Padmakumari et al., IJRS, 2012).

profiles of liquid water content, droplet number concentration, and effective radii are underestimated when compared with the corresponding aircraft profiles. It is also illustrated that there is possible dust aerosols acting as ice nuclei.

5. Process Parameterization

A simple parameterization for cloud droplet effective radius, useful in the numerical models was proposed from CAIPEEX observations of 2009 (Nair et al., 2012, AR). A linear relationship between the cloud droplet number concentration and adiabatic fraction (a measure of mixing between the cloud and its environment) was suggested as a simple formulation that will be useful for large scale models to predict cloud droplet number concentration, when cloud liquid water content only is diagnosed. Filter samples collected on the CAIPEEX aircraft are analysed in a thermal gradient diffusion chamber (TGDC) (developed at Pune University) designed to process the ice nuclei (IN) sample. IN activated by deposition mode over ice supersaturation of 6-24% and at a temperature range of -18.5 to -13.5 oC were found to be less than 5 L-1. These samples correspond to first observations at several vertical levels including the cloud layer and over several geographically distinct locations in India during the monsoon season. These observations illustrate that the Meyers IN parameterization currently used in the numerical models overestimate IN concentration at all supersaturations by an order. The simulations indicate that this can have a significant impact on the spatial distribution of mixed phase and ice clouds predictions.

6. Rain Drop Formation in Monsoon Clouds

The effective radius in developing cloud increases with height and it becomes more than a critical effective radius when the collision coalescence becomes very effective. The height of this critical effective radius (12-14 μm) depends

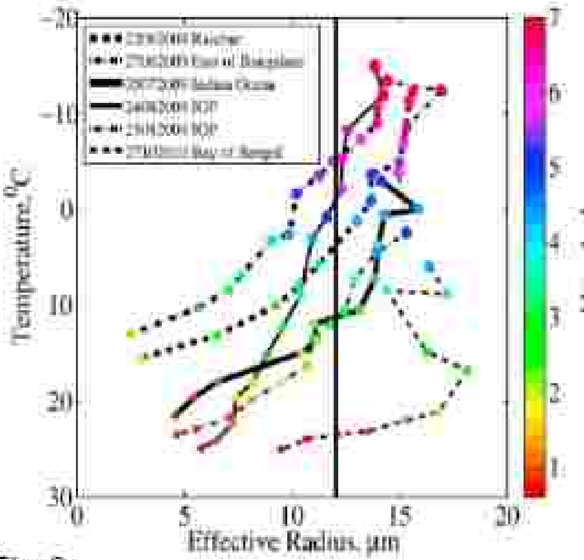

Fig.6a

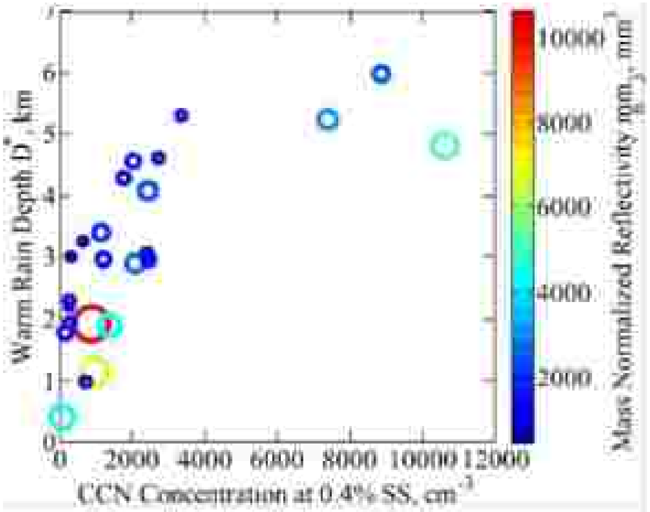

Fig.6b

Fig.6a&b Vertical variation of effective radius (a: vertical line is effective radiuys threshold for warm rain initiation 12 μm) shows that warm rain initiated at lower heights over the Bay of Bengal compared to moderately polluted peninsular land region and very highly polluted Indo Gangetic Plains (IGP). Higher CCN increases the warm rain depth (b) and presence of Giant CCN (GCCN; indicated by size of symbols, color is mass normalized reflectivity) reduces the warm rain depth. Each point in the plot is an observation from CAIPEEX. (derived from Konwar et al., 2012 JGR).

linearly on the aerosol concentration at the cloud base as illustrated from CAIPEEX and several other field campaigns around the world (Freud et al., 2011). Increase in warm rain depth with aerosol number concentration (Figure 6) in several cloud observations during CAIPEEX has been illustrated by Konwar et al., (2012 JGR).

It has been further illustrated from the 2D and 3D bin microphysics simulations (Khain et al., 2013, JGR) and CAIPEEX observations that the height of first raindrop formation in monsoon clouds depends linearly on the droplet number concentration at cloud base. First raindrops form in slightly diluted cloudy volumes at the tops of bubble cores. First rain formation is determined largely by the basic condensation and collision mechanisms in ascending adiabatic volumes. These results also indicated that we can predict the height of the formation of first rain drops considering the processes of nucleation, diffusion growth and collisions. This idea has lead to the formulation of an autoconversion parameterization using CAIPEEX observations.

7. Cloud Microphysics in the Premonsoon and Monsoon Clouds and Dispersion

In polluted conditions, with more aerosol particles, droplet size is much smaller and spectrum is narrower as collision-coalescence is suppressed, compared to the cleaner conditions. A simple parameterization for cloud droplet effective radius, useful in the numerical models was proposed from CAIPEEX observations of 2009 (Nair et al., 2012, AR). The aerosol effect on cloud microphysical properties and droplet dispersion characteristics were addressed by (Pandithurai et al., 2012 JGR; Prabha et al., 2012b JGR). It is shown that the entrainment effect can drastically influence the droplet dispersion and is heterogeneous with height, while raindrop formation occurred in the slightly mixed cloud parcels (Prabha et al 2012b, JGR), indicating that entrainment effects did not play a role in the raindrop/large drop formation.

The vertical variation of spectral width and mean radius in different aerosol conditions during monsoon is illustrated in Fig. 7. Mean radius increases rapidly above cloud base in the clean monsoon. Raindrops form at a lower level in clean monsoon, while at elevated layer in the high aerosol conditions (indicated with vertical pointing arrow). Mixing at cloud edges reduces the droplet size and spectral width, which is illustrated with the adiabatic fraction (Fig.7). Adiabatic fraction is ratio of the liquid water content measured in the cloud and the adiabatic estimate of liquid water content. The low adiabatic content cloud parcels exhibit reduced droplet mean radius and spectral width. High adiabatic fraction parcels have maximum spectral width and mean radius, indicating large droplets/drops in adiabatic parcels, also the region for rain drop formation. The results also indicate that the evaporation of cloud droplets through entrainment and mixing mechanism is very important and may lead to near linear variation of mean radius with height. Meanwhile in adiabatic regions, the droplet diffusional growth and collision coalescence prevails, which lead to a more non linear variation of mean radius with height. As evident, the collision coalescence is more active in the clean monsoon cloud at lower elevations. In the case of polluted monsoon cloud, collision coalescence become active at higher levels in the cloud.

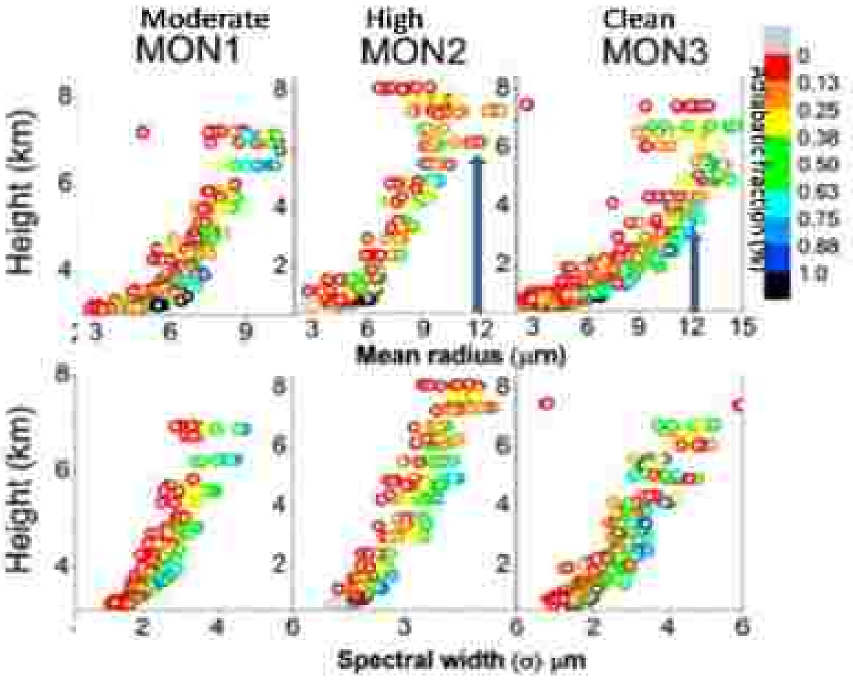

Fig 7 Vertical variation of mean radius and spectral width of cloud droplet size distribution in three different aerosol environments in monsoon clouds (derived from Prabha et al., 2012, JGR)

8. Dispersion Effect

Pandithurai et al (2012, JGR) showed that the aerosol indirect effect may be offset by the dispersion effect up to 39 % (Fig.8) and this will have implications to climate/weather model results where dispersion effect is not incorporated.

9. Elevated Aerosol Layers and Mechanism of their Formation

The fine mode (0.1-3.0 ?m) aerosol vertical profiles up to 6 km at different regions showed different vertical structures mostly influenced by the atmospheric boundary layer (ABL) depth as well as the origin of air mass trajectories and the presence of clouds (Padmakumari et al., 2013, AE). Elevated aerosol layers are observed during pre-monsoon and during monsoon. During monsoon, aerosol number concentration showed strong vertical gradient. The coarse mode (>3 ?m) aerosol vertical profiles also showed elevated layers at higher altitudes due to the incursion of dry air laden with dust. The spatial distribution shows significant variation at the elevated layers as compared to that in the boundary layer during pre-monsoon, while high variability is observed in the boundary layer during monsoon.

Spatial and vertical distribution of aerosols near the foothills of the Himalayas during May 2009 near the foothills of the Himalayas is investigated by Padmakumari et al. (2013 QJRMS). Elevated aerosol layers up to 4 km (Fig. 9) with varying concentrations were observed which are attributed to sources from local anthropogenic activities and biomass burning, dust from local and long-range transport. The aerosol size distributions indicated increases in both fine and coarse mode aerosols in elevated layers. Single scattering albedo profiles depicted the presence of both absorbing and non-absorbing type aerosols on different days. Clouds observed above the elevated aerosol layers showed higher droplet concentrations exceeding 1000 cm?3 with small effective radii <6 ?m.

The origin of these elevated aerosol layers were investigated by Prabha et al (2012a, JGR). Horizontal flights across the Himalayan slopes were used to investigate the mechanism that favors transport across the valley to Tibetan Plateau. Turbulence measurements from a horizontal flight path are used to illustrate the scale interactions in the vertically sheared flow below the high-level subtropical westerly jet. Large eddies that scale 10-12 km near the slopes (Fig. 10) could bring pollution from the valley to the Tibetan Plateau through a circulation adhering to the slopes. There is a subsidence region away from the slopes could contribute to the build-up of pollution in elevated layers over the Plains. The vertical velocity and

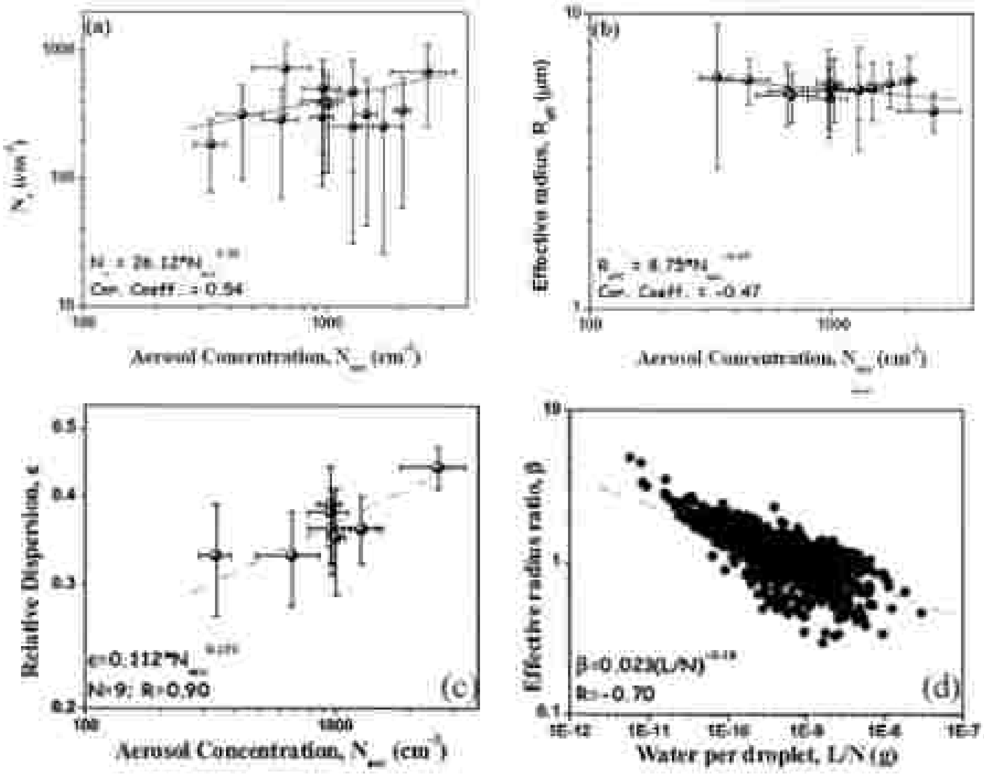

Fig.8 Variation of cloud droplet number concentration (a), Effective radius (b) relative dispersion (ratio of spectral width and mean radius) with the aerosol number concentration and effective radius ratio (β) for cloud liquid water per droplet. (Derived from Pandithurai et al., 2012 JGR).

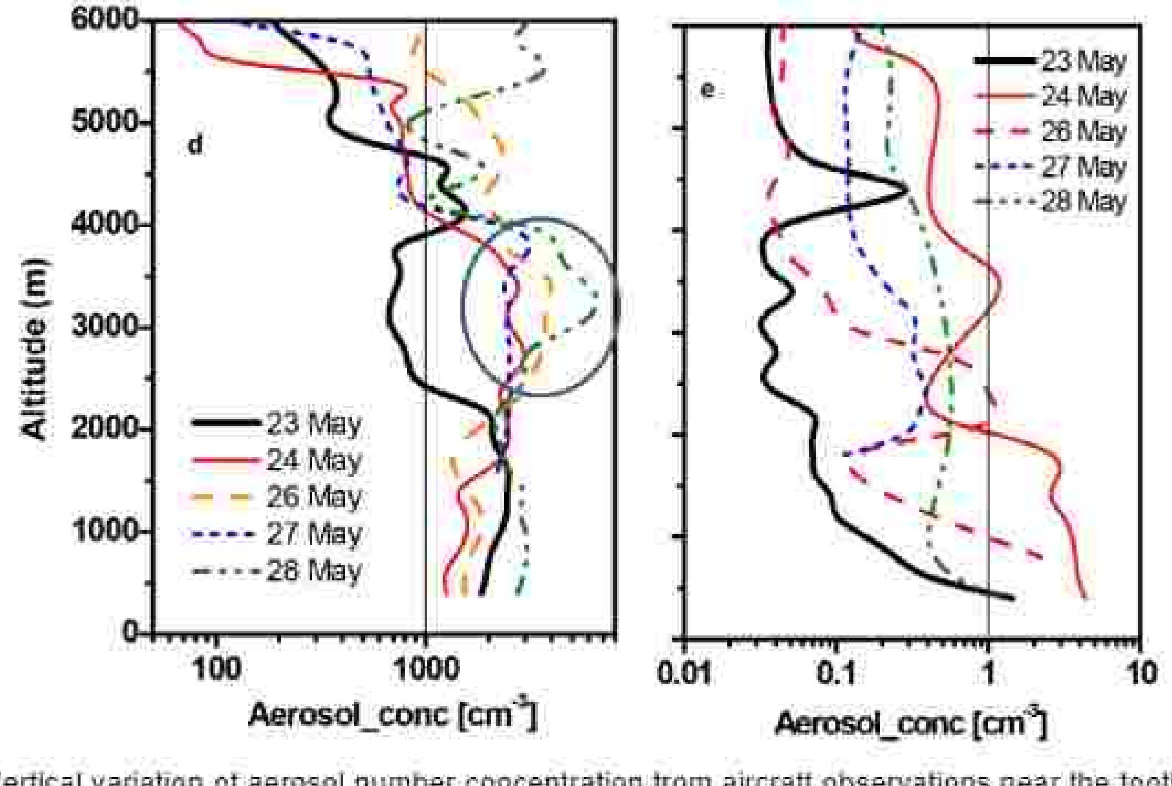

Fig.9 Vertical variation of aerosol number concentration from aircraft observations near the foothills of Himalayas (Padmakumari et al., 2013, QJRMS)

temperature spectra from research flight data showed clear indications of (-5/3) slope in the mesoscale range. A conceptual understanding of the flow in the region close to the foot hills and its role in the distribution of aerosol and cloud condensation nuclei was illustrated in this study.

CAIPEEX observations together with WRF-Chem model simulations was used to investigate the dust emission from Thar desert and its role in the elevated aerosol layers and warming and subsequent influence on the cloud microphysics of propagating systems from BoB during monsoon onset of 2009 (Dipu et al., 2012, AE). It is observed that aerosol loading increased over the central Indian region in spite of the increase in surface rainfall, attributed to increase in elevated layer aerosols (2-5 km level above surface). The origin and influence of elevated aerosol layer have been investigated with the help of WRF-Chem simulations by conducting sensitivity experiments for dust emissions based on erodible fraction over the Thar Desert region attributing to enhanced dust emissions by a factor of 1.25. This resulted in an increased radiative heating in the elevated layers, which leads to an increase in the ice mixing ratio and ice water content associated with the monsoon onset (Fig.11). It is illustrated that even natural dust emissions (without changes in anthropogenic emissions) may also influence the spatial and temporal distribution of cloud and precipitation and the hydrological cycle.

Special research flights carried out on 19 and 20 October, 2011 in the Bay of Bengal in the vicinity of a depression illustrated the aerosol-cloud interactions over marine environment (Deshpande et al., 2013 AR). The concentration of aitken/accumulation mode particles was high at 500 m above sea surface level over the ocean after the passage of the depression. They attributed the source of these particles and their subsequent growth at about 200 km from coastline to oxidation of dimethyl sulfide (DMS) because of upwelling of

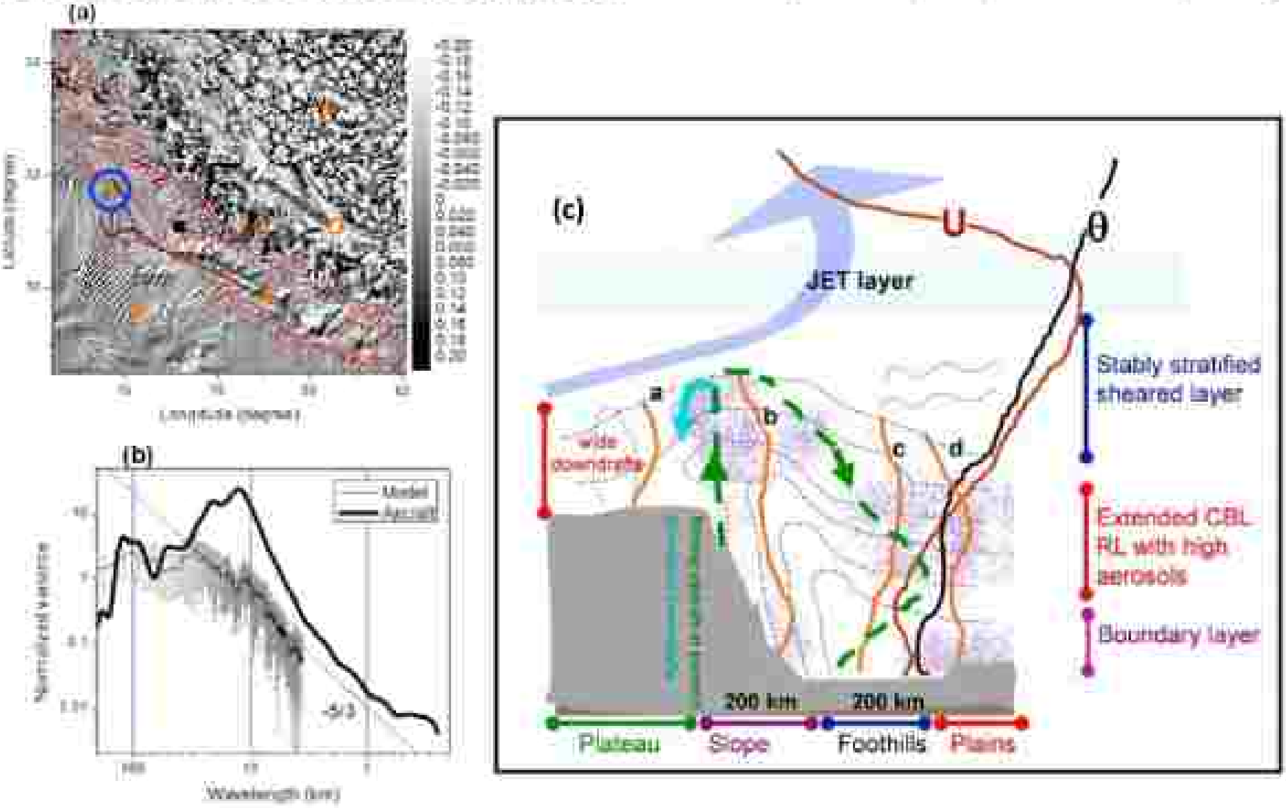

Fig.10 Horizontal distribution of vertical velocity at 6.6 km above mean sea level (a) CAIPEEX flight tracks are shown with thick line, also indicates regions of (i) gravity waves across slopes along CAIPEEX flight track., (ii) gravity waves away from slopes, (iii) strong updrafts on the slopes in the pockets, (iv) downdraft area on the summit, (v) narrow convective updrafts and wide downdrafts on the Plateau. The vertical velocity specra from the CAIPEEX aircraft is compared with high resolution model (b). (c) shows a conceptual understanding derived from CAIPEEX observations and numerical model for the aerosol spatial distribution and transport across Indo Ganges Valley. (Derived from Prabha et al., 2012a JGR).

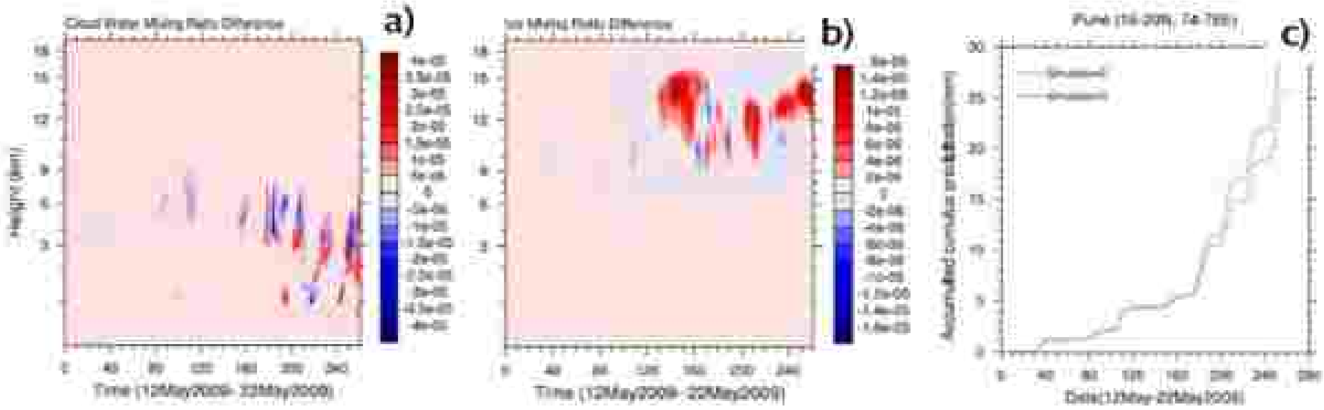

Fig.11 Difference in Cloud water mixing ratio (a), ice water mixing ratio (b) and accumulated precipitation from (c) from a sensitivity experiment by increasing Dust emission from Thar Desert (d). The experiment was conducted for the dry to wet transition during end of May 2009. It shows that natural emissions itself can contribute to a radiative-dynamically driven differences in the precipitation and cloud fields. (derived from Dipu et al., 2012, AE)

the deep ocean water during the depression and anthropogenic aerosols transported from inland. No evidence of increasing particle concentration and growth has been observed at about 60 km from coastline towards southeast.

Particle size distribution in cloud free zone (CFZ) and cloud shadow zone (CSZ) and the radiative forcing associated with them were investigated by Konwar et al., (2015, JGR). It was shown that extinction coefficient decreases with increasing distances from the cloud edges. Large deviations of effective radius of particles from their mean values are observed in highly humid conditions, however, there was positive correlation with relative humidity indicating swelling of aerosols in humidified environment (Fig.12). Mean radiative surface forcing (SF) and top of the atmosphere (TOA) forcing in the cloud free zone (CFZ) and cloud shadow zone (CSZ) indicated that mean surface cooling may be increased by 4% due to the aerosols in the near cloud regions and mean TOA forcing was increased by nearly 20% in the Cloud shadow region.

10. Vertical Profiling of Black Carbon

Vertical variation of black carbon (BC) play an important role in the direct and indirect effect by acting as an absorbing aerosol or as cloud condensation or ice nuclei which help formation of clouds. CAIPEEX observations of BC conducted over two locations were used to investigate the aerosol induced radiative forcing for central India to the north and the pristine ocean to the south to illustrate the north south asymmetry in the heating (Manoj et al., 2011, CD). In that study, a seminal

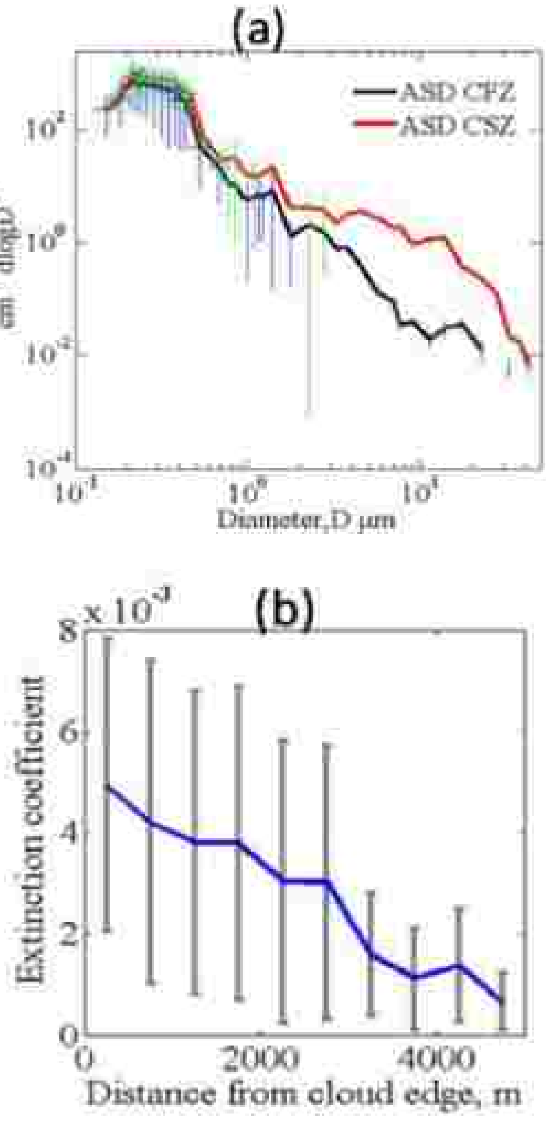

Fig.12 a & b

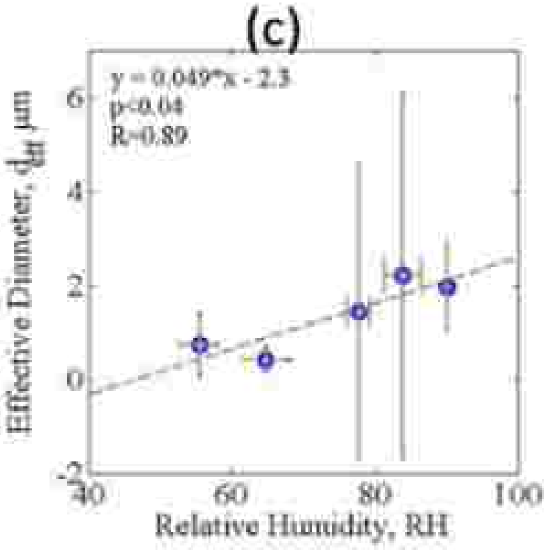

Fig.12 Combined aerosol size distribution from Passive Cavity Aerosol Spectrometer Probe (PCASP; 0.1 to 3 ?m) and Cloud Aerosol Spectrometer (CAS 0.5-50 ?m) (derived from Konwar et al., 2015, JGR).

role played by the absorbing aerosols in the transition from break to active spells was illustrated through modification of the north-south temperature gradient at lower levels.

Safai et al., (2012 STE) illustrated that the BC observations onboard the aircraft from Bangalore and Hyderabad. BC mass loadings decreased monotonically from 103 to 104 ng/m3 at the surface to ~102 ng/m3 at an altitude of about 7 km; although layers at intermediate levels containing anomalously high BC loadings were frequently encountered that were attributed mainly to the convective transport from surface sources accompanied by changes in the local boundary layer and atmospheric stability. The presence of BC in cloud in the regions where clouds are observed have important implications for cloud microphysics and subsequent rainfall mechanism over this region. Apart from this, the effects on human health are equally important.

Aircraft observations on vertical profiles of Black Carbon (BC) observations conducted during CAIPEEX I in monsoon 2009 over Guwahati, in the Brahmaputra River Valley (BRV) region, NE India was illustrated by Rahul et al., (2013, SR). They noted that surface/near surface loading of BC due to anthropogenic processes caused a heating of 2 K/day. The large-scale Walker and Hadley atmospheric circulations associated with the Indian summer monsoon helped in the formation of a second layer of BC in the upper atmosphere. Elevated layer of BC generates an upper atmospheric heating of 2 K/day with the lofting of BC aerosols.

Simultaneous aircraft observations of Black Carbon (BC) mass concentrations and cloud microphysical parameters were used by Paniker et al., (2014, AE) to illustrate possible 'semi direct effect' or the cloud burning effect (Fig.13). Elevated pollution layers of BC (concentration exceeding 1 ?g m-3) observed resulted in instantaneous vertical heating rate induced by BC in cloud layers to be 2.65 K day-1, leading to a significant reduction in the measured cloud liquid water content (LWC) over the site. BC stimulated heating was found to be reducing the cloud fraction (CFR) and may be contributing to a "cloud burning effect (Semi direct

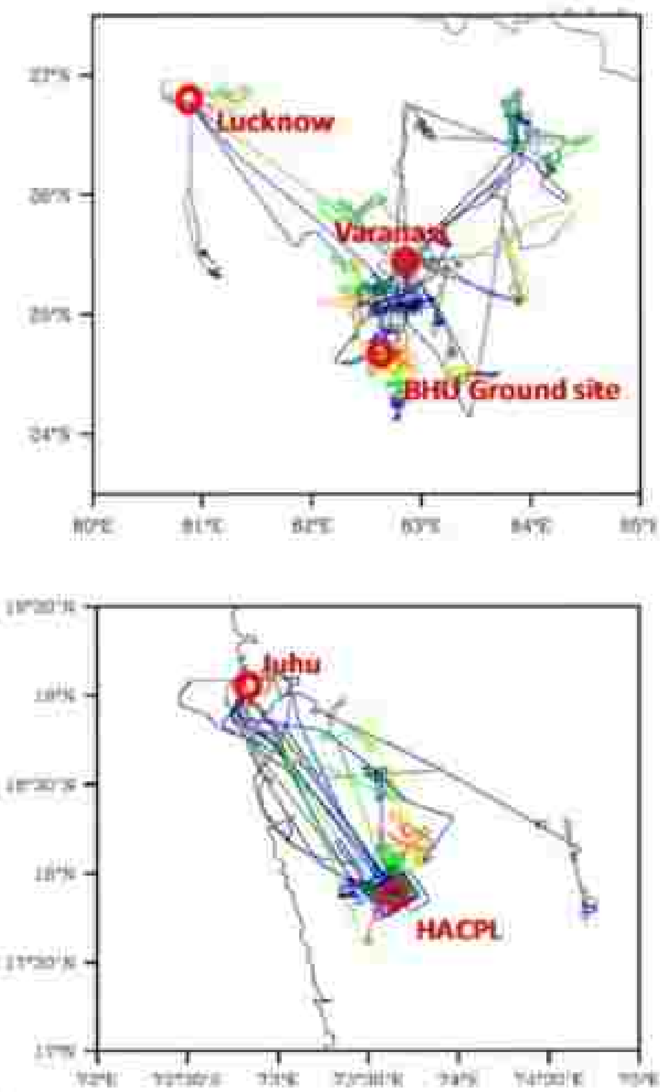

Fig.13 Flight tracks from Varanasi (9-30th Sept 2014) and from Juhu Airport during the CAIPEEX Phase III campaign.

effect)" over the region. The estimated instantaneous BC induced radiative forcing in the cloud regime was +12.7 to + 45.1Wm-2 during the experimental period. This large warming and reduction in cloudiness can decrease the precipitation over this vulnerable region.

11. Rainfall Characteristics over the West Coast and over Western Ghat

The mechanism responsible for high rainfall over the Indian west coast region has been investigated by studying dynamical, thermodynamical and microphysical processes over the region for the monsoon season by Maheshkumar et al., (2013 CD). The moist adiabatic and multi-level inversion stratifications were esisting during the high and low rainfall spells, respectively. In the moist adiabatic stratification regime, shallow and deep convective clouds coexist. The low updrafts (as indicated by CAIPEEX observations) provided sufficient time required for warm rain processes to produce rainfall from shallow clouds. The updrafts at the high spectrum end go above freezing level to generate ice particles produced due to mixed-phase rainfall process from deep convective clouds.

Suppression of rainfall over the rainfall over the rain shadow region was discussed by Konwar et al., (2010 ACPD) from CAIPEEX observations. Low rainfall over the rain-shadow region of Western Ghats is investigated by Narkhedkar et al., (2015, CD). They noted that convergence at 850 hPa and divergence at 400 hPa level is due to dynamical forcing and generates high frequency of occurrence of congestus clouds. These congestus clouds are continental and have high cloud bases and have large number of small droplets. The high cloud bases reduce the depth of warm region in the cloud leading to an inefficient warm rain process. The thermodynamic structure showed dry surface level and warm and moist middle troposphere with tongues of dry air and multilevel inversions which have been attributed to advection of aerosol-rich dry air. They illustrated the integrated impact of these factors is to produce low rainfall over the rain-shadow region of the north peninsular India.

CAIPEEX Aircraft observations over the WG revealed that forced updrafts foster rapid condensational growth of cloud droplets, triggering coalescence process within few hundred meters of cloud depth (Konwar et al., 2013, JGR), giving the idea that the clouds are dynamically forced. Bi and mono-modal drop size distribution are observed during light and heavy rainfall respectively. With shallow storm heights, small raindrops mainly contribute to both types of rainfall. The DSDs are parameterized and their radar reflectivity factor-rainfall intensity relationships were evaluated, suggesting the dominance of collision-coalescence processes.

12. CAIPEEX Phase III

The CAIPEEX Phase III was planned to take place in two parts. Part I in 2014 with an emphasis on convective clouds and their vertical structure during the course of the monsoon season and investigating the convection invigoration by aerosols. Beechcraft B200 aircraft was hired with several state of the art aerosol and cloud physics instruments. In 2014, the Phase III of CAIPEEX was conducted in the Ganga Basin with Varanasi as the base. The main objective of the experiment was to investigate the hypothesis that pollution may invigorate clouds. The ground based observational network in this region by various research groups adds value to the airborne observations to bring it to a regional campaign. There was a special emphasis in the program to make chemistry measurements in clouds, which could not be the focus of earlier CAIPEEX I and II campaigns.

The Phase III of CAIPEEX started in May 2014 with a set up of ground based and airborne observations started on 9th Sept 2014. The aircraft observations together with the ground based observations were conducted during 2014. 49 Hours of airborne observations were conducted from Varanasi during the Phase III. Ground based observations were conducted from the rural campus of Banaras Hindu University. The Phase III also carried out several aerosol and precipitation chemistry measurements on board the aircraft such as Particle in Liquid Sampler (PILS), Photo Acoustic Extinctiometer (PAX) for black carbon measurements, Cavity Ring Down Spectrometer (CRDS) for CO_2, CH_4, CO and H_2O.

IITM has a High Altitude Cloud Physics Laboratory (HACPL) at Mahabaleswar, where in situ observations of clouds are conducted with ground based observations and with X-band and Ka-band radars. 26 Hours of airborne observations were carried out in 2014 in coordination with the HACPL and Radar observations. Phase III data is currently undergoing corrections.

It was also proposed to conduct the cloud seeding experiment in 2015-2016 as part II of Phase III experiment. However, to collect more randomized samples so that scientifically based guidelines for the cloud seeding can be derived, there is requirement for a C-band radar. CAIPEEX

Phase III experiment is continuing in Varanasi with detailed airborne observations and ground based observations investigating aerosol-cloud interaction.

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