Role of Topography and Aerosols in the Rainfall over the Western Ghats and Rain Shadow Regions as Inferred from Aircraft Measurements

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ABSTRACT

The topography and aerosol roles in the heavy rainfall zone at the Western Ghats and the scarce rainfall farther east at the rain shadow were studied during Cloud Aerosol Interaction and Precipitation Enhancement EXperiment (CAIPEEX-2009) conducted over the Indian sub-continent using an instrumented research aircraft. Analysis of cloud microphysics (cloud droplet number concentration (CDNC) and effective radii (Re)) and aerosol number concentrations showed that the warm rain initiation starts at early stages (lower cloud depths) over the coastal areas and becomes even lower at the crest of the western slopes, probably due to intense washout of the aerosols by the rain. However, the clouds lose their microphysically maritime character farther east over the rain shadow regions, where the clouds have to grow to higher depths to initiate the rain process. The aerosol and Cloud Condensation Nuclei (CCN) concentrations support the hypothesis that the shallow convective clouds (i.e., with tops < 6 km) lose their ability to rain over the rain shadow due to increased aerosol concentrations, which are probably attributed to air pollution.

Keywords: *Cloud microphysics, Aerosols, Warm rain depth, CCN, West coast, CAIPEEX.*

1. Introduction

Atmospheric aerosols aid as cloud condensation nuclei (CCN) and play an important role in modifying the cloud micro as well as macro physical properties. Over the Indian sub-continent aerosol indirect effects were revealed by many studies using airborne, satellite and ground-based measurements (Padmakumari et al., 2017; Morwal et al., 2012; Pandithurai et al., 2012; Konwar et al., 2012; Harikishan et al., 2015). Also, aerosols through their direct effects modify the environmental temperature structure and atmospheric circulation, and thereby influence the precipitation processes. Earlier studies showed a significant relationship between pre-monsoon aerosols and subsequent monsoon rainfall (Devara et al., 2003). The elevated heat pump hypothesis proposed by Lau and Kim (2006) revealed that aerosols play a significant role in increasing the rainfall over northern India during May and June. It was also found that over central India (CI) heating of the lower atmosphere by absorbing aerosols during monsoon breaks influence transition from break to active condition through enhancement of the north-south temperature gradient and increase in low-level moisture convergence to CI (Manoj et al. 2011).

During summer monsoon season (JJAS) west coast of India gets heavy rainfall. Earlier many studies have been carried out to understand the mechanism of heavy rainfall over the west coast (Rao 1976; Grossman and Duran 1984; Grossman and Garcia 1990; Roca and Ramanathan 2000; Francis and Gadgil 2006; Medina et al. 2010). Recently Maheskumar et al., 2014 proposed a new mechanism of rainfall process over the west coast using dynamical, thermodynamical, cloud microphysics and the associated processes therein. In their study cloud microphysics has been addressed using the aircraft observations conducted over the west coast during Cloud Aerosol Interaction and Precipitation Enhancement EXperiment (CAIPEEX).

CAIPEEX is a National Program conducted over different parts of the country using a research aircraft during May-September 2009. The Arabian sea branch of the SW monsoon first hits the West coast of the Indian sub-continent and rain heavily over the western slopes of the Ghats. Over the eastern slopes and further east over the plains, the rain shadow effect suppresses the rainfall. In the present study the aircraft observations carried out during the peak monsoon month of July over the ocean, Western Ghats, to the east of Western Ghats and rain shadow area are used to understand the role of topography and aerosols in the rainfall process over the Western Ghats and rain shadow regions. The objectives of this study are to (i)find the role of cloud–aerosol interactions in the primarily dynamically controlled distribution of rainfall (ii)understand the sensitivity to aerosols which would explain a possible further reduction of precipitation due to air pollution and to (iii) explore the potential for rain enhancement by cloud seeding in case of sensitivity to aerosols.

2. Data and Methodology

An instrumented aircraft was used during CAIPEEX- 2009. The research aircraft carried a suit of instruments for the measurements of state parameters such as temperature, pressure, relative humidity, and wind speed; aerosol and cloud microphysics. The suit of instruments with measured parameters, range, accuracy, resolution and frequency are detailed in Kulkarni et al., 2012. Passive Cavity Aerosol Spectrometer Probe (PCASP-SPP200) manufactured by Droplet Measurement Technologies (DMT), USA was used to measure aerosol size distribution in the range of 0.1 to 3 µm. The CCN counter from DMT was used to measure cloud condensation nuclei at different super-saturations (SS) such as 0.2%, 0.4% and 0.6%. Cloud liquid water content (LWC) was measured from DMT hot-wire LWC probe in the range of 0.01 – 3 gm-3. Cloud measurements are made with DMT's Cloud Droplet Probe (CDP). CDP measures the droplet size distribution in the range of 2 – 50 µm and total cloud droplet number concentration (CDNC). Cloud droplet effective radius (Re), which is defined as the ratio of the third to the second moment of the cloud droplet size distribution (Hansen and Travis, 1974) has been computed. The resolution of the data collected was 1 Hz (~ 100 m).

Aerosol types and their vertical and spatial distribution along the flight track are obtained from Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) on board the Cloud-Aerosol Lidar Pathfinder Satellite Observations (CALIPSO) (Winker et al., 2007). The different aerosol types are clean continental, polluted continental, dust, polluted dust, clean marine, and smoke (Omar, 2009). To represent the air mass flow and source of the observed aerosol concentrations, HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model is used to obtain 8 days back trajectories based on the Global Data Assimilation System (GDAS) data products.

3. Synoptic Conditions and Cloud Profiling

During 2009, the monsoon covered the entire country by 3 July which is 12 days earlier than the normal date of 15 July. The cross-equatorial flow was weaker than normal during the major part of the season except for a brief period from the last week of June to the third week of July. During July, the synoptic activity was near normal and hence the rainfall activity during this month was normal. The rainfall over most of the subdivisions along the monsoon trough zone region and along the west coast was normal/excess due to the strengthening of monsoon over these regions in association with the passage of fast moving synoptic scale systems from the Bay region along the monsoon trough zone (Southwest monsoon 2009, end of season report, IMD). From 6th July onwards there exists an offshore trough along the west coast.

On 7th July, westerly monsoon flow continued to prevail and caused heavy rains on the west coast. The overcast prevented good development inland. The flight track was from the base station Bengaluru towards the coastal waters near Mangaluru and returned back through the Western Ghats. Over the coastal waters at about 15000 ft thick haze was observed and tops of convective clouds were emerging above the haze layer. Cloud profiling was carried out over the sea from 15000 ft to 1000 ft and the bases were at ~1500 ft. Some

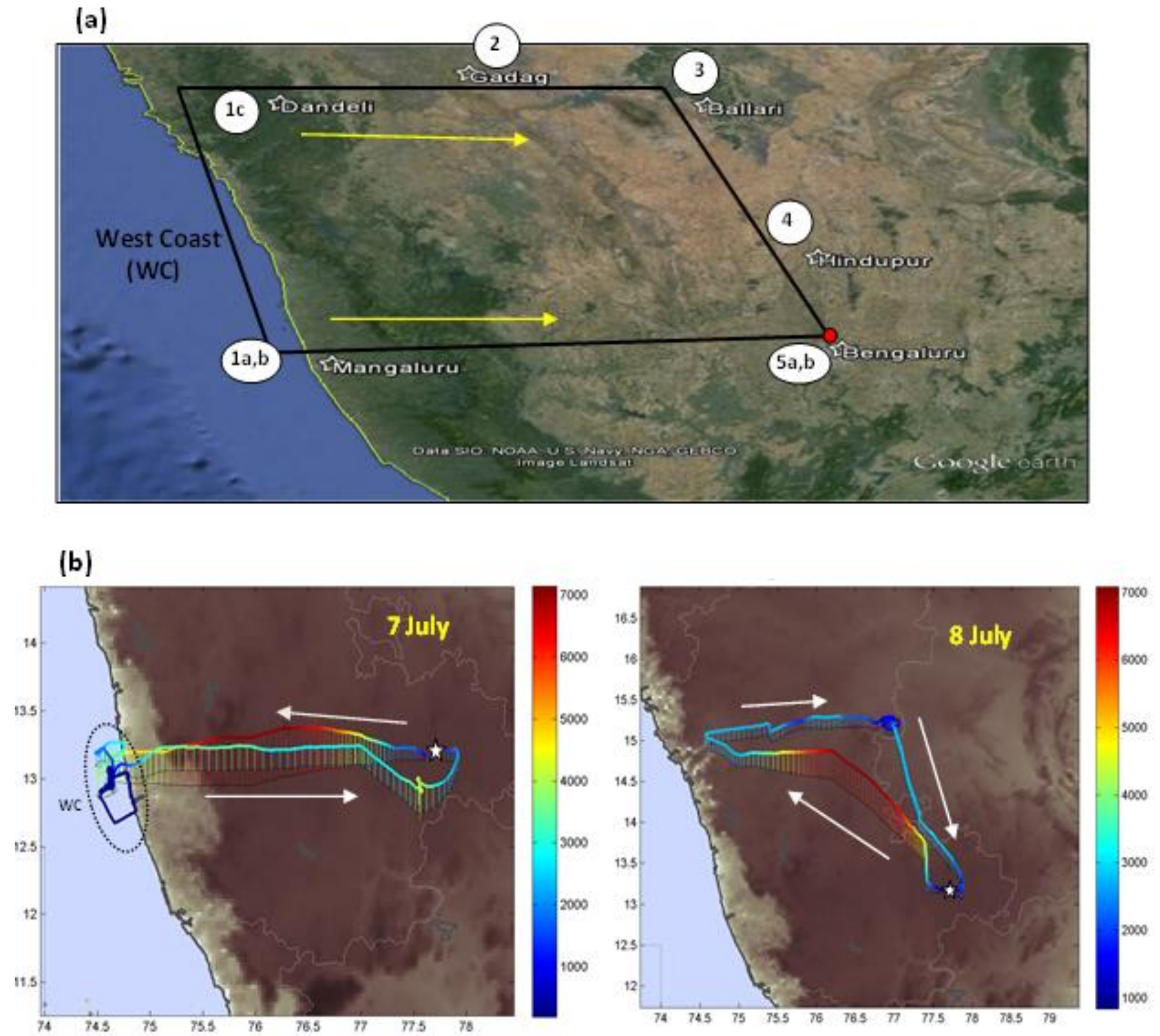

Figure 1: (a) The study area represents the ocean, west coast, and inland covering the rain shadow areas. The numbers 1 to 5 represent the locations where aircraft cloud profiling is done and the letters a, b represent multiple profiles. (b) Represents flight tracks on two different days from the base location Bengaluru.

rectangular type measurements were conducted to observe the low-level aerosols and winds.

Over the south of Bengaluru city clouds at 13000 ft were present and the profiling was carried out in those clouds. The bases were at about 6000 ft. The convective nature of the clouds decayed and the clouds became shallower and broken gradually further east from the top of the slope. The clouds regained some convective nature at the longitude of Bengaluru due to the faint surface heating that penetrated through the higher layers that precipitated lightly occasionally. The clouds in Bengaluru were only slightly less maritime. On 8th July also the weather prevailed as similar to that on 7th July. The main objective was to sample the clouds from the slopes of the Western Ghats towards the rain shadow region and document the varying characteristics. This turned out to be a gradient flight from the northwestern Ghats to inland and then south to Bengaluru.

4. Results & Discussion

The research flights conducted from the base location Bengaluru towards the Arabian sea through the rain shadow regions and over the Western Ghats during 7th and 8th July 2009 is shown in Figure 1. Figure 1a represents the study area and Figures 1b represents the flight tracks on 7th and 8th July.

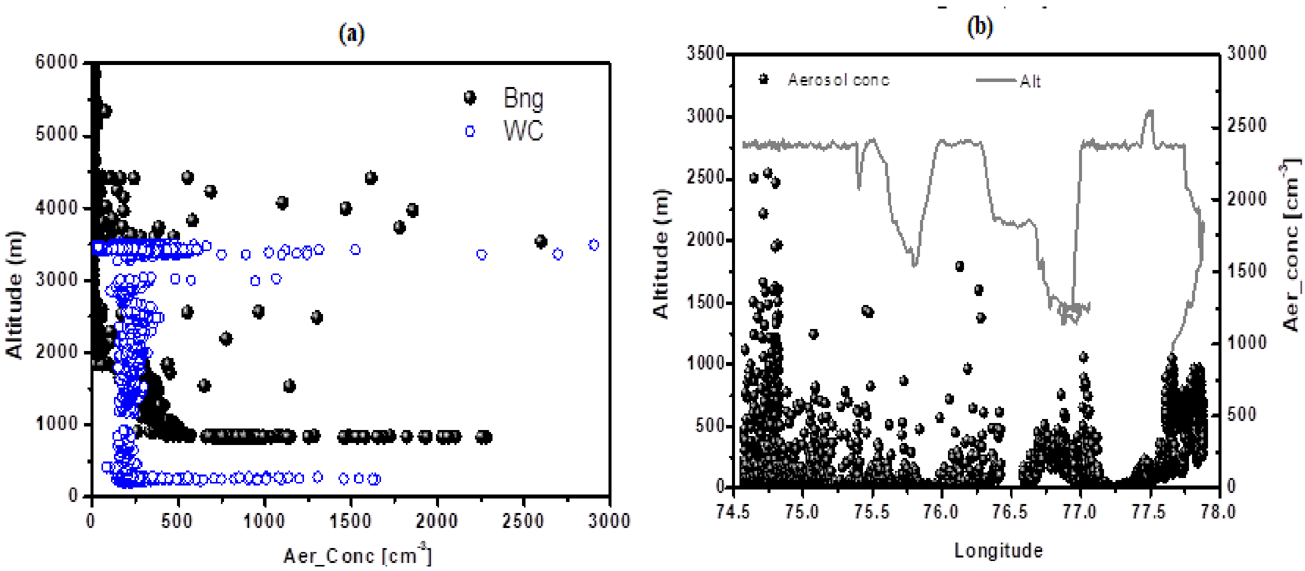

Figure 2: Aerosol number concentration (a) vertical distribution at Bengaluru and west coast (WC), (b) spatial distribution from Bengaluru to WC at same altitude.

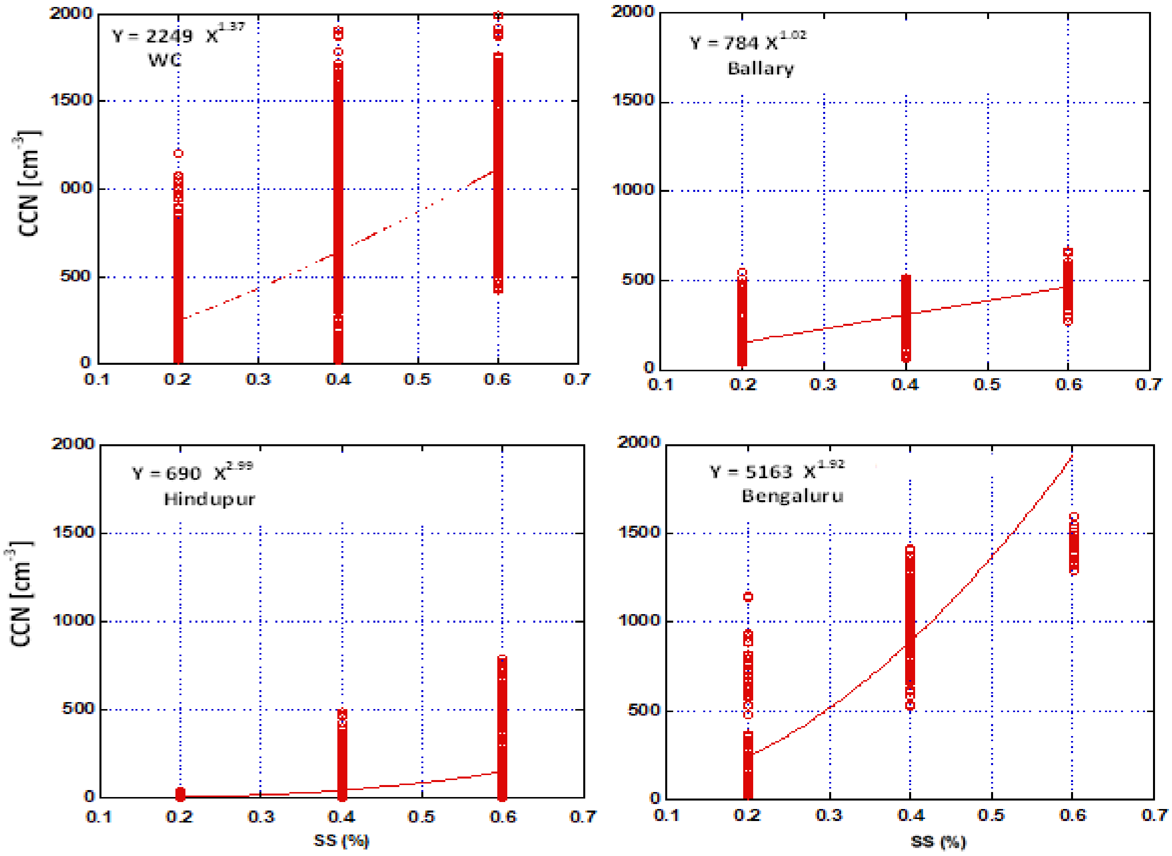

Figure 3: CCN spectra at different super saturations (SS) below the cloud base at different locations.

4.1 Aerosol characteristics

The spatial distribution of aerosol number concentration at a constant altitude of 2500 m is shown in Figure 2a. High aerosol number concentration (~ 2500 cm-3) is observed over the ocean and coastal region. While towards inland east of the west coast, concentration decreased to 500-1000 cm-3. The gaps in the distribution represent the cloud passes being screened out. Figure 2b shows the vertical distribution of aerosols over the west coast and Bengaluru. Surface concentrations

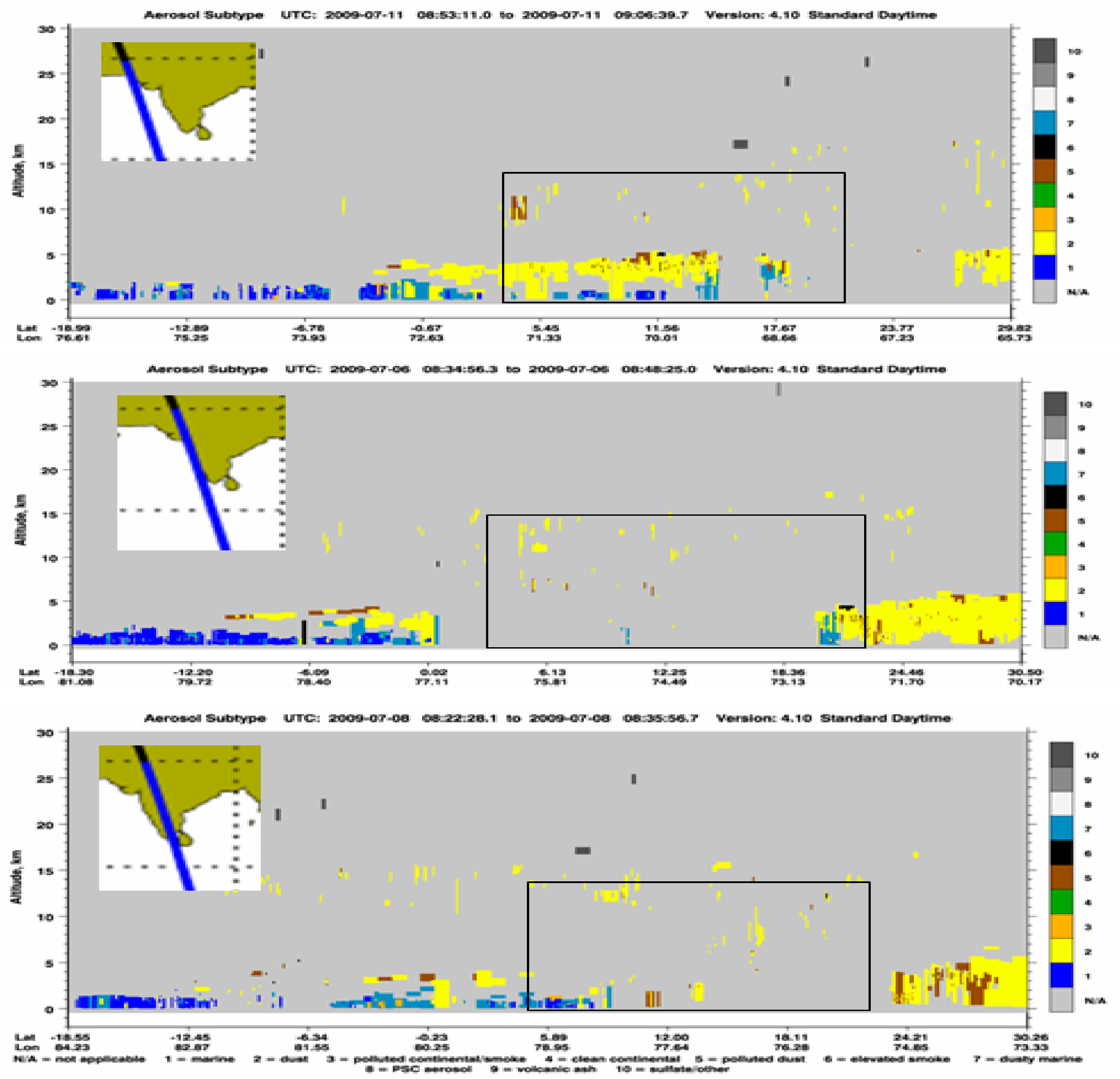

Figure 4: CALIPSO derived different aerosol types when the track is over ocean, west coast and inland.

over Bengaluru are comparatively higher than over the west coast, which is mostly contributed by the local anthropogenic sources. Aerosol concentrations over Bengaluru started decreasing with height up to 2500 m with occasional higher concentrations. Again a layer of higher concentrations were observed above 3500 m which were mostly transported from long distances. While over the west coast the concentrations varied up to 250 cm-3 and were constant up to 3 km, above which the concentrations increased more than 500 cm-3 and exhibited an elevated layer at around 3.5 km.

CCN spectra over the oceanic region also showed high number concentrations at all SSs (Figure 3). The abundance of transported dust from the west and sea spray aerosols contributed for the higher CCN number. While east of the west coast, these aerosols were washed out due to heavy precipitation which resulted in less number of CCNs. Further east over Bengaluru the anthropogenic aerosols contributed to an increase in CCN number.

Figure 4 shows the CALIPSO tracks and observations of different aerosol types over the study area spanning from the ocean, coastal and inland during 6 to 11 July 2009. It is observed that over the oceanic region marine and dust components were dominant. Dust layer is present between 2 and 5 km. While near the coast there were traces of polluted dust apart from dust and

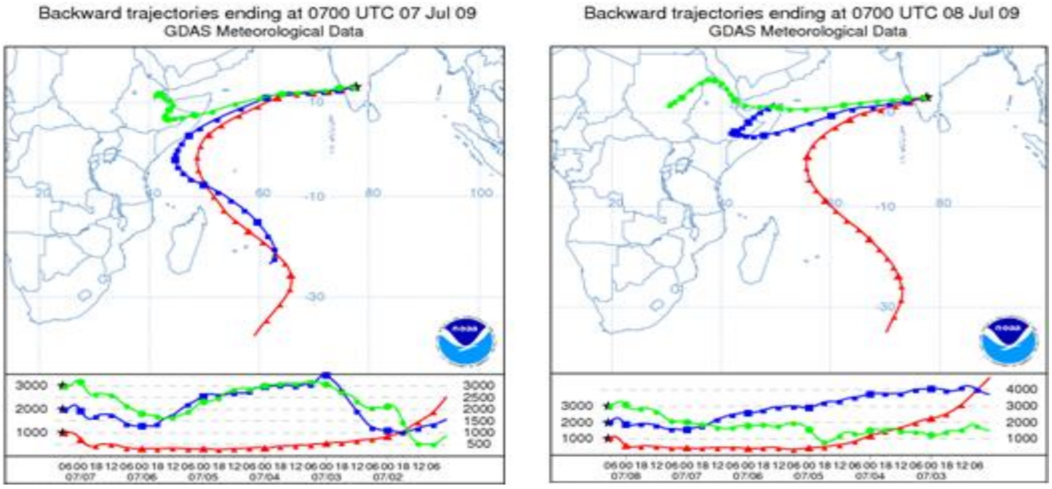

Figure 5: Five days back trajectories at different altitudes on 7th and 8th July 2009.

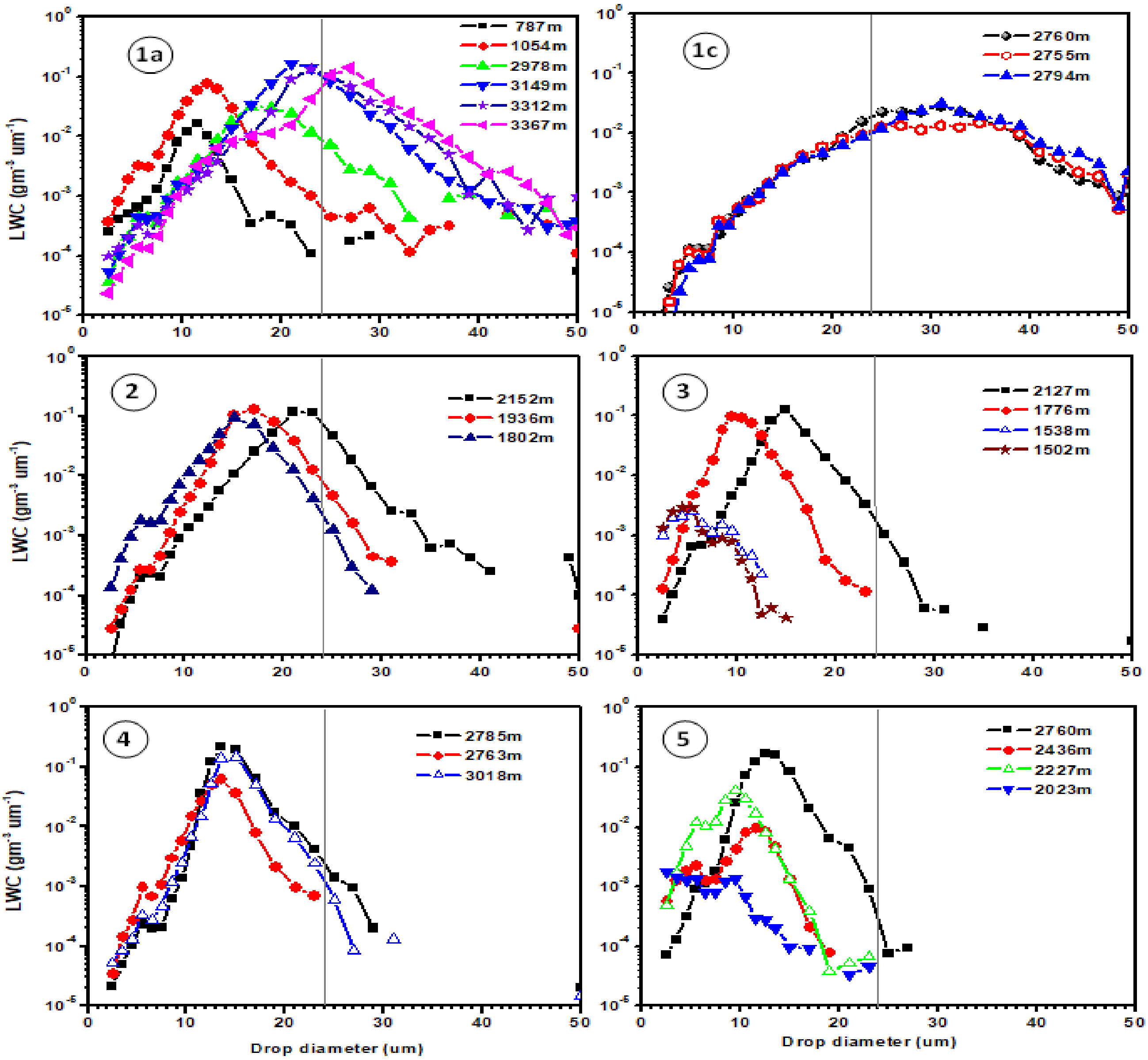

Figure 6: Droplet size distribution with respect to LWC at different locations represented in Figure 1(a)

marine components. These aerosols are not observed at lower altitudes due to the presence of low level clouds over this area. Inland, these aerosols got modified due to anthropogenic influence, and the presence of polluted dust is seen. Dust component is present over the ocean, coastal and land as well. The back trajectories (Figure 5) reveal that below 2 km the air mass flow is entirely oceanic, while above 2 km the flow is from the Arabia region, thus bringing in more desert dust to land across the ocean.

4.2 Cloud microphysics

Figure 6 shows the droplet size distributions observed over all the five locations from off the coast of Arabian sea to inland towards Bengaluru as marked in Figure 1. Over the ocean the distribution is found to be narrower near the cloud base and broader at higher cloud depths indicating the general maritime nature of the profiled clouds. The trajectory analysis (Figure 5) reveal that the transported dust from the west gets subsided over the observational area and gets trapped in the existing off-shore trough active during the period.

The droplets were found to grow with increase in LWC and reached the threshold for warm rain initiation (24 µm) at around 3 km at 0.1 gm-3 LWC (Figure 1a). Over the top of the Western Ghats the droplet spectra was broader that exhibited the pure maritime nature of the clouds. Cloud could reach the warm rain initiation at lower altitude of ~ 2.7 km itself at lower LWC of 0.05 gm-3 as compared to that over the ocean.

Further east, clouds started losing the maritime nature and slowly attaining the continentality over Gadag, Bellary, Hindupur and Bengaluru. The droplet spectra observed over these places were narrower as compared to over ocean and the Western Ghats. The LWC values were around 0.2 gm-3. Over Gadag, clouds could reach the warm rain potential due to the influence of maritime airmass. While, over other places clouds could not reach the warm rain potential due to the dominance of continental airmass.

Figure 7 shows the vertical distribution of CDNC and Re over the places discussed above. It is seen that the cloud bases over the ocean and adjoining west coast regions were much lower (~ 700m) when compared to the regions to the east (~2000m). Availability of abundance of moisture and giant CCN have helped for the cloud formation at the lower levels. While over Bengaluru, the cloud bases lifted due to reduction in marine airmass, moisture and presence of polluted CCN. CDNC is found to be higher towards evening hours (descent profiles) as more number of CCNs were available due to solar heating induced convection and boundary layer processes. Re over the ocean and west coast is found to reach the threshold value of warm rain initiation while compared to the stations inland.

4.3 Aerosol cloud interactions

The clouds over the Arabian Sea and over the Western Ghats (1a &1b) were thermodynamically maritime with heavy desert dust. The clouds were raining out over the Arabian sea (1a) and over the western slopes of the Western Ghats (1b). Heavy dust haze was found over the west coast extending up to the depth of about 4 km. Larger droplets appeared at the cloud base, probably induced by dust and sea-salt giant CCN. The clouds grew to 3 km for the onset of warm rain. The clouds consolidated over the western slopes with tops that coincided with the top of the haze layer at 4 km. The heavier rain over the western slopes (1b) washed out the aerosols and consumed the instability. Therefore, clouds down the slopes (2) were weak and initiated warm rain at about 2500 m despite the higher bases.

The Clouds acquired gradually more continental nature over the eastern plains (3 & 4) and became polluted towards Bengaluru (5). Convection was subdued just to the east of the top of the Western Ghats, and gradually recovered further east. When the air moves further east (3), the solar heating during daytime renews the convection, which becomes gradually deeper. The added air pollution increases the altitude for the initiation of warm rain. The clouds have to grow deeper (4000m to 6500m) to initiate the warm rain process due to their “continentalization”.

The clouds were raining out on the Western Ghats, and became gradually less maritime toward the

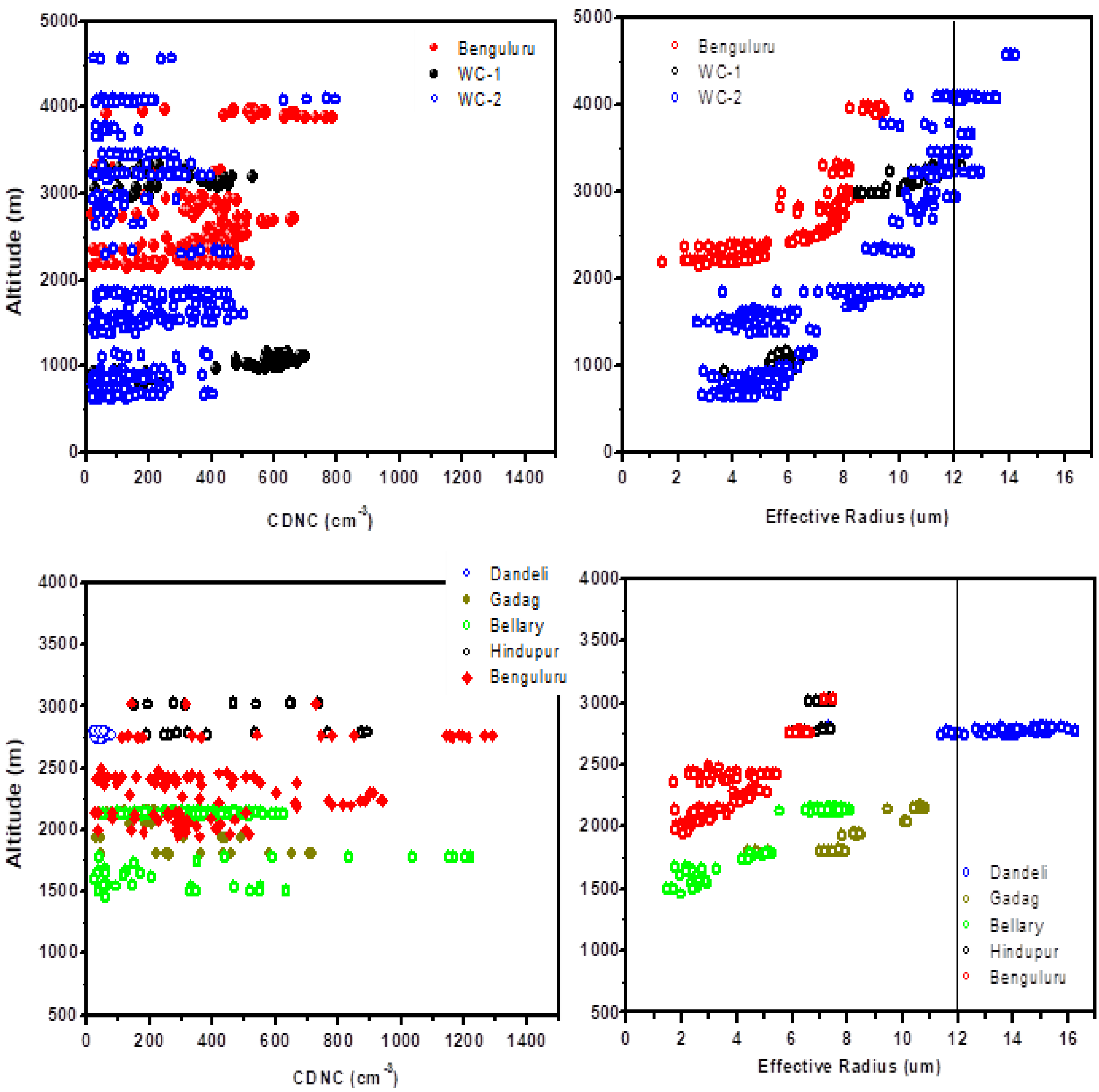

Figure 7: First panel shows the vertical distribution of CDNC and effective radii at Bengaluru and west coast. Second panel shows the same but at different locations noted in Figure 1(a).

east. The clouds were still almost as maritime over Gadag, and became less maritime over Bellary. The clouds became much more continental towards Bangalore, with slightly more maritime composition to its north over Hindupur. This pattern shows that the western part of the rain shadow is still quite maritime. It has low rain because the clouds exhausted all the instability over the western slopes. When the air moves further east, the solar heating during daytime renews the convection, which becomes deeper further east. At the same time, the continentality of the clouds increases eastward, so that they have to grow deeper to start precipitating.

5. Conclusions

Rainfall processes in the clouds occur in a variety of pathways. Further, atmospheric aerosols over the topography from the Western Ghats and towards the land have been found to play an important role in cloud microphysics. To understand the pathways through which aerosols modify clouds and lead to precipitation, CAIPEEX-2009 was designed and the observations provided a suitable opportunity to study the variability in the aerosol and cloud microphysical properties over the rainy regions (west coast and the Western Ghats) and rain shadow regions to the east. One of the significant results showed that the warm rain initiation starts at early stages (lower cloud depths) over the coastal areas and becomes even lower at the crest of the western slopes, probably due to intense washout of the aerosols by the rain. However, the clouds lose their microphysically maritime character farther east over the rain shadow regions, where the clouds have to grow to higher depths to initiate the process. The aerosol and CCN concentrations support the hypothesis that the shallow convective clouds (i.e., with tops < 6 km) lose their ability to rain over the rain shadow due to increased aerosols concentrations, which are probably contributed to by air pollution.

The orographic rain clouds over the Western Ghats appear to wash out much of the desert dust and small CCN, and become more maritime just to the east of the crest of the Ghats than over the sea. However, these clouds acquire new pollution aerosols quickly as they travel farther east and lose much of their ability to produce warm rain.

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