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Interrelation between microphysical and optical properties of cloud and rainfall in the Indian region

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Ground and satellite based measurements of microphysical and optical parameters of cloud are analysed for three tropical locations Kolkata, Guwahati and Bangalore during the year 2006 to find an interrelation between cloud optical depth, cloud effective radius, cloud liquid water content and rain. The present study suggests that a relation exists between cloud effective radius and cloud liquid water content. A minimum threshold of cloud optical depth is required for the precipitation to initiate. However, the threshold value depends on weather conditions of the tropical location. Cloud droplets with effective radii above 8 micron are mostly effective for the rain formation. Again, a threshold value of 5 is obtained for cloud optical depth for precipitation formation. There also exists a positive relation of accumulated rainfall with cloud effective radius and cloud optical depth as observed at a particular location.

Keywords: Cloud effective radius, Cloud liquid water content, Cloud optical depth, Rainfall

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1 Introduction

The knowledge of optical and microphysical properties of cloud and their variations in space and time is crucial as cloud strongly modulates the energy balance of Earth[1] and its atmosphere through their interaction with terrestrial radiation as demonstrated from modeling studies. The relationship between thermodynamic structure of the atmosphere and the large scale circulation is the main determining factor for distribution and properties of cloud in the tropics. The temperature and moisture profile of the tropical atmosphere is influenced by the interaction between the cloud and general circulation and thereby, the climate of the Earth is influenced[2]. The change in cloud amount and vertical structure for climate change is indicated by General Circulation Model (GCM) simulations with a cloud feedback, which enhances global warming[3-5]. Changes in cloud water content and optical thickness studies suggest that the change in cloud optical properties may result in a negative feedback comparable in size to the positive feedback associated with cloud cover changes[6,7]. None of the GCM simulations to date include corresponding changes in cloud microphysical properties (e.g. particle size), which could easily influence conclusions so far obtained[8,9]. Numerous studies have been done on cloud optical depth and cloud effective radius with visible and near-infrared radiometers on aircraft[10-18] and on satellites[19-21]. The basic theory, revealed from all the above studies, is that the reflection function of water absorbing band of cloud is a function of cloud particle size in the near infrared region. The reflection function of non absorbing band of cloud is a function of cloud optical depth in the visible region. Short-wave optical properties (i.e. optical depth, single-scattering albedo and asymmetry parameter) of water clouds are considered using several cloud drop distributions, as GCM radiation schemes need optical properties of clouds, which depend on the size distribution of cloud particles[22]. Presently, some of the studies use constant value of cloud effective radius[23]. However, in another study, a scheme of expressing optical depth, single-scatter albedo and asymmetry as functions of liquid water content and effective radius is shown[24]. But these microphysical properties are not independent of each other. Modifications are made by expressing the effective radius as a linear function or a cubic root of liquid water content[25]. From all the parameterizations above, it is very clear that the effective radius does not depend upon the total droplet concentration. Realistically, effective radius depends simultaneously upon liquid water content, total droplet concentration and entrainment and mixing which can be supported by reports of the literature. An investigation shows the relationships between the effective radius, liquid water content and total droplet concentration using microphysical data from subtropical marine stratocumulus, continental and maritime convective clouds and hill cap clouds in middle latitudes[26]. According to that investigation, there is a '1/3' power law between the effective radius and liquid water content with the pre-factor depending on cloud types and total droplet concentration. Although, experimental evidence has been found for this '1/3' power law, the theoretical explanation is not available. Thus, the effective radius of the cloud droplets was found to be a robust parameter for a given environment and cloud depth. Some investigations on the relation between cloud water content, effective radius and cloud depth in the various aerosol regimes have been done which provide insights into some profound physical processes that dominate the evolution of the clouds drop size distributions[27]. The relationship between cloud optical parameters and rain intensity at the ground is investigated and the result shows a positive correlation between rain intensity and optical thickness, in the range of the data ($\tau < 60$ and rain intensity < 20 mm h^{-1})[28].

The method of deriving optical depth and cloud effective radii from infrared and microwave radiometry and validating the technique with *in situ* aircraft measurement is available in the literature[29]. However, multi-layer cloud cannot be handled with the same, as the ground based measurements are of low resolution. The method of single measurement of RADAR reflectivity is used for deriving cloud liquid water content (LWC) and effective radius[30]. Tropical region has got special importance as there is a strong seasonal variation of climate parameters. Quite a number of studies have been done for investigating cloud optical and microphysical parameters but no investigation has been made to find the interrelation between cloud optical and microphysical parameters for the tropical region in order to indicate the possibility of prediction of cloud LWC and rainfall.

In the present study, an attempt has been made to find an interrelation among cloud optical depth, effective radius of cloud droplets, cloud liquid water content and rainfall at three Indian locations, namely, Kolkata, Guwahati and Bangalore to investigate the interactive role played by the optical and microphysical properties of cloud in the formation of rain at the tropical region.

2 Instrument characteristics

MODIS is a 36-band scanning spectro-radiometer. Four of these, visible (0.645 μm) and near-infrared (1.64, 2.13, and 3.75 μm) spectral bands are used in daytime shortwave cloud retrieval algorithm over land surfaces, with 0.858 or 1.240 μm, replacing 0.645 μm over ocean and bright snow/sea ice surfaces, respectively. Other bands in the thermal region, such as 8.55, 11.03, 12.02, 13.335, 13.635, 13.935 and 14.235 μm bands, are used for cloud cover and cloud top properties (including cloud top altitude, cloud top temperature and thermodynamic phase).

Radiosonde balloon is released from a location over which characteristics of the troposphere are desired to be known. Radiosonde measurements are obtained twice a day at around 0000 and 1200 hrs GMT (0630 and 1830 hrs IST) by the India Meteorological Department at Kolkata, India (22°34'N, 88°29'E).

3 Theoretical basis

Cloud optical thickness and effective radius are the two parameters that are exclusively required to determine shortwave cloud radiative properties. Therefore, parameterization of these properties requires a global data base. Such data seem only to be derivable from space borne remote sensing observations. Therefore, MODIS is ideally suited to cloud remote sensing applications and retrieval purposes. Although remote sensing methods for the determination of cloud optical and microphysical properties are acceptable, more theoretical and experimental studies are required in order to assess the soundness and accuracy of these methods when applied to measurements on a global scale. The asymptotic theory[13] for the determination of cloud optical thickness has demonstrated the theoretical foundation of the optical thickness determination and its efficient implementation to experimental observations. Success of this method lies in incorporating the component of multi-wavelength algorithm for simultaneously determining the cloud particle phase, optical thickness and effective particle radius. In spite of all the above, more aircraft validation experiments are required in order to assess the validity of these methods, as many factors affect the successful retrieval of these parameters when applied to real data in a real atmosphere.

A radiative transfer model is first used to compute the radiance to retrieve the cloud optical thickness and effective particle radius. To normalize the radiance, $I^{\lambda}(0,-\mu,\varphi)$ at wavelength λ in terms of the incident solar flux $F_0(\lambda)$, such that the reflection function $R^{\lambda}(\tau_c, r_e, \mu, \mu_0, \phi)$ is defined by:

$$R^{\lambda}(\tau_c, r_e, \mu, \mu_0, \phi) = \frac{I^{\lambda}(0,-\mu,\phi)}{\mu_0 F_0(\lambda)} \quad \ldots(1)$$

where, τ_c, is the total optical thickness of the atmosphere (or cloud); r_e, the effective particle radius:

$$r_e = \frac{\int_0^{\omega} n(r)dr}{\int_o^{\omega} r^2 n(r)dr} \quad \ldots(2)$$

where, $n(r)$ is the particle size distribution; and r, the particle radius; μ_0, the cosine of the solar zenith angle; μ, the absolute value of the cosine of the zenith angle, measured with respect to the positive direction; and ϕ, the relative azimuth angle between the direction of propagation of the emerging radiation and the incident solar direction.

For a sufficiently optically thick cloud, numerical results for the reflection function must agree with known asymptotic expressions. The reflection properties of optically thick layers depend essentially on two parameters: the scaled optical thickness, $\tau_{c'}$, and the similarity parameter, s, as suggested by numerical simulations as well as asymptotic theory, is defined by:

$$\tau_{c'} = (1 - \omega_0 g)\tau_c \quad \ldots(3)$$

$$s = \left(\frac{1-\omega_0}{1-\omega_0 g}\right)^{1/2} \quad \ldots(4)$$

where, g, is the asymmetry factor; and ω_0, the single scattering albedo of a small volume of cloud air. In addition, the reflectance properties of the Earth atmosphere system depend on the reflectance (albedo) of the underlying surface. The similarity parameter, in turn, depends primarily on the effective particle radius. In addition to the scaled optical thickness, the similarity parameter and the reflectance of the underlying surface, the details of the single scattering phase function affect the directional reflectance of the cloud layer. Realistically, reflection function is not dependent on the exact nature of the cloud particle size distribution, depending primarily on the effective radius and to a lesser extent on the effective variance.

For a band with a finite bandwidth, Eq. (1) must be integrated over wavelength and weighted by the band's spectral response $f(\lambda)$ as well as by the incoming solar flux $F_0(\lambda)$. Hence, Eq. (1) is written as:

$$R(\tau_c, r_e, \mu, \mu_0, \phi) = \frac{\int_{\lambda} R^2(\tau_c r_e, \mu, \mu_0, \phi) f(\lambda) F_0(\lambda) d\lambda}{\int_{\lambda} f(\lambda) F_0(\lambda) d\lambda} \quad \ldots(5)$$

Values of the reflection function must be stored at three geometrical angles: optical thicknesses, prescribed effective particle radii, and surface albedos. This forms a rather large lookup table and potentially causes sorting and computational inefficiencies. The determination of total optical thickness and effective particle radii from spectral reflectance measurements constitutes the inverse problem and is typically solved by comparing the measured reflectance with entries in a lookup table and searching for the combination of total optical thickness and effective particle radii that gives the best fit.

3.1 Salonen model for obtaining liquid water content

The liquid water content is not generally an observable quantity. A two-part calculation method has been used in diagnosing the weather forecast model. The first part contains the cloud detection using a critical humidity function and the second part contains the determination of the liquid water content. Based on this approach, the critical humidity, as defined by Geleyn[31], has been used for the detection of clouds at each pressure level. According to Geleyn, the critical humidity function is given by:

$$U_c = 1-\alpha.\sigma(1-\sigma).[1+\beta(\sigma-0.5)] \quad \ldots(6)$$

where, the parameters, $\alpha = 1.0$; and $\beta = 1.732$; and σ, is the ratio of the pressure on the considered level and at the surface level.

If the measured humidity (U) is higher than the critical humidity (U_c) at the same pressure level, the measurement level is assumed to be in cloud. The linear interpolation has been used for the calculations of the base and top of the clouds. Within cloud layers, the water density w (g m^{-3}), is a function[32] of the height, h (m) and air temperature, t [°C]:

$$w = w_o\{(h-h_b)/h_r\}^a(1+c.t) \quad \text{for } t>=0°C; \text{ and}$$
$$w = w_o\{(h-h_b)/h_r\}^a \exp(ct) \quad \text{for } t<0°C \quad \ldots(7)$$

where, $w_o = 0.17$ [g m^{-3}]; $c = 0.04$ [1/°C]; $h_r = 1500$ [m]; h_b = cloud base height [m]; a = 1.0, is the parameter for height dependence.
The cloud liquid water density, w_l is given by:

$$w_l(t,h)=w(t,h)\,p_w(t) \quad \ldots(8)$$

where, $p_w(t)$, is liquid water fraction and is approximated by the function:

$$p_w(t) = 1 \quad \text{for } 0°C<t$$
$$= 1+t/20 \quad \text{for } -20°C< t< 0°C; \text{ and}$$
$$= 0 \quad \text{for } t< -20°C \quad \ldots(9)$$

It is evident from the above liquid water fraction $p_w(t)$ and cloud liquid w_l [g m^{-3}] that for temperature above 0°C, only cloud liquid water exists and below –20°C temperature, only solid water exists and in the intermediate temperature (i.e. -20°C<t<0°C), both may exist.

After getting the cloud liquid water, the amount of liquid water can be obtained by integrating the liquid water density over the corresponding height.

$$\text{Cloud liquid water} = \int w_l(t,h)\,dh$$
$$= \int w(t,h)\,p_w(t)\,dh \; [\text{g m}^{-2}] \quad \ldots(10)$$

where, terms being their usual meanings.

4 Data

4.1 MODIS data

MODIS is an extensive program using sensors on two satellites that each provides complete daily coverage of the earth. The data have a variety of resolutions: spectral, spatial and temporal. Because the MODIS sensor is carried on both the terra and aqua satellites, it is generally possible to obtain images in the morning (terra) and the afternoon (aqua) for any particular location. Night time data are also available in the thermal range of the spectrum. Comprehensive cloud measurements were taken by remote sensing instruments of MODIS. Cloud optical thickness is a vertically integrated quantity, while the satellite-derived effective radius represents some radiative penetration depth into the cloud. The effective radius is preferred to mean or mode radius since it accounts for the size distribution of the droplets within the cloud. The underlying principle of the model is the asymptotic theory. This theory is based on the fact that reflectance in the non absorbing wavelengths (visible) is mainly a function of total optical thickness, while reflectance in the absorbing wavelengths (near and mid infrared) is governed by effective particle radii. For large optical thickness, the reflection function is close to the known asymptotic equations. When the optical thickness is large enough, total optical thickness and effective particle radii can be determined nearly independent of each other. The data are used in this study for effective radius, cloud optical depth and liquid water path for the year 2006 for three important tropical locations, viz. Kolkata, Guwahati and Bangalore.

4.2 Radiosonde data

Meteorologists measure atmospheric conditions from the earth's surface to an altitude of approximately 30 km above sea level through twice daily radiosonde ascents. These balloon-borne instruments are sent aloft just prior to 0000 and 1200 hrs UTC on each day. During their ascent, they radio back to the ground-based receiving station a nearly continuous stream of information until the balloon bursts at approximately 10 mbar. Radiosonde observations (also called RAOB) include the observed air temperature, pressure, moisture and wind information at various levels in the atmosphere. Within two hours after the radiosonde has been launched, the RAOB data have been encoded and transmitted over a communications network to the National Meteorological Center. At this center, the data can be processed for analysis on upper air charts and for use in numerical weather prediction models. To accomplish this task, all upper air stations are to report RAOB data for certain mandatory pressure levels. To speed the transmission process, the RAOB operator encodes only the temperature and dew point data for significant pressure levels along with the mandatory pressure levels. The significant pressure levels are those points ascertained from the plotted sounding where a significant change in the temperature and or dew point profile is detected.

4.3 Precipitation data

Archival facility of Indian Institute of Tropical Meteorology (IITM) for the meteorological observational data collected through different field experiments of the IITM and that received from different organizations is also available at the web portal of the Institute. The data of accumulated rain is taken for three important tropical locations, viz. Kolkata, Guwahati and Bangalore for the year 2006.

4.4 Liquid water content (LWC) data

Salonen model is used to calculate liquid water content data from Radiosonde observation.

5 Results

Cloud effective radius against cloud LWC calculated from Radiosonde data over three tropical locations Kolkata, Guwahati and Bangalore, located in different rain climate region, using Salonen's method during the year 2006 is plotted in Fig. 1. The nature of variation shows that there is a clear functional relationship between effective radius (r_{eff}) and LWC. For LWC less than 500 gm m^{-3}, effective radius is generally between 10 and 20 microns. When LWC exceeds 500 gm m^{-3}, LWC is almost linearly related with effective radius. The maximum value of cloud liquid water content observable in India is in the range of 2.5 - 3 kg m^{-3}. In the present study, compared to Kolkata and Bangalore, Guwahati shows a more prominent increasing trend of cloud effective radius with respect to cloud LWC.

The evaluation of the relationship between cloud parameters and rainfall amount is important for precipitating clouds that prevail in the tropical region. Again, accumulated rain amount is plotted against cloud optical depths for three tropical locations with different climatic conditions in Fig. 2. These plots suggest a threshold value of cloud optical depth in the range 2 - 5 for the formation of precipitation. The threshold depends on the location of the tropical station. Once precipitation starts, rain amount is linearly related with cloud optical depth. It is found that 70% of the rain events occurred below the value

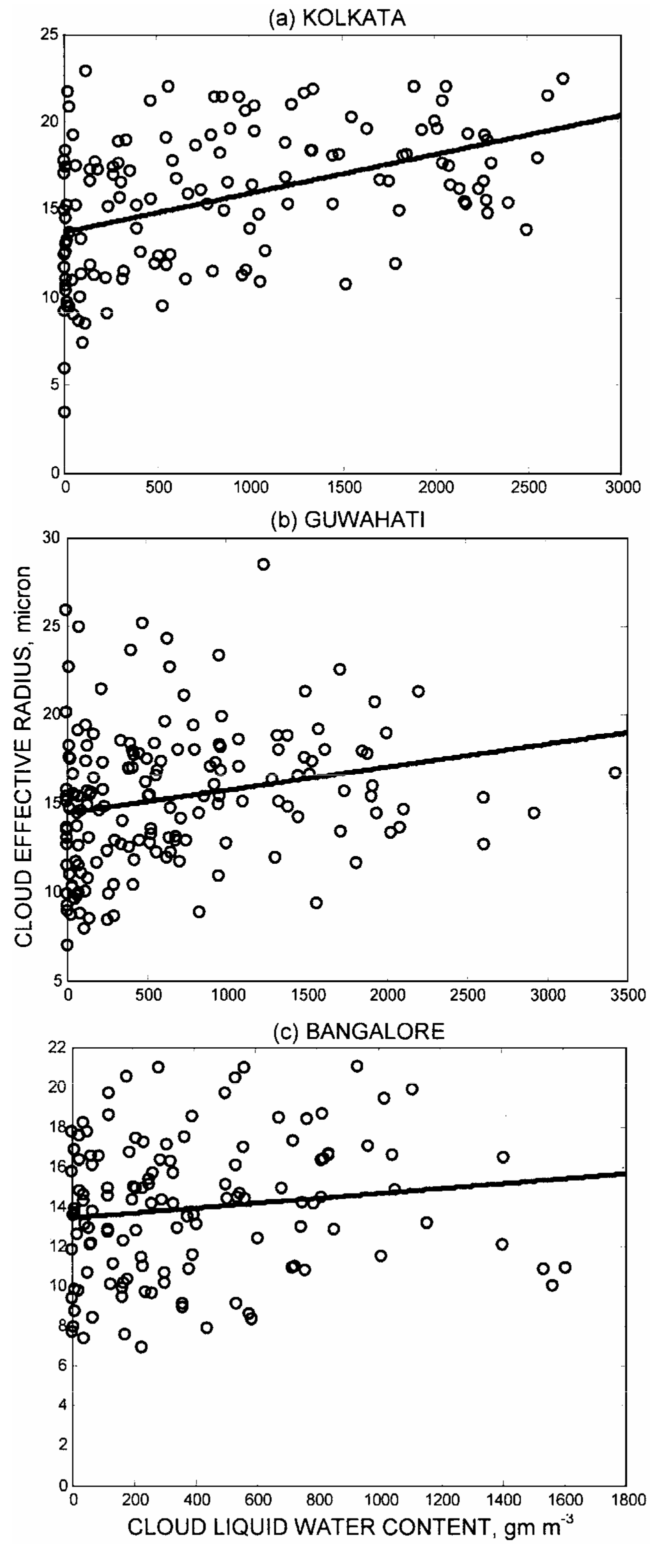

Fig. 1 — Variation of cloud effective radius obtained from MODIS measurements against cloud LWC obtained from radiosonde measurement using Salonen's model during 2006 at: (a) Kolkata; (b) Guwahati; and (c) Bangalore

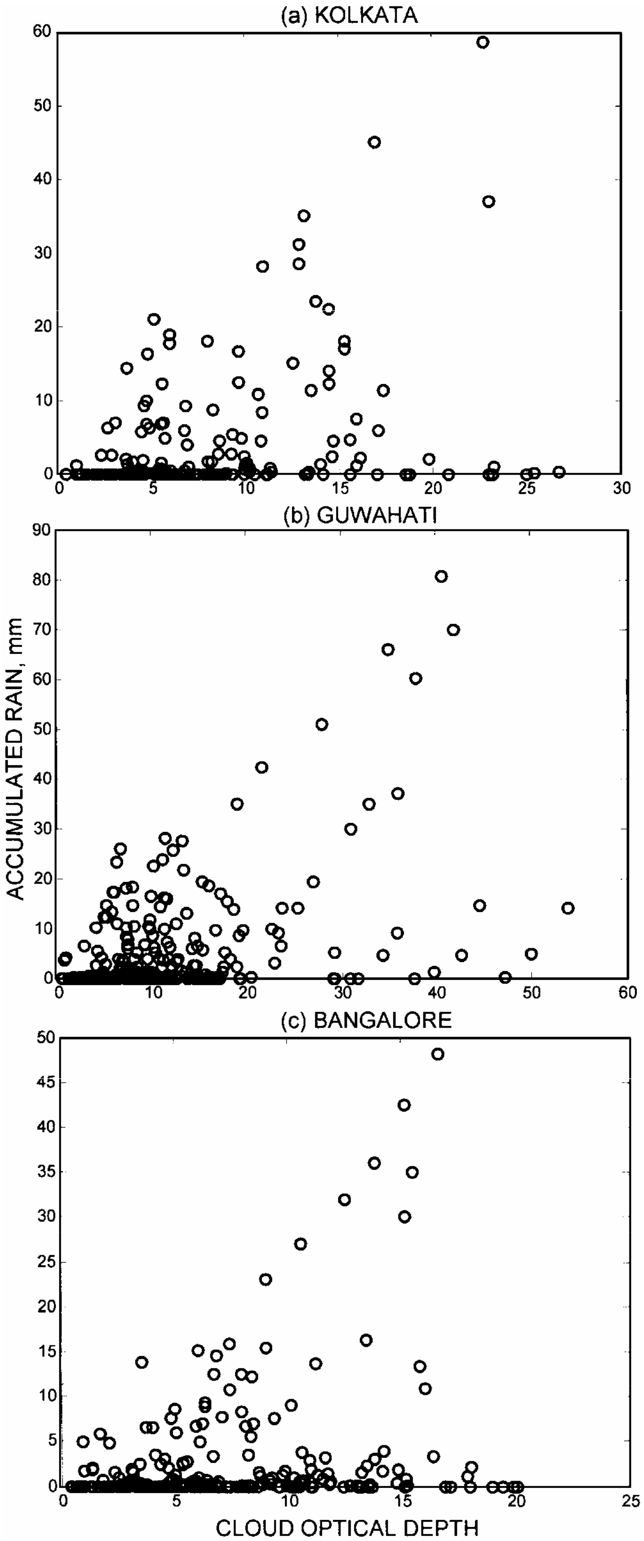

Fig. 2 — Variation of rainfall obtained from IITM measurements against cloud optical depth obtained from MODIS measurement during 2006 at: (a) Kolkata; (b) Guwahati; and (c) Bangalore

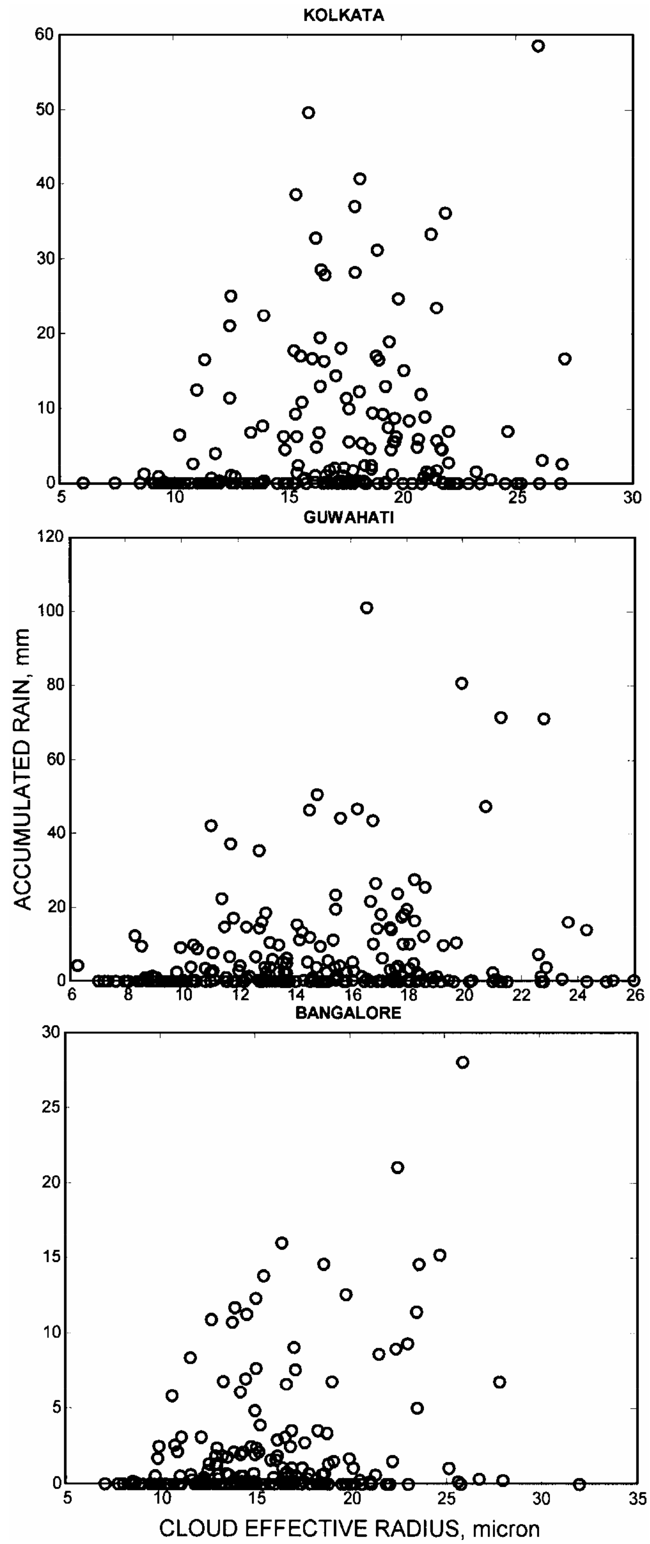

Fig. 3 — Variation of rainfall against cloud effective radius during 2006 at: (a) Kolkata; (b) Guwahati; and (c) Bangalore

of optical depth of 15. The positive relation is clearly evident at rainfall greater than 10 mm. It is found that a greater value of cloud optical depth is required for Guwahati, located far away from sea coast, for the same amount of precipitation compared to two other locations. The amount of rain observed against cloud effective radius for Kolkata, Guwahati and Bangalore are shown in Fig. 3. It is seen that a minimum value in the range of 8-10 micron of cloud effective radius is required for the precipitation to form. From the relation between the accumulated rain amount and the effective radius, it is clear that 75% of precipitating clouds occur for the effective radius in the range of 12-20 micron.

6 Conclusion

The interrelationship between cloud LWC, effective radius and optical depth is highly varying in the tropical region. The rainfall amount in this region depends on the cloud parameter in a complex manner. The relationship between rainfall amount and the cloud parameters varies significantly from the near coastal location to land locked locations in the Indian tropical region. From the present study, the threshold values of cloud effective radius and optical depths are indicated for formation of precipitation. Also this study suggests that for an intense rain, cloud effective radius can be a decisive factor in determining total amount of rain. It must be emphasized that the data for more locations are needed to have a working model interrelating rainfall amount and cloud parameters.

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