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Physics of monsoon rain processes*

P. C. S. DEVARA and BH. V. RAMANA MURTY
Indian Institute of Tropical Meteorology, Pune

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सार — वर्षा की दो मूल प्रक्रियाओं अर्थात् गर्म वर्षा (पूर्णत: द्रव प्रक्रियाएं) एवं ठंडी वर्षा (तीन चरणी प्रक्रियाएं) से संबंधित सिद्धांतों एवं संबद्ध परिघटनाओं जो मेघों में वर्षा उत्पन्न करने के लिए उत्तरदायी हैं, की समीक्षा की गई है। भारत के कुछ क्षेत्रों में किए गए प्रेक्षणों के आधार पर ग्रीष्म मानसून के दौरान बरसने वाले मेघों में इन प्रक्रियाओं के कार्यान्वयन की सीमा को इंगित किया गया है। अभी तक के परिणामों से पता चला है कि भारत में मानसून की वर्षा मुख्यत: ठंडी प्रक्रिया आंशिक रूप से गर्म एवं ठंडी प्रक्रियाओं के मेल से होती है, पर गर्म प्रक्रियाओं की वजह से होने वाली वर्षा लगभग नगण्य है।

ABSTRACT. The principles and related phenomena involved in the two basic rain processes, namely, the warm rain (all liquid process) and the cold rain (three phase process), which govern formation of rain in clouds are reviewed. The extent of operation of these processes in the raining clouds during the summer monsoon has been pointed out on the basis of observations made over certain regions in India. The results, obtained so far, suggest that the monsoon rain occurs in India predominantly due to cold process, partly due to a combination of cold and warm processes and negligibly due to warm process.

1. Introduction

The study of monsoon rain is of great importance on account of the prevailing conflicting reports in the literature about the understanding of the precipitation mechanisms involved and also of its potential value to weather modification in India. In the rain-bearing clouds in summer monsoon in India, the rain process operating may be the warm process or the cold process or a combination of both. Attempts were made by several workers in the country as early as in early 50s to examine the rain processes and their operational coverages in the monsoon rain-formation over different regions in India. The valuable findings made in this connection were published in a report of symposium on 'Artificial Rain' held at New Delhi in 1953. Since the cloud-top height indicates the type of rain process involved in the monsoon rain, it may be mentioned here of the analysis of the heights of tops of low clouds over India by Pramanik and Koteswaram (1955). According to them, the freezing level over India in the monsoon season is fairly steady all over the country at about 16,000 to 18,000 ft. They found that about 80 to 90 per cent of the clouds over northwest India, Uttar Pradesh, Bihar, central parts of the country and the east coast of the Peninsula and less than 90 per cent of the clouds over the rest of the country had tops below the freezing level. These findings suggest predominance of warm rain process in low clouds in most of the country during the monsoon season. The study of the mechanisms involved in the basic processes which occur in the formation of rain would help in the understanding of the circumstances under which a cloud could give rain during the monsoon season over India. With this idea, an attempt has been made in this paper to review the present state of knowledge on the monsoon rain microphysical processes. The theme of the paper is divided into two parts. After summarizing the background of the different stages of the formation of clouds and development of precipitation, the first part reviews the microphysical aspects of the warm and cold rain processes with reference to the developments made in the field and the work done in India. The second part of the paper deals with the relative contributions of warm and cold rain processes which operate in the raining clouds during the summer monsoon as assessed by the radar and microphysical observations made over certain regions in India.

2. Cloud formation and precipitation development

In general, formation of clouds and development of precipitation depend on dynamic and microphysical processes. The study of microphysical processes will have crucial role in the understanding of precipitation mechanisms. It is known recently that feedback mechanisms exist between cloud microphysics and cloud dynamics and they influence directly the chain of events leading to the developments of precipitation (Fukuta 1980; Cotton 1982). The dynamic processes involve motions of the air which give rise to the favourable conditions for formation of clouds and precipitation whereas the microphysical processes involve the formation and growth of individual drops or ice crystals.

*Partly based on review talk delivered at 'National Symposium on Early Results of Monsoon Experiments', held at India Meteorological Department, New Delhi, during 9-11 March 1981.

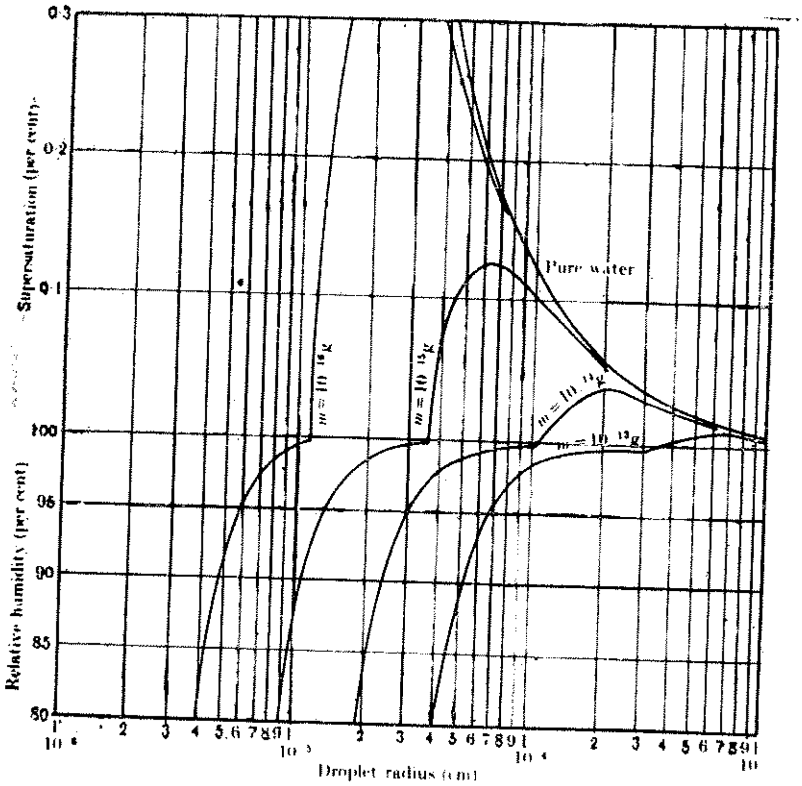

Fig. 1. The equilibrium relative humidity (or supersaturation) as a function of droplet radius for solution droplets containing the identical masses of sodium chloride (*After* Mason 1971)

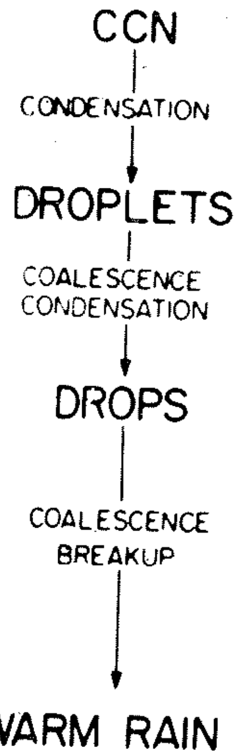

Fig. 2. Schematic diagram showing the evolution of warm rain originating from cloud condensation nuclei (CCN)

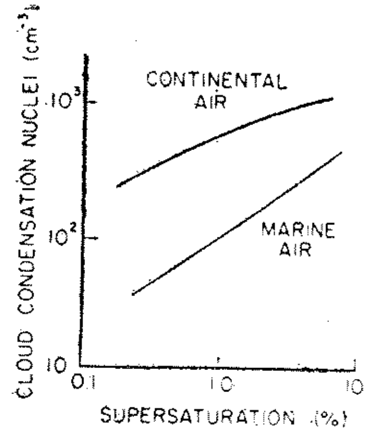

Fig. 3. Average cloud condensation nucleus spectra based on measurements made in continental and marine air masses

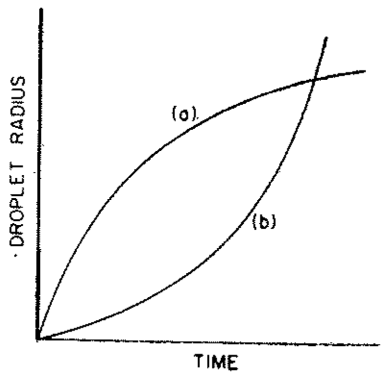

Fig. 4. Schematic curves of droplet growth by (a) condensation from the vapour phase and (b) coalescence of droplets

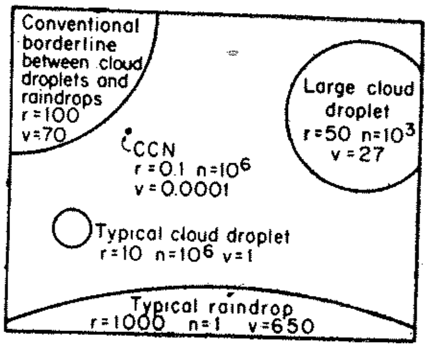

Fig. 5. Relative sizes of cloud droplets and raindrops; '*r*' with radius in micrometres, '*n*' the number per litre of the air and '*v*' the terminal fall speed in cm/sec

Since the upward motion determines the rate of cooling caused by expansion, the dynamic processes are always prerequisite to the microphysical processes. In this paper, emphasis is given to cloud microphysical processes in monsoon clouds assuming that the requisite dynamic processes obtain.

2.1. *Condensation and drop formation*

The development of precipitation depends on the growth of droplets by condensation and their subsequent growth by either collision-coalescence or ice-crystal process. In other words, whatever may be the ultimate process that occurs in the precipitation development, the aspect of condensation and drop formation is common to both warm rain and cold rain processes of rain-formation. Almost at the end of the 16th century, Grand (1680) and Mariotte (1686) introduced the idea of condensation for the growth of raindrops. A few decades later, Barlow (1715) contemplated the idea of coalescence of droplet growth for formation of rain. Since then many studies have been made on the topic both experimentally and theoretically. After Thomson (1870) derived the famous law on the dependence of water vapour pressure on the curvature of water surface, it became very clear that rain cannot form by condensation in clean air. On the other hand, if a droplet is formed on a soluble nucleus the equilibrium vapour pressure at its surface is reduced and condensation will be able to set in at a lower supersaturation met with in practice. These situations for drops containing various masses of sodium chloride are shown in Fig. 1. For example, if a soluble nucleus of mass 10^{-14} g is considered, it forms into a drop of 1.0 micron at 100 per cent relative humidity. If the humidity slightly increases, *i.e.*, supersaturation sets in, the drop attains a critical value above which the equilibrium is disturbed and it grows. Thus a cloud drop forms on soluble nucleus at much lower supersaturation than on non-soluble nucleus of the same size. The nuclei which are effective at the slight supersaturations that occur in natural clouds are present in the troposphere in the concentration range of 25 to 1000 cm^{-3}.

2.2. *Ice formation*

When the condensation process continues below 0°C, it results usually in the form of liquid drops which are supercooled. It agrees with the observational fact that clouds at temperatures down to —15° C and lower are normally composed by liquid drops rather than ice crystals. This indicates that the process of ice formation also requires nucleation, just as it is required for formation of drops. The numbers range from less than 10 m^{-3} of air at temperatures higher than —10° C to more than 10^6 m^{-3} below —30° C. These nuclei are often crystalline particles whose surface initiates ice formation during condensation by epitaxy or oriented overgrowth. Organic and inorganic substances can initiate the orientation of water molecules to form the ice lattice of ice embryo. Wegener (1911) introduced the idea of rain-formation through the melting of ice particles. He explained the efficacy of this process by the rapid growth by the sublimation of ice crystals in the presence of supercooled cloud droplets and the resulting vapour pressure gradient. Bergeron (1935) also came to the same conclusion and deserves the credit for a more general acceptance of the process. Findeisen, who made many aircraft observations in cloud, stated very clearly that rain originates from snow or hail (1939). Summing up these developments, inspite of the many advances in this area in the recent past, one can say that basically there are two mechanisms of rain-formation : (*i*) the warm rain or all liquid process, and (*ii*) the Bergeron-Findeisen or the cold rain or three phase process. In recent years, there has been growing evidence of the impact of warm rain process on the evolution of cold rain process in supercooled clouds (Cotton 1972; Rokicki and Young 1978; Nelson 1979; Cotton 1982).

3. The warm rain process

This process takes place in clouds whose tops do not extend above the freezing or 0° C level in the atmosphere and the existence of this process is obvious because clouds with tops below the 0° C level definitely produce rain. The precipitation by this process commences with the formation of cloud droplets by condensation of water vapour on aerosol particles and grows by collision-coalescence of droplets. The evolution of warm rain originating from cloud condensation nuclei is shown schematically in Fig. 2. In this section, the role of aerosols in the formation of clouds and precipitation by warm rain process, the growth of cloud droplets by collision-coalescence process and its relationship with the cloud-electrical, — thermodynamical and — microphysical parameters are discussed. The observations made in relation to these aspects are explained.

3.1. *Cloud Condensation Nuclei (CCN)*

These are the aerosols which serve as nuclei upon which cloud droplets form. One of the factors which influences rain-formation is the initial drop size distribution in clouds which in turn is controlled by the size spectrum of the CCN (Twomey and Squires 1959; Twomey and Warner 1967; Hindman *et al,* 1977(a) and Johnson 1981). These are in size range generally upward of 0.01 microns and are usually hygroscopic in nature (Ramana Murty *et al.* 1967). The concentration of cloud droplets is determined largely by the concentration of CCN in the air below the cloud base (Squires 1958; Juisto 1967; Twomey and Wojciechowski 1969; Warner 1969; Takahashi 1981). Recently, Johnson (1982) reported the presence of aerosol particles of sizes larger than 10 microns in the air below the cloud base and suggested that they are regular component of atmospheric aerosols. Fig. 3 depicts the world-wide measurements of CCN concentration for continental and marine air masses at various supersaturation values. It can be seen clearly that CCN concentrations are higher in continental air masses than in marine air masses. Also, it can be inferred from this figure that CCN concentrations decrease by a factor of 5 between the surface and 5 km, while over oceans they remain fairly constant. Over the oceans, the concentration of active CCN is found to be 50-200 cm^{-3} and over the continental regions, it is roughly 500-1000 cm^{-3} (List 1979). These concentrations of CCN can be seen at 0.1 per cent supersaturation in the above

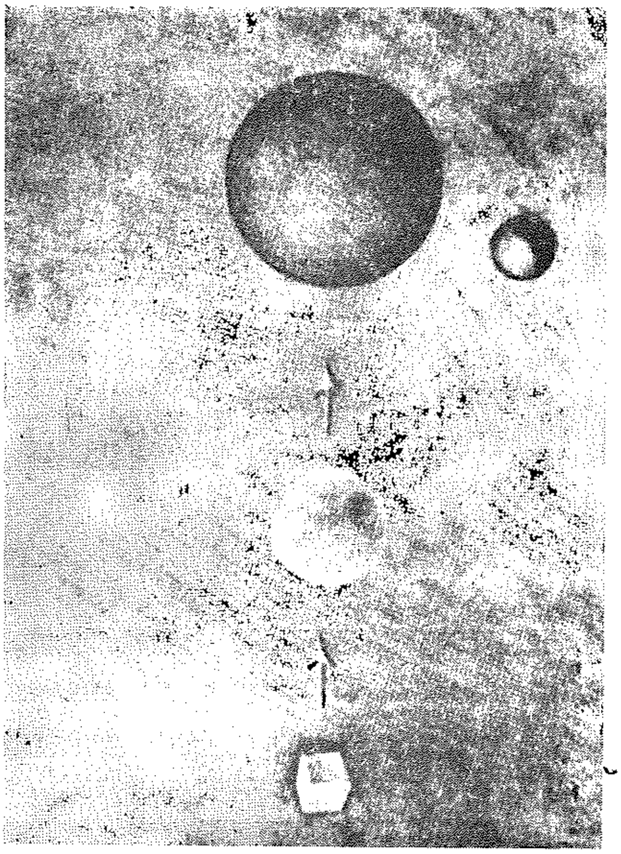

Fig. 6. Condensation of water vapour on gaint size (radius >1 micron) salt particle and its transformation into a large cloud drop

figure. Squires (1956, 1958) and Squires and Twomey (1958) reported that maritime clouds produce precipitation particles more readily than do continental clouds because of less concentration of CCN in maritime air masses than in continental air masses. Cotton (1982) also arrived at the same conclusion and suggested a broader droplet spectrum for the maritime, warm-based clouds.

Several workers studied the composition characteristics and vertical distributions of CCN (Dinger *et al.* 1970; Fitzgerald 1974; Mamane *et al.*, 1980; Sax and Hudson 1981; Fitch and Cress 1981). According to them, the marine character of aerosols appears confined to the immediate few kilometres above the surface of the ocean. At higher levels, systematic differences between continental and oceanic environments disappear. Most of the investigations on the vertical distribution of CCN, suggest that nuclei are of continental origin and possibly forming in the lower troposphere from trace gases emitted from land surfaces (Fitzgerald 1973; Friend *et al.* 1973; Sax and Hudson 1981). Ammonium sulphate is a common pollutant in the troposphere and stratosphere. Also, some studies (for example Twomey 1971) have indicated that CCN could be made up of this compound mixed with other materials. The specific sources of CCN are still obscure.

3.2. *Laboratory experiments on CCN*

Measurements on concentration of cloud condensation nuclei and their temporal and spatial variations over a region have received the attention of cloud physicists to understand the formation of clouds and precipitation. Junge and McLaren (1971) have conducted many laboratory experiments using cloud diffusion chambers and reported that the cloud nuclei spectra are dependent on aerosol size. Number of experiments have also been conducted in India to study the concentrations and size distributions of CCN. Measurements have been made during the summer monsoon of 1974, using a chemical diffusion chamber, on the concentration of CCN in the lower troposphere over the Arabian Sea (25 km off the coast of Bombay) and over Bombay (18° 51′ N, 72° 49′ E, 11 m amsl), Pune (18° 32′N, 73° 51′ E, 559 m amsl) and Rihand (24° 12′N, 83° 3′E, 310.5 m amsl) regions (Ramachandra Murty *et al.* 1976, 1978). The study suggested that there is an association between the CCN, computed droplet concentration and monsoon rainfall.

The CCN in the downwind of industrial complexes and the thermal power plants could influence the microstructure of clouds *vis-a-vis* the rainfall (Selvam *et al.* 1976). Numerous studies have been made of the concentrations and size distributions of CCN in regions adjacent to or downwind of large industrial sources such as paper mills (Hobbs *et al.* 1970; Eagen *et al.* 1974; Hindman 1976; Hindman *et al.* 1977 a, b, c), coal-fired electric power plants (Van Valin and Pueschel 1978; Hobbs *et al.* 1979, 1980). All these studies have indicated a strong interaction between the CCN behaviour and the associated precipitation mechanism. Though such a link has also been postulated between the rainfall anomalies and the anomalies in CCN concentrations measured in the smoke from sugarcane fires (Warner and Twomey 1967; Woodscock and Jones 1970; Warner 1971) and in the plume from fuel-oil burners (Benech *et al.* 1980; Radke *et al.* 1980) and in forest-fires (Radke *et al.* 1978; Stith *et al.* 1980), the exact mechanism which can explain the relationship satisfactorily has not been clear.

3.3. *Giant condensation nuclei*

Even though the concentration of CCN is important in determining the total number and average size of cloud droplets, they only partly control the stability of the cloud. Raindrops usually form as a result of collisions between a few larger cloud drops (10-20 microns radius) and the background of much smaller droplets (5-10 microns radius). It is considered that these larger drops form on the giant size (radius greater than 1 micron) condensation nuclei. These nuclei are composed of sea-salt, originate from drops ejected into the air when air bubbles, in breaking waves, burst at the ocean surface (Blanchard and Woodcock 1957; Mason 1957; Day and Todd 1964). By virtue of their chemical affinity for water, these particles commence to take up water at relative humidities above 75 per cent and can, therefore, form droplets well before they enter the cloud base, obtaining a head start in the race to form large drops. Fig. 6 displays this process where condensation of water vapour on giant size salt particle and its transformation into a large cloud drop take place.

Extensive measurements have been made by Ramana Murty *et al.* (1967) on concentrations and source

TABLE 1

Height variation of giant size aerosol concentration (number/m³) during summer monsoon season (Biswas *et al.* 1968)

Height (ft)	Total hygroscopic aerosols	Larger giant size(> 7 microns) of hygroscopic aerosols	Non-hygroscopic aerosols	Chloride aerosols	Percentage of hygroscopic aerosols in the total	Percentage of chlorides in hygroscopic aerosols
Ground	6810	1640	107540	N.A	5.95	N.A.
1,000	1900	590	30280	150	5.90	8.38
3,000	2220	460	32900	140	6.32	7.25
5,000	2690	840	17240	790	13.49	42.47
7,000	1000	230	17010	290	5.55	16.48
9,000	580	110	13400	550	4.15	5.10
10,000	600	350	6670	30	8.25	4.35

regions of hygroscopic, non-hygroscopic and ice-forming nuclei in ground air-layers of Delhi. Their results suggested that the warm rain process played a significant role in the formation of precipitation in tropical regions such as Delhi and that the major source for hygroscopic nuclei at Delhi was the sea. A series of aircraft and ground-based measurements have been made by Biswas *et al.* (1968) on giant size condensation nuclei in the regions around Delhi during the summer monsoon of 1965-67. The mean concentrations of total hygroscopic, non-hygroscopic and chloride nuclei observed, at different heights, during this period, are shown in Table 1. By considering the optimum concentration which is required of giant hygroscopic nuclei in cloud air is about 1 per litre for efficient rain-formation, their results pointed out the deficiency (less than 1 per litre) in giant condensation nuclei over north India under certain meteorological conditions during the summer monsoon season. The study of vertical distribution of these nuclei concentrations revealed that in monsoon months, the total number of hygroscopic particles measured over north India increases with height up to 5000 ft and decreases at higher levels. This effect is considered to be due to the cloud base which is at about that level during the period acting as a potent aerosol-sink.

Recent investigations have revealed the importance of aerosol particles of sizes larger than 10 microns in the understanding of the initial phase of cloud microstructure (Johnson 1982; Cotton 1982). Johnson (1976) named these aerosols as 'Ultragiant-aerosol particles' to distinguish them from the giant-aerosol particles, which have been assumed to have an upper size limit of 10 microns (Ludlam 1980). The widespread presence of these particles in the atmosphere has been evidenced from many observational studies (Jaenicke and Schutz 1978; Hobbs *et al.* 1976, 1977, 1978; Rosinkski *et al.* 1979). These particles are predominantly insoluble and over continental areas, these are considered to be mostly soil fragments carried aloft by the wind (Johnson 1976). As the particles larger than 20-25 microns regularly appear in the natural atmosphere, it has been suggested that these insoluble particles can directly initiate the coalescence growth without the prior growth by condensation (Johnson 1979).

3.4. *Droplet growth by condensation and collision-coalescence*

The cloud droplets initially form by condensation of water vapour on cloud condensation nuclei and after attaining certain stage, the condensation process becomes inefficient (for fixed values of supersaturation, rate of growth of a droplet and its radius are inversely related). The mechanism governing the growth of droplet is shown in Fig. 4. The drops, therefore, rarely grow larger than of radius 20 microns by condensation. In view of the large number of drops competing for the available water vapour, the modal radius of the cloud drops is usually between 5 and 10 microns. In one of the recent studies, Takahashi (1981) noticed a critical modal radius of 15 microns for initiation of warm rain in Hawaii and observed more spectrum broadening after the cloud drop attains a critical value. The drops of this size-range cannot reach the ground as precipitation since they evaporate very quickly when they do fall out of the cloud into unsaturated air. The smallest precipitation particles, therefore, are drizzle drops of radius of about 100 microns whereas raindrop range from 0.5 to 3 mm. Thus the key difference between the cloud and the precipitation is only the particle size. This can be clearly seen from Fig. 5. For example, if a cloud drop of modal size, say, 10 microns is considered for its growth into a raindrop of size 1000 microns, it requires increase in mass by a factor of one million. Therefore, about a million cloud drops have to coalesce for the operation of rain process. Since the large drops fall faster than the small ones, they should overtake and collect those which are in their path, becoming larger, falling faster and sweeping up small droplets more rapidly. These stages are clearly demonstrated in Fig. 7.

As the large drops fall, the air in their path is pushed out of the way. The small drops, therefore, tend to be carried out of the path of the large drops along with the air. Thus, a fraction of the small drops in the path collides and a fraction coalesces with the large drops. The fraction of the drops in the path which is collected is called the collection efficiency. This is a critical parameter which enters into the life cycle of warm rain process.

3.5. *Theoretical computations of droplet growth by collision-coalescence*

Collision-coalescence process is the only one which can cause rain-formation in clouds the tops of which are at temperatures above 0° C. The droplet growth by this process is governed by four principal factors : (*i*) rate of water vapour transfer to the drop (environmental supersaturation), (*ii*) heat transfer away from the drop, (*iii*) Kelvin curvature effect and (*iv*) solubility of the nucleus. Langmuir (1948) was the first to make calculation of the collision efficiencies of the

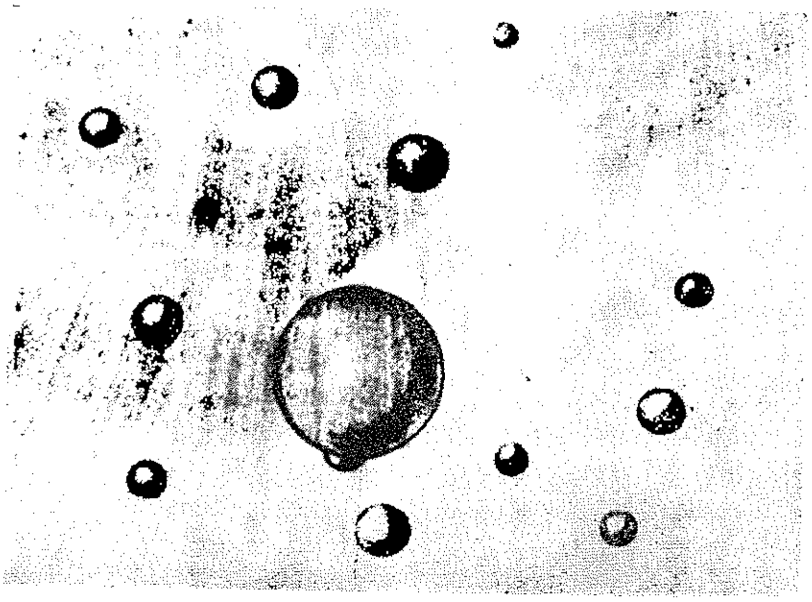

Fig. 7. Growth of a large cloud drop by the collision-coalescence process in a warm cloud

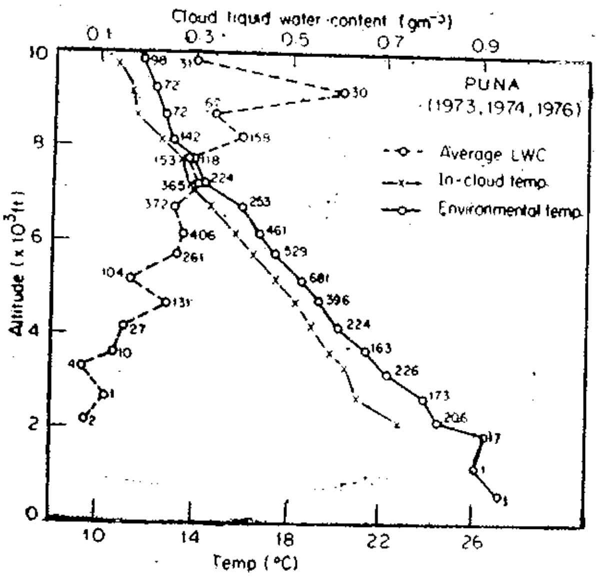

Fig. 8. Vertical profiles of average cloud liquid water content (LWC), temperatures inside the cloud and its immediate environment for Pune. The figures indicate the number of observations

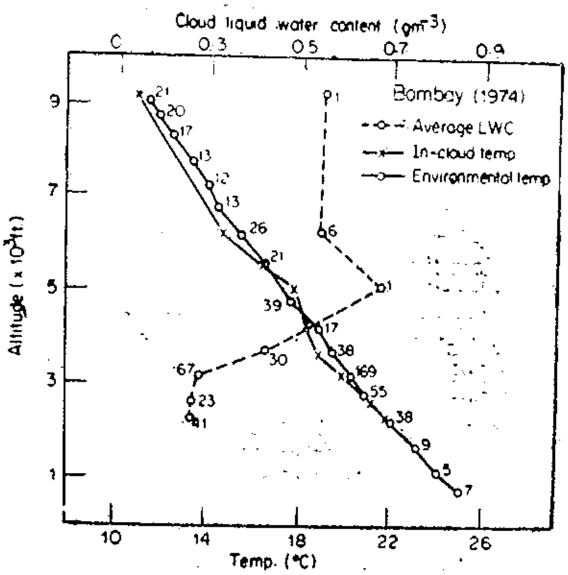

Fig. 9. Vertical profiles of average cloud liquid water content (LWC), temperatures inside the cloud and its immediate environment for Bombay. The figures indicate the number of observations

drops of given radii falling under the influence of gravity through a cloud of smaller drops. He suggested that when the drops grow to a certain size ($\simeq$ 6 mm), they will breakup (either spontaneously or by collisions amongst the droplets) due to hydrodynamic instability and the resultant fragments will grew again to the breakup size and the process continues like a chain reaction. Further investigations in this context have indicated that droplets of diameter 2-3 mm or even smaller also can trigger breakup (Magarvey and Geldart 1962; Cotton and Gokhale 1967; Brazier-Smith *et al.* 1972; McTaggart-Cowan and List 1975). Also, it has been found both experimentally and theoretically that collision-induced breakup is more important than the spontaneous breakup in the evolution of droplet spectrum (Brazier-Smith *et al.* 1973; Young 1975; Gillespie and List 1976; Srivastava 1978; Brown 1981). The collision efficiency depends on the size of both the large and the small drop. Das (1950) computed the droplet trajectories taking the size of the droplets (collected) into account and obtained new values of collision efficiency for different combinations of collector and collected drops. Subsequently he computed dropsize spectra and liquid water content for different initlal conditions and compared his values with observed spectra. It was shown that the number of large drops in a cloud cannot increase by coalescence, unless the drop spectrum has a very large range or a sharp peak (Das 1956).

The results of the theoretical studies showed that the computed cloud droplet spectra are very much narrower than the observed spectra (Twomey 1966; Berry 1967; Scott 1968; Twomey 1976; Cotton 1975, 1982). This discrepancy between observed and computed spectra was once thought to be due to the omission of factors like turbulence and mixing of environmental air into the cloud, in the numerical simulation of droplet growth. By numerically simulating the turbulent updraft, Warner (1969) showed that turbulence does not sensibly broaden the cloud dropsize spectrum. The effects of mixing up of environmental air on cloud droplet spectra were also studied by Warner (1973) who attributed that mixing broadens the spectra but in a way not observed in natural clouds. With the same idea, Manton (1979), Baker and Latham (1979), and Telford and Chai (1980) have partially succeeded in explaining the initial production of large drops capable of triggering coalescence in continental clouds. Fitzgerald (1972) found good agreement between the observed and computed spectra within a few hundred metres from cloud base. However, such agreement has not been found in spectra observed at higher levels in the cloud where coalescence may have an appreciable effect on dropsize distribution.

Results of theoretical investigations on droplet growth suggest that the understanding of basic characteristics of the cloud base spectra is incomplete. Also, they suggest that larger drops of radius more than 20 microns should be present in order that precipitation be initiated by warm rain process (Lee 1980; Johnson 1982). Srivastava and Roy (1962) developed cloud models to study the evolution of rain. They found that the shape of the droplet spectrum at different levels was uniquely determined by two parameters, namely, the updraft structure and the assumed constant value of supersaturation. Several possible factors have been considered for the formation of larger size drops. They include (*i*) the presence of an unusually small number of CCN, (*ii*) the presence of unusually large CCN and (*iii*) the presence of CCN composed particularly of hygroscopic substances. It is generally considered that, for facilitating warm rain process, not only large number of large size drops should be present but the spectrum should contain sufficient number of drops in smaller size also for the requirement of collision and collection (Takahashi 1976, 1981; Johnson 1978, 1982). However, the mechanism of production of the initial larger drops remains unclear (Telford 1975; Johnson 1982).

3.6. *Influence of cloud — electrical, thermodynamical, and microphysical parameters on droplet growth by collision-coalescence process*

3.6.1. *Electrical measurements*

The knowledge of the effect of electric fields and drop charges on the collision and coalescence of cloud drops is important for the physical understanding of the rain-formation in clouds. This aspect has been recognised fully after Cochet (1952) who concluded that charged water drops could accelerate the collision and coalesence process. It is known from several experimental and theoretical studies that the presence of electric field significantly enhances coalescence (Sartor 1954, 1960; Goyer *et al.* 1960; Lindblad and Semomin 1963, Davis 1965; Beard and Pruppacher 1968; Abbot 1974; Dayan and Gallily 1975; Schlamp *et al.* 1976; Cohen and Gallily 1977). Also, these studies suggest that the effective electric field values which can greatly enhance the collection efficiency of drops are of the order of those present in pre-thunderstorm and thunderstorm conditions.

In India, laboratory experiments have been conducted on the collision-coalescence of pairs of water drops of equal size in two oil media (kerosene and mustard) with and without external electric field (Paul *et al.* 1979). The results suggested that the collection efficiency was zero without external field and it increased with external electric field. Also, it was noticed that the collection efficiency was more when the collected drop was slightly smaller than the collector drop when compared to that when the drops were of equal size. Aircraft measurements have been made of electric field and cloud drop charge over the Arabian Sea and in a few regions (Bombay, Pune and Rihard) in India during 1973-74 (Ramachandra Murty *et al.* 1976 and Mary Selvam *et al.* 1977). The results of the investigations suggested that the electric field (3 V cm^{-1}) and charge (10^{-16} coloumb) values observed in warm monsoon clouds were two orders of magnitude smaller than the experimentally determined values required to increase collision-coalescence process. However, the charges carried by the cloud droplets in warm monsoon clouds are sufficiently large to enhance the collection efficiencies of droplets with radii less than 10 microns. Recently, Pruppacher and Klett (1978) and Cotton (1982) conclude that weak electric fields and weak charges that are generally expected to be present in developing cumulus clouds may not be much helpful for the initiation and development of warm rain.

3.6.2. *Thermodynamical and microphysical measurements*

It is known that droplet growth in a cloud depends mainly on the portions of the cloud where the liquid water content (LWC) is high and so the space-time

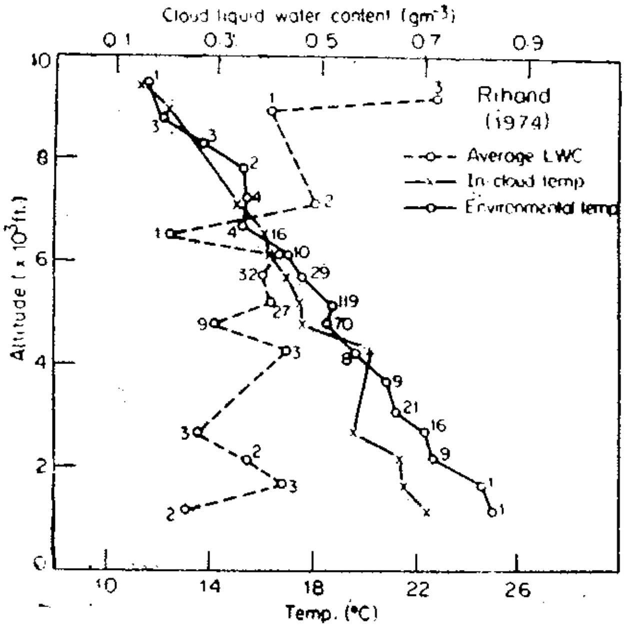

Fig. 10. Vertical profiles of average cloud liquid water content (LWC), temperatures inside the cloud and its immediate environment for Rihand. The figures indicate the number of observations

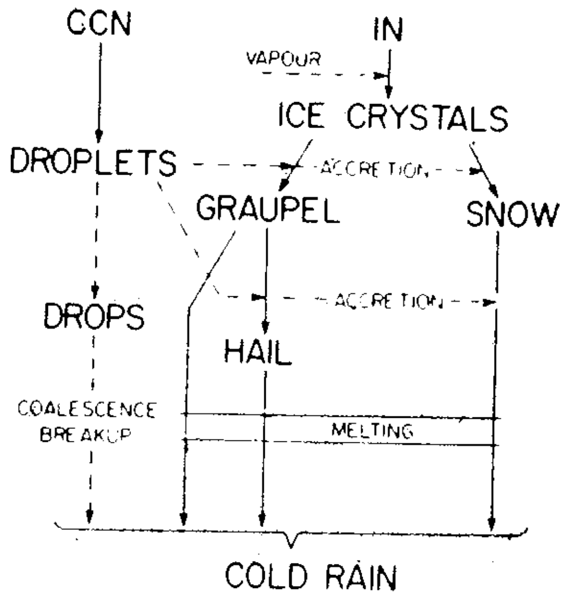

Fig. 12. Schematic diagram showing the evolution of cold rain originating from ice nuclei (IN)

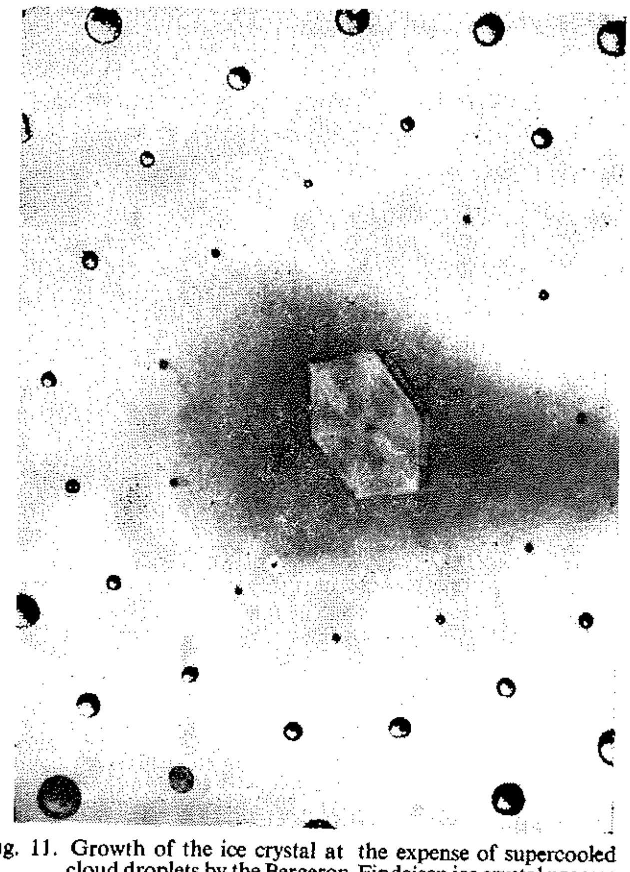

Fig. 11. Growth of the ice crystal at the expense of supercooled cloud droplets by the Bergeron-Findeisen ice crystal process in a cold cloud. At the centre is an ice crystal in shape of an hexagonal plate and supercooled cloud droplets around the ice crystal can be seen

character of LWC in a cloud plays an important role in the onset and control of precipitation by warm rain process (Twomey 1976; Heymsfield *et al.* 1978; Cotton 1982). Johnson (1980) reported that cloud-base temperature also considerably influences the activation of cloud droplets. Extensive aircraft in-cloud observations have been made of LWC, temperature and dropsize distribution in monsoon clouds over the Arabian Sea and over Bombay, Pune and Rihand regions (Ramachandra Murty *et al.,* 1976; Mary Selvam *et al.* 1977). The vertical profiles of average cloud liquid water content (LWC), temperatures inside the cloud and its immediate environments for Pune, Bombay and Rihand are shown in Figs. 8, 9 and 10. The vertical profiles of average LWC at Pune showed a progressive increase up to 9000 ft and thereafter decreased. At Bombay, It increased up to 5000 ft and thereafter showed no marked variation. At Rihand, LWC was small and less uniform up to a height of 6500 ft and thereafter it increased.

The temperature profiles at Pune and Rihand revealed colder cloud-base compared to its immediate environment with a maximum difference of about 3° C at the cloud-base level and decreased with height from the base of the cloud more uniformly at Pune that at Rihand. At Bombay, this difference was less than 1° C at some levels, the in-cloud temperature was warmer than the environment. These features suggest tentatively according to Johnson (1980), that colder cloud bases observed at Pune will activate more cloud droplets to trigger collision-coalescence process.

The profiles of cloud dropsize distribution at Pune indicated that the concentration of bigger drops (radius $\geqslant$ 25 microns) varied between 0.18 and 0.71 cm^{-3} and increased rapidly with height above the cloud-base indicating that the size distribution experiences a broadening effect with increasing distance from the cloud base. At Bombay, the concentration of bigger drops varied between 0.05 and 0.74 cm^{-3}

4. The cold rain process

This process is usually called Bergeron-Findeisen process. It takes place in clouds whose tops extend beyond the freezing level and it operates in a mixed cloud consisting of supercooled drops and ice crystals. The vapour pressure over ice is less than that over water for a given temperature. The maximum vapour pressure difference over water and ice is 0.27 mb and occurs at —12°C. Therefore, if both phases are present side by side in a water cloud, the ice crystals grow at the expense of the supercooled drops by diffusion. Fig. 11 shows the way in which an ice crystal grows at the expense of supercooled cloud droplets in cold rain process.

In the cloud environment, the vapour pressure difference between the ice crystals and the water drops is much greater than that between drop and its environment. Therefore, the ice crystals grow, by condensation, at the expense of the water drops and fall faster than the remaining cloud droplets. The ice crystals which have grown and become bigger melt into drops after leaving the freezing level. The drops grow further by collision-coalescence in the cloud layer, if any, below the freezing level and ultimately reach the ground in the form of raindrops. In convective or orographic clouds with updrafts comparable to or higher than the fall velocities of snow crystals, different precipitation mechanisms exist leading to graupel, soft hail, hail and sometimes giant wet snow flakes. The investigations made of the various source regions of ice-forming nuclei and ice nucleation mechanisms for the initiation and development of precipitation by cold rain process are discussed and are explained in the light of the work done in India.

4.1. *Ice-forming nuclei*

The aerosols which could assist ice crystal formation in clouds are called ice-forming nuclei or ice nuclei. Fig. 12 shows the evolution of cold rain originating from ice nuclei. The concentrations of these nuclei reported by several workers varied widely depending upon the type of instruments used for the measurements (Mason 1971). The reason for this is attributed to the difficulty of measuring ice nucleus concentration, like the uncertainty over nucleation modes, particle sizes and nucleation activation times etc. Majority of the particles, which can nucleate ice at fairly high temperatures (above —15° C) are made up of clay, probably Kaolinite (Mason and Maybank 1958; Prodi *et al.* 1982). The source regions of the ice nuclei can be terrestrial and extra-terrestrial (Maruyama and Katigawa 1967). Also, some of the organic substances like metaldehyde, phloroglucinol are found to possess ice nucleating ability (Fukuta 1966). Some of the decomposed vegetation (leaf-derived nuclei) has been found to act as ice nuclei (Schnell and Vali 1972).

Extensive ground-based measurements on ice-forming nuclei have been made by Ramana Murty *et al.* (1967) over Delhi, an inland region. The results pointed out that preponderance of ice-forming nuclei (number per litre —20° C) and predominance of cold rain process for rain-formation in clouds during monsoon season in tropical areas such as Delhi 28° 35′ N, 77° 12′ E, 210 m amsl). In order to study the nature, concentration and dominant source regions of ice-forming nuclei, Kapoor *et al.* (1969) extended the above measurements to a few other places in India Bombay (19° 0.7′ N, 72° 51′ E , 14 m amsl, Lonavala (18° 45′ N, 73° 24′ E, 625 m amsl). Pune (18° 32′ N, 73° 51′ E 559 m amsl) and Calcutta (22° 39′ N, 88° 29° E, 6 m amsl). They found that the concentration of ice-forming nuclei at Calcutta (coastal region) was smaller than that at Delhi (inland region). This feature suggests that the mechanism of rain development in coastal regions, atleast in the tropics, does not frequently involve ice phase but may be associated predominantly with collision-coalescence process. Also the presence of higher concentrations of ice-forming nuclei at Delhi once again suggests that clouds in such region develop precipitation predominantly by cold rain process.

4.2. *Ice crystals in clouds*

Ice crystals play a vital role in many aspects of the behaviour of the supercooled clouds. The number of ice crystals that are formed in the cloud was at one time thought to depend solely on cloud summit temperature and upon the ice nucleus spectrum, *i.e.*, the number of aerosol particles in the cloud capable of assisting ice crystals to form at various temperatures. Fukuta and Schaller (1982) explained theoretically the formation of ice crystals in clouds by means of heterogeneous ice nucleation and they conclude that the condensation-freezing nucleation mechanism is responsible for the ice crystal formation in developing clouds. Several field investigations have shown that in certain clouds the concentration of ice crystals may be several orders of magnitude greater than the measured concentration of ice nuclei (Hobbs 1969; Koenig 1968). In maritime clouds, the concentration of ice crystal can exceed the concentration of ice nuclei by a factor of about 10^4 at — 10° C (Mossop 1970). The discrepancy may be partly due to the fact that the methods used for measuring the concentration of ice nuclei do not simulate properly the conditions under which ice nuclei act in clouds. Although several mechanisms have been proposed to explain the discrepancy (Mossop 1970), the phenomenon is still not clearly understood.

4.3. *Laboratory experiments on ice nucleation*

Extensive laboratory experiments have been conducted to study the ice nucleation mechanisms and to ascertain their significance in rainfall. A study made by Ramana Murty and Roy (1961) in surface air layers at Delhi had shown that the rise in concentration of ice nuclei during many instances of occurrence of rain shower was due to its origin from the sea surface, although the coincidence of many of the days of occurrence of high ice nuclei concentration with dates of rainfall singularities in association with meteor

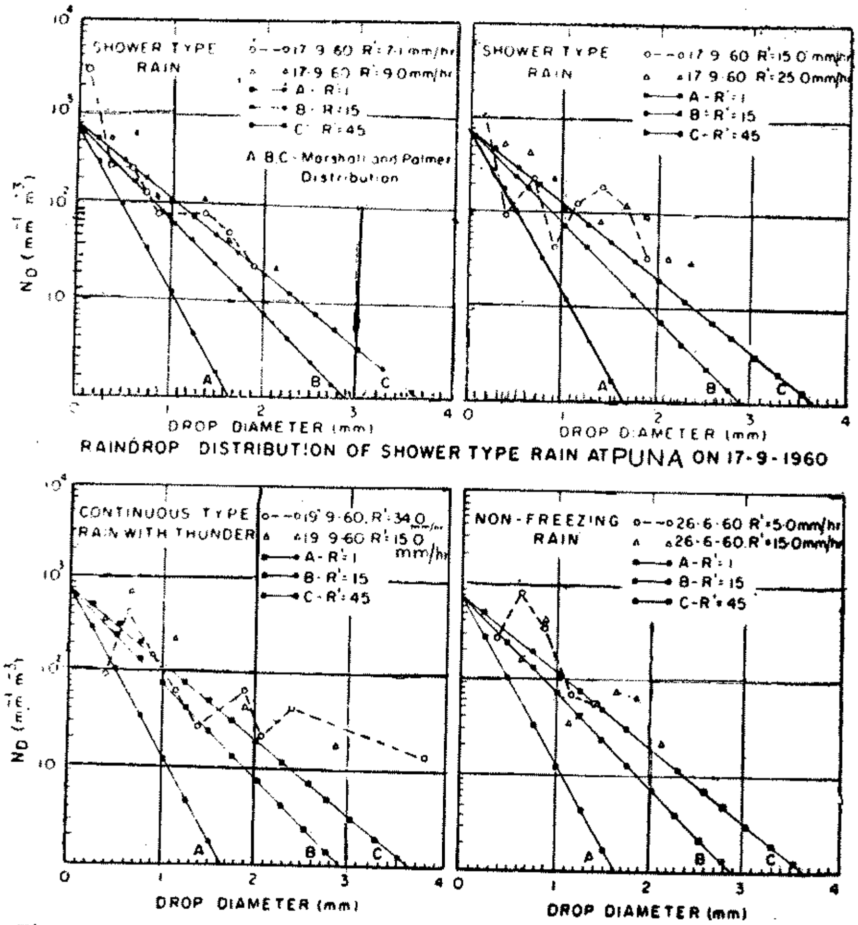

Fig. 13. Raindrop distribution of shower type rain without thunder, continuous type rain with thunder and non-freezing rain observed at Pune

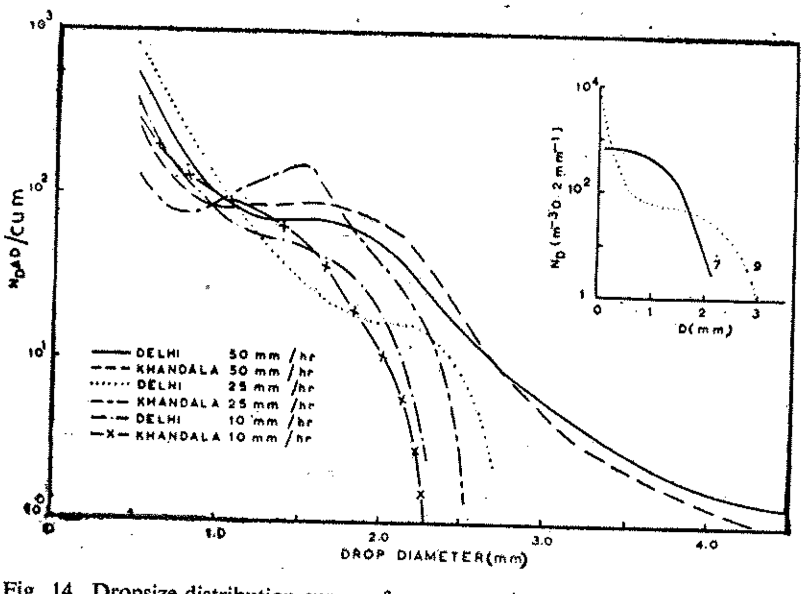

Fig. 14. Dropsize distribution curves of monsoon rain at Delhi and Khandala (Inset : Blanchard's curves for orographic and non-orographic rain)

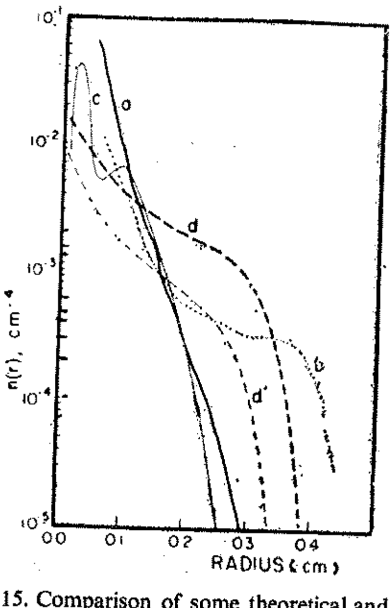

Fig. 15. Comparison of some theoretical and observed raindrop spectra. Curves (a) and (b) are observed distributions for rainfall rates 100 and 410 mm hr^{-1}. Curves (d) and (d′) are equilibrium distributions for rainfall rates 510 and 125 mm hr^{-1} form by the action of coalescence and spontaneous drop breakup. Curve (c) is a theoretical distribution for a rainfall rate of about 75 mm hr^{-1}

showers suggested the extra-terrestrial origin of those nuclei.

Laboratory experiments have been conducted on the freezing of rain water drops, under various conditions of temperature, with various solutes, to study their ability in ice nucleation of several insoluble nuclei. The study indicated that ammonium sulphate can accelerate the ice nucleation (Murty and Murty 1971 & 1972 a). Since the majority of cloud condensation nuclei, both in maritime and continental air, is of composition similar to that of ammonium sulphate (Twomey 1971), it is expected that, under favourable meteorological conditions, these aerosol particles may be carried to higher levels and influence rain-formation by cold rain process.

The results of one of the experiments conducted in the above context suggested that freezing of water drops will be accelerated when the drops are subjected to simultaneous supercooling and evaporation, due to a new effect called 'dynamic effect of evaporation' (Murty and Murty 1972 a, b). The acceleration of the freezing of water drop by the dynamic effect has been attributed to the change in the free energy of the drop under the influence of evaporation. Also, experiments conducted on freezing of water drops containing different soluble salts (solute effect) pointed out that sulphates accelerated freezing (Murty and Murty 1972 a). This feature has been attributed to the formation of the critical embryo for ice- formation as a consequence of water molecules being attracted to the polarized ions and collected around them in a fashion more or less similar to that of ice (Murty and Murty 1973 b). The combined effect due to evaporation (dynamic effect) and due to acqueous solution (solute effect) could increase the drop freezing events by about 2 to 3 orders of magnitude at relatively warm temperatures (Murty 1973).

The ice nucleating efficiency of several inorganic and organic materials has been reported and the effect of particle size on the temperature of the ice nucleation has been evidenced by many experimental studies (Layton 1973; Rosinski 1979; Prodi *et al.* 1982). It is found that some of the complexes (like $AgIO_3 + KIO_3 + NaIO_3$) can help freeze water at as warm temperature as — 1° C (Murty and Murty 1973 a, b; 1974 a). Also, these experiments have shown that two commonly known substances, namely, calcium oxide (quick lime) and portland cement possess good ice nucleating property (Murty and Murty 1974 b). These experiments helped to explain partially the discrepancy between the observed ice crystal and ice nuclei concentrations in clouds and to identify new nucleation mechanisms (Murty and Murty 1972 b; Murty 1973). Experiments conducted on some of the herb-derived nuclei originating from the Indian plants like 'Cair Wood' revealed that these nuclei could freeze water at about —4° C. Their nucleating property was attributed to the iodine content of the plants (Unpublished).

More recent laboratory experiments suggested that high crystal concentrations could be due to the ejection of secondary ice particles when supercooled drops freeze upon graupel particles (Hallett and Mossop 1974; Chisnell and Latham 1976; Koenig 1977; Hallett 1978). The generation of secondary ice particles in clouds by crystal-crystal collisions has also been suggested by Vardiman (1978). These findings made possible to explain the evolution of cold rain precipitation processes in supercooled clouds from the warm rain precipitation (Cotton 1972, 1982; Rokicki and Young 1978; Nelson 1979). The multiplication of ice crystals takes place within the temperature range —3°C to —8°C provided there are moderately large drops (radius greater than 12 microns) present. These conditions may be satisfied in cumuli of maritime characteristics provided the cloud-base temperature is warm enough. On the other hand, if the cloud has high droplet concentration and colder base temperature, the multiplication process will be inactive and the concentration of ice crystal will agree reasonally well with the concentration of ice nuclei (Gagin 1965, 1975). The exact physical mechanism by which the secondary ice particles are produced is not clearly known.

5. Raindrop size distribution

Precipitation may be initiated through either coalescence process or ice-crystal process or by both. After precipitation particles are formed, they grow by sweeping out cloud droplets/accretion or by combining with one another and finally reach the ground as rain. The size distribution of raindrop varies considerably with the character of the rain, with the type of the cloud from which they fall and also with the rainfall intensity. Thus the study of dropsize distribution in rain helps in determining the mechanism by which the precipitation develops in different types of rain such as thunderstorm, showers, continuous steady rain and orographic rain. One such example is depicted in Fig. 13 which displays the raindrop size distribution, at Pune, in typical shower type of rain without thunder (from cumuliform clouds), continuous type of rain with occasional thunder (from stratiform and cumuliform clouds mixed) and non-freezing rain during typical monsoon rain from stratiform clouds. The dropsize distribution curves of orographic monsoon rain at Khandala and non-orographic monsoon rain at Delhi are shown in Fig. 14. Attempts have been made by numerous workers to establish empirical relations between the raindrop size and rain intensity for various types of precipitation (Laws and Parson 1943; Marshall and Palmer 1948; Best 1950, 1951; Blanchard 1953, Jones 1956; Mueller and Jones 1960; Atlas 1963; Fujiwara 1967). In India, much work has been done on this important aspect, both theoretically (Roy and Srivastava 1958; Srivastava 1960; Srivastava and Roy 1962; Ramana Murty and Roy 1962) and experimentally (Kelkar 1945, 1959, 1960, 1968; Ramanadham and Vidvavathi 1957; Ramana Murty and Gupta 1959; Sivaramakrishnan 1960, 1961; Sivaramakrishnan and Mary Selvam 1967; Srivastava and Kapoor 1961) to elucidate the basic rain process underlying rain-formation in clouds.

On account of the variation of the terminal velocity of a water drop with size, the dropsize distibution on the ground always differs from that in air. Marshall and Palmer (1948) showed that the size distribution of raindrops reaching the ground may be represented by the expression :

$$N(D)=N_0 \exp(-\Lambda D)$$

$$\Lambda=41\ R^{-0.21}\ \mathrm{cm}^{-1};\ N_0=0.08\ \mathrm{cm}^{-4}$$

where $N(D)$. ΛD is the concentration of raindrops in the diameter range D to $D+\Lambda D$ and R is the rainfall in mm hr^{-1}. Mason and Ramanadham (1954) examined, theoretically, the variations in the distribution at the ground and concluded that they were due to three main reasons: (a) the growth of raindrop by accretion with cloud droplets, (b) coalescence between raindrops of different sizes and (c) differential rates of evaporation of raindrops of different sizes as they fall from cloud base to ground.

Theoretical investigations have been made on raindrop size distributions in rain-showers from large stationary warm cumulus clouds (Roy and Srivastava 1958; Srivastava 1960; Srivastava and Roy 1962). The results suggested that raindrop sizes as obtained from theoretical computations under certain assumptions were in agreement with the accepted theory of coalescence growth of raindrops. The anomalies, observed in the study, regarding the time interval between the cumulus cloud development and precipitation release and width of raindrop spectrum, were explained by Ramana Murty and Roy (1962) on the basis of existing theories at that time (East 1957; Scorer and Ludlam 1953).

By assuming Marshall-Palmer distribution at the melting level, Sivaraman and Sivaramakrishnan (1962) made theoretical studies on the raindrop size distribution at the ground during continuous rain from steady stratiform clouds. The study has shown good agreement with the theoretical calculations made by Mason and Ramanadham (1954) and also with the experimental observations made during the same period (Sivaramakrishnan 1961).

Extensive measurements have been made on dropsize distribution in orographic monsoon showers at Khandala during August 1956 and non-orographic monsoon showers at Delhi during July-October 1956 (Ramana Murty and Gupta 1959). The results suggested an agreement between the observed distribution and the distribution proposed by Marshall and Palmer (1948) for very low rain intensities (upto 5 mm/hr) and such agreement fails as the rainfall rate increases.

Using the well known formula of Best (1950), Sivaramakrishnan and Mary Selvam (1967) studied the size distribution of raindrops in the tropics and suggested suitable values for the Best's constants for different types of rain (continuous type of rain with thunder, shower and non-freezing rain). Kelkar (1968) also used the Best's formula for studying the raindrop size distribution at Pune and pointed out that the formula holds good for individual samples of general monsoon rains and thunderstorm rains and fails in cases where the liquid water content is multimodal (generally bimodal) or J-shaped.

Sivaramakrishnan (1960-63, 1965, 1968) studied thoroughly the raindrop size distribution and associated parameters like liquid water content etc and their relation with rate of rainfall and electric charge carried by rain. The study suggests that the measurement of rain current (*i.e.*, the total charge brought down by rain per sq. cm per second) helps in understanding the type of process involved in the rain. His findings made at Pune during the monsoon season of 1967 clearly indicated the absence of electric charge in rains originated by warm process. He further emphasised the importance of this measurement in explaining the variation of dropsize distribution between two rain-measurements, especially when the liquid water content and intensity of rainfall are same in both cases.

Srivastava and Kapoor (1961) made measurements on dropsize distribution in two different types of rain (*a*) widespread continuous and relatively steady type (cold stratiform clouds) in which rain initiates due to Bergeron-Findeisen mechanism and (*b*) showery and temporary and localised type (very tall and highly supercooled clouds as in a thunderstorm) in which the rainfall is largely due to collision-coalescence process. The results suggest a close agreement between the observed and Marshall-Pamer distribution in the case of cold rain process whereas the observed spectrum deviates from the Marshall-Palmer's in the case of rain of showery type. The raindrop spectra computed theoretically and experimentally by Srivastava (1971) for different rainfall rates formed by the action of coalescence and drop breakup are shown in Fig. 15. The spectra does not resemble the Marshall-Palmer distribution and were narrow. The smallest drops may evaporate. The size of larger drops was limited which could be due to the limited depth of cloud.

6. Evaluation of rain processes in monsoon clouds

The nature of rain processes involved in monsoon clouds can be studied by means of radars operating at microwave frequencies. This technique has been widely in use since the last few decades and it gives mostly qualitative information on cloud characteristics and associated parameters. On the other hand, the detection of rain process in monsoon clouds can also be made by studying the microphysical characteristics of clouds. In this section, results are discussed of the presence and contribution to season's total rainfall of the three main processes, *viz.*, cold rain, warm rain and combination of both which govern the formation and development of precipitation in monsoon clouds based on radar investigations made over certain regions in India. Results are also discussed of the identification of rain processes in monsoon rain through the cloud microphysical observations carried out at a few places in India.

6.1. *Radar studies*

The advantage of radar for cloud physics study lies mainly on its ability to scan through many clouds and monitor when and where precipitation begins to form in any part of them. Substantial data have been collected on convective cloud characteristics (Jones 1950; Braham 1958; Battan 1963). In India, extensive

TABLE 2

Occurrence of different rain processes and their contributions to season's total rainfall observed at Delhi (Ramana Murty *et al.* 1960) and at Calcutta (Roy and Mukherjee 1969)

Rain process	Delhi	Calcutta
(a) Percentage frequency of occurrence		
Warm	41	25
Cold	16	12
Combined	43	63
(b) Percentage contribution of rainfall to season's total		
Warm	1.8	5·0
Cold	52.6	50.0
Combined	45.6	45.0

investigations have been made with the help of microwave radars in different regions (Delhi, Calcutta, Pune, Bombay and Madras) to study the three rain processes, namely, warm, cold and combination of both which occur in rain-bearing clouds in monsoon. Results of these measurements relating to summer monsoon are discussed in the paragraphs to follow. The dominant rain process was inferred based on the characteristics of the radar echo observed. The percentage contribution of rainfall to the season's total by the different processes was also estimated for Delhi and Calcutta.

(*i*) *Delhi and Calcutta*

The frequency of occurrence of different rain processes and their percentage contributions to season's total rainfall (July to September) have been studied in detail with the help of radar and self recording raingauges at Delhi 1958-59 (Ramana Murty *et al.* 1960) and at Calcutta during 1962-64 (Roy and Mukherjee 1969). The radar Plan-Position Indicator (PPI) pictures observed at Delhi during the above period on A, B and C class days which are respectively representative of cold, combination of warm and cold—and warm-rainy days, are shown in Fig. 14. The results of analysis are given in Table 2. The inference is that purely cold process contributes about 50 per cent to the season's total rainfall at both Delhi and Calcutta. The combined process of cold and warm rain contributes about 45 per cent and purely warm process contributes only about 5 per cent.

(*ii*) *Pune*

It has been reported from the radar pictures made on 68 occasions during the monsoons (June to September) of 1953-59 that melting band, which is proof of occurrence of cold rain process, was noticed on 19 occasions. Also, these studies suggested a 28 per cent frequency of occurrence of rain by cold process at Pune. The occurrence of melting band at Pune was explained by Pisharoty (1962) on the basis of Scorer's lee wave theory (Scorer 1949). According to him, the ascending part of the crests of the lee waves, occurring in the upper troposphere, serve as the generating areas for the precipitation that occurs within the so called 'rain shadow' regions during the monsoon. Rain originating as snow flakes are carried forward by the prevailing wind and produce the melting. No study was made of the percentage contribution to the season's total by the different rain processes.

(*iii*) *Bombay*

There was recorded evidence of melting band occurrence on only one occasion at Alibag on 30 July 1961 (Srivastava *et al.*, 1966). The melting band noticed on this occasion on the windward side of the mountain was understood to occur when the upper winds are weak and the monsoon circulation is less pronounced.

(*iv*) *Madras*

Efforts have been made by Lakshmanaswamy and Rao (1974) and by Jayanthi *et al.* (1980) to study the frequency of radar echo tops in different months over the Madras region. Their findings point out that during the monsoon, about 80 per cent of the cloud echoes equalled or exceeded the freezing level, suggesting association of cold process and the combined cold and warm process of rain formation on these occasions. About 20 per cent of the rain occasions are associated with warm process.

Radar observations made by many workers (Kulshrestha 1962; Seshadri 1963; Bhattacharya and De 1966; Raghavan 1975) in different regions in India and the results of the investigations reported in the monograph by Miller and Kesavamurthy (1967) suggest the occurrence of rain from tall cumulus clouds extending beyond the 0° C temperature level. The dominant rain process in such clouds may be the combination of warm and cold processes. The field observations of the atmospheric aerosols, atmospheric electric field, raindrop charge, radar-estimated cloud top heights (from Bombay), rain intensity, made at Mahabaleshwar during the summer monsoon of 1977 also suggested that heavy rainfall was from the tall cumulus clouds with tops above 8 km (Selvam *et al.* 1980) which corroborated the findings at other places in India.

6.2. *Other studies*

The study of halogens in atmospheric samples finds application in cloud physics (Woodcook *et al.* 1971). In bulk marine aerosols and precipitation generally the Cl/Na ratio is nearly equal to the sea water value of 1.8. However, values both above and below this ratio are reported in literature (Junge 1968). The results of the study relating to the chemical composition of rainwater originating from cold convective clouds and cold layer type clouds during the summer monsoon of 1977 suggested that the ratio values of Cl/Na in rainwater could serve as an index for the identification of the warm/cold rain process. When the ratio value exceeded 1.8, the presence of melting band was noticed from the radar observations (Khemani *et al.* 1982). Also, by estimating the ratio value of chloride

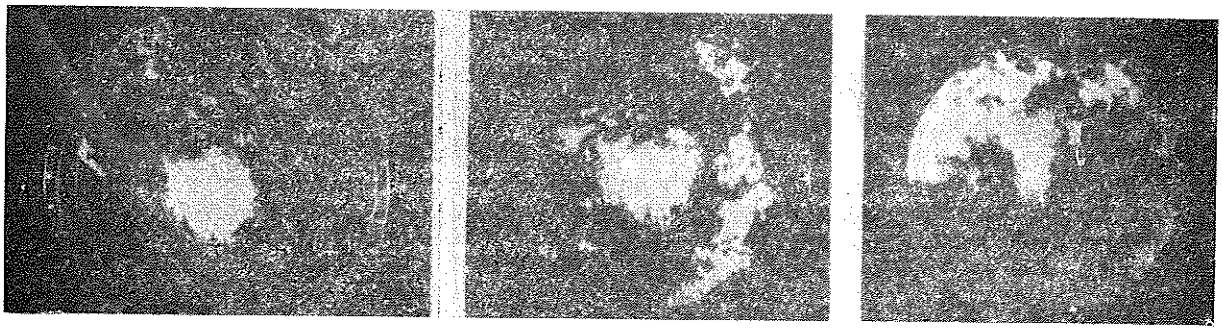

Fig. 16. Radar Plan-Position Indicator (PPI) pictures taken at Delhi during different rain occurrences

nuclei concentration to the ice-forming nuclei concentration, Kapoor *et al.* (1969) were able to infer the dominating rain process operating in the cloud. Khemani *et al.* (1976) have made measurements at Pune on gaseous and particulate pollutants during 1970-75 and found a significant correlation between concentration of atmospheric sulphurdioxide and ammonia with the summer monsoon rainfall.

7. Summary and conclusions

The behaviour of aerosols in the formation of precipitation depends strongly on their size distribution and on their composition. The main factor which determines the size distribution of CCN is their origin. Though there are different opinions about the origin of CCN, there appears to be a widespread and probably fairly uniform source of CCN over both the oceans and the land. The most likely sources are the gas-to-particle conversion mechanism. In recent years, several studies were concerned with measurements of supersaturation spectra of CCN. These spectra depend on the size distribution and chemical composition of CCN. The discrepancies prevailing in the literature between the size distribution and the supersaturation spectra suggest a strong dependence of the chemical composition on the size of the particles. Observations that are available now by direct analysis could be used to compare the inferences derived from the spectrum data (Junge 1968).

Extensive measurements have been made in India on the cloud-microphysical, — dynamical and — electrical characteristics. But, these investigations should continue so as to enable a clear picture to be depicted about the evolution of the warm rain process. The information obtained so far on the aspect of droplet growth from the theoretical and experimental investigations is incomplete and it requires further knowledge to explain fully the discrepancy between the computed and the observed droplet spectra. Development of realistic cloud models incorporating the microphysical and dynamical interactions would clarify the situation to a satisfactory stage.

Considerable progress has been made in India on the laboratory studies relating to the ice nucleating behaviour of various soluble and insoluble atmospheric nuclei with a view to explaining the discrepancy between the measured concentration of ice crystals in clouds and ice nuclei in clear air. These measurements have enabled to identify new ice-forming nuclei and new nucleation mechanisms. But much is to be done to understand clearly the mechanism of ice crystal production in supercooled clouds. This may require relatively simple, reproducible and reliable field instruments for measuring the concentration of atmospheric ice nuclei under conditions which approximate to those occurring in natural clouds and simultaneous laboratory studies of the ice crystal habits at different temperatures and supersaturations which can be met with in natural clouds.

Despite the recent progress in explaining the high ice crystal concentrations in clouds due to the ejection of secondary ice particles when supercooled drops freeze upon graupel particles, the exact physical mechanism which can explain the secondary process of ice-crystal production is not clearly understood. More detailed knowledge of the basic physics and of the cloud parameters is required for the complete understanding of the mechanisms in the ice-crystal economy of natural clouds and thereby the cold process in monsoon rain.

It is quite evident from the radar measurements made in different regions of India during monsoon season that the precipitation occurs predominantly due to cold rain process, partly due to mixed process and negligibly due to warm rain process. Also, these measurements pointed out that the warm rain process occurs in convective cloud fields when the rainfall is showery and scattered in nature. The combined rain process occurs also in similar situations, but the intensity and duration of showers in this case is larger. The three phase or cold rain process occurs in situations of widespread continuous type rainfields. The intensity of rainfall is generally less and the presence of melting band becomes clearly discernible. But the band gets disrupted when the intensity of rainfall increases due to buildup of convective cells through the melting band region. Besides these qualitative measurements, information on cloud microphysical characteristics would be very valuable for the physical understanding of the formation of precipitation in monsoon clouds. In India, such measurements have yet to be made in clouds which involve cold rain process.

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