Characteristics of cloud drop spectra on rain and non-rain occasions

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Measurements on drop size spectra were made in cumulus clouds over Pune (inland) region on a large number of days during the summer monsoon seasons. The measurements of the cloud drop spectra on the days with rain and with no rain in the experimental area made in 1976, 1979 and 1980 (the rain being observed within the clouds) have been studied. The average spectra were broader and concentration of drops with diameter > 50 \( \mu \text{m} \) (\( N_d \)), liquid water content (LWC), mean volume diameter (MVD) and dispersion were found to be greater on the days with rain as compared to those on the days with no rain. Total concentration (\( N_t \)) and concentration of drops < 20 \( \mu \text{m} \) (\( N_s \)) were lower on the occasions of rain with respect to those of no rain. The average drop size distributions were bimodal on the days with rain, while they were unimodal on the days with no rain. The variations of cloud drop spectra preceding the rain, at the initial stage of rain and following the rain are discussed.

1 Introduction

A knowledge of cloud drop size distribution is important for the study of cloud physics, cloud development and rain formation. The processes which determine droplet size distribution in cumulus clouds are not completely understood although CCN spectrum and the entrainment between the cloud and the surrounding clear air are known to be important factors. Weickmann and Aufm Kampe showed drop size spectra ranging from 6 to 66 \( \mu \text{m} \) diameter in fair weather cumulus clouds and from 6 to 200 \( \mu \text{m} \) in cumulonimbus clouds. Squires obtained drop spectra of 4-92 \( \mu \text{m} \) and 4-165 \( \mu \text{m} \) diameter in dark stratus and Hawaiian orographic clouds, respectively. Skhirtladze measured drops in the diameter range 2-70 \( \mu \text{m} \) by photoelectric counter in cumulus clouds over Cuba. Cloud drop spectra were also measured with a forward scattering spectrometer probe. The onset of precipitation in continental clouds containing a high nucleus concentration may be considerably accelerated, if the collection efficiencies are increased by small-scale atmospheric turbulence. The growth rate of rain drops during fall depends upon the cloud type which, in turn, is determined by the vertical wind shear. Takahashi et al. observed that the summits of trade wind cumuli are regions of active raindrop growth.

In an earlier study, Paul and Pillai obtained broader droplet spectra over the Pune (inland) region than over the Arabian sea, and this was mentioned to be due to the presence of an industrial complex belt upwind of the experimental site at Pune. In this paper, a comparative study of the cloud drop spectra in rain and non-rain situations and also at different stages of rain over the same region has been made.

2 Measurements

Measurements on drop size spectra were made in cumulus clouds from a DC-3 aircraft at different levels over Pune (lat. 18°32'N, long. 73°51'E, 559 m MSL) region during different summer monsoon seasons in the courses of warm cloud seeding experiments. The experimental site near Pune is about 150 km from the nearest west coast on the Arabian sea and is situated on the lee side of the Western Ghats. Winds are mostly westerly at different levels during the summer monsoon. The clouds over the Pune region are modified maritime during the period of observations. During the monsoon, the winds usually come from the Arabian sea and on the way get modified due to the presence of an industrial complex belt. In this paper, the measurements on the drop size spectra in cumulus clouds (1-3 km thick) made in the years 1976, 1979 and 1980 on the days with rain in the experimental area have been compared with those on the days with no rain in the said area, the occurrence/non-occurrence of rain being noticed visually within the clouds on board the aircraft. The cloud-base level was about 1400 m MSL. In general, the measurements were made at 400 - 600m above the cloud-base and the samples were collected towards the centre of a horizontal cross-section of the cloud. For 24-h rainfall for each day, the average of
measurements from 40 raingauges in the experimental area of 40 km × 40 km was considered. The network of raingauges was installed in connection with warm cloud seeding experiments in the area. On the days with rain, 37 samples were collected from 24 clouds for 11 days, while on the days with no rain, 27 samples were collected from 23 clouds for 11 days. On a given day, cloud drop samples were usually collected from two or three neighboring cumulus clouds or from clouds of the same cumulus cluster.

A mechanical semi-automatic cloud drop sampler containing magnesium oxide coated glass slides of size 3.5 cm × 0.6 cm (holder size 4.4 cm × 1.0 cm) was used for sampling the cloud drops. Each slide was exposed for 14.8 m s⁻¹ in the cloud at an impact speed of 54 m s⁻¹. The crater sizes were measured using an optical microscope of magnification 80X and 400X for cloud drop sizes > 20 μm and < 20 μm, respectively. The exposure was made in cloud air in a position away (about 50 cm) from the aircraft. The volume of cloud sampled for each exposure was about 300 cm³. True drop sizes were obtained from proper calibrations, made earlier, of the ratio of actual to crater size for different cloud drop sizes in the oxide layer (15-20 μm thick). The craters in the oxide film with mean diameters 11.5, 34.5, 58.5, 84.8, 112.9, 149.1 and 241.2 μm corresponded to cloud drops of mean diameters 5.7, 16.1, 25.7, 35.2, 44.8, 57.4 and 90.0 μm, respectively. The details of calibrations were reported elsewhere. Corrections were made in respect of collection efficiencies for different drop sizes. The collection efficiencies were 43%, 73%, 85%, 93%, 98% and 100% for cloud drops of diameters 4 μm, 7μm, 10μm, 14μm, 18μm and >18μm, respectively, at a true air speed of 54 m s⁻¹.

3 Results and discussion

The heights referred to in this paper are above the mean sea level and the cloud drop sizes are in diameters. The standard deviations are shown in Figs. 1 and 2 and Tables I and 2. Microphysical parameters such as maximum size (MS), total cloud drop concentration (NT), concentration of drops with diameter greater than 50 μm (Nₜ), concentration of drops with diameter less than 20 μm (Nₑ), liquid water content (LWC), mean volume diameter (MVD) and dispersion of drops were computed from the cloud drop size spectra. The term ‘maximum size’ here means the maximum drop diameter out of all the samples in a given set of data under study. The term ‘dispersion’ is the ratio of the standard deviation of the drop size distribution to the arithmetic mean of the same distribution. The values given in this paper for all the parameters are average values.

3.1 Variation of cloud drop spectra on the days with rain/no rain as observed within the clouds from the aircraft

During the hours of sampling, on certain days, sometimes rain was visually noticed on board the aircraft, within some clouds in the flight path, in the experimental area. The occurrence of rain could also be detected by the hitting sound of the rain drops falling from above and their splashing on the wind shield of the aircraft. However, at a given instant, one part of the cloud (that was sampled) was raining, while the other parts of the same cloud might be or might not be raining. The average cloud drop spectra on the days with rain and with no rain as observed within the clouds, in the experimental area, are presented in Fig. 1. On the two occasions, nearby dates are compared. The values of the cloud physical parameters are given in Table 1.

The maximum size (130 μm) on the days with rain was much greater than that (80 μm) on the days with no rain. The mean distribution in the former case was bimodal (primary and secondary peaks at 3 μm and 10 μm radius, respectively), while in the other case it was unimodal (peak at 3 μm). The bimodal distribution suggests the growth of some drops by coalescence process. The said drops grew by collision-coalescence of smaller sized drops to the size having the secondary peak concentration. Almost all maritime and some continental stratocumulus clouds contain biomodal populations of drops—one of cloud droplets and the other of drizzle-sized drops. The cloud droplet spectra in maritime cumulus clouds are often bimodal. On the days with rain, NT was seven times that on the days with no rain (highly significant at 0.24 % level), applying Wilcoxon-Mann Whitney test. The values of LWC, MVD and dispersion were greater (significant at 0.48 %, 2 % and 3 % levels, respectively), while NT and Nₑ to some extent smaller (not significant in either case) on the former occasion as compared to the latter. The values of LWC were about 0.42 and 0.23 g m⁻³ on the two occasions, i.e. with rain and no rain, respectively. A drizzle water content larger than 0.2 g m⁻³ near the cloud top is required if large drops are to form and fall against the updraft. The increase of the dispersion is partly a reflection of the increase in frequency of bimodal distribution in cumulus clouds. The concentrations...
Fig. 1—Cloud drop spectra on the days with (a) rain and (b) no rain as observed within the clouds.
of drops of size 4-18 µm were lower, while those of drops of all sizes >18 µm were higher on the days with rain (with respect to the days with no rain). The appreciably higher concentrations of drops > 18 µm (particularly those > 50 µm), much greater maximum size and significantly higher values of LWC, MVD and dispersion indicate active growth of cloud drops on the days with rain. The relatively lower concentrations of small-sized cloud drops (and hence the total number of drops) on the days with rain as compared to those with no rain suggest participation of small-sized drops in the growth of bigger drops. The larger drops grew by coalescence process at the cost of small-sized drops. Condensation can indirectly affect the growth rate of droplets larger than 25 µm radius by enhancing the growth of the smaller droplets which are then captured more efficiently by the larger ones. The formation of warm rain from cumulus clouds of 2-3 km thickness, over the Hawaiian Islands, was facilitated by the low concentration of cloud droplets 4.

The values of Nl on the days with rain were 0.153, 0.959, 0.300, 0.342, 0.124, 0.373, 0.421, 0.547, 0.635, 1.640 and 0.207 cm⁻³ against the rainfall 0.18, 5.53, 0.0, 0.84, 1.40, 5.73, 5.99, 11.03, 8.00, 21.94 and 0.17 mm, respectively (correlation coefficient 0.894; SD 0.209; highly significant at 0.02 % level). Those on the days with no rain observed were 0.365, 0.093, 0.015, 0.010, 0.161, 0.200, 0.0, 0.0, 0.0, 0.0 and 0.0 cm⁻³ against the rainfall 0.91, 0.36, 0.0, 0.20, 0.0, 5.02, 0.77, 0.0, 0.03, 1.65 and 0.37 mm, respectively (correlation coefficient 0.372; SD 0.117; significant at 26 % level, i.e. not significant). These indicate active growth of drops on the days with rain.

### Table 1—Cloud drop characteristics on the days with rain/no rain observed within the clouds

<table>
<thead>
<tr>
<th>Cloud height (m)</th>
<th>MS (µm)</th>
<th>Nl (cm⁻³)</th>
<th>NT (cm⁻³)</th>
<th>NS (cm⁻³)</th>
<th>LWC (g m⁻³)</th>
<th>MVD (µm)</th>
<th>Dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Days with rain</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1976</td>
<td>130</td>
<td>0.469</td>
<td>300</td>
<td>282</td>
<td>0.4223</td>
<td>13.7</td>
<td>0.64</td>
</tr>
<tr>
<td>(540)</td>
<td></td>
<td>(0.696)</td>
<td>(151)</td>
<td>(154)</td>
<td>(0.3367)</td>
<td>(3.9)</td>
<td>(0.18)</td>
</tr>
<tr>
<td><strong>Days with no rain</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>80</td>
<td>0.067</td>
<td>318</td>
<td>311</td>
<td>0.2285</td>
<td>11.2</td>
<td>0.54</td>
</tr>
<tr>
<td>(370)</td>
<td></td>
<td>(0.174)</td>
<td>(159)</td>
<td>(160)</td>
<td>(0.1287)</td>
<td>(2.0)</td>
<td>(0.15)</td>
</tr>
</tbody>
</table>

Note: (i) Rainfall values are the mean 24-h rainfall per rainguage (total 40 rain-gauges) recorded at ground at 0830 hrs IST in the experimental area on the following day.
(ii) Values in the brackets are the standard deviations.

3.2 Cloud drop spectra at different stages of rain

The average cloud drop spectra, on the days with rain observed within the clouds, over the experimental area, before the occurrence of rain (stage A), at the initial stage of rain (stage B) and after the occurrence of rain (stage C) are shown in Fig.2. On the average, the spectra obtained were 35 min before rain for stage A, 30 s before rain for stage B and 23 min after rain for stage C. For stage B, samples 0-2 min before/after rain (noticed), were considered. The average of different days' values was taken as the number of cloud drop samples collected for all the three stages of rain on a single day which was very small. The values of different parameters are given in Table 2.

The maximum size increased much from 93 µm at stage A to 130 µm at stage B and then decreased much to 87 µm at stage C. The mean distributions were trimodal (peaks at 3 µm, 7 µm, 13 µm), trimodal (peaks at 3 µm, 10 µm, 24 µm) and tetramodal (peaks at 3 µm, 7 µm, 10 µm, 24 µm) at the respective three stages under comparison. The values of Nl, LWC, MVD and dispersion increased much from stage A to stage B (highly significant at 0.007%, 0.1%, 0.01%, and 0.03% levels, respectively) and then decreased much from stage B to stage C (significant at 1% and 4% levels for Nl, dispersion, respectively, and not significant for LWC and MVD). The values of NS and NT decreased much from stage A to stage B (significant at 8% level for NS and not significant for
Fig. 2—Cloud drop spectra at different stages of rain
Table 2.—Cloud drop characteristics with respect to rain on the days with rain observed
(values in brackets are standard deviations)

<table>
<thead>
<tr>
<th>Cloud height (a.m.s.l.) m</th>
<th>MS µm</th>
<th>( N_L ) cm(^{-3} )</th>
<th>( N_T ) cm(^{-3} )</th>
<th>( N_S ) cm(^{-3} )</th>
<th>LWC g m(^{-3} )</th>
<th>MVD µm</th>
<th>Dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage A: Before rain</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1647 (234)</td>
<td>93</td>
<td>0.096 (0.232)</td>
<td>327 (154)</td>
<td>321 (149)</td>
<td>0.2353</td>
<td>10.7</td>
<td>0.53</td>
</tr>
<tr>
<td>Stage B: Initial stage of rain</td>
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<td></td>
<td></td>
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<tr>
<td>2078 (507)</td>
<td>130</td>
<td>0.968 (0.860)</td>
<td>266 (144)</td>
<td>242 (145)</td>
<td>0.6075</td>
<td>16.5</td>
<td>0.77</td>
</tr>
<tr>
<td>Stage C: After rain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2417 (616)</td>
<td>87</td>
<td>0.295 (0.387)</td>
<td>307 (147)</td>
<td>280 (159)</td>
<td>0.4485</td>
<td>14.6</td>
<td>0.62</td>
</tr>
</tbody>
</table>

Note:
(i) For stage A: 15 samples, sampled at 1513 hrs IST (29 min); 10 days; Rain noticed at 1548 hrs IST (44 min)
(ii) For stage B: 14 samples, sampled at 1546 hrs IST (27 min); 11 days; Rain noticed at 1544 hrs IST (44 min); Samples 0-2 min before/after rain (noticed) were considered.
(iii) For stage C: 8 samples, sampled at 1546 hrs IST (27 min); 6 days; Rain noticed at 1523 hrs IST (35 min)

\( N_L \) and then increased at stage C (not significant). The above observations indicate active growth of drops just before rain or in the beginning of rain. The concentrations of large-sized (>50 µm), moderate-sized (20-50 µm) and small-sized (<20 µm) drops were 0.096, 5.9 and 321 cm\(^{-3} \), respectively, before rain; 0.968, 23 and 242 cm\(^{-3} \), respectively, in the beginning of rain and 0.295, 27 and 280 cm\(^{-3} \), respectively, after rain. It appears that the number of large and moderate-sized drops increased much, while that of small-sized drops reduced much just before rain started and/or in the beginning of rain. Also, the large drops were mostly rained out, while the moderate and small-sized drops were not rained out at the end of rain. The concentration of small-sized drops increased again after the rain and this might probably be due to fresh condensation of water vapour on small-sized CCN particles (present in the cloud air), which were not washed out in the rain or this might be due to entrainment of sub-saturated air leading to evaporation and fresh activation or reactivation of CCN (Ref. 17). The concentrations of drops of size < 20 µm decreased, while those of size > 20 µm increased from stage A to stage B. The concentrations of drops of size < 30 µm increased, while those of size ≥ 30 µm decreased from stage B to stage C. The giant aerosol particles are scavenged mainly at the beginning of a rain event\(^8\).

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