MICROPHYSICAL STRUCTURE OF PRECIPITATING CLOUDS IN WINTER MONEX

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1. INTRODUCTION

Most precipitation near the equator occurs in "cloud clusters", which are identified by their distinctive mesoscale upper-level cloud shield seen in satellite imagery. Field experiments such as GATE and MONEX[1] have provided observations of the precipitation structure of cloud clusters (see reviews by Houze and Betts, 1981, and Houze and Hobbs, 1982). Radar data obtained in these experiments show that the precipitation within intense cloud clusters can be subdivided into convective and stratiform regions, with some 30-50 % of the total precipitation falling in the stratiform regions (Houze, 1977; Gamache and Houze, 1983; Houze and Rappaport, 1984; Churchill and Houze, 1984a; Leary, 1984).

Relatively little is known about the microphysical structure of tropical cloud clusters. Raindrop size distributions observed in GATE have been studied to obtain relationships among radar reflectivity, rainwater content of the air, and surface rainfall rate (Cunning and Sax, 1977; Austin and Geotis, 1979). Leary (1980) used the GATE observed raindrop size distributions to deduce mesoscale downdraft motion and evaporation rates below cloud base in the stratiform regions of GATE cloud clusters. Leary and Houze (1979) used these raindrop size distributions to infer indirectly the probable nature of ice particles occurring above the melting layer in the stratiform regions.

Direct observations of ice-particles in cloud clusters were obtained during MONEX with two-dimensional Particle Measuring Systems (PMS) probes aboard a NOAA[2] WP-3D aircraft. Churchill and Houze (1984a) have examined these data in a case study of cloud clusters that occurred over the South China Sea on 10 December 1978 during Winter MONEX[3]. Our present paper extends this work by including data collected on other days of Winter MONEX.

During Winter MONEX, the WP-3D aircraft was used as a dropwinsonde platform. Consequently most flights were at altitudes of 7300-7400 m. This nearly constant flight level, maintained throughout the experiment, provided microphysical sampling at nearly uniform atmospheric conditions (generally -14 to -19 deg C) in nine different clusters over the South China Sea. In the three clusters sampled on 10 December, Churchill and Houze (1984a) found that at these altitudes in the regions of convective precipitation, active cells contained ice particles in concentrations of the order of hundreds per liter, and the dominant growth mechanism appeared to be riming. In the stratiform regions of clusters, ice particle concentrations were one to two orders of magnitude lower than in the convective regions; areas of weaker stratiform precipitation had concentrations 1-10 per liter, while areas of stronger stratiform precipitation generally had between 10 and 100 per liter. The dominant ice-particle growth mechanisms in the stratiform regions appeared to be vapor deposition and aggregation.

In this paper, we extend the study of Churchill and Houze (1984a) beyond the case study of 10 December 1978 by examining the ice-particle images obtained in all nine cloud clusters penetrated by the aircraft at the 7300-7400 m level. In this effort we seek to determine whether the ice particles observed in cloud clusters throughout Winter MONEX were similar in concentration, size, type and growth mechanism to those observed on 10 December 1978.

2. DATA AND METHODS OF ANALYSIS

Digitized ice-particle images were obtained on board the WP-3D aircraft with the two-dimensional PMS probes. These probes were developed by Knollenberg (1970), and various aspects of their operation, characteristics and uses have been discussed by Cannon (1976), Heymsfield (1976) and Houze et al. (1981). In this study, we use data from the "cloud

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[1] *GATE and MONEX were the Global Atmospheric Research Programme's Atlantic Tropical and Monsoon Experiments, respectively.*

[2] *National Oceanic and Atmospheric Administration.*

[3] *MONEX was divided into Winter MONEX, staged over Indonesia, Malaysia and surrounding seas during December 1978 to February 1979, and Summer MONEX, which was held over India, the Arabian Sea and the Bay of Bengal during June to July, 1979.*

Table 1. Summary of Winter MONEX flights on which this study is based. The aircraft used was a NOAA WP-3D. Types of precipitation are convective (CV), strong stratiform (SSF), weak stratiform (WSF), and very weak stratiform (VWSF).

Date (1978)	Time Period (GMT)	Altitude Range (m)	Type of Precipitation
7 December	1028-1031	7354-7361	CV
	1119-1122	7356-7357	SSF
10 December	0905-0910	7214-7434	CV
	0940-1012	7352-7360	WSF
	1031-1041	7351-7360	SSF
	1042-1045	7356-7359	WSF
11 December	0954-0958	7345-7512	CV
	1001-1011	7338-7375	SSF
	1031-1101	7364-7375	WSF
12 December	1004-1007	7352-7358	CV
	1017-1053	7352-7361	WSF
16 December	0930-0935	7354-7357	VWSF
	0951-1009	7352-7360	VWSF
	1010-1019	7346-7365	WSF
17 December	0541-0558	7339-7343	SSF
	0600-0602	7350-7383	CV
	0612-0619	7350-7354	WSF

probe", which detected particles up to 1.6 mm in dimension.

Descriptions of the ice-particle data and methods used to analyze them are given in the Appendix of Churchill and Houze (1984a). In the present study we followed the same procedures, so we will only summarize them briefly here. The particle images on magnetic tape were processed to determine 2 s average particle concentrations along the flight track. From these we calculated 1 min average concentrations (1 min of flight time corresponds to about 10 km in horizontal distance travelled). Microfilm images of all the particles sampled were generated from the data tapes. For each minute of flight time, approximately 30 images on microfilm were selected objectively for visual examination. Each particle examined was classified according to size and type. The size categories were small (less than 0.5 mm in dimension), medium (0.5-1.2 mm) and large (greater than 1.2 mm). The categories of type were columns, branched crystals, nearly round particles, and particles of indeterminable shape. Examples of images in each size and type category are given in Fig. A2 of Churchill and Houze (1984a).

The ice-particle concentrations, types and sizes determined by the above methods were stratified by Churchill and Houze (1984a) according to whether the precipitation through which the aircraft was flying was convective, strong stratiform or weak stratiform. The distinction between convective and stratiform was made subjectively on the basis of the appearance of radar echo detected by the C-band (5 cm wavelength) lower fuselage radar aboard the WP-3D aircraft[4]. The distinction between weak and strong stratiform precipitation was made objectively, according to whether the reflectivity factor was less than or greater than 20 dBZ, respectively, in the vicinity of the aircraft. In the present paper, we follow the same procedures, except that we have identified a further precipitation category, very weak stratiform, which refers to precipitation too weak to be detected by the lower fuselage radar (less than about 1 dBZ).

The size of the data sample we have used is indicated in Table 1, which lists the dates, times, altitudes and types of precipitation encountered for all the flights included in this study.

3. CONCENTRATIONS OF ICE PARTICLES

The one-minute average ice-particle concentrations observed on all of the flights through the four identified categories of precipitation are summarized in histograms in Fig. 1a. The data for the stratiform categories are replotted in Fig. 1b in histograms using a smaller size increment.

In Fig. 1a, all of the observed ice-particle concentrations were less than 50 per liter in very weak stratiform precipitation. The weak stratiform precipitation was rather similar; 98% of the concentrations were less than 50 per liter. However, occasional concentrations of 50-100 per liter occurred. In the strong stratiform precipitation, the occurrence of concentrations of 50-100 per liter became much more frequent (14 % of the samples), and occasional concentrations of over 100 per liter were observed. In convective cells,

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[4] *The characteristics of this radar are given by Houze et al. (1981).*

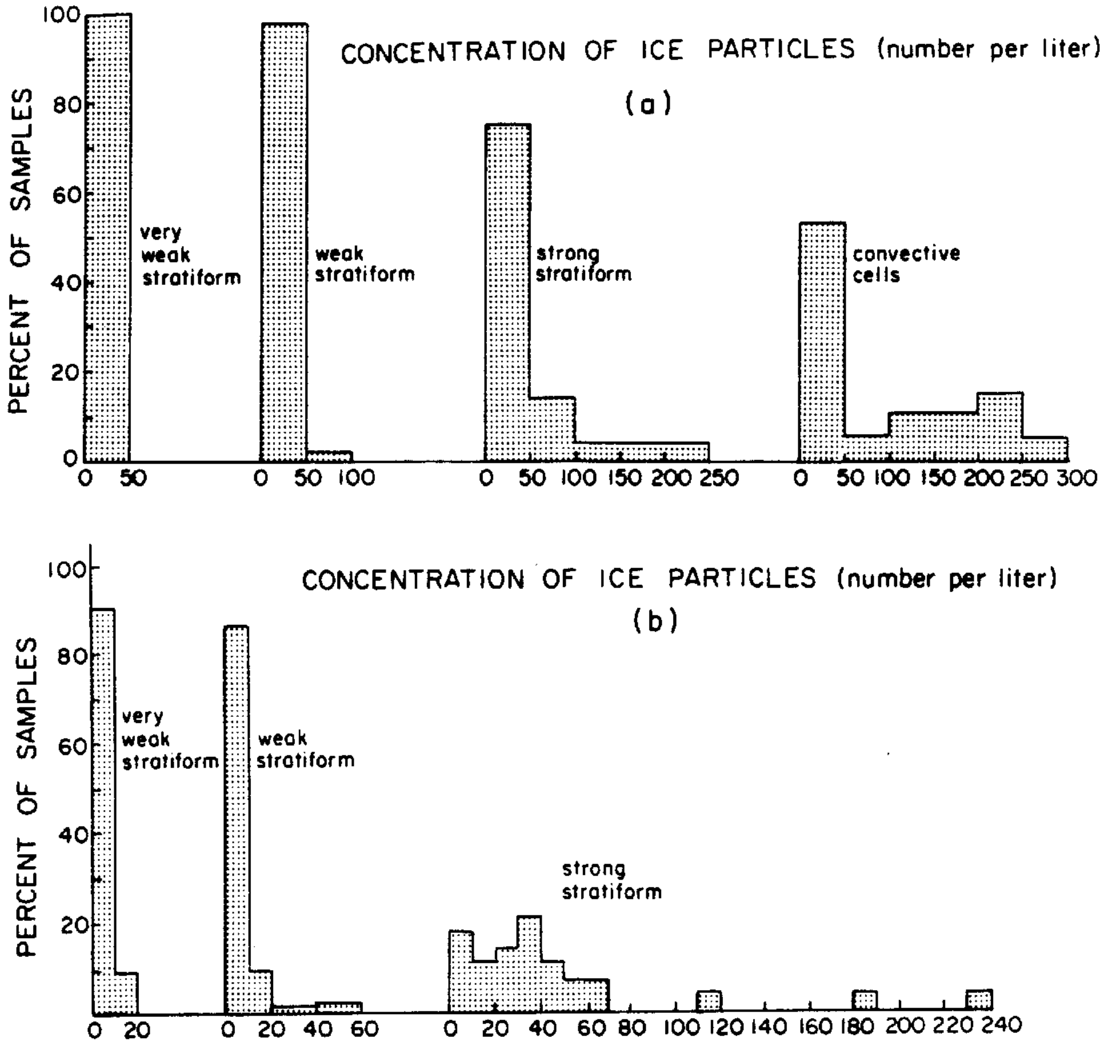

Figure 1. Concentrations of ice particles observed with the PMS cloud probe (upper particle size limit 1.6 mm) aboard the NOAA WP-3D aircraft during Winter MONEX. Observations were made at altitudes of 7300 - 7400 m (-14 to -19 deg C) and the concentrations referred to were 1 min averages. The categories very weak stratiform, weak stratiform, strong stratiform and convective cells describe the precipitation through which the aircraft was flying. In (a) an increment of 50 per liter on the abscissa was used in plotting the histograms. In (b) an increment of 10 per liter was used to show more detail in the stratiform categories.

concentrations of over 100 per liter were quite common; 43 % of the samples were in the 100–300 per liter range. Thus, a systematic trend of decreasing frequency of low concentrations and increasing frequency of high concentrations was seen in progressing from weaker stratiform to stronger stratiform to convective precipitation.

The distributions of ice-particle concentrations in the stratiform regions are seen with more precision in Fig. 1b. Very similar distributions occurred in the very weak and weak stratiform regions, where nearly all concentrations were less than 10 per liter. Only a few samples of over 20 per liter were observed in the weak stratiform precipitation. A quite different type of distribution occurred in the strong stratiform regions, where the observed concentrations were spread fairly evenly over the range of 0–70 per liter. The occasional samples of over 100 per liter in the strong stratiform category probably occurred in the vicinity of active or recently active convective cells.

The dominance of concentrations of less than 10 per liter in the weaker stratiform categories and 20–70 per liter in the strong stratiform precipitation agrees very closely with the results obtained by Churchill and Houze (1984a) for the 10 December case study.

4. TYPES AND SIZES OF ICE PARTICLES

The types and sizes of ice particles identified by visual examination of the particle images on microfilm are summarized in Table 2.

In convective precipitation (Table 2a), there was never any evidence of columns or branched crystals. A few nearly round particles (probably graupel or frozen drops)

Table 2. Frequency distribution of ice particles in size and type for convective precipitation, strong stratiform, weak stratiform and very weak stratiform during Winter MONEX. Numbers indicate the precentage of particles sampled for each kind of precipitation. Small particles were less than 0.5 mm in dimension, medium particles were 0.5 - 1.2 mm, and large particles were greater than 1.2 mm.

(a) Convective

	Columns	Branched Crystals	Indeterminable	Nearly Round
Small	0	0	90.4	0.8
Medium	0	0	6.2	0.1
Large	0	0	2.4	0.1

(b) Strong Stratiform

	Columns	Branched Crystals	Indeterminable	Nearly Round
Small	0.3	0	60.2	0
Medium	1.3	0	32.4	0.1
Large	0	0.1	5.5	0.1

(c) Weak Stratiform

	Columns	Branched Crystals	Indeterminable	Nearly Round
Small	1.4	0.1	55.4	1.7
Medium	2.5	2.6	26.4	0.3
Large	0.3	2.6	6.8	0

(d) Very Weak Stratiform

	Columns	Branched Crystals	Indeterminable	Nearly Round
Small	0	0	72.7	0
Medium	0	0.3	24.8	0
Large	0	0	2.2	0

were seen. However, most particles (99.0 %) were of indeterminable shape, and most of these (90.4 % of the total sample) were in the small size category. This distribution is similar to that found for convective cells by Churchill and Houze (1984a) in the 10 December case study. In convective cells, growth of ice particles by riming is expected because of the high condensation rates and rapid growth of particles in convective clouds (Houghton, 1968), and our observed distribution does not contradict this expectation. The absence of pristine crystal shapes indicates that any growth by vapor deposition was not effective. The indeterminable particles, which dominated the data, probably included graupel or other highly rimed particles.

The observed high concentrations of ice particles in convective cells (Fig. 1a) together with their small sizes, indicated by Table 2a, suggest that many of the small indeterminable particles seen in our data may have been the product of splintering or some other mode of ice multiplication. Laboratory experiments suggest that ice multiplication occurs at -3 to -8 deg, when ice particles and supercooled water are both present and have certain properties (e.g. Hallett and Mossop, 1974; Mossop and Hallett, 1974; Mossop, 1976, 1978). The -3 to -8 deg C level was at about the 5000 - 6000 m level in Winter MONEX. Small fragments of ice produced by ice multiplication at this altitude could have been carried up to flight level (7300 - 7400 m) by the convective updrafts.

The size-type distribution for ice particles in strong stratiform precipitation (Table 2b) has characteristics that are transitional between the convective cells (Table 2a, just discussed) and weak stratiform precipitation (Table 2c, to be discussed below). This result is similar to that found on 10 December by Churchill and Houze (1984a) and is quite reasonable since strong stratiform precipitation was generally found near active or recently active convective cells. This type of precipitation apparently consisted of a mixture of debris from convection and purely stratiform precipitation particles.

The ice particles in weak stratiform precipitation differed sharply from those seen in convective cells (compare Tables 2a and c). Pristine crystalline shapes (i.e. columns and branched crystals) were much in evidence in the weak stratiform precipitation, whereas they were completely lacking in the convective cells. Thus, growth by vapor deposition, not apparent in the convection, was prominent in the weak stratiform regions. Another major difference between the convection and the weak stratiform precipitation is in the size distribution of indeterminable particles. In the convective cells, the indeterminable particles were nearly all small. However, in the weak stratiform regions, small indeterminable particles accounted for only about 55 % of the total sample, while the medium-sized indeterminable particles accounted for about one-fourth of the total. The tendency of indeterminable particles in the weak stratiform to have sizes larger than in convective precipitation probably indicates that many of the indeterminable particles in the weak stratiform precipitation were aggregates. Indeed, many of the indeterminable particle images had the appearance ascribed by Heymsfield and Musil (1982) to aggregation of ice particles. However, the shadowgrams provided by the PMS probes do not allow unambiguous identification of aggregates; therefore, the presence of aggregation must be considered highly consistent with but not conclusively shown by the data.

The small nearly round particles seen in 1.7 % of the weak stratiform samples may have been branched crystals or aggregates whose true structure, because of their small size, either could not be adequately resolved by the PMS probe or could not be adequately portrayed in our microfilm output. These particles were not generally perfectly round, like a frozen drop, and since very little liquid water (generally less than 0.1 gram per cubic meter) was detected at flight level, it seems unlikely that these were rimed particles. The small nearly round particles in weak stratiform precipitation were often accompanied by columns, so it may have been that the nearly round particles were columns being seen on end, as the columns assumed random orientations while passing through the probe.

The size-type distribution for ice-particles in weak stratiform precipitation (Table 2c) is similar to that found on 10 December by Churchill and Houze (1984a). We conclude, as they did, that the observed particles indicate ice-particle growth by vapor deposition and probably aggregation, and that the presence of branched crystals at flight level indicates that growth occurred at water saturation at altitudes above 8 km (where temperatures were -20 to -25 deg C). The stratiform regions penetrated by the aircraft commonly extended over distances of 100 - 300 km (corresponding to penetration times of 10 to 30 min, see Table 1). The water saturation must have been produced by mesoscale ascent that was strong enough across these regions to produce the saturation but weak enough to allow the particles to fall to flight level. Mesoscale ascent of this character at upper levels is consistent with conceptual models of the stratiform regions of tropical cloud clusters (Houze and Betts, 1981; Houze and Hobbs, 1982; Houze, 1982) and with various modeling and diagnostic studies of the stratiform regions of tropical cloud clusters (Brown, 1979; Leary and Houze, 1979; Gamache and Houze, 1982; Johnson, 1982; Houze and Rappaport, 1983; Churchill and Houze, 1984b). The Johnson (1982) and Churchill and Houze (1984b) studies, using different approaches, diagnosed mesoscale updraft motion at upper levels in the stratiform region of one of the 10 December 1978 Winter MONEX cloud clusters.

In the very weak stratiform precipitation (Table 2d), the size-type distributions resembled those of the weak and strong stratiform precipitation in that about 25 % of the particles were in the medium-size, undeterminable-shape category. However, there were more smaller particles (72.7 %) than in the other two stratiform categories, and there was very little evidence of columnar or branched crystalline structure (zero in all column and branched categories except for 0.3 % in the medium sized branched category). No nearly round particles were seen. Evidently, the very weak stratiform precipitation was associated with dissipating stratiform regions, where larger particles had generally fallen out without being replenished, since mesoscale updraft activity and concomitant particle growth had weakened or ceased. The near absence of branched crystals (which grow at water saturation) further indicates decreased updraft motion. Without upward motions in the cloud, evaporation may have contributed along with fallout to the decreased sizes of particles.

5. CONCLUSIONS

Analysis of ice particle images obtained aboard an aircraft flying at the 7300-7400 m (-14 to -19 deg C) level in winter monsoon cloud clusters over the South China Sea has been accomplished by stratifying the data according to radar observations of the type of precipitation in which the ice-particle images were obtained.

In convective cells, 1 min average ice-particle concentrations of 100-300 per liter were found frequently. The absence of vapor grown particles and aggregates indicated that riming was the dominant ice-particle growth mechanism in convection. The high concentrations and small sizes of the ice particles seen in cells suggested that ice multiplication may have been active in the convection.

Strong stratiform precipitation (i.e. stratiform precipitation with radar reflectivity greater than 20 dBZ) had ice-particle concentrations spread fairly uniformly over the range of 0-70 per liter, with occasional values of over 200 per liter. These occasional high concentrations, together with the observed types and sizes of ice particles, indicated that the strong stratiform precipitation, typically found near active or recently active convection, was a mixture of debris from cells and particles of purely stratiform origin.

Weak stratiform precipitation (with radar echo intensity between 1 and 20 dBZ) exhibited ice particles of a purely non-convective character. Nearly all the concentrations of ice particles (86 %) were less than 10 per liter. Vapor grown particles (i.e. columns and branched crystals) were frequently in evidence, and the indeterminable-shaped particles had sizes and general appearances suggesting they were aggregates of crystals. These particle structures and apparent growth mechanisms are consistent with the presence of mesoscale ascent in the upper levels of the stratiform regions of clusters.

In very weak stratiform precipitation (not detectable by the airborne radar), ice-particle characteristics were suggestive of dissipating stratiform cloud structure, in which mesoscale updraft motion had weakened or died out.

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