OBSERVATIONS OF LIQUID WATER PERSISTENCE AND THE DEVELOPMENT OF ICE IN OKLAHOMA CONVECTIVE CLOUDS.

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Abstract. During late spring of 1986 and September of 1987 the University of North Dakota operated an instrumented aircraft in convective clouds over Oklahoma to help assess the potential for rain increase cloud modification over the state. The Oklahoma Rainfall Enhancement Program seeding plan focuses on seeding growing clouds which contain a persistent region of supercooled liquid water but are lacking in ice crystals. The objectives of this study were to determine the persistence of supercooled liquid water in the sampled clouds and to determine where, when and how the ice phase developed in these clouds. The persistence of supercooled liquid water was examined in terms of cloud top lifetime, defined as the projected time from first penetration to zero liquid water content at the sampling level. Ice particle data were studied in primarily a qualitative sense.

In general, the clouds had high liquid water contents initially, but cloud top lifetimes were relatively short. Liquid water decay rates had a large standard deviation. The development of ice occurred very rapidly in many of the clouds, although there were several missions where ice development was not significant. The ice phase was apparently being enhanced in lower portions of the clouds, perhaps through ingestion of ice from neighboring cells or by ice multiplication.

1. INTRODUCTION

As part of the Southwest Cooperative Program the Bureau of Reclamation sponsored two field measurement programs which utilized the University of North Dakota Department of Atmospheric Sciences Citation research aircraft to collect data in convective clouds over Oklahoma. These airborne missions were conducted in cooperation with the Oklahoma Water Resources Board (OWRB) to help assess the potential for rain increase cloud modification over the state. In a technical report (Mathis and Gibeau, 1985) the OWRB and Aeromet, Inc., set forth a plan for a cloud modification project entitled the Oklahoma Rainfall Enhancement Program (OREP). Due to a dearth of knowledge regarding the microphysical properties of clouds over the state, this plan is based largely on the results of studies conducted over portions of west Texas, including the Bureau of Reclamation HIPLEX program (e.g., Jurica et al., 1983; Long, 1980). While it is reasonable to assume that there should be many similarities in the cloud properties over these adjoining areas, significant differences may exist, dictating changes to the OREP plan. It is essential, therefore, that more insight be gained into the nature of Oklahoma clouds prior to the OREP implementation.

The OREP seeding plan focuses on convective clouds which reach above the freezing level and contain supercooled liquid water (SLW). When ice crystals are present and substantial amounts of SLW remain available for a sufficient length of time, ice particles can grow to precipitation size. The latent heat released through the freezing process also contributes to the buoyancy and therefore the dynamics of these clouds. A seeding opportunity may exist in those clouds which contain a persistent region of supercooled water but are lacking in natural ice crystals. The objectives of the analyses performed under this contract were to determine the persistence of SLW in the sampled clouds and to determine where, when and how the ice phase develops in the clouds.

2. THE DATA

The data upon which this study is based consist entirely of in situ cloud observations from the UND Citation II research aircraft. There were no supporting radar or mesoscale data collected during the Citation flights. The sampling capabilities of the Citation included measurements of the state parameters, three-dimensional winds and cloud microphysical properties. These measurement systems were supplemented by hand-held 35 mm photographs, side-looking 16 mm time-lapse films (in 1986), forward-looking video (in 1987) and voice notes from the flight scientist. Cloud microphysics probes included Particle Measuring Systems FSSP (2-47 μm range), 2D-C (31-992 μm) and 1D-P (300-4500 μm) probes, and a Johnson-Williams (JW) liquid water content meter. Most of the data were displayed in real time for interpretation by the flight scientist. This information was used in making operational decisions during data collection missions.

The JW measurements of liquid water content (LWC) were used in this study rather than values derived from FSSP data. During the 1986 study the FSSP instrument was inoperative for all but the first and last missions. In addition, the FSSP seemed to strongly underestimate LWC values in cloud regions where the JW values exceeded 2.8 g m^{-3}. The JW values were in reasonable agreement with adiabatic LWCs.

The aircraft was based in Norman, Oklahoma for the periods 27 May - 9 June, 1986, and 8-28 September, 1987. Cloud systems were sampled over the western two-thirds of the state, where average annual precipitation is notably less than in the east. The aircraft was launched whenever potential cloud candidates were observed visually or if conditions appeared favorable from radar or satellite data. Cloud types of interest included isolated cumulus congestus and feeder cells associated with convective complexes. Flights were restricted to daylight hours to facilitate cloud identification and to enhance mission safety.

Favorable weather conditions were encountered during both study periods. In 1986, 77 clouds were sampled two or more times in the course of the ten flight missions, and in 1987 55 clouds were sampled repeatedly on nine flights. Climatologically, this is still a rather limited data set. However, work by Pflaum, et al., (1989), indicates that this cloud activity was representative of these seasonal time periods.

3. FLIGHT PROFILES

Cloud sampling legs were flown generally in the vicinity of either the -5°C or -12°C level. Cloud candidates were selected visually based on an appearance of positive vertical growth, a minimum diameter 1 km and a "hard" or sharp boundary at cloud top. The initial penetrations were normally made within about 300-600 m of cloud top shortly after the top rose above the sampling level. The decision to repenetrate a cloud was based primarily on measured parameters from the first pass. The OREP design parameters, which were used as a guideline for this study, call for peak LWC of at least 1.0 g m^{-3}, updraft speed of 2.5 m s^{-1} or more and less than 10 $liter^{-1}$ concentration of ice crystals at aircraft penetration levels. Some clouds not meeting these criteria were sampled repeatedly because they were along the path of penetration through other towers or because no other suitable candidates were at hand. Sampling of the cloud continued until the SLW was nearly depleted at the flight level or until operational or safety considerations precluded further measurement.

In the 1986 project an emphasis was placed on sampling at the colder (-12°C) temperatures because the OREP design plan was structured toward a static or microphysical seeding approach. An analysis of the 1986 data set, however, indicated that the SLW probably did not persist in the sampled clouds long enough to enable static seeding to work. It was discovered, though, that there was initially an ample supply of SLW that could perhaps be utilized in a dynamic seeding approach. Thus, the 1987 measurement program focused on sampling at the -5°C level where clouds could be seeded for dynamic effects earlier in their lifetimes.

4. PERSISTENCE OF SUPERCOOLED LIQUID WATER

The persistence of SLW was examined in this study in terms of "cloud top" lifetime, as described by Schemenauer and Isaac (1984), hereafter referred to as SI. The lifetime was computed from the mean first pass LWC and a rate of change of LWC. The rate of change, or decay rate (DR), was calculated as the difference between the mean LWC of the first and last sampling passes through a given cloud divided by the time between the midpoints of the passes. The decay rates were assumed to be linear. A cloud top lifetime was thus the projected time from first penetration to 0.0 g m^{-3} LWC at the sampling level. Mean lifetimes for each day and for the whole study period were computed using mean values of first pass LWC and mean decay rates.

4.1 Total data set

The mean first pass LWC (LWC1), DR and projected cloud top lifetime of clouds sampled two or more times are given in Table 1a. This does not include data from those cells which were sampled at more than one temperature level. Table 1b contains values for a subset of these clouds which met the first pass OREP design criteria. A large amount of variability is evident from cloud to cloud and from flight to flight. The standard deviation of the DR is nearly equal to the mean, signifying that a wide range of cloud top lifetimes was likely in the study clouds. The distribution of DR, given in Table 2, shows that approximately one third of the cloud samples had DR ≤ 0.05 g m^{-3} min^{-1}. This potential variability of lifetimes was also evident in the projected lifetimes calculated for each of the individual sampled clouds. Table 3 shows that one fourth of the projected lifetimes were greater than 15 minutes.

Table 1 Daily and total period mean lifetime of clouds

	a. All Clouds				b. Clouds Meeting OREP Pass 1 Criteria			
Date 1986	# Cells	Mean Pass 1 LWC ($g\ m^{-3}$)	Mean Decay Rate ($g\ m^{-3}\ min^{-1}$)	Mean Lifetime (min)	# Cells	Mean Pass 1 LWC ($g\ m^{-3}\ min^{-1}$)	Mean Decay Rate ($g\ m^{-3}\ min^{-1}$)	Mean Lifetime (min)
5/27	3	0.97 ±.17	.048 ±.044	20	2	1.07 ±.03	.063 ±.051	17
5/28	5	1.46 ±.74	.061 ±.065	24	4	1.60 ±.77	.056 ±.074	29
5/31	10	0.86 ±.17	.119 ±.078	7	9	0.89 ±.15	.100 ±.053	9
6/1-1	10	0.73 ±.38	.153 ±.108	5	6	0.89 ±.24	.197 ±.110	5
6/1-2	3	0.47 ±.30	.044 ±.028	11	1	0.80 ± -	.062 ±. -	13
6/2-1	9	0.85 ±.44	.121 ±.077	7	5	1.16 ±.29	.147 ±.050	8
6/2-2	8	0.71 ±.29	.064 ±.075	11	6	0.75 ±.32	.040 ±.071	19
6/3	10	0.88 ±.47	.099 ±.114	9	4	0.98 ±.43	.086 ±.112	11
6/6	13	1.00 ±.59	.129 ±.132	8	9	1.18 ±.64	.142 ±.156	8
6/9	6	0.66 ±.11	.096 ±.055	7	3	0.73 ±.07	.094 ±.049	8
1986 Total	77	0.87 ±.45	.106 ±.095	8	49	1.01 ±.49	.110 ±.101	9
Excluding 6/1-1					43	1.03 ±.47	.097 ±.094	11
1987								
9/9-1	5	0.95 ±.49	.024 ±.059	40	4	1.10 ±.40	.037 ±.060	30
9/9-2	6	0.92 ±.34	.124 ±.105	7	5	1.03 ±.25	.139 ±.111	7
9/10	2	0.47 ±.02	.041 ±.049	12	1	.48	.006	80
9/11	7	0.69 ±.39	.062 ±.057	11	5	.85 ±.34	.081 ±.057	11
9/14	4	0.70 ±.34	.117 ±.025	6	2	.91 ±.42	.098 ±.018	9
9/15	6	0.81 ±.31	.103 ±.093	8	6	.81 ±.31	.103 ±.093	8
9/20-1	8	0.76 ±.23	.014 ±.054	54	6	.66 ±.16	.014 ±.063	47
9/20-2	7	0.50 ±.24	.056 ±.055	9	2	.75 ±.28	.120 ±.016	6
9/27	10	0.83 ±.31	.086 ±.077	10	10	.83 ±.31	.086 ±.077	10
1987 Total	55	0.76 ±.33	.070 ±.075	11	41	.85 ±.30	.079 ±.080	11

Table 2. Distribution of calculated LWC decay rates

Decay Rate ($g\ m^{-3}\ min^{-1}$)	Freq.	Cum. Freq. (%)
≤ -.05	3	2
≤ 0.00	9	9
≤ .05	34	35
≤ .10	41	66
≤ .15	18	80
≤ .20	13	89
≤ .25	6	94
≤ .30	3	96
≤ .35	3	98
≤ .40	1	99
> .40	1	100

Table 3. Distribution of projected cloud top lifetimes

Lifetime (min)	Freq.	Cum. Freq. (%)
≤ 5	22	18
≤ 10	43	54
≤ 15	24	74
≤ 20	11	83
≤ 25	6	88
≤ 30	1	89
≤ 35	2	91
≤ 40	1	92
> 40	10	100

The mean lifetimes are low for most missions, but the variability of LWC and DR means that there were clouds which persisted for significantly longer times. For example, in the 1986 project, the clouds sampled on the first two days clearly seemed to be most suitable for seeding, at least in terms of the persistence of SLW. This is also true for the first flights of 9 and 20 September, 1987. On the other hand, the first flight of 1 June, 1986, found clouds embedded in altostratus that were very short-lived and would likely be poor seeding candidates. Thus, mean values for the 1986 OREP clouds were also computed excluding those samples from 1 June.

The computed values of LWC1, mean DR and cloud top lifetime for the total project are very similar to those reported by SI for clouds sampled in 1977 near Thunder Bay, Ontario: 0.88 ± 0.55 $g\ m^{-3}$, $-0.104 \pm .17$ $g\ m^{-3}\ min^{-1}$, and 8 min, respectively. SI classified these clouds as having short lifetimes and high LWCs, providing an environment where warm and cold rain processes as well as ice multiplication can occur. They felt that these lifetimes were too short and that, consequently, the clouds would be poor candidates for seeding with silver iodide. However, they did suggest that the use of dry ice would improve their seedability.

Table 4. Data stratified by cloud seedability

	Cloud Type	# Cells	D	avg. w	avg. LWC	peak LWC
1986	S	5	2.1	2.2	1.37	2.2
	SNS	9	1.4	2.2	.98	1.5
	NS	28	1.3	2.2	.99	1.7
1987	S	10	2.8	3.9	.92	1.7
	SNS	21	1.8	3.8	.79	1.6
	NS	7	1.8	5.0	.97	1.7

4.2 Stratification by OREP criteria

The 1987 cloud set, as a whole, was somewhat drier than the 1986 set and had a markedly lower decay rate. This gave rise to an average calculated cloud top lifetime that was nearly 40% greater in 1987. When comparing only the OREP clouds, however, the combination of lower LWC1 and lower DR in 1987 produced an average cloud top lifetime similar to that for 1986. Based on this limited set of observations it is not known if the differences in LWC1, DR and lifetime are seasonal in nature or whether they represent a random interannual variability. They do not appear to be the result of a change in emphasis on sampling levels from 1986 to 1987 (see section 4.3).

In an attempt to determine why cloud lifetimes varied markedly from day to day a rather restrictive subset of apparently "seedable" clouds was defined. These were OREP clouds which had projected lifetimes ≥ 14 minutes and which developed ice slowly, if at all (no detectable ice before the fourth sampling pass, ~7 minutes from time of first penetration). The first pass characteristics of these seedable clouds are presented in Table 4 as cloud type S. Characteristics of non-seedable clouds which were sampled on days with seedable clouds (type SNS) and characteristics of clouds on days when there were no seedable clouds (NS) are also shown.

The seedable clouds were, on the average, substantially larger than the others. The greater first pass diameter (D) likely promoted the longevity of these clouds by reducing the effects of entrainment. On seedable days, the seedable clouds also had higher LWC than the non-seedable clouds.

Another interesting first-pass characteristic is that the average updraft speed (w) for clouds sampled on seedable days was less than that on non-seedable days. This is in agreement with a more general observation derived from other supporting data that the seedable clouds were found on days or in areas where only weak to moderate convection was occurring. On several of these seedable days atmospheric soundings revealed the presence of a weak mid-level temperature inversion. These observations show that the clouds most suitable for seeding were not associated with strong or severe convective situations. A reason for this may be that the more vigorous clouds reached colder temperatures earlier in their lifetimes and therefore initiated the ice process sooner. It may also be that the stronger updrafts promoted a more rapid recycling of ice within cloud or ingestion of ice from neighboring cells. Entrainment may have also been enhanced by larger updraft velocities.

For most missions in 1986 the mean lifetime of the OREP subset is larger than that of the total cloud set. This indicates that the stratification criteria had a net positive effect on the selection process. However, no such effect was found for the 1987 data set. The fact that the stratification criteria had no effect on the cloud selection process in 1987 but had a net positive effect in 1986 may be due to the nature of the clouds excluded by the screening. In 1986 over 70% of the clouds which did not meet OREP criteria failed due to high ice concentrations. In 1987, the primary reason for excluding clouds (85%) was a low LWC1. The fact that the exclusion of clouds with high initial ice concentrations improved cloud top lifetimes while exclusion of those with lower initial LWC did not, suggests that the ice plays a more significant role in the availability of liquid water.

This postulate is supported by the correlations of the computed cloud top lifetimes with LWC1 and DR. Figures 1a and 1b illustrate these relationships for both years. There was a strong correlation between lifetime and DR, as one would expect, but little or no correlation between lifetime and LWC1. A regression of lifetimes versus LWC1 and DR indicates that approximately 90% of the variance in the lifetimes is explained by the variability of the DR. Thus, the persistence of SLW appears to be more highly dependent on depletion processes such as conversion to ice or entrainment than on the initial liquid water content of the clouds.

4.3 Stratification by temperature and termination type

The clouds in this study were also stratified by penetration temperature and by termination type. Table 5 shows that in 1986 there was little difference in LWC1 or DR between warm and cold cloud penetrations. Temperatures warmer than -10°C were classified as warm. However, in 1987, the cold clouds had a much higher average decay rate. This

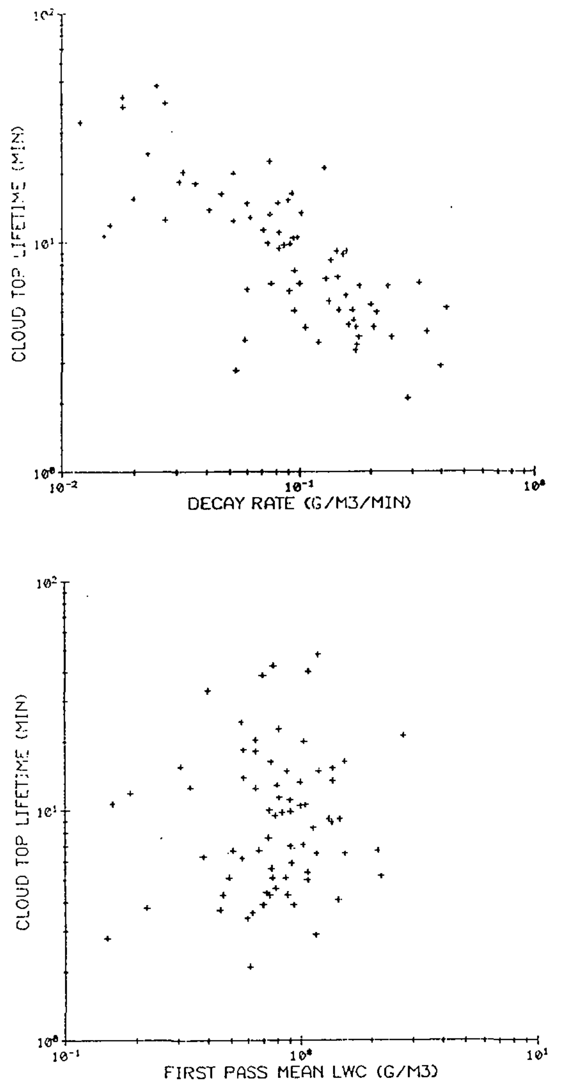

Fig. 1a. Cloud top lifetime as a function of liquid water decay and as a function of first pass mean liquid water content, for 1986 clouds.

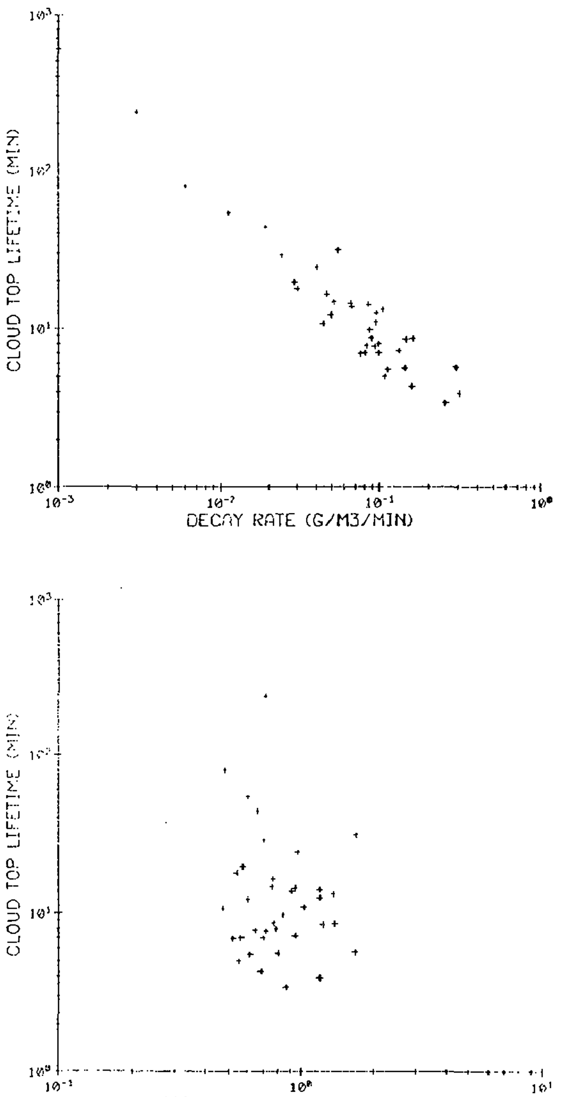

Fig. 1b. As in Fig. 1a. for 1987 clouds.

statistic may be biased by the fact that half of the colder penetrations were made on one flight, 9/9-2, which had the highest DR of all 1987 missions.

A comparison of warm and cold samples considering reasons for termination type is presented in Table 6. Termination types may be interpreted as follows:

Dissipation	- a loss of liquid water and/ or updraft;
Glaciation	- peak 2D concentrations > 50 liter^{-1};
Safety	- primarily cloud radar reflectivities >40 dBz associated with graupel and/or small hail;
Operations	- descents for aircraft de-icing, congested cloud fields, changes in flight tracks to focus on nearby cells.

The 1986 cloud data set showed that the majority (almost 2/3) of the clouds sampled at colder temperatures developed ice compared to only about 1/3 of those sampled at warmer temperatures. The 1987 clouds, however, showed no such preference.

5. DEVELOPMENT OF ICE

A second important factor which determines the seedability of clouds is the natural development of ice crystals. For seeding to be effective it must convert the SLW to ice at a faster rate or in a more favorable portion of the cloud than would have occurred naturally. Within the scope of this study the development of ice was examined in primarily a qualitative sense.

The rate at which ice developed, as measured by time from first penetration, varied from flight to flight. On a number of missions, some of the clouds never contained detectable ice particles at flight altitudes and in others it took

Table 5. Data stratified by penetration temperature

		Warmer than -10°C			Colder than -10°C		
		Avg. LWC Pass 1 (gm^{-3})	Avg. Decay Rate ($gm^{-3}\ min^{-1}$)	N	Avg. LWC Pass 1 (gm^{-3})	Avg. Decay Rate ($gm^{-3}\ min^{-1}$)	N
1986	All Clouds	.93	.103	42	.90	.109	35
	OREP Clouds	1.05	.104	31	1.14	.103	18
1987	All Clouds	.73	.060	42	.83	.101	13
	OREP Clouds	.82	.068	32	.94	.120	9

Table 6. Data stratified by termination type and temperature

		Dissipation	Glaciation	Safety	Operational
1986	Warm	55%	31%	7%	7%
	Cold	29%	49%	14%	8%
1987	Warm	38%	12%	14%	36%
	Cold	46%	8%	23%	23%

from five to over 13 minutes before significant concentrations could be detected. By comparison, many missions saw rapid ice development within the candidate clouds. Significant concentrations of ice crystals ($10\ \ell^{-1}$) were generally present by the third pass or roughly four minutes after initial penetration. A number of clouds even contained high ice concentrations on the first pass and would not meet the OREP criteria.

There are indications that ice ingestion may have played a significant role in the development of high ice crystal concentrations. Embedded cells were sampled on several occasions and all contained high quantities of ice on the first pass or shortly thereafter. Most of the towers on the first flight of June 1, 1986 were embedded in a sub-freezing altostratus layer. It was also noted that towers which grew up close (within a kilometer) to an older cell tended to develop ice early in their lifetime. These turrets were normally part of a small convective complex and were joined to the mature portion of the system at lower levels. It is possible that ice particles were being ingested at those levels and brought up to cloud top.

Another generalization that may be made concerning ice development is that it seemed to occur primarily low in the cloud, at relatively warm temperatures. This may be inferred from the crystal habits - very few plates or dendritic crystals were observed in any of the cloud turrets. Those are the types of ice particles which would be expected to grow in the -10°C to -20°C temperature range. Instead, there was a preponderance of graupel, columns, frozen drops, and irregular particles (as in Fig. 2) at all sampled temperatures (-5°C to -13°C). This suggests that processes such as ice multiplication (e.g., Mossop, 1976) or ice ingestion from neighboring cells may have been dominant in those clouds which eventually developed detectable ice crystal concentrations.

Data from one of the clouds sampled on May 27 support the possibility of a Hallett - Mossop ice multiplication process. This cumulus congestus was penetrated nine times over a 23 minute period, at temperatures between -5°C and -8°C. The estimated cloud top temperature was no colder than -9°C. During the second pass, at -7°C, the cloud contained relatively high concentrations of both large and small droplets (181 cm^{-3} of diameter >23 μm and 87 cm^{-3} of diameter <14 μm) (Fig.3). The ratio of small to large droplet concentrations (0.5) is within the range of values found in clouds in which ice multiplication has been observed (Mossop, 1985). The 2D data (Fig. 2) show round and nearly-round images in passes 4-6, representing liquid and possibly frozen drops up to 1 mm in

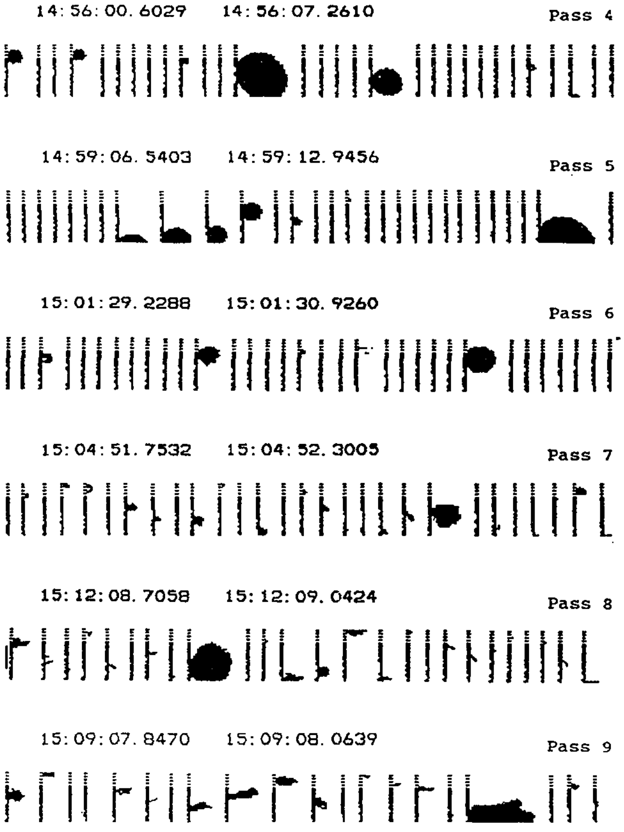

Fig. 2. 2D images from cloud C on May 27, 1986. Time of initial penetration was 144908. Length of vertical bars corresponds to 1 mm.

size in concentrations generally <1 ℓ^{-1}. Ice particles of this size could be active rimers for the production of secondary ice particles. Columns first appeared in pass 7 mixed with irregular and nearly-round particles (up to 37 ℓ^{-1}). Irregular particles, graupel and columns predominated in passes 8 and 9 (>80 ℓ^{-1}) as the liquid water content was depleted.

6. SUMMARY

The following general characteristics of the sampled cloud water and ice contents were determined:

1. The supercooled liquid water content of the study clouds was observed to decay at a fairly rapid rate. Cloud top lifetimes of 8, 9 and 11 minutes were calculated for all multiple pass clouds and for two select subsets in 1986, and 11 minutes for all clouds in 1987.

2. The liquid water decay rates had a large standard deviation, suggesting that a fair percentage of the clouds may be expected to contain SLW for significantly longer periods of time. The longer-level clouds occurred under conditions of weak to moderate convection.

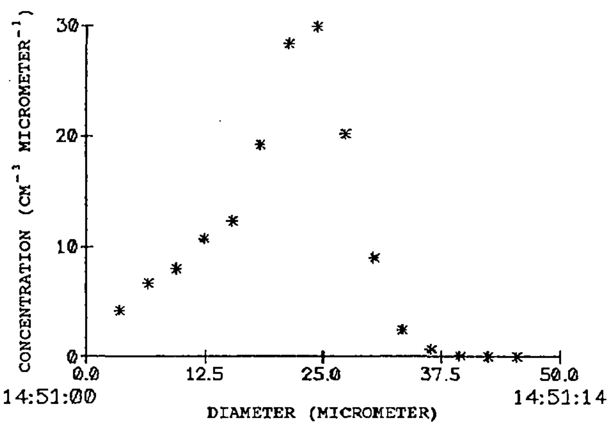

Fig. 3. FSSP droplet spectrum for cloud C pass 2 on May 27, 1986.

3. The initial LWCs of the clouds meeting OREP criteria were substantial, with a first pass average of 0.94 $g\ m^{-3}$.

4. The development of ice occurred very rapidly in many of the clouds, particularly those which grew up close to older towers or were embedded in cold cloud layers. There were several missions, however, where ice development was not significant over the sampled life of the clouds.

5. It appears as though the ice phase is being initiated in lower portions of the clouds. Evidence for this includes a lack of crystal habits normally formed at colder temperatures and the rapid glaciation of towers below the -12°C level.

6. Much of the cloud ice may be the result of ice multiplication and/or ingestion or recirculation from neighboring cells.

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