Water-Ice and Water-Updraft Relationships near −10°C within Populations of Florida Cumuli

ROBERT I. SAX[1] AND VERNON W. KELLER[2]

NOAA National Hurricane and Experimental Meteorology Laboratory, Coral Gables, FL 33146

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ABSTRACT

From an in-cloud microphysical data set collected in Florida convective towers that were penetrated close to their tops near −10°C, evidence is presented to show a sequential development of cloud water, rainwater, graupel and crystalline ice as the cloud ages. Of particular interest is the very rapid onset of graupel that appears on repeat penetrations of some, but not all, towers. A separate data set shows a large scatter in the relationship between maximum value of cloud water and vertical velocity which points to the conclusion that measurements of cloud water, by itself, can be misleading as an indication of growth activity. The sequential pass data showing the evolution of ice and water are consistent with a rime-splintering, secondary ice production hypothesis.

1. Introduction

During late spring and summer afternoons (May–September), south Florida is characterized meteorologically by the almost daily occurrence of deep convection driven by a mesoscale dual sea breeze circulation. Cloud-base level is typically between 0.5 and 0.8 km (~ +22°C), while cloud tops late in the day frequently can exceed 10 km (−40°C). During midafternoon on most days there exists a large population of cloud towers in various stages of development with tops near the −10°C level. As part of NOAA's Florida Area Cumulus Experiment (FACE), several types of aircraft, specially equipped to obtain cloud physics measurements, were used to carry out penetrations of convective towers near their tops in the temperature range −4° to −12°C (altitude ~6 km). The penetrations were carried out on both single-pass (ensemble) and repeated-pass (case study) bases.

Hallett *et al.* (1978) examined the evolution of ice in Florida cumuli on an individual case study basis and interpreted the results from the framework of quantitative development of a rime-splintering hypothesis for secondary ice generation. It was not possible, however, in the context of that study to examine the question of the representativeness of those particular selected case studies in relation to ice evolution within a broader population of towers such as those typically chosen for treatment in FACE. In the present paper we are able to take a more inclusive sample of repeated cloud passes to provide insight into the evolution of several microphysical variables within an ensemble of towers.

The data presented in this paper were obtained from the NOAA DC-6 and C-130 aircraft in 1975 and from a leased Piper Navajo aircraft in 1976. An automated continuous formvar replicator[3] was common to the DC-6 and Navajo aircraft, and the concentration of ice crystals, graupel and raindrops (splashes) was derived from analyses of data collected with this instrument.[4] As discussed by Sax *et al.* (1979), graupel particles are characterized on the formvar by an appearance ranging from sharp-edged agglomerates in regions of very little cloud water to dense, heavily rimed and, at times, slushy masses in regions of cloud with high water contents. Crystals were generally columnar or star-shaped (end-on columns) in appearance, although plates were observed occasionally. Splash drops (drops large enough to break up upon impact) were determined from circular craters on the film which contained a rather distinctive pattern of smaller drops along the periphery. Graupel particles and splash drops were counted only if the crater diameter exceeded 300 μm, while crystals generally were smaller than 300 μm along the major axis. The 16 mm formvar-coated film was analyzed on a frame-by-

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[1] Present affiliation: Joseph Oat Corporation, Camden, NJ.

[2] Present affiliation: NASA, MSFC, Huntsville, AL.

[3] Designed and built by Dr. John Hallett and his staff at the Desert Research Institute, Reno, NV.

[4] At DC-6 and Navajo airspeeds the sampling volume of the replicator is 1 ℓ s^{-1}; the threshold size for detection of liquid droplets is ~5 μm and for ice crystals is ~50 μm. For an observed particle concentration of 10 ℓ$^{-1}$, it can be shown from Poisson statistics that the actual concentration can be expected to be between 6 and 14 ℓ$^{-1}$ 85% of the time, and between 8 and 12 ℓ$^{-1}$ 57% of the time.

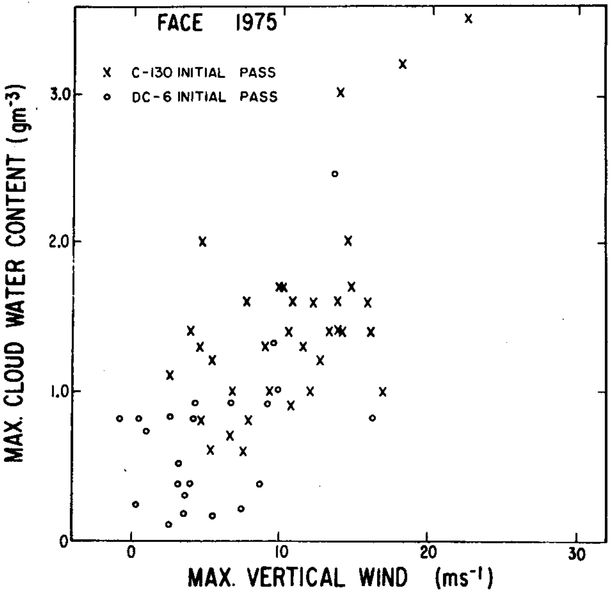

FIG. 1. Relationship between maximum content of cloud water (Johnson-Williams) and maximum vertical wind sampled during initial penetrations near the tops of Florida convective clouds at about the −10°C level; included are 35 passes with the NOAA C-130 and 22 passes with the NOAA DC-6 aircraft. All passes were carried out in unseeded convective towers, although the group of C-130 penetrations shown here are only from towers in which the unarmed flare release switch was activated at least once.

frame basis corresponding in most cases to an in-cloud spatial resolution of ~ 2 m.

Johnson-Williams (JW) heated wires provided the measurement of cloud water contents from all aircraft on a spatial scale of ~ 100 m. Draft-scale (100 m) air vertical velocity data in 1975 were obtained from the DC-6 with a combination of integrated radar altimeter, aircraft pitch and aircraft angle-of-attack measurements, and from the C-130 with a vertical accelerometer system coupled to a static pressure feedback to accommodate systematic drift. Baseline data obtained during straight and level flight in clear air indicate that the DC-6 vertical winds should not be considered accurate to better than about ± 2 m s^{-1}, while errors from the C-130 vertical winds appear to be about ± 0.5 m s^{-1}. Reliable air vertical velocity data were not available from the Navajo aircraft in 1976.

For the purposes of this paper, we use only microphysical data obtained on days during which no cloud seeding activities were conducted. We examine the manner in which cloud water content, raindrop concentration, graupel concentration and ice crystal concentration are related to each other in the tops of clouds near −10°C, and we investigate the association between updraft and cloud water contents from the point of view of using the latter to infer the stage of development of the cloud element. It is well to keep in mind here that the cloud depth between the base and the sampling level always was about 5 km, of which approximately the lowest 3.5 km exists at temperatures warmer than 0°C.

2. Relationship between vertical velocity and cloud water

Since slower ascent rates allow more time for the growth of water droplets by coalescence and since the JW instrument is primarily sensitive to cloud droplets smaller than 40 μm in diameter (Ruskin and Scott, 1974), it is reasonable to expect that the highest values of cloud water at a given sampling level should occur in towers with the strongest updrafts. Fig. 1 shows a plot of maximum vertical velocity versus maximum JW cloud water for a series of cloud passes. The maximum in both cases, and as used subsequently throughout this paper, is defined as the mean of the five consecutive point (1 s) values of each parameter centered around the highest point value. The peak values of each parameter are not necessarily coincident with each other on each cloud pass, though generally they do occur together in the same general region of the cloud envelope. Data obtained from both the DC-6 and the C-130 in 1975 are used in this diagram. The DC-6 data are from a sampling of all clouds penetrated, while the C-130 data are only from penetrated clouds judged (during the penetration) to be suitable for seeding (flare ejector activated but not armed). All towers in the data set were penetrated within ~ 0.8 km of their tops. It can be seen that as a group, the C-130 towers on initial penetration contain more cloud water and higher peak vertical velocities than do those sampled by the DC-6. We do not consider the difference in JW water contents to be a function of instrument or exposure variations since larger data samples from the two aircraft do not tend to show systematic biases in comparable types of clouds.

It is apparent that considerable scatter exists between these two variables throughout the sampling range. For the population, in general, the highest values of peak vertical velocity are loosely associated with the highest values of peak JW water content, but there is no clear-cut relationship for water contents $\lesssim 1.4$ g m^{-3} and updraft velocities $\lesssim 10$ m s^{-1}. For example, high (>10 m s^{-1}) peak updraft clouds in this sample invariably are found to have maximum cloud water contents in excess of 0.8 g m^{-3}, but many clouds with maximum water contents higher than 0.8 g m^{-3} contain peak updrafts of less than 10 m s^{-1}. A similar analysis was carried out attempting to relate the 5-point maximum value of one parameter to the mean of the 5-point value of the other parameter occurring at exactly the same time (position) within the cloud. The result of those analyses was similar to that presented in Fig. 1 with a large scatter of points at vertical velocities of less than 10 m s^{-1} and JW water contents of less than 1.4 g m^{-3}.

It is evident from the data presented in Fig. 1 that measurement of JW cloud water, by itself, can be misleading with respect to inferences about how vigorously the tower is growing at the time of penetration. Assuming that, for a given updraft velocity at a given level below cloud top, mixing of environmental air does not vary substantially from one cloud to another of similar size, and further prescribing that cloud base and sampling levels as well as CCN activity spectra are fairly consistent from one tower to another, we offer the suggestion that the lack of a distinct correlation between velocity and cloud water may be caused by temporal variability (pulsations) in updraft structure, leading to regions of moderate water contents in towers in which the updraft has been momentarily reduced. Pulsating or "hesitation" type growth is visually observed to occur quite frequently within a population of Florida convective clouds, and such a mode of development would certainly complicate correlations that might be expected given the continuous updraft assumptions discussed at the beginning of this section.

3. Evolution of water and ice

The evolution of cloud water, rainwater, graupel and crystalline ice as a function of time after initial penetration is shown in Figs. 2, 3, 4 and 5, respectively, for 19 convective towers that were penetrated at least twice. All passes shown in these figures were carried out with the Navajo aircraft during the FACE Program in 1976. Initial passes were all carried out in towers which appeared to be actively growing (rising bubble) and which possessed a sharp outline (cauliflower shape) with tops just at or slightly ($\leq$600 m) above the sampling level. We reemphasize that only clouds penetrated on days during which no seeding activity took place are included in the sample. The data set includes 19 initial penetrations, 19 second penetrations (executed from 94 to 220 s after first penetrations), four third penetrations (executed from 245 to 379 s after first penetration), and two fourth penetrations. As part of the overall data set, three sequences of tower penetrations have been selected as case studies to demonstrate specific features of the tower's microphysical life history at the sampling level. When viewed in combination, the data present an overall picture of the in-cloud evolution of water and ice at the pene-

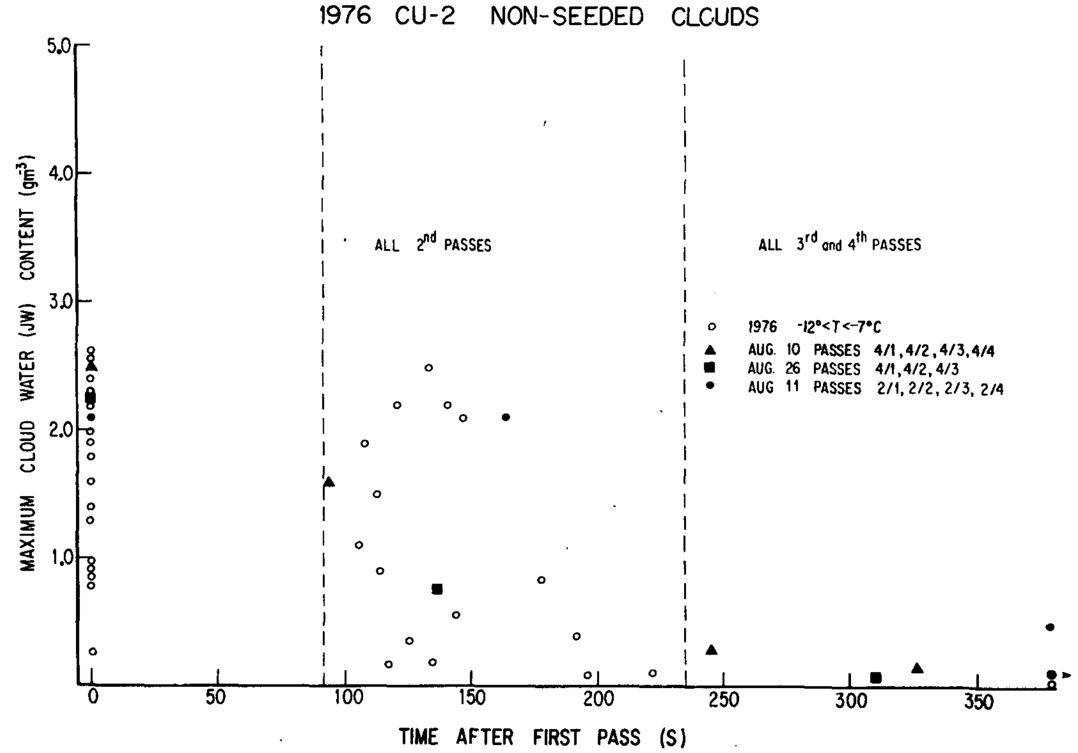

FIG. 2. Evolution of cloud water content (Johnson-Williams) with time in a group of 19 convective towers penetrated at least twice by the Navajo aircraft in 1976; included in the ensemble are case studies of one cloud penetrated three times and two clouds penetrated four times. This group of towers and the three case studies appear together in Figs. 2–5; all penetrations were carried out near the tops of the towers in the temperature range −7 to −12°C.

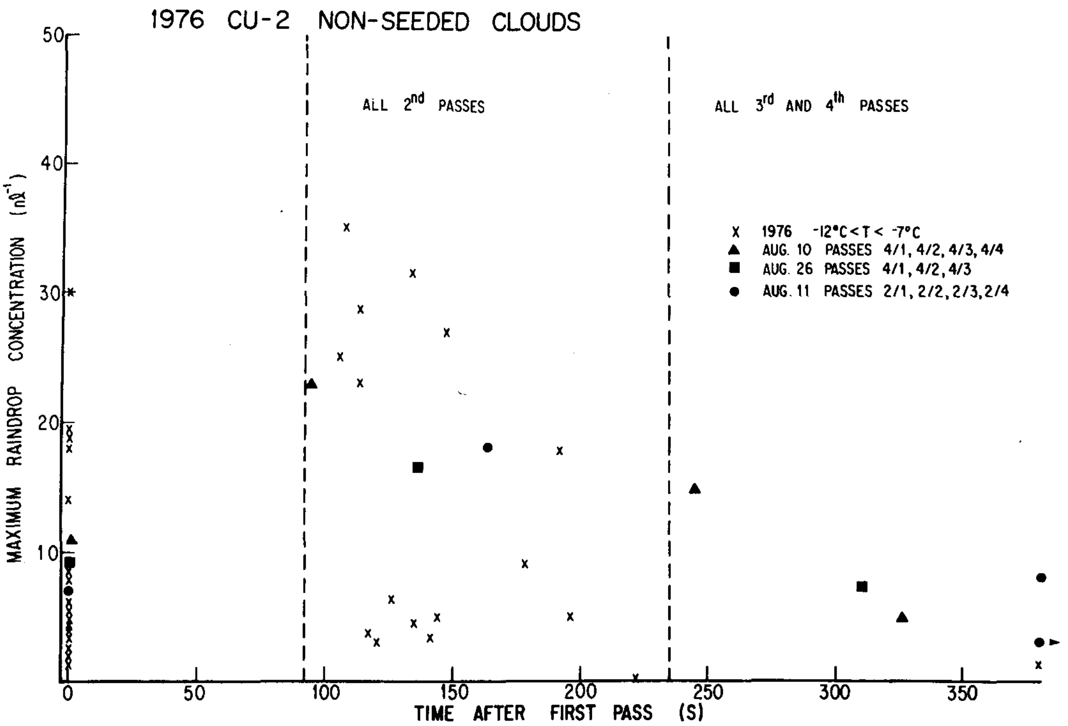

FIG. 3. Evolution of splash drop concentration (as determined from formvar replicator analysis) with time; drops are those with crater diameters exceeding 300 μm.

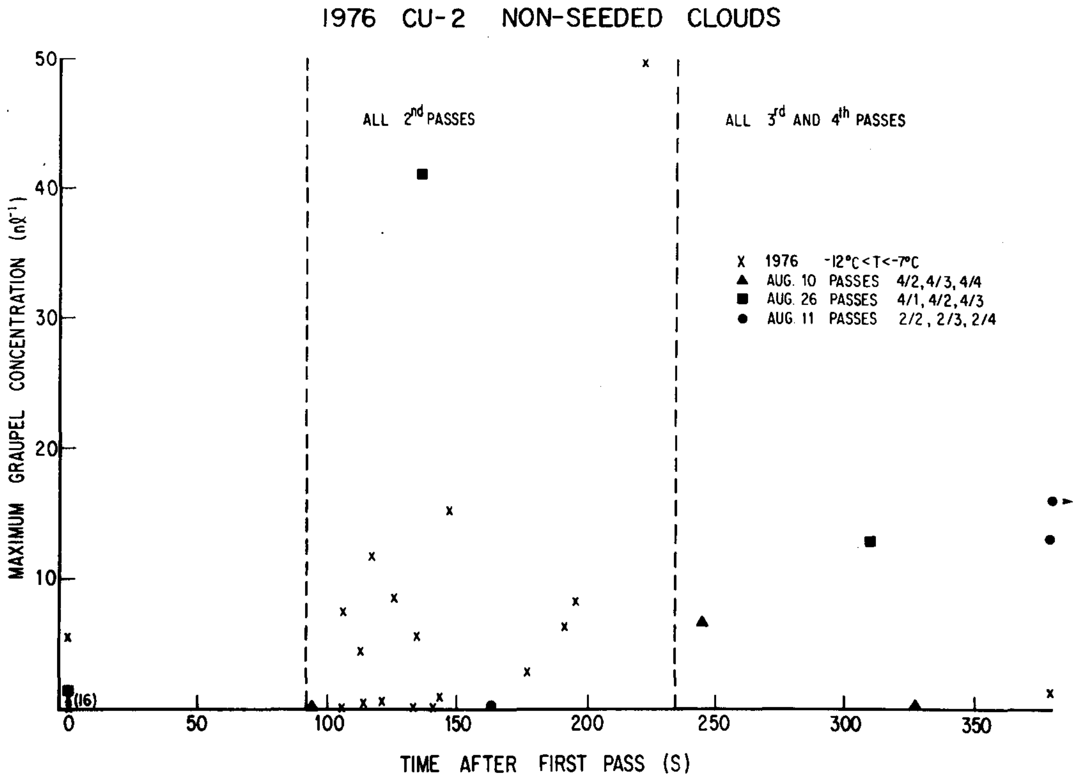

FIG. 4. Evolution with time of concentration of graupel of diameter > 300 μm (from formvar analysis); note the absence of graupel on initial penetrations.

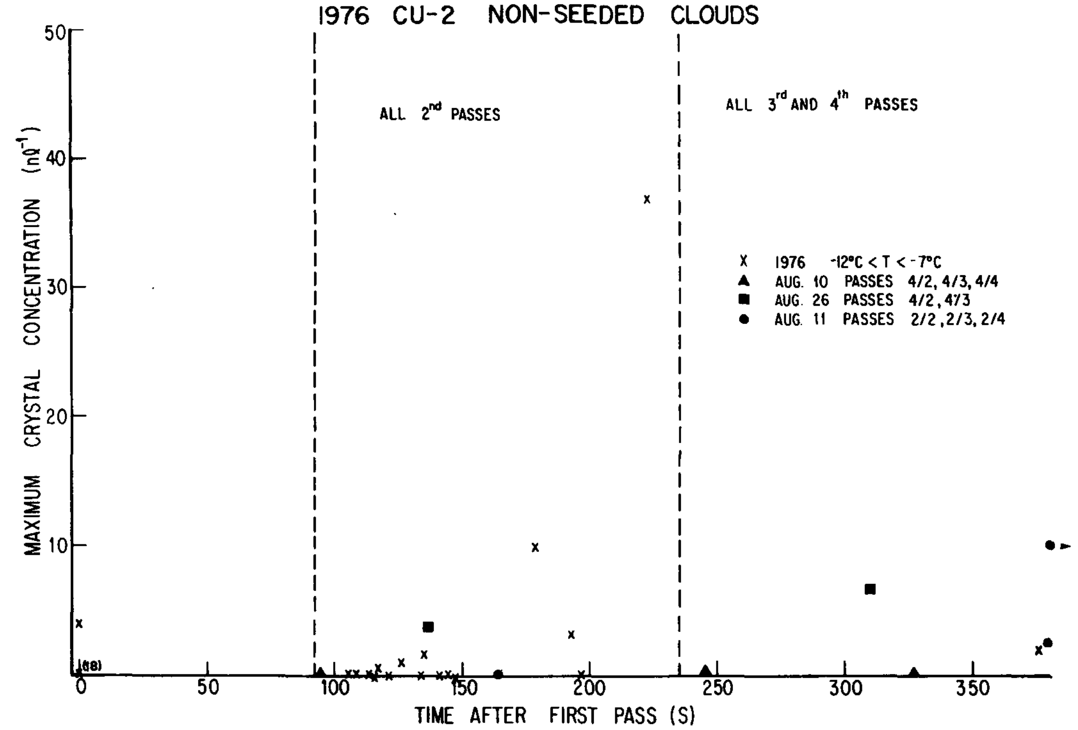

FIG. 5. Evolution with time of vapor grown ice crystals as determined from an analysis of formvar replicator data.

tration level. All of the clouds presented here failed to grow substantially above the penetration level during the sequence of passes, so the sample is biased toward towers which, though initially active, quickly lost their buoyancy.

The complete set of 1976 data used in this analysis is presented in Table 1. The reader's attention is particularly drawn to the following columns: pass time interval (Δt), JW water 5-point max value, splash drop 5-point max value, graupel 5-point max value, and ice crystal 5-point max value. The table contains information about the same cloud passes as presented by Sax *et al.* (1979), with the splash drop data and the 5-point max values of each parameter presented here for the first time. The mean values presented in the table were calculated across the entire cloud envelope. The three initial passes appearing in the above referenced paper that were over the top of a growing tower have been omitted from the table, and modifications to the table for subsequent passes in those cases have been made accordingly.

From an examination of Figs. 2–5 and Table 1 it can be seen that cloud water decreases as the cloud ages to the point where it is found to be almost nonexistent within ~4 min after the initial penetration. Rainwater, present to some degree on first passes, increases in a short time and then decreases as the cloud begins to dissipate. Ice in the form of graupel shows an increase in concentration for some, but not for all, second penetrations occurring more than 100 s after the first pass. However, in the older stages of the cloud's life cycle (usually by the time of the third penetration) the maximum concentration of graupel fails in most cases to show a continued increase. Crystalline ice, on the other hand, is evident in only a few of the clouds penetrated a second time, with some increase observed during third penetrations. Some clouds failed to develop any appreciable concentration of crystals even by the time of third and fourth penetrations.

As can be seen in Fig. 2, maximum cloud water contents, as manifested by the JW sensor, exceed 0.8 g m^{-3} on 18 of the 19 initial penetrations. A wide variability in maximum cloud water is found on second penetrations; 11 of 19 clouds exceeded 0.8 g m^{-3} but 7 of 19 clouds had <0.6 g m^{-3}. On third penetration, none of the four clouds sampled had maximum water contents > 0.5 g m^{-3}.

From Fig. 3 it can be seen that maximum raindrop[5] concentrations on initial penetration varied

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[5] The concentration of raindrops is deduced from patterns of splashes on formvar; for the purposes of this analysis, splash drops were counted as a raindrop if their crater diameter exceeded ~300 μm, a size, from the work of MacCready and Todd (1964), which corresponds here to an actual drop diameter of ~150 mm.

TABLE 1. Microphysical statistics for unseeded clouds penetrated at least twice during FACE 76.

						JW Water				Splash Drops					Graupel					Crystals			
Date	Time (GMT)	Pass (ID)	Duration (s)	Temperature (^{o}C)	Δt (s)	1-pt Max (gm^{-3})	5-pt Max (gm^{-3})	Mean (gm^{-3})	>1.0 gm^{-3} (%)	1-pt Max (ℓ^{-1})	5-pt Max (ℓ^{-1})	Mean (ℓ^{-1})	Med (ℓ^{-1})	$\geq$10 ℓ^{-1} (%)	1-pt Max (ℓ^{-1})	5-pt Max (ℓ^{-1})	Mean (ℓ^{-1})	Med (ℓ^{-1})	$\geq$10 ℓ^{-1} (%)	1-pt Max (ℓ^{-1})	5-pt Max (ℓ^{-1})	Mean (ℓ^{-1})	Med (ℓ^{-1})
6/27	185152	4/1	4	-7	---	2.6	2.2	2.2	100	11	8	8	8	25	0	0	0	0	0	0	0	0	0
	185406	4/2	13	-7	134	2.7	2.5	2.1	100	41	32	23	20	92	0	0	0	0	0	0	0	0	0
6/30	184257	10/1	5	-8	---	0.6	0.3	0.2	0	9	4	4	4	0	0	0	0	0	0	0	0	0	0
	184454	10/2	26	-8	117	0.4	0.2	0.0	0	8	4	1	0	0	19	12	2	0	8	2	1	0	0
	220820	21/1	6	-8	---	1.7	0.9	0.7	43	44	19	17	8	33	0	0	0	0	0	0	0	0	0
	221008	21/2	16	-8	108	2.1	1.9	1.4	76	50	35	31	31	94	1	0	0	0	0	0	0	0	0
	224738	26/1	11	-8	---	1.9	0.9	0.8	36	12	6	5	6	9	0	0	0	0	0	0	0	0	0
	224944	26/2	12	-8	126	0.5	0.3	0.3	0	15	6	5	3	17	15	9	4	1	25	5	1	1	0
7/06	182208	3/1	4	-10	---	1.5	1.0	0.8	33	28	9	9	3	25	0	0	0	0	0	0	0	0	0
	182550	3/2	38	-11	222	0.1	0.1	0.1	0	0	0	0	0	0	86	50	28	18	66	57	37	22	23
7/07	194105	5/1	13	-11	---	2.9	2.5	1.9	83	23	18	15	13	100	0	0	0	0	0	0	0	0	0
	194332	5/2	34	-11	147	2.8	2.1	1.1	40	34	27	17	18	79	25	15	4	2	21	0	0	0	0
7/18	190439	3/1	12	-10	---	2.7	2.3	1.7	82	30	19	8	6	42	3	1	1	0	0	0	0	0	0
	190625	3/2	15	-10	106	1.5	1.1	0.6	10	31	25	20	21	93	19	7	4	3	7	0	0	0	0
	202145	14/1	11	-11	---	1.8	1.3	0.8	35	11	4	3	2	9	0	0	0	0	0	0	0	0	0
	202409	14/2	7	-11	144	0.9	0.5	0.4	0	8	5	4	4	0	2	1	1	0	0	1	0	0	0
7/20	205253	3/1	11	-8	---	3.0	2.6	2.1	86	2	2	1	1	0	0	0	0	0	0	0	0	0	0
	205454	3/2	19	-10	121	2.6	2.2	1.3	54	5	3	2	1	0	3	1	0	0	0	0	0	0	0
8/10	200724	4/1	9	-10	---	2.7	2.4	1.4	58	25	11	6	2	22	0	0	0	0	0	0	0	0	0
	200858	4/2	18	-10	94	2.0	1.6	1.1	67	27	23	13	15	67	1	0	0	0	0	0	0	0	0
	201129	4/3	7	-10	245	0.6	0.3	0.3	0	24	15	13	15	86	11	7	5	3	29	1	0	0	0
	201250	4/4	5	-10	326	0.3	0.1	0.1	0	9	5	5	5	0	1	0	0	0	0	0	0	0	0
8/11	183618	2/1	28	-8	---	2.8	2.1	1.8	78	9	7	3	1	0	0	0	0	0	0	0	0	0	0
	183902	2/2	51	-9	164	2.3	2.1	1.1	59	23	18	7	4	27	0	0	0	0	0	0	0	0	0
	184246	2/3	54	-10	388	0.6	0.4	0.3	0	12	8	4	3	7	33	13	7	5	20	8	2	0	0
	184626	2/4	43	-10	608	0.1	0.1	0.0	0	10	3	1	1	2	30	16	9	7	40	36	10	3	0
	191845	4/2	11	-9	---	1.5	1.4	1.0	73	39	30	22	22	91	1	0	0	0	0	12	4	2	0
	192157	4/3	39	-10	192	0.5	0.4	0.2	0	24	18	7	5	33	10	6	1	0	3	7	3	0	0
	192513	5/1	6	-9	---	2.3	1.6	1.2	60	13	6	6	6	17	0	0	0	0	0	0	0	0	0
	192706	5/2	19	-9	113	1.9	1.5	1.0	46	39	29	24	23	84	13	4	2	0	5	1	0	0	0
8/15	185214	1/1	17	-8	---	2.3	1.8	1.5	88	12	5	2	1	6	0	0	0	0	0	0	0	0	0
	185512	1/2	20	-9	178	1.0	0.8	0.5	0	16	9	7	7	20	6	3	1	0	0	24	10	2	0
	185833	1/3	15	-9	379	0.0	0.0	0.0	0	2	1	1	0	0	5	1	1	0	0	6	1	2	0
	194154	5/1	18	-8	---	2.5	2.0	1.7	80	5	2	1	0	0	0	0	0	0	0	0	0	0	0
	194415	5/2	27	-8	141	2.3	2.2	1.6	85	10	3	2	1	3	0	0	0	0	0	0	0	0	0
8/22	202046	3/1	14	-8	---	3.0	2.4	2.0	90	6	2	2	2	0	0	0	0	0	0	0	0	0	0
	202402	3/2	14	-8	196	0.1	0.1	0.0	0	7	5	2	0	0	13	8	4	2	7	0	0	0	0
8/26	185111	4/1	10	-7	---	2.7	2.2	2.0	80	11	9	8	9	30	4	1	1	0	0	1	0	0	0
	185327	4/2	11	-8	136	0.9	0.8	0.6	0	26	17	14	15	82	73	41	24	13	64	10	4	3	2
	185621	4/3	12	-9	310	0.1	0.1	0.0	0	17	7	7	7	25	16	13	8	5	33	15	7	4	3
	185736	5/1	13	-8	---	2.4	1.9	1.2	56	25	14	10	8	38	0	0	0	0	0	0	0	0	0
	185930	5/2	10	-8	114	1.4	0.9	0.7	13	38	23	26	29	100	2	0	0	0	0	0	0	0	0
8/31	185433	3/1	8	-12	---	1.0	0.8	0.6	0	10	6	4	5	13	11	5	5	3	13	0	0	0	0
	185648	3/2	9	-12	135	0.3	0.2	0.1	0	9	5	3	3	0	9	5	4	3	0	4	2	1	0

from a peak of about 30 ℓ^{-1} in one cloud to <6 ℓ^{-1} in 9 clouds. The 19 clouds were found to contain a readily detectable (~1 ℓ^{-1}) quantity of raindrops, but only 6 of the 19 clouds contained raindrops in maximum concentrations exceeding 10 ℓ^{-1}. On second penetrations, however, 10 of the 19 clouds were found to have a maximum raindrop concentration of more than 10 ℓ^{-1}, and seven of those clouds exceeded 20 ℓ^{-1}. On third penetrations, only one of the four clouds contained raindrops in maximum concentrations exceeding 10 ℓ^{-1}.

Fig. 4 shows that 16 of the 19 clouds were completely free of graupel on initial penetration; the remaining three clouds contained a maximum concentration of $\leq$5 ℓ^{-1}. By the time of second penetration, however, 13 of 19 clouds were found to contain some ice in the form of graupel and, of those, nine had maximum concentrations of 5 ℓ^{-1} or more. The highest concentration observed during any second pass was ~50 ℓ^{-1}. Note that the maximum concentration of graupel observed was the same as that of raindrops. By the time of the third penetration, all four clouds contained graupel, with two of the four having maximum concentrations > 10 ℓ^{-1}.

It can be seen from Fig. 5 that, with the exception of one notable case, the maximum concentration of crystalline ice did not exceed 10 ℓ^{-1} during any cloud penetration. In fact, on first penetration, only one of the 19 clouds was observed to contain any crystals and most (13 of 19) failed to have an appreciable (>1 ℓ^{-1}) concentration on the second pass. A maximum concentration of crystals of almost 40 ℓ^{-1} was observed in one cloud nearly 4 min after initial penetration, and it was this tower that also had developed, in the same period, the largest concentration of graupel (Fig. 4) observed in the data set. Of course, all inferences regarding the crystal concentrations are subject to the detection size threshold of the replicator. However, since diffusional growth of columnar crystals to 50 μm occurs rapidly (major axis growth rate of ~1 μm s^{-1}) it is unlikely that large quantities of very small crystals, once produced, can escape eventual detection during a series of repeated penetrations several minutes apart.

Each of Figs. 2–5 includes data from three case study clouds. The cloud on 10 August was penetrated four times in quick succession (at t = 0, 90, 250 and 330 s). At the time of initial penetration the cloud was growing vigorously with its top just above the sampling temperature level of −10°C. Cloud growth slowed appreciably by the time of the second penetration and by the time of the third penetration the tower was in a decaying stage of its life cycle. The fourth penetration was carried out through what the flight notes referred to as cloud "debris." Its maximum cloud water, initially 2.5 g m^{-3}, decreased to 1.6 g m^{-3} on second penetration and then sharply decreased to 0.3 g m^{-3} on third penetration and to 0.1 g m^{-3} on final penetration. The cloud's maximum raindrop concentration, initially 11 ℓ^{-1}, increased to 23 ℓ^{-1} on second penetration but decreased to 15 ℓ^{-1} on third penetration and was <10 ℓ^{-1} by the time of the final penetration. The cloud contained no graupel on either the first or second penetration, but developed some (~6 ℓ^{-1}) by the time of the third penetration. However, no graupel was evident on the final penetration. The cloud failed to develop ice in the form of crystals at any time in its life history during which measurements were made.

The microphysical evolution profile for the cloud tower penetrated three times on 26 August was similar to that of the tower repeatedly penetrated on 10 August in the sense of the marked decrease in JW water from pass to pass and the increase and then decrease in the concentration of splash drops. The ice phase, however, appeared to evolve more quickly in the 26 August case because both graupel and crystals were evident by the time (t = 136 s) of the second penetration. The concentration of crystals remained appreciably high even by the time (t = 310 s) of the third pass. Visually, the 26 August tower appeared to go through the same growth and decay process as the tower on the 10th, and the reason that it was able to develop graupel and crystalline ice in a manner of evolution very different from the previous cloud case is unknown. We suspect that the answer lies with the spatial and temporal evolution of the updraft profile, but no measurements are available in this data set to address this linkage.

The case study cloud that developed on 11 August underwent a microphysical evolution similar to the 10 and 26 August clouds in rainwater generation, but was noticeably different in terms of the other parameters. In this case, the JW cloud water remained essentially unchanged in the interval (164 s) between the first pass and the second, and then decreased considerably by the time (t = 388 s) of the third pass. The occurrence of detectable quantities of ice, both graupel and crystals, was delayed until the JW water had decreased, and appreciable quantities of both kinds of ice were still evident at the time (t = 608 s) of the fourth penetration. The 11 August case tower remained as an identifiable entity more than twice as long as did the 10 August cloud.

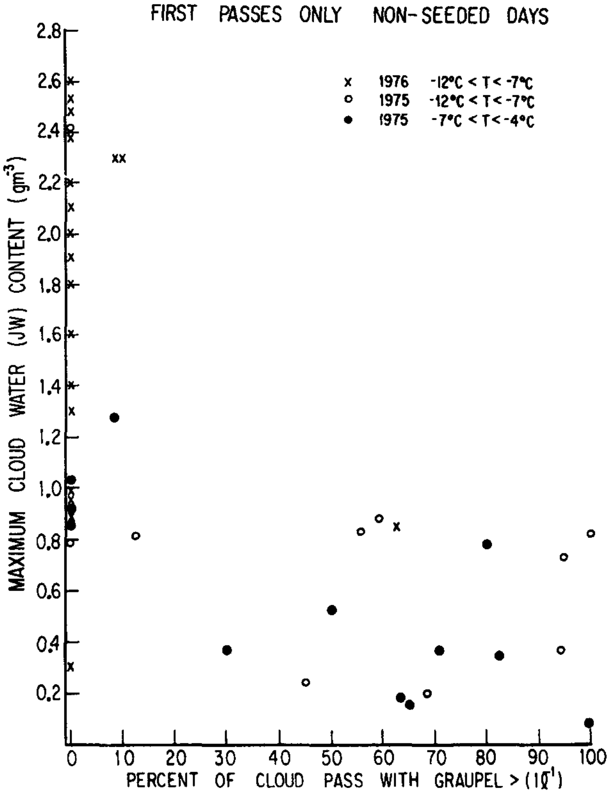

FIG. 6. Relationship between maximum cloud water content and extent of graupel in concentrations > 1 ℓ^{-1} through initial traverses of 19 clouds penetrated by the Navajo in 1976 and 22 clouds penetrated by the NOAA DC-6 in 1975. Note that clouds with the higher water contents are generally graupel-free.

4. Relationship of cloud water to graupel

In Fig. 6, the maximum cloud water content is plotted against the percentage of the tower traverse in which graupel was encountered in concentrations exceeding 1 ℓ^{-1}. Data acquired during initial cloud penetrations from both the DC-6 (in 1975) and the Navajo (in 1976) are presented. It can be seen that the towers that have graupel distributed internally throughout large regions (>20% of the traverse) also contain rather low amounts (<1.0 g m^{-3}) of cloud water. Without exception, all towers with maximum water content exceeding 1.0 g m^{-3} have no more than 10% of the traverse with graupel concentration > 1 ℓ^{-1}. In most cases (14 of 17), towers with maximum water content exceeding 1.0 g m^{-3} contain no graupel at all. The presence or absence of graupel in clouds penetrated by the DC-6 in 1975 does not appear to be temperature dependent in the range −4 to −12°C, although the sample in both temperature ranges is rather small.

It can be seen from Fig. 6 that the clouds penetrated in 1976 by the Navajo aircraft contain, as a group, far less graupel on initial penetration than did those penetrated by the DC-6 in 1975. Only five of

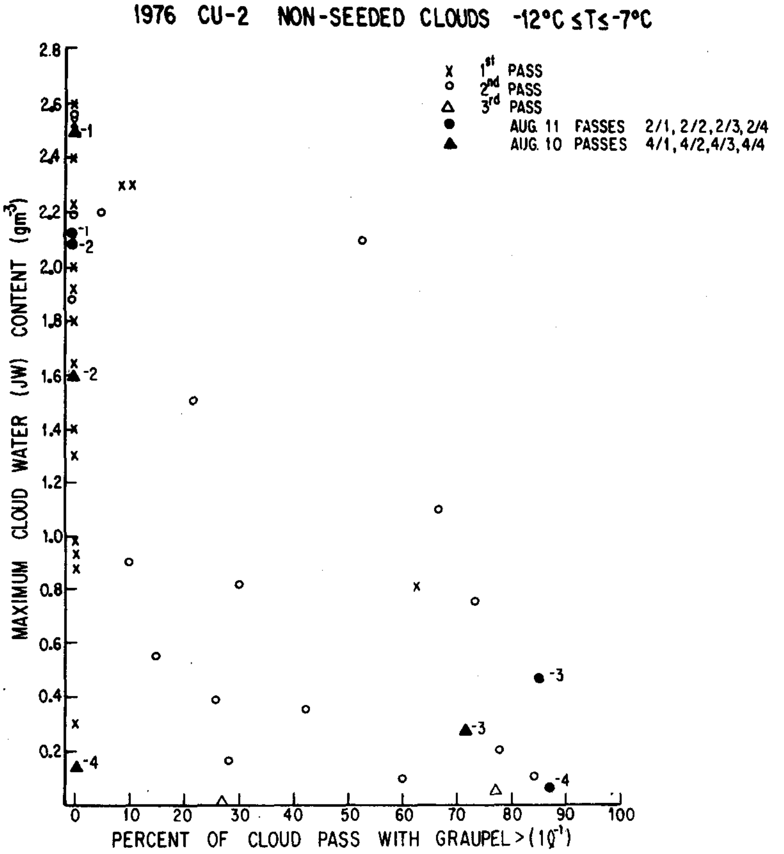

FIG. 7. Relationship between maximum cloud water content and extent of graupel in concentrations > 1 ℓ^{-1} through initial and repeated traverses of clouds sampled by the Navajo in 1976. Note that the highest frequency of graupel encountered is generally associated with the lower maximum water contents, although there are cases of clouds with low water contents which do not contain much graupel.

22 clouds were completely free of graupel on initial penetration in the 1975 (DC-6) data set. This contrasts with 16 of 19 clouds free of graupel on initial penetration in the 1976 data set. The clouds in 1976, as a group, also were found to contain much higher maximum cloud water contents relative to their 1975 counterparts penetrated by the DC-6. We believe these differences are related mainly to visibility and maneuverability characteristics of the two aircraft. In the smaller and more maneuverable Navajo it was possible to select and penetrate growing towers more quickly than in the DC-6. As discussed by Sax *et al.* (1979), differences in instrumentation response characteristics and exposure may also have contributed to the rather large dichotomy of water contents between the two years shown in Fig. 6.

The evolution of the cloud water-graupel relationship during a series of repeat penetrations is shown in Fig. 7. This analysis includes only clouds sampled from the Navajo in 1976. It can be seen that, although the presence of graupel on initial penetration is a rare event (occurring in only three of 19 clouds), the likelihood of encountering graupel through a substantial portion of the cloud on a second penetration is considerable. Only five of 19 clouds penetrated for the second time were found to be essentially graupel free, while six of the clouds were found to contain graupel in concentrations exceeding 1 ℓ^{-1} over at least 50% of the traverse. Maximum cloud water contents on second passes were found to be much reduced, as a group, over those encountered on initial penetration. Although 14 of 19 clouds penetrated initially contained maximum water contents > 1.0 g m^{-3}, only 9 of the 19 did so on the second penetration. Only four clouds were penetrated a third time, and it can be seen that in all cases the water content was very low (<0.5 g m^{-3}). The percentage of the traverses with graupel >1 ℓ^{-1}, however, varied between 25 and 90%. These clouds were dissipating rapidly and graupel was precipitating out. Of the two clouds penetrated a fourth time, one contained no graupel and the other contained graupel in concentrations exceeding 1 ℓ^{-1} over nearly 90% of its traversed region.

The solid triangles and circles in Fig. 7 depict two case studies of clouds that were penetrated four times. The number beside each of these data points indicates the pass sequence. The cloud on 11 August (solid circle) shows no graupel, but almost identical amounts of maximum cloud water on the first two passes followed by a combination of marked water decrease and graupel increase on its third penetration and a continuing decline in water content (but not in percentage of traverse with graupel) on its final penetration. The cloud penetrated on 10 August (solid triangle) also showed no graupel on the first two passes, followed by a substantial spread of graupel through the cloud in conjunction with a decrease in water content on the third pass. A dramatic reduction in graupel was evident on the final pass.

5. Relevance of the observational data to an ice multiplication hypothesis

One of the main features that emerges from studies of the microphysical characteristics of Florida cumuli is the rapidity with which towers can advance through their life cycle. A vigorously growing, sharply defined, "boiling" cloud element containing an abundant quantity of supercooled water near the −10°C level can change, within the span of 3–5 min, to a collapsing, wispy appearing, diffuse precipitating mass with hardly any supercooled water remaining in the form of cloud droplets. This is of particular importance to cumulus modification research attempts (such as FACE) because of its direct bearing on the time window of microphysical suitability for application of a dynamic seeding technique.

The present study provides evidence that cumulus clouds in Florida undergo a sequential microphysical evolution in which, at the −10°C sampling level near the tops of towers which fail to grow substantially, cloud water diminishes as splash drop and graupel concentrations increase, and, toward the end of the life cycle, crystalline ice begins to appear in concentrations large enough to be detected. These observational data are consistent with the conceptual hypothesis advanced by Hallett *et al.* (1978), which shows that, at a sampling level above the generation zone, a readily detectable manifestation of the Hallett-Mossop (1974) multiplication mechanism working in deep convective clouds with an abundance of large drops would be a rapid proliferation of ice in the form of graupel. Detection of crystalline ice particles, on the other hand, would be strongly dependent on the rate at which they were swept up by the larger cloud drops and the changing character of the draft structure in which they were imbedded.

The role of the time history of the updraft profile on the detection of graupel and crystals at a given temperature level (e.g., −10°C) cannot be overemphasized. Very strong updrafts through a large region of the cloud envelope would be detrimental to an effective secondary ice production mechanism, because a downward flux of graupel through the generation zone would be prohibited. Therefore, ice would not be detected at −10°C because it cannot be produced at lower levels. On the other hand, in the latter stages of cloud development, as the updraft and water content decrease markedly, the upward flux through −10°C of graupel produced at warmer temperatures would be curtailed and the graupel concentration detected at that level would cease to increase and, as the cloud continued to precipitate, begin to decrease (as in the 10 August case study in Fig. 7).

The presence of large cloud drops is of vital importance to the rapid production of graupel, both in the initiation and in the sustenance of the ice multiplication process. Unless entrainment or recycling of ice particles from neighboring cloud debris occurs, the formation of initial graupel, the so-called "proto ice," which is necessary to produce, as a byproduct of accretion, the first crystals, must necessarily result from the freezing (by a currently unspecified means) of drops large enough to begin riming efficiently almost immediately. If small cloud droplets are frozen, the time necessary for them to grow by diffusion to a size large enough to rime effectively would delay subsequent multiplication of graupel well beyond the time scales observed. Therefore, in new growing towers isolated from old cloud debris, the presence of an appreciable concentration of large drops must precede the buildup of high concentrations of graupel, a deduction in line with the observations presented here.

6. Summary and conclusions

Specially instrumented aircraft have been used to penetrate cumulus towers close to their tops near the −10°C isotherm level. Measurements of vertical wind and cloud water were obtained from initial NOAA C-130 penetrations of 35 clouds in 1975 and from NOAA DC-6 penetrations of 22 clouds also in 1975. Considerable scatter was found to exist between maximum values of Johnson-Williams (JW) cloud water and maximum values of vertical velocity. We offer the suggestion that pulsations in the updraft may help explain some of the scatter and conclude that the measurement of JW cloud water *by itself* can be misleading with respect to the tower's growth activity at the time of penetration.

A group of 19 clouds was penetrated at least twice by a Piper Navajo aircraft in 1976 and measurements of cloud water, rainwater, graupel and crystalline ice were obtained. Reliable vertical velocity data were not obtained during these cloud penetrations. As a group, the clouds sampled by the Navajo in 1976 contained more cloud water and much less graupel than did those sampled by the DC-6 in 1975. We interpret this to mean that the clouds in 1976 were, as a group, sampled earlier in their lifetime than were those in 1975 with the DC-6.

The main thrust of this work is that there appears to be a progressive sequence of cloud water, rainwater, graupel and crystalline ice detected near the $-10°C$ level in clouds sampled near their tops during 1976. We suggest that this is consistent with the concepts of Hallet *et al.* (1978), who hypothesize that proliferation of ice in the form of graupel would be a readily detectable manifestation of an ice multiplication mechanism that relies upon the sweep-up of crystals by large drops to produce rapid glaciation.

The variability in the decay of the JW cloud water mass observed from one cloud to another is undoubtedly related to the detailed structure of the updraft and the manner in which mixing of drier ambient air is occurring near the top of the cloud envelope. The three case studies presented demonstrate the variabilities encountered in the evolutionary sequence of the four parameters. In two of the cases the decrease in cloud water was evident by the time of the second penetration ($\Delta t \sim 2$ min), while in the third case the cloud water did not decrease until sometime after the second penetration carried out ~3 min following the first. The occurrence of graupel was a rare event on initial penetrations where peak cloud water contents were high. In most cases, the onset of a rapid increase in graupel appears coincident with the marked decline in the JW water mass. The graupel concentration appears to be somewhat associated with the concentration of splash drops $\geqslant 300$ μm diameter, although not all clouds with splash drops present on initial pass develop graupel on the second pass.

REFERENCES

Hallett, J., and S. C. Mossop, 1974: Production of secondary ice particles during the riming process. *Nature*, **249**, 26–28.

——, R. I. Sax, D. Lamb and A. S. R. Murty, 1978: Aircraft measurements of ice in Florida cumuli. *Quart. J. Roy. Meteor. Soc.*, **104**, 631–651.

MacCready, P. B., Jr., and C. J. Todd, 1964: Continuous particle sampler. *J. Appl. Meteor.*, **3**, 450–460.

Ruskin, R. E., and W. D. Scott, 1974: Weather modification instruments and their use. *Weather and Climate Modification*, W. N. Hess, Ed., Wiley, 842 pp. (see pp. 136–205).

Sax, R. I., J. Thomas, M. Bonebrake and J. Hallett, 1979: Ice evolution within seeded and nonseeded Florida cumuli. *J. Appl. Meteor.*, **18**, 203–214.