Ice Evolution within Seeded and Nonseeded Florida Cumuli

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ABSTRACT

From in-cloud microphysical data collected during the Florida Area Cumulus Experiment (FACE), evidence is presented documenting the presence of significantly greater quantities of crystalline ice near the −10°C sampling level in convective towers previously seeded with AgI pyrotechnics compared to those growing naturally under similar environmental conditions. This finding helps to verify the first link in the dynamical seeding hypothesis—the conversion of supercooled water to ice. Evidence is also presented to show the development of significantly greater concentrations of crystalline ice in clouds seeded during 1976 compared to clouds seeded during 1975. It is suggested that, although some changes in experimental resources and sampling procedures took place between the two years, the observed differences in the evolution of ice crystal concentration were, to a large extent, related to a switch in the type of flare used in seeding. It is contended that a physical basis therefore exists for partitioning of the FACE rainfall results.as a function of flare type useage.

The evolution of cloud water and ice in the form of graupel is also discussed in the framework of delineating differences between groupings of data based on a four-way (1975 seed, 1975 no-seed, 1976 seed and 1976 no-seed) partitioning scheme.

1. Introduction

NOAA's Florida Area Cumulus Experiment (FACE) has been designed to evaluate the effects of dynamic seeding on convective organization and rainfall over a 13 000 km^2 target area within south Florida. A detailed discussion of dynamic seeding theory and the design and procedures utilized in the FACE program has been provided by Woodley and Sax (1976). The experiment, initiated in 1970, has consistently involved the release of pyrotechnically generated silver iodide (AgI) as an ice-phase nucleant and the use of aircraft for the delivery of the nucleant directly into the supercooled active cloud regions.

Woodley *et al.* (1978) have discussed the rainfall results from FACE and have provided some evidence for an enhancement of seeding effect during the period (after July 1975) in which a pyrotechnic manufactured by Nuclei Engineering, Inc. (NEI)[1] was predominantly used. Sax *et al.* (1979) have discussed the characteristics of the pyrotechnics used throughout the FACE program and have shown from cold chamber tests that the AgI nucleant emitted by the NEI flare appears to be several orders of magnitude more effective at warm (> −10°C) temperatures than that emitted by a flare manufactured by Olin-Mathieson Corporation (Olin), which was used almost exclusively before August 1975. This very large difference in nucleating effectiveness could be expected to manifest itself in the glaciating behavior of clouds seeded with the two types of flares if the cold chamber tests are at all representative of processes occurring in the atmosphere.

This paper treats a series of microphysical observations obtained from repenetrations of seeded and nonseeded Florida cumuli during the summers of 1975 and 1976. The microphysical data were collected by means of specialized instrumentation mounted onboard the seeding aircraft. The 1975 seeded cloud data were collected during July, when mainly Olin flares were expended, while the 1976 seeded cloud data were obtained during a period when only NEI flares were released from the sampling aircraft. A complicating factor is the use in FACE 1975 of a pyrotechnic manufactured to U.S. Navy specifications. This flare contains the same TB-1 chemical formulation as that of NEI, but has been found, from cold chamber tests, to be about an order of magnitude less effective at tempera-

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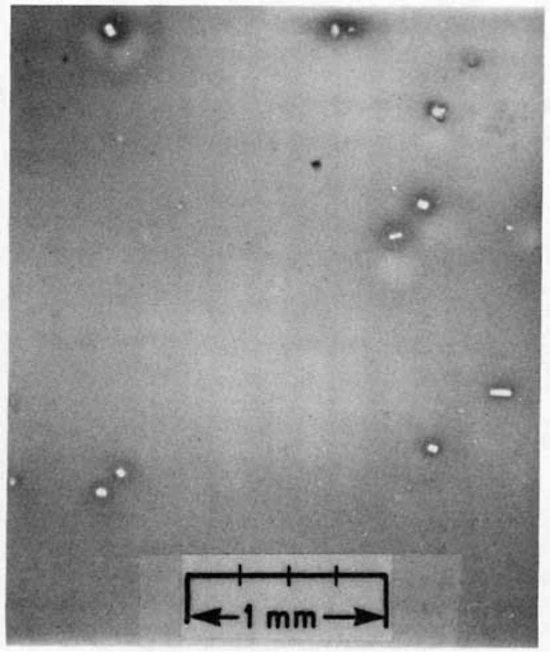

FIG. 1. Section of one frame (~10 cm^3 volume) of Formvar film collected from a seeded cloud during FACE 76; ice crystals in the form of unrimed columns with various aspect ratios can be readily distinguished; columns shown here are all smaller than 100 μm along the major axis.

tures warmer than −10°C (Sax *et al.*, 1979). The Navy pyrotechnic was expended during July 1975 in a ratio of about 1:2 with the Olin flare and was randomly, but homogeneously, mixed throughout the firing rack.

2. Data collection and analysis

During the 1975 field program, collection of in-cloud microphysical data was accomplished by means of the NOAA DC-6 aircraft which was equipped with, among other instrumentation, a Formvar replicator of the DRI design (Hallett, 1976), a Lyman-alpha total water evaporator (Ruskin and Scott, 1974), a Johnson-Williams (JW) heated wire for the measurement of cloud water content, and a foil impactor device for the determination of precipitation particle spectra. Air vertical velocities on the scale of 100 m were determined from a combination of aircraft pitch, angle of attack and integrated radar altimeter data.

The aircraft employed to obtain in-cloud microphysical data during the FACE 1976 field program was a twin-engine pressurized Piper Navajo which, because of weight restrictions, contractural time and cost limitations, and program priorities, could be equipped only minimally for cloud physics research purposes. Nevertheless, to insure compatibility with certain key observations that were obtained during the previous year and that relate to the evolution of cloud microstructure as a function of seeding, considerable effort was expended in instrumenting the aircraft with the same DRI Formvar replicator as had been used in the DC-6.[2] The aircraft was also instrumented with a JW cloud water sensor and a Ball variometer, which is highly sensitive to changes in aircraft vertical motion. Unfortunately, the aircraft vertical motion data were found to be an unreliable indicator of air vertical velocity because of the inability to objectively account for pilot influence on the response of the aircraft to cloud updrafts. The JW and Formvar data, however, represent an important set of observations with which to intercompare the partitioning and evolution of cloud water and ice within convective towers penetrated during the two program years.

An intercomparison of the evolution of the water and ice budgets at the sampling level (generally −5 to −10°C) in clouds penetrated during both years must be made with the reservation that aircraft maneuverability during FACE 1976 greatly exceeded that available in FACE 1975, thus permitting a much shorter time interval between initial and subsequent penetrations of the same cloud.

At the cloud penetration airspeeds of the DC-6 and the Navajo, the sampling volume for the DRI Formvar replicator is about 1 ℓ s^{-1}. The film from the Formvar replicator was carefully analyzed on a frame-by-frame (resolution ~0.02 s) basis for the presence of vapor-grown crystalline ice and graupel. The crystals usually appeared in the form of columns, as shown in Fig. 1, although platelike structure was also evidenced on many occasions. There was a consistent attempt to be conservative in the ice analysis, and any small irregular-shaped fragments[3] were not counted as either crystals or graupel. Crystal lengths were typically less than 300 μm along the major axis, and in instances where extremely large concentrations of crystals appeared (as in some portions of seeded clouds) most were smaller than 100 μm. In general, the crystals recognizable as such were rimed only lightly—if at all. As would be expected, graupel particles appeared to vary greatly in degree of riming, ranging from what appeared to be sharp-edged agglomerates of ice in regions of cloud with little water to a very dense, slushy mass in regions of cloud with high water content.

For the purpose of this study, only data obtained in clouds which were penetrated two or more times have been analyzed. Care was taken to insure that only repeated passes through the same tower penetrated previously were included for analysis. Flight logs, voice tapes, navigation data and nose camera photography were used to document the positioning of the

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[2] The replicator arm on the Navajo was positioned about 1 m aft of the nose tip, while its location on the DC-6 in 1975 was just aft the entry door, about 6 m from the nose tip; in both cases the sampling slit was about 50 cm beyond the aircraft skin.

[3] Such small irregular fragments were often found on the Formvar film in conjunction with graupel and were the result of graupel breakup on impact with either the replicator arm slit or the film substrate.

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aircraft relative to each cloud tower. In cases with data collected during 1976 where the first pass was over the top of a cloud which subsequently grew through the sampling level, it has been assumed that the cloud contained no substantial quantity of ice initially. This assumption is based on data presented later in the text (Tables 3 and 4) showing that in initial passes through 27 clouds sampled in 1976, the concentration of graupel was found to exceed 10 ℓ^{-1} only three times while the concentration of crystals exceeded 10 ℓ^{-1} only once. Of the 27 clouds penetrated (10 seeded and 17 not seeded), 18 were found to have no detectable graupel initially while 23 were found to be completely devoid of crystals. The four seeded and three nonseeded towers which were penetrated over the top initially all displayed a sharply defined cauliflower appearance and were all growing vigorously just below the aircraft flight level.

3. Evolution of ice as a function of seeding

Tables 1 and 2, respectively, show microphysical data obtained from a series of 11 nonseeded[4] and 9 seeded clouds which were penetrated two or more times during the FACE 1975 program. The evolution of crystal concentration in each group of cloud passes is of particular interest, since diffusional growth of ice might reasonably be expected to occur following nucleation of the small cloud droplets. It can be seen from Table 1 that in none of the unseeded clouds in 1975 was a concentration of vapor-grown ice in excess of 50 ℓ^{-1} observed. In the seeded cloud group, however, it can be seen that in three second passes the concentration of crystals exceeded 50 ℓ^{-1} for a substantial (25–35%) portion of the traverse. The highest mean concentration in the no-seed group was 5 ℓ^{-1}, while in the seed category the mean concentration of crystalline ice equaled or exceeded 10 ℓ^{-1} during 5 repeat passes. Although second penetrations through seeded clouds failed to show a substantial increase in crystals on only 3 of 9 occasions, second penetrations through unseeded clouds failed to show such an increase on 9 of 11 occasions. The time intervals between initial and second passes within each group were, with one exception (7/31), similar and averaged about 5 min. The majority of penetrations in the no-seed group were carried out in the temperature range −6 to −8°C, while those in the seeded group were carried out mostly between −8 and −10°C. The bias toward warmer temperatures may, at least partially, account for the detection of fewer crystals in the no-seed group.

It can be seen from Tables 1 and 2 that both the nonseeded and seeded clouds in the 1975 group contained, during some portion of their life history, large amounts (in some instances approaching or exceeding 50 ℓ^{-1}) of ice particles in the form of graupel. This type of ice could result from the direct nucleation of raindrops (by ice-forming nuclei), the scavenging of small crystals by large drops with subsequent freezing, or the growth of crystals through the diffusion process to a size large enough to accrete cloud droplets. The concentration of raindrops at the −10°C level is found to be of order 10 ℓ^{-1} in the types of clouds typically sampled in the summertime Florida environment (Hallett *et al.*, 1978), but a direct nucleation process by itself cannot likely account for the large amount of graupel encountered in some clouds because of a scarcity of ice-forming nuclei active at such warm temperatures. Hallett *et al.* (1978) have shown that large concentrations of graupel can develop rapidly under certain prescribed conditions in dissipating convective clouds of moderate water contents through a mechanism of secondary production of crystals followed by a scavenging/accretion process. Diffusional growth of a crystal to an ice particle large enough for riming to occur is generally a much slower process than that of the scavenging of the crystal by a large cloud drop; it is difficult to explain rapid increases in graupel by such a diffusional growth mechanism in clouds of short lifetimes without invoking a complex set of assumptions relating to recycling of particles during the dynamical history of the cloud.

The seeded clouds, as a group, appear to contain more graupel, but the distinction is not as marked as with the crystalline ice data. During the total sampling interval, the mean concentration of graupel increased by more than 5 ℓ^{-1} in 6 of the 9 seeded clouds, but it did so to that extent only in 3 of the 11 nonseeded clouds. The peak concentration of graupel increased by more than 40 ℓ^{-1} in 3 of the 9 seeded clouds, while the largest increase in maximum graupel concentration in the 1975 nonseeded cloud group was 37 ℓ^{-1}. It is well to point out that the production of graupel represents a much greater source of heat for dynamic seeding effects than does the conversion of a relatively small fraction (<1%) of the supercooled cloud water droplets to ice crystals.

Tables 3 and 4 show microphysical data obtained, respectively, from a series of 21 nonseeded and 14 seeded clouds which were penetrated successively two or more times during the FACE 1976 program. The interval between initial and second passes in each group averaged slightly more than 2 min. Both groups of clouds were sampled mainly in the temperature range −8 to −11°C. There is a very marked difference in crystal concentration between the seed and no-seed groups as reflected in the maximum, mean and median values, and in the percentage of the traverse in which crystal concentration exceeded 50 ℓ^{-1}. For example, on six different second passes in the seed group, the maximum concentration of crystals was found to exceed 100 ℓ^{-1}. In contrast, the maximum concentration of crystals ever detected in the no-seed group was 57 ℓ^{-1}. The percentage of the traverse in which the concentra-

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[4] The "flares" column in Tables 1 and 3 indicates the number of times the ejector switch was activated, although on no-seed days, of course, AgI pyrotechnics were not actually released.

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TABLE 1. Microphysical statistics for unseeded clouds penetrated at least twice during FACE 75.

							JW water			Nonseeded clouds—1975							
										Graupel				Crystals			
Date	Time (GMT)	Pass ID	Duration (s)	Temperature (°C)	Number of flares	Δt (s)	Max (g m^{-3})	Mean (g m^{-3})	>1.0 g m^{-3} (%)	Max (ℓ^{-1})	Mean (ℓ^{-1})	Med (ℓ^{-1})	$\geq 10\ \ell^{-1}$ (%)	Max (ℓ^{-1})	Mean (ℓ^{-1})	Med (ℓ^{-1})	$\geq 50\ \ell^{-1}$ (%)
7/17	184025	A/1	17	−5	0	—	0.4	0.3	0	5	2	1	0	0	0	0	0
	184421	A/2	17	−5	0	236	0.3	0.1	0	5	2	2	0	0	0	0	0
	184738	B/1	22	−6	0	—	1.6	0.9	58	3	0	0	0	0	0	0	0
	185111	B/2	26	−5	0	211	1.5	1.0	68	6	1	0	0	2	0	0	0
	185535	B/3	26	−5	0	477	0.8	0.2	0	15	4	3	8	0	0	0	0
7/18	181401	C/1	11	−6	0	—	1.1	0.8	9	1	0	0	0	0	0	0	0
	181818	C/2	16	−6	0	257	0.9	0.3	0	38	16	18	65	0	0	0	0
7/20	190111	G/1	34	−9	0	—	0.1	0.1	0	48	18	16	85	5	0	0	0
	190650	G/2	50	−9	0	339	0.2	0.1	0	28	14	14	67	0	0	0	0
7/21	181923	D/1	9	−6	0	—	0.9	0.4	0	4	2	2	0	0	0	0	0
	182517	D/2	21	−6	0	354	0.8	0.5	0	17	5	5	4	0	0	0	0
	183100	D/3	21	−6	3	637	0.3	0.1	0	13	5	5	23	8	1	0	0
	183721	E/1	50	−6	0	—	0.6	0.2	0	12	5	6	8	0	0	0	0
	184359	E/2	47	−5	0	398	0.4	0.2	0	15	5	4	6	46	1	0	0
	185526	E/3	25	−5	0	1085	N/A	N/A	N/A	36	15	12	72	0	0	0	0
7/22	185349	B/1	13	−5	0	—	1.0	0.6	15	1	0	0	0	0	0	0	0
	185902	B/2	11	−5	0	313	0.1	0.0	0	6	4	3	0	0	0	0	0
	190529	C/1	16	−5	0	—	1.3	0.8	50	1	0	0	0	0	0	0	0
	190928	C/2	22	−5	0	239	1.6	1.1	63	10	4	3	5	0	0	0	0
7/27	195034	F/1	23	−8	0	—	0.4	0.2	0	43	20	20	80	37	4	0	0
	195544	F/2	10	−7	0	310	0.1	0.1	0	33	16	21	62	20	5	4	0
	204239	K/1	38	−8	0	—	0.3	0.2	0	23	8	6	32	11	0	0	0
	204825	K/2	52	−8	0	346	0.4	0.1	0	30	16	17	76	13	3	1	0
7/31	174410	C/1	23	−5	0	—	0.2	0.1	0	10	4	5	4	0	0	0	0
	175726	C/3	55	−5	0	796	0.2	0.1	0	13	6	5	10	16	1	0	0

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Table 2. Microphysical statistics for seeded clouds penetrated at least twice during FACE 75.

							JW water			Seeded clouds—1975							
										Graupel				Crystals			
Date	Time (GMT)	Pass ID	Duration (s)	Temperature (°C)	Number of flares	Δt (s)	Max (g m^{-3})	Mean (g m^{-3})	>1.0 g m^{-3} (%)	Max (ℓ^{-1})	Mean (ℓ^{-1})	Med (ℓ^{-1})	$\geqslant 10\ \ell^{-1}$ (%)	Max (ℓ^{-1})	Mean (ℓ^{-1})	Med (ℓ^{-1})	$\geqslant 50\ \ell^{-1}$ (%)
7/20	192205	W/1	20	−9	1	—	0.2	0.1	0	11	7	7	10	6	1	0	0
	192706	W/2	32	−9	0	301	0.1	0.1	0	54	16	14	78	43	20	0	0
	203953	Y/1	21	−9	3	—	0.9	0.2	0	17	5	5	14	0	0	0	0
	204509	Y/2	54	−9	0	316	0.1	0.0	0	32	16	16	75	0	0	0	0
7/22	195418	W/1	37	−9	9	—	1.0	0.6	0	23	9	9	49	0	0	0	0
	200023	W/2	52	−9	0	365	0.4	0.1	0	13	8	8	25	28	1	0	0
7/23	183341	E/1	16	−10	7	—	1.3	0.8	38	8	4	3	0	2	0	0	0
	183904	E/2	11	−9	0	324	0.4	0.1	0	3	1	0	0	8	1	0	0
	184053	W/1	15	−8	5	—	1.6	0.9	60	25	7	7	31	0	0	0	0
	184745	W/2	11	−8	0	412	0.0	0.0	0	33	20	19	80	0	0	0	0
	185431	X/1	16	−9	5	—	1.1	0.6	25	32	22	27	88	12	2	0	0
	190021	X/2	18	−8	0	350	0.0	0.0	0	34	26	33	85	113	22	0	25
	193504	G/1	17	−8	9	—	1.4	0.9	29	27	13	16	67	37	11	12	0
	194039	G/2	20	−8	0	335	0.4	0.1	0	35	24	24	100	130	45	27	36
	194601	G/3	16	−8	0	657	0.1	0.0	0	33	16	13	62	82	12	3	8
	202848	Y/1	27	−10	2	—	1.1	0.4	15	20	9	8	42	8	1	0	0
	203432	Y/2	15	−8	0	344	0.0	0.0	0	95	42	43	88	48	10	2	0
7/27	215344	P/1	19	−8	9	—	0.8	0.5	0	29	13	11	68	2	0	0	0
	215925	P/2	24	−7	2	341	0.5	0.4	0	77	37	33	100	118	44	37	23

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TABLE 3. Microphysical statistics for unseeded clouds penetrated at least twice during FACE 76.

							JW water			Non-seeded clouds—1976							
										Graupel				Crystals			
Date	Time (GMT)	Pass (ID)	Duration (s)	Temperature (°C)	Number of flares	Δt (s)	Max (g m^{-3})	Mean (g m^{-3})	>1.0 g m^{-3} (%)	Max (ℓ^{-1})	Mean (ℓ^{-1})	Med (ℓ^{-1})	$\geq 10\ \ell^{-1}$ (%)	Max (ℓ^{-1})	Mean (ℓ^{-1})	Med (ℓ^{-1})	$\geq 50\ \ell^{-1}$ (%)
6/27	185152	4/1	4	−7	0	—	2.6	2.2	100	0	0	0	0	0	0	0	0
	185406	4/2	13	−7	0	134	2.7	2.1	100	0	0	0	0	0	0	0	0
6/30	181722	6/1	13	−8	4	—	1.0	0.4	0	Data not available							
	181949	6/2	35	−8		147	0.6	0.3	0	1	0	0	0	1	0	0	0
	184135	10/1	—	—	2	—	Over cloud top			No penetration							
	184257	10/2	5	−8	0	82	0.6	0.2	0	0	0	0	0	0	0	0	0
	184454	10/3	26	−8	0	199	0.4	0.0	0	19	2	0	8	2	0	0	0
	184926	11/1	—	—	2	—	Over cloud top			No penetration							
	185221	11/2	28	−8	5	175	0.8	0.4	0	44	12	5	39	2	0	0	0
	220820	21/1	6	−8	10	—	1.7	0.7	43	0	0	0	0	0	0	0	0
	221008	21/2	16	−8	3	108	2.1	1.4	76	1	0	0	0	0	0	0	0
	224738	26/1	11	−8	3	—	1.9	0.8	36	0	0	0	0	0	0	0	0
	224944	26/2	12	−8	1	126	0.5	0.3	0	15	4	1	25	5	1	0	0
7/06	182020	3/1	—	—	2	—	Over cloud top			No penetration							
	182208	3/2	4	−10	2	108	1.5	0.8	33	0	0	0	0	0	0	0	0
	182550	3/3	38	−11	0	330	0.1	0.1	0	86	28	18	66	57	22	23	5
7/07	194105	5/1	13	−11	0	—	2.9	1.9	83	0	0	0	0	0	0	0	0
	194332	5/2	34	−11	0	147	2.8	1.1	40	25	4	2	21	0	0	0	0
7/18	190439	3/1	12	−10	4	—	2.7	1.7	82	3	1	0	0	0	0	0	0
	190625	3/2	15	−10	0	106	1.5	0.6	10	19	4	3	7	0	0	0	0
	202145	14/1	11	−11	1	—	1.8	0.8	35	0	0	0	0	0	0	0	0
	202409	14/2	7	−11	0	144	0.9	0.4	0	2	1	0	0	1	0	0	0
7/20	205253	3/1	11	−8	6	—	3.0	2.1	86	0	0	0	0	0	0	0	0
	205454	3/2	19	−10	2	121	2.6	1.3	54	3	0	0	0	0	0	0	0

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TABLE 3.—(*Continued*)

							Non-seeded clouds—1976											
							JW water			Graupel				Crystals				
Date	Time (GMT)	Pass ID	Duration (s)	Temperature (°C)	Number of flares	Δt (s)	Max $(g\ m^{-3})$	Mean $(g\ m^{-3})$	>1.0 $g\ m^{-3}$ (%)	Max (ℓ^{-1})	Mean (ℓ^{-1})	Med (ℓ^{-1})	$\geqslant 10\ \ell^{-1}$ (%)	Max (ℓ^{-1})	Mean (ℓ^{-1})	Med (ℓ^{-1})	$\geqslant 50\ \ell^{-1}$ (%)
8/10	200724	4/1	9	−10	0	—	2.7	1.4	58	0	0	0	0	0	0	0	0
	200858	4/2	18	−10	0	94	2.0	1.1	67	1	0	0	0	0	0	0	0
	201129	4/3	7	−10	0	245	0.6	0.3	0	11	5	3	29	1	0	0	0
	201250	4/4	5	−10	0	326	0.3	0.1	0	1	0	0	0	0	0	0	0
8/11	183618	2/1	28	−8	5	—	2.8	1.8	78	0	0	0	0	0	0	0	0
	183902	2/2	51	−9	0	164	2.3	1.1	59	0	0	0	0	0	0	0	0
	184246	2/3	54	−10	0	388	0.6	0.3	0	33	7	5	20	8	0	0	0
	184626	2/4	43	−10	0	608	0.1	0.0	0	30	9	7	40	36	3	0	0
	191845	4/2	11	−9	0	—	1.5	1.0	73	1	0	0	0	12	2	0	0
	192157	4/3	39	−10	0	192	0.5	0.2	0	10	1	0	3	7	0	0	0
	192513	5/1	6	−9	0	—	2.3	1.2	60	0	0	0	0	0	0	0	0
	192706	5/2	19	−9	0	113	1.9	1.0	46	13	2	0	5	1	0	0	0
8/15	185214	1/1	17	−8	0	—	2.3	1.5	88	0	0	0	0	0	0	0	0
	185512	1/2	20	−9	0	178	1.0	0.5	0	6	1	0	0	24	2	0	0
	185833	1/3	15	−9	0	379	0.0	0.0	0	5	1	0	0	6	2	0	0
	194154	5/1	18	−8	11	—	2.5	1.7	80	0	0	0	0	0	0	0	0
	194415	5/2	27	−8	8	141	2.3	1.6	85	0	0	0	0	0	0	0	0
8/22	202046	3/1	14	−8	0	—	3.0	2.0	90	0	0	0	0	0	0	0	0
	202402	3/2	14	−8	0	196	0.1	0.0	0	13	4	2	7	0	0	0	0
8/26	185111	4/1	10	−7	4	—	2.7	2.0	80	4	1	0	0	1	0	0	0
	185327	4/2	11	−8	0	136	0.9	0.6	0	73	24	13	64	10	3	2	0
	185621	4/3	12	−9	0	310	0.1	0.0	0	16	8	5	33	15	4	3	0
	185736	5/1	13	−8	0	—	2.4	1.2	56	0	0	0	0	0	0	0	0
	185930	5/2	10	−8	0	114	1.4	0.7	13	2	0	0	0	0	0	0	0
8/31	185433	3/1	8	−12	0	—	1.0	0.6	0	11	5	3	13	0	0	0	0
	185648	3/2	9	−12	0	135	0.3	0.1	0	9	4	3	0	4	1	0	0

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TABLE 4. Microphysical statistics for seeded clouds penetrated at least twice during FACE 76.

							Seeded clouds—1976											
							JW water			Graupel				Crystals				
Date	Time (GMT)	Pass ID	Duration (s)	Temperature (°C)	Number of flares	Δt (s)	Max (g m^{-3})	Mean (g m^{-3})	>1.0 g m^{-3} (%)	Max (ℓ^{-1})	Mean (ℓ^{-1})	Med (ℓ^{-1})	$\geqslant 10\ \ell^{-1}$ (%)	Max (ℓ^{-1})	Mean (ℓ^{-1})	Med (ℓ^{-1})	$\geqslant 50\ \ell^{-1}$ (%)
6/28	200153	11/1	14	−8	2	—	2.8	1.3	64	0	0	0	0	0	0	0	0
	200412	11/2	31	−8	2	139	2.9	2.3	94	1	0	0	0	0	0	0	0
	200719	11/3	30	−8	3	326	2.3	1.0	57	29	5	4	17	9	1	0	0
	201008	11/4	20	−8	0	495	0.6	0.3	0	32	14	10	50	92	35	37	30
7/14	184322	3/1	10	−10	4	—	1.6	1.0	57	0	0	0	0	0	0	0	0
	184548	3/2	15	−11	0	146	0.3	0.1	0	20	5	1	27	1	0	0	0
	185147	3/3	22	−11	0	505	0.1	0.0	0	43	16	13	64	69	18	15	9
	185716	3/4	9	−11	1	—	1.6	0.8	39	1	0	0	0	0	0	0	0
	185921	3/5	13	−11	0	125	0.6	0.1	0	27	5	1	23	1	0	0	0
7/19	195212	6/1	—	—	2	—	Over cloud top				No penetration						
	195548	6/2	19	−11	0	216	1.7	0.6	19	115	25	12	53	1483	462	288	74
7/21	190628	2/1	2	−12	5	—	2.1	0.9	25	0	0	0	0	0	0	0	0
	190746	2/2	12	−11	5	78	2.9	2.0	82	1	0	0	0	1216	113	0	17
	191002	2/3	22	−11	2	214	2.7	1.5	63	125	24	9	50	987	235	24	41
	193403	7/1	15	−11	7	—	2.8	2.1	84	0	0	0	0	0	0	0	0
	193619	7/2	27	−9	9	136	3.0	1.9	82	15	1	0	4	30	1	0	4
7/23	203510	5/1	—	—	4	—	Over cloud top				No penetration						
	203713	5/2	1	−11	0	123	0.8	0.6	0	3	3	—	0	0	0	0	0
	205643	6/3	5	−10	3	—	2.4	1.7	80	11	6	7	40	0	0	0	0
	205851	6/4	7	−10	0	128	0.5	0.3	0	22	14	11	57	40	13	9	0
8/21	191740	2/1	—	—	2	—	Over cloud top				No penetration						
	192153	2/2	23	−11	0	253	0.5	0.1	0	71	13	2	30	233	26	2	13
	192052	3/1	10	−9	7	—	2.4	1.4	86	9	2	0	0	0	0	0	0
	192334	3/2	22	−11	0	162	0.6	0.3	0	66	21	9	55	413	103	18	36
	200100	6/1	—	—	7	—	Over cloud top				No penetration						
	200318	6/2	1	−12	0	138	0.4	0.4	0	74	74	—	100	344	344	—	100
8/30	191454	3/2	21	−9	7	—	2.5	1.4	68	37	7	4	29	5	1	0	0
	191808	3/3	42	−9	0	194	1.4	0.8	27	27	3	0	14	19	2	0	0
	192110	4/1	8	−8	5	—	2.7	2.1	91	0	0	0	0	0	0	0	0
	192331	4/2	16	−8	1	—	2.8	1.9	78	1	0	0	0	0	0	0	0
	192631	4/3	11	−9	5	—	1.7	0.8	47	9	3	1	0	4	1	0	0
	*193123	4/4	29	−9	10	*	2.9	1.2	49	46	9	7	34	112	35	4	34
8/31	192539	5/2	17	−11	7	—	2.5	1.7	80	1	0	0	0	3	0	0	0
	192728	5/3	61	−12	0	109	2.7	1.8	89	48	11	8	43	757	81	33	36
	193000	5/4	24	−12	0	261	0.1	0.0	0	26	7	4	33	310	112	110	79

* 4/4 was carried out through original 4/1, 4/2 and 4/3 with Δt, therefore, 613, 472 and 292, respectively.

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tion of crystals exceeded 50 ℓ^{-1} was 5% during one pass and zero on all other passes in the no-seed group. In 7 of the 14 seeded clouds, on the other hand, the crystal concentration exceeded 50 ℓ^{-1} for more than 25% of the traverse at some point in the life cycle of the cloud. On only two occasions in the seeded grouping did a cloud fail to have, on the repeat pass sequence, an appreciable maximum concentration (>15 ℓ^{-1}) of crystals. A pronounced absence of crystals on repeat passes was observed in 18 of the 21 nonseeded clouds.

As was found with the cloud sample in 1975, the graupel concentration appeared somewhat larger in the seeded cloud group in 1976. Increases in maximum graupel concentrations in the excess of 40 ℓ^{-1} were observed on repeated passes in 3 of the nonseeded and 8 of the seeded clouds, 2 of the latter having graupel peaks of more than 100 ℓ^{-1}. Increases in mean graupel concentration exceeded 5 ℓ^{-1} in 10 of the 14 seeded clouds, but in only 4 of the 21 nonseeded clouds.

It can be observed from the data tables that on initial penetration, both seeded and nonseeded clouds in 1975 contained a higher concentration of graupel than did the clouds sampled during 1976. This suggests the possibility that the clouds in 1975 were initially penetrated later in their life cycle relative to those sampled in 1976. This is also reflected in the observation that, of the total of 20 clouds in the 1975 data set, 9 were found to contain some crystalline ice on initial penetration; only 4 of 35 clouds sampled in 1976 were found to contain crystals on initial penetration.

4. Evolution of ice as a function of year of data collection

Differences in the evolution of ice crystals with time in clouds seeded in 1976 (through use of the NEI pyrotechnic) as compared with those seeded in 1975 (through use primarily of the Olin pyrotechnic) are readily apparent from an examination of Tables 2 and 4. The highest concentration of crystals observed in any cloud seeded in 1975 was 130 ℓ^{-1}, and only 3 of 9 clouds seeded in that year's group contained crystals in concentrations exceeding 50 ℓ^{-1}. In contrast, 9 of the 14 seeded clouds in the 1976 group contained crystal concentrations that exceeded 50 ℓ^{-1} during some part of their life cycle, and maximum crystal concentrations exceeding 400 ℓ^{-1} occurred in 4 of the clouds. No marked differences in crystal concentration are evident between the two years in clouds not seeded.

The maximum concentration of crystals as a function of time from initial penetration of the cloud is plotted in Figs. 2 and 3 for the seed and no-seed groups of data respectively. It should not be construed from these two figures that the maximum crystal concentration evolves linearly with time. The cloud-by-cloud data points have been connected with lines only for ease of intercomparison. It should be noticed also that only cases where the cloud was found to contain some crystals are included in the figures.

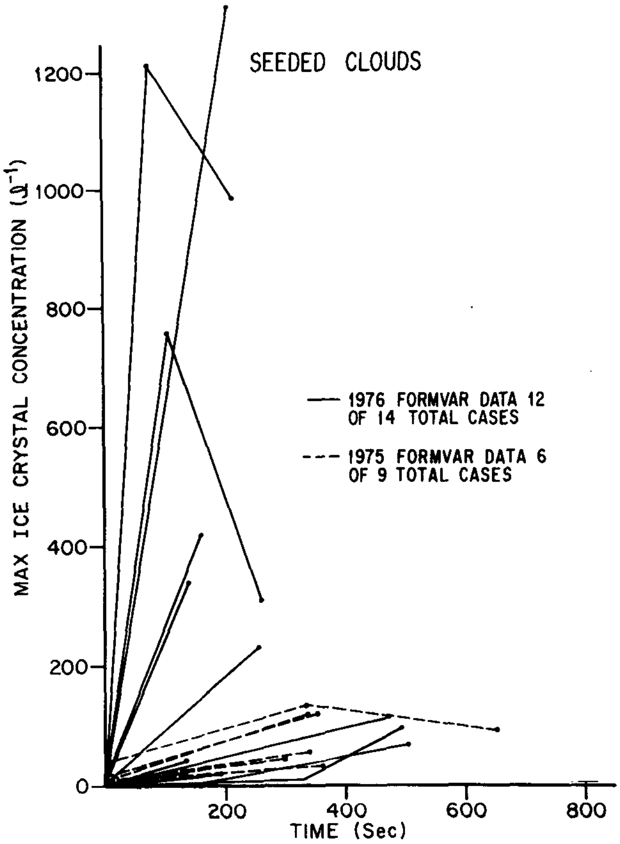

FIG. 2. Evolution of maximum ice crystal concentration with time in clouds seeded during the FACE 75 and FACE 76 programs; cases not shown contained no crystals upon repeat penetration.

It can be seen that most of the seeded clouds (12 of 14 in 1976 and 6 of 9 in 1975) are found to contain

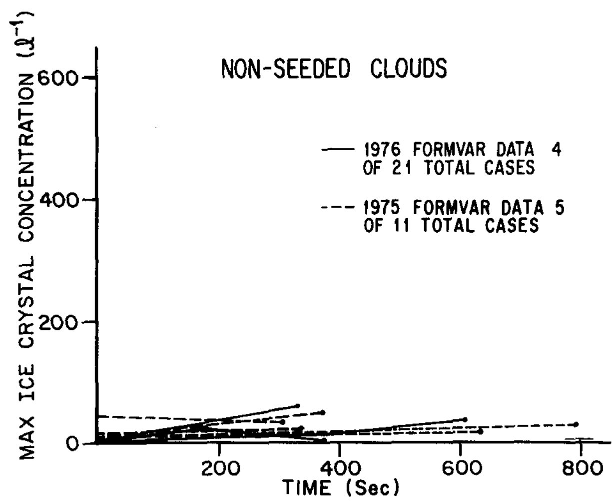

FIG. 3. Evolution of maximum ice crystal concentration with time in naturally-developing (unseeded) Florida cumuli; all cases not shown contained no crystals during any penetrations.

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TABLE 5. Statistical significance level of key microphysical variables using Student one-tailed t-test; data are grouped in four stratifications.

		1975 Seed > No seed	1976 Seed > No seed	No seed 1976 > 1975	Seed 1976 > 1975
Crystal increase					
	Maximum	0.01	<0.01	>0.40	0.04
	Mean	0.01	<0.01	0.27	0.05
	Median	0.08	0.02	0.31	0.14
Graupel increase					
	Maximum	0.10	<0.01	0.17	0.05
	Mean	0.04	0.01	>0.40	0.28
	Median	0.05	0.05	>0.40	>0.40
Cloud water					
	Maximum	0.10	>0.40	<0.01	<0.01
	Mean	0.27	>0.40	<0.01	<0.01
Pass time interval		0.22	0.16	<0.01*	0.03*

* 1975 > 1976.

crystalline ice at some point in their life history, while relatively few of the nonseeded clouds (4 of 21 in 1976 and 5 of 11 in 1975) have been found to do so. No differences in the evolution of maximum crystal concentration are discernible between the two years of data in the no-seed group (Fig. 3), but a considerable difference in the two-year population of data appears dramatically evident from the seeded group (Fig. 2). The 6 clouds with the highest concentration of crystals appear in the 1976 seeded data set. There is an order of magnitude difference between the maximum concentration of crystals detected in clouds seeded in 1976 with the NEI pyrotechnic and that detected in the clouds seeded in 1975 with mainly the Olin pyrotechnic.

Changes in the concentration of graupel in seeded clouds as a function of year are not presented in graphical form, but a comparison of Tables 2 and 4 reveals the presence of large amounts of graupel in both sets of data. The maximum concentration of graupel in the seeded 1975 clouds was generally much higher *on initial penetration* than that encountered in the 1976 clouds. Therefore, the *increase* in maximum graupel concentration with time is substantially greater in the case of the cloud group seeded in 1976. This tendency is not reflected as strongly in the mean and median concentrations of graupel, a finding which may be partly a result of the typically much shorter time interval between penetrations in 1976. It is reasonable to expect that any large difference in crystal concentration would eventually manifest itself in a difference in graupel concentration during the latter part of the cloud's life cycle.

5. Discussion

The Student one-tailed t-test was used to determine the statistical significance level of the increases in the concentrations of crystals and graupel, with a four-way partitioning of the data presented in Tables 1–4. Differences in the cloud water contents, as well as the time interval between penetrations, were also examined for statistical significance. The ice data are presented in terms of the maximum, mean and median *increases* observed from the lowest (first pass) values to the highest (succeeding pass) values. The cloud water data are referenced to maximum values observed during any portion of the cloud's life history. The matrix of significance levels is given in Table 5.

In testing for the hypothesis that, within a given year's data set, the seeded clouds developed more crystals and graupel than did the nonseeded clouds, one finds strong statistical support. This is particularly true with the group of clouds in 1976 with 5% or better significance in all ice categories. Neither the cloud water (JW) nor time interval differences are found to be significant (to 5% level or better) in data obtained within either given year.

A statistical comparison of the two years of data grouped according to seed decision provides no surprises in terms of ice increases in the no-seed category. The unseeded clouds in 1976 did not develop any significantly greater quantities of ice, either in the form of crystals or graupel, than did their counterparts in 1975. As could be expected from an examination of Fig. 2, however, the seeded clouds in 1976 were found to develop significantly more crystals, both in maximum and mean concentration than did those seeded in 1975. The increase in maximum graupel in the seeded 1976 clouds was also found to be significantly greater than that in the seeded clouds in 1975, though the increase was not reflected to a statistically significant degree in the mean or median values.

The statistically significant difference in maximum and mean cloud water between the 1976 data set and that in 1975, both seeded and unseeded, is thought to be at least partly attributable to differences in the response characteristics of the JW instrumentation. The JW used on the Navajo aircraft in 1976 consistently showed about a 15% higher reading of cloud water content when it was mounted with the JW used in 1975 and flown through a series of cloud towers similar

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to those penetrated during the FACE program. A "cleaner" exposure to the airstream in its forward side position on the Navajo relative to its upper fuselage position on the DC-6 may also have contributed to an additional bias toward higher JW readings in 1976. Also, an upward adjustment (~30%) in the JW measurements to account for an incorrect airspeed setting on the DC-6 instrument should be applied to all cloud water data obtained in 1975. The DC-6 JW water contents in 1975 were noticeably lower than those calculated from the drop size distributions that were derived from data obtained from the formvar replicator mounted on the side of the fuselage forward of the JW position. It would appear, therefore, that, as a group, the cumuli penetrated during 1976 contained more cloud water than those penetrated during 1975, but probably not as much more cloud water as one would be led to believe from the JW data presented here. The presence of more cloud water on initial penetration in the clouds sampled in 1976 is consistent with the view that that group of clouds was penetrated earlier in their life cycle. If contact nucleation is the principal means of inducing drop freezing through seeding with AgI, the rate of production of ice particles should be proportional to the concentration of water droplets. Therefore, towers containing higher values of cloud water content at the time of seeding could reasonably be expected to glaciate more efficiently than those with low water contents, and this could well be a contributing factor to the year-to-year discrepancies in ice content discussed earlier.

The more maneuverable Navajo aircraft resulted in a substantially shorter time interval between consecutive penetrations through the same cloud tower in 1976. While the DC-6 in 1975 required about 5 min to execute a 90–270° maneuver and repenetrate a tower on a reciprocal heading, the Navajo in 1976 could carry out a similar flight pattern in about half that time. This is reflected in Table 5, with the hypothesis that the pass time interval during penetrations in 1975 was significantly greater than that in 1976 shown accepted at better than the 5% level for both the seed and no-seed categories. The faster repenetration times associated with the 1976 group may, in part, be responsible for the much greater concentrations of crystals observed in seeded clouds. In some cases (Figs. 1) a noticeable decrease in maximum crystal concentration occurs at the sampling level after 2 or 3 min from the time of initial penetration. Even in those cases, however, the crystal concentration remaining after 5 min is still substantially greater than that detected in the same time frame in clouds penetrated by the DC-6 in 1975.

6. Summary and conclusions

It has been shown that the concentration of crystalline ice observed in clouds seeded in 1976 greatly exceeds that detected in clouds seeded in 1975. Nonseeded clouds in both years show no substantial differences in the concentration of either crystalline or graupel ice. Significant increases (following initial penetration) of maximum and mean crystal concentration as well as maximum graupel concentration are found in the 1976 seeded clouds relative to those seeded in 1975. Within both years (1975 and 1976) clouds seeded were found to contain significantly greater amounts of ice, both in the form of crystals and graupel, than those not seeded.

Higher water contents were found in both the seeded and nonseeded clouds penetrated during 1976 (relative to those penetrated during 1975), but differences in instrument configuration, exposure and response may partly account for this. Since the ice crystal and graupel data show no significant differences in the nonseeded cloud group when partitioned by year, we have reason to believe that the Formvar replicator is providing reliable data in the seeded sample sets and that the year-to-year differences in that group are accurately reflected.

Three explanations can be advanced for the detection of significantly greater concentrations of ice particles (both crystals and graupel) in the case of clouds seeded in 1976 relative to those seeded in 1975: 1) the pyrotechnics (NEI) used in 1976 nucleated more effectively in the region near −10°C than did those (mainly Olin) used in 1975; 2) the towers sampled in 1976 were systematically seeded earlier in their lifetime than those sampled in 1975, and thus contained more cloud water and were able to produce ice at a faster rate; and 3) the detection of ice was more difficult in seeded clouds sampled in 1975 relative to those sampled in 1976 because the significantly longer aircraft repenetration times (in 1975) made it more difficult to locate the treated cloud regions with precision and, even if located accurately, the "nucleant plume" would be more diffuse thus lowering the peak concentrations accordingly.

It is our opinion that, while the second and third explanations may well be factors contributing toward a bias in finding greater quantities of ice in seeded clouds sampled in 1976, the order of magnitude differences, so strikingly apparent in Fig. 2, most reasonably must be directly related to substantial differences in nucleating effectiveness between the types of flares used in the two years. Sax *et al.*, (1979) have described such nucleating differences. The physical data presented here point to the conclusion that a stratification of the FACE rainfall results based on flare type is warranted.

The combination of maximum crystal concentration in excess of 25 ℓ^{-1} and maximum JW water contents of 0.5 g m^{-3} or more during a tower repenetration occurred in 9 of 14 seeded clouds in 1976, but did not occur in nonseeded clouds in that year. This coexistence of crystalline ice and supercooled water provides direct evidence that the initial stage of dynamic seeding—the conversion, during the cloud's active growth stage, of supercooled water to ice through the injection of silver iodide—is proceeding as hypothesized.

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REFERENCES

Hallett, J., 1976: Cloud particle replicator for use on a pressurized aircraft. Supplement to Final Report No. AFGL-TR-76-0149, Air Force Geophysics Laboratory, Hanscom AFB, 47 pp.

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

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., D. M. Garvey and F. P. Parungo, 1979: Characteristics of AgI pyrotechnic nucleant used in NOAA's Florida Area Cumulus Experiment. *J. Appl. Meteor.*, **18**, 195–202.

Woodley, W. L. and R. I. Sax, 1976: The Florida Area Cumulus Experiment: Rationale, design, procedures, results, and future course. NOAA Tech. Rep. ERL 354–WMPO6, 206 pp.

——, J. A. Jordan, J. Simpson, R. Biondini, and J. Flueck, 1978: NOAA's Florida Area Cumulus Experiment rainfall results: 1970–1976. *J. Appl. Meteor.* (submitted for publication).

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