The Importance of Natural Glaciation on the Modification of Tropical Maritime Cumuli by Silver Iodide Seeding

ROBERT I. SAX

Atmospheric Physics and Chemistry Laboratory, ESSA, Coral Gables, Fla.

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In order to determine if natural glaciation proceeds rapidly or extensively enough in tropical maritime cumuli to influence attempts to modify their dynamical behavior by seeding with silver iodide, a detailed study was made of the clouds observed during the 1965 Project Stormfury experiments. From photographic coverage, notes on visual observations, and instrumentation on-board penetrating aircraft, data were compiled on cloud liquid water content, volume-median drop size, in-cloud temperature profile, and the dynamical life histories of both seeded and non-seeded clouds. The validity of applying Koenig's numerical splintering model to tropical maritime cumuli, as well as an assessment of the effectiveness of silver iodide seeding, were determined by comparing the dynamical behavior of paired seeded and non-seeded clouds with glaciation times predicted by the model. Dynamical studies were initiated on two independently developed parametrized numerical cumulus models, and an excellent correlation between predicted and observed cumulus growth was found if no natural glaciation at temperatures >-15C was assumed.

The results of this study suggest that natural glaciation does not proceed rapidly and/or extensively enough in the critical cloud updraft areas to alter the effectiveness of modifying tropical maritime cumuli by causing artificial glaciation with silver iodide.

1. Introduction

The technique of modifying supercooled cumuli by silver iodide seeding is based on the idea that silver iodide particles will act as freezing nuclei at a much higher temperature than naturally-occurring nuclei. Instead of remaining liquid until temperatures of the order of -25C have been reached, the seeded cloud can freeze and release its latent heat of fusion in the temperature range of -4 to -8C, thus gaining additional buoyancy. The cumulus growth resulting from the increased buoyancy can best be demonstrated on days when an existing inversion layer is strong enough to prevent penetration by the natural, unseeded cumuli, but not sufficiently strong to prevent penetration by the warmed, seeded cumuli. Explosive cumulus growth can occur if the atmosphere above such an inversion is unstable and not too dry.

Such a seeding modification hypothesis based on a growth increase caused by buoyancy from fusion heating fundamentally assumes that the organized updraft region of the cloud remains essentially liquid until the time of seeding. The effectiveness of artificial seeding would be drastically reduced if a significant portion of the water content in an updraft area is rapidly consumed by ice from natural glaciation at temperatures >-15C. In the extreme case of rapid natural glaciation of updraft water content near temperatures of -5C, no change in growth behavior between seeded and non-seeded clouds could be expected.

From a cumulus modification viewpoint, therefore, observations of ice particles existing in cumuli topping below the -15C level are particularly important. A great deal of evidence has accumulated during the past decade giving credence to the idea that ice occurs far more frequently at temperatures >-15C in the free atmosphere than previously thought possible, and apparently in greater concentrations than can be explained by the presence of natural freezing nuclei. Murgatroyd and Garrod (1960) found significant quantities of ice in British cumuli whose tops were no colder than -11C. Koenig (1963) showed evidence from the University of Chicago's Project Whitetop experiments indicating that approximately 30% of the cumulus clouds studied in Missouri completely glaciated, apparently naturally, at temperatures >-10C. Mossop *et al.* (1968) report finding ice crystals in an Australian cumulus cloud which never reached a temperature <-4C. Koenig (1968) sampled ice particles in Californian orographic clouds which failed to grow above the -9C isotherm. The author himself has observed evidence of ice particles at "warm" temperatures during an ESSA cloud physics project in Puerto Rico during the summer of 1967.

Although the presence of some isolated large ice particles at temperatures >-10C can be explained by a stochastic freezing process (Gokhale, 1965), a complete and rapid glaciation of natural clouds would certainly require a more efficient process. Hypothesizing that large water droplets eject splinters of ice as they freeze, and that such splinters can act as freezing nuclei for other liquid droplets which, in turn, eject more splinters as they freeze, Koenig (1966), using laboratory

TABLE 1. Theoretical time for natural cloud glaciation by the ice-splintering mechanism as a function of cloud liquid water and mean drop size (after Koenig, 1966).

% of cloud LWC glaciated	Cloud LWC (g/m)^3	Average Drop Diam. (microns)	Time (seconds)	Average Drop Diam. (microns)	Time (seconds)	Average Drop Diam. (microns)	Time (seconds)
10	0·5	30	760	60	550	90	500
10	1·0	30	420	60	320	90	300
10	2·0	30	240	60	Not Computed	90	180
50	0·5	30	860	60	640	90	600
50	1·0	30	460	60	380	90	340
50	2·0	30	270	60	Not Computed	90	210
95	0·5	30	1280	60	910	90	880
95	1·0	30	660	60	520	90	500
95	2·0	30	400	60	Not Computed	90	280

data on splinter production as studied by Latham and Mason (1961), devised a numerical model for a chain-reaction type of ice-multiplication glaciation in cumuli topping at temperatures > -10C. His computed glaciation times are a function of the cloud's liquid water content and drop-size distribution, but turn out to be remarkably insensitive to the number of initial ice particles present in the cloud. A summary of his results, based on an initial 10 μ ice particle concentration of 1 m^{-3}, is given in Table 1.

The above computations have strong implications on dynamical cumulus modification by silver iodide seeding. The predicted time for 95% glaciation by a natural ice-multiplication mechanism in a cloud with a broad drop-size distribution is within the 5–10 min needed for complete artificial glaciation by silver iodide seeding. It would appear to follow that trying to induce artificial glaciation by seeding clouds possessing a broad drop size distribution, such as tropical maritime cumuli, should be ineffective in altering the life history of such clouds since almost complete natural glaciation by an ice-multiplication mechanism is predicted to occur in approximately the same time interval. This study is an attempt to determine if natural glaciation occurs both significantly and rapidly enough in tropical maritime cumuli to impair the effectiveness of cumulus modification by artificial seeding techniques.

2. Analytical procedure and acquisition of data

All data were obtained from the 1965 Project Stormfury cumulus modification experiments during which randomized seeding operations were conducted on 23 tropical maritime cumuli in the Caribbean. Only 14 of the clouds were actually seeded, the remainder being used as control clouds. Two ESSA DC-6 aircraft, equipped to measure such physical parameters as liquid water content, volume-median drop size, ambient temperature, humidity, wind speed and direction, and vertical accelerations, made cloud penetrations at 10,000 and 19,000 ft, and a Naval Research Laboratory aircraft, equipped with a Formvar replicating device (Averitt and Ruskin, 1967) penetrated clouds at the 17,000-ft level. The cloud's life history was carefully analyzed from 16-mm color motion pictures taken from the command and control aircraft (a radar-equipped WC-121) and from 35-mm movies taken from both sides of the two DC-6 penetrating aircraft. Color slides and Hasselblad pictures, along with the original notes taken by meteorologists on board the various participating aircraft provided a clear reconstruction of the cloud's growth from time of first visual sighting.

The liquid water data were obtained by means of a Johnson-Williams meter in combination with a hot wire instrument described in detail by Levine (1965). Essentially, this system consists of a nickel-iron wire loop cloud unit sensitive to drops $\lesssim 100\,\mu$ in diameter, and a rain instrument made of the same kind of wire wound on a grooved ceramic cone and sensitive to drops $> 100\,\mu$ in diameter. Because the responses of the two instruments are dependent upon drop size, the volume-median drop diameter can be determined if a drop distribution is assumed.[1]

In order to test the applicability of the splintering model to the Stormfury clouds, it was necessary to focus attention on an analysis of physical parameters such

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[1] An exponential log-normal distribution was assumed, both for calibration of the instrument and for the actual clouds. In this case the volume-median corresponds closely with the mean, and the two terms can be interchanged without introducing a large error.

TABLE 2. Liquid water contents and volume-median drop sizes for nine clouds studied during Project Stormfury. (JW refers to the Johnson-Williams meter.)

Date (1965)	Cloud	Run	Seed or No Seed	Average JW LWC (g/m^3)	Average Total LWC (g/m^3)	% LWC greater than JW size drops	Average Volume Median Drop Size (microns)	Maximum LWC (total) g/m^3	Flight Altitude (feet)
28 July	1	1	No Seed	0·31	1·07	71	67	3·1	19,000
	3	1	Seed	0·27	0·79	66	83	1·6	19,000
29 July	1	2	Seed	0·31	1·13	73	85	2·1	19,000
	1	2	Seed	0·13	1·08	88	99	1·7	10,000
	2	1	No Seed	0·12	0·50	76	132	1·0	19,000
3 August	4	2	Seed	0·14	0·46	70	109	0·6	19,000
5 August	3	1	Seed	0·13	0·43	70	120	1·6	19,000
	1	1	No Seed	–	0·15	–	–	0·3	19,000
10 August	2	1	No Seed	0·29	1·30	78	89	2·1	19,000
	3	1	Seed	0·19	0·79	76	105	1·8	19,000

as cloud liquid water content profile, volume-median drop size, cloud life history, and environmental conditions. This also served to point out any internal physical differences between the control and seeded Stormfury clouds. In order to determine if natural glaciation is important enough to alter the effectiveness of silver iodide seeding in tropical maritime cumuli, the behavior of the Stormfury clouds was analyzed by using two independently developed dynamical models, both of which assumed no natural glaciation at temperatures >-15C. If natural glaciation is as rapid and widespread in the updraft regions of tropical maritime cumuli as the splintering model seems to imply, the dynamical models would not be expected to give a good correlation between predicted and observed cloud top heights, particularly for the non-seeded cases.

3. Discussion of the physical analysis

Reliable physical data from the Levine instrument could only be obtained at the 19,000-ft penetration level for nine of the Stormfury clouds, five of which were seeded.[2] A complete summary of the data obtained is shown in Table 2. With the exception of the 5 August control cloud, these cases had water contents and volume-median drop sizes comparable to those used in Koenig's calculations (Table 1), thus enabling their time of glaciation by an ice-multiplication mechanism to be easily predicted. A good test for the validity of Koenig's model could be made by determining if natural glaciation occurred in these clouds in the time and to the extent predicted by the model.

Because the NRL aircraft could not fly above 17,000 ft, the Formvar replicator was sampling at temperatures too warm for mixed phase conditions except on 5 August when the freezing level was exceptionally low and the sampling took place at -4C. Except for 5 August, therefore, direct evidence of the extent of cloud glaciation could not be obtained, and an indirect deductive means of determining natural glaciation had to be used. If a cloud fails to grow above a certain level for a substantial period of time (15–20 min), and is then seeded, any sudden growth of the cloud can most likely be attributed to additional buoyancy caused by the latent heat release of freezing water. Significant growth can only occur if a large percentage of the cloudy updraft area is supercooled liquid water at the time of seeding. Also, if a seeded cloud can grow, while an unseeded cloud, possessing the same physical properties, is unable to grow in an identical environment, such behavioral difference can most likely be attributed to fusion heat release and rules out the possibility of rapid natural glaciation in the unseeded case. Such an analysis of the dynamical behavior of the Stormfury clouds was used as the primary means of assessing the rate and importance of a natural glaciation mechanism and its effect on the modification of tropical maritime cumuli by silver iodide seeding.

4. The cloud data

Table 3 summarizes the important data analyzed for each of the nine clouds thought to have reliable Levine water measurements. Fig. 1 gives the temperature pro-

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[2] Because of the abundance of large drops in tropical cumuli, the Levine cloud instrument wire frequently broke and data were lost; the problem of preventing such breakage is currently being studied by ESSA's Research Flight Facility.

TABLE 3. Supercooling times and cloud growth histories for nine clouds studied during Project Stormfury.

Date (1965)	Action	Time of First observation T_o (GMT)	Top Temp at T_o (°C)	Time of Action T_1 (GMT)	Top Temp at T_1 (°C)	Time Supercooled until Action Time (min)	Growth to Action Time (ft)	Growth after Action Time (ft)	Total Time of Supercooling Control Cases (min)
28 July	Control	2010:00	−6·0	2033:00	−8·0	23·0	1500	2500	30·0
	Seed	2202:30	−7·5	2217:30	−5·0	15·0	−1500	17500	(Seeded)
29 July	Seed	1755:00	−9·0	1810:30	−19·0	15·5	4000	14000	(Seeded)
	Control	1920:00	−9·0	1929:30	−14·0	9·5	2500	None	15·0
3 August	Seed	2142:00	−19·0	2158:30	−22·0	16·5	2500	10500	(Seeded)
5 August	Control	1641:00	−9·0	1657:30	−14·0	16·5	2000	4000	21·0
	Seed	1747:30	−12·0	1805:30	−18·0	18·0	4000	11000	(Seeded)
10 August	Control	1913:00	−11·0	1916:00	−11·0	Unknown	None	None	Unknown
	Seed	1940:00	−8·0	1957:30	−17·0	17·5	4000	14000	(Seeded)

file through each cloud (except for the 5 August control) as measured at 19,000 ft by the vortex thermometer on board the DC-6. The 5 August control cloud was penetrated incorrectly at the edge instead of through the center, thus accounting both for its extreme dryness and for the temperature profile omission. The following brief analysis of each cloud has been given in much greater detail by Sax (1967).

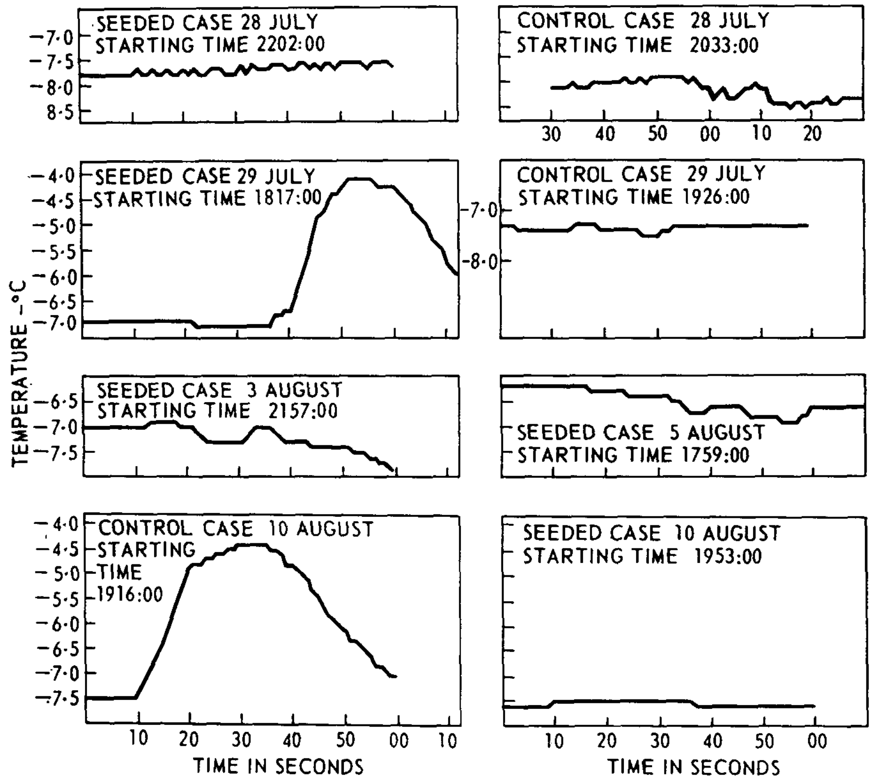

FIG. 1. Temperature profiles at the 19,000-ft level for eight of the Stormfury clouds.

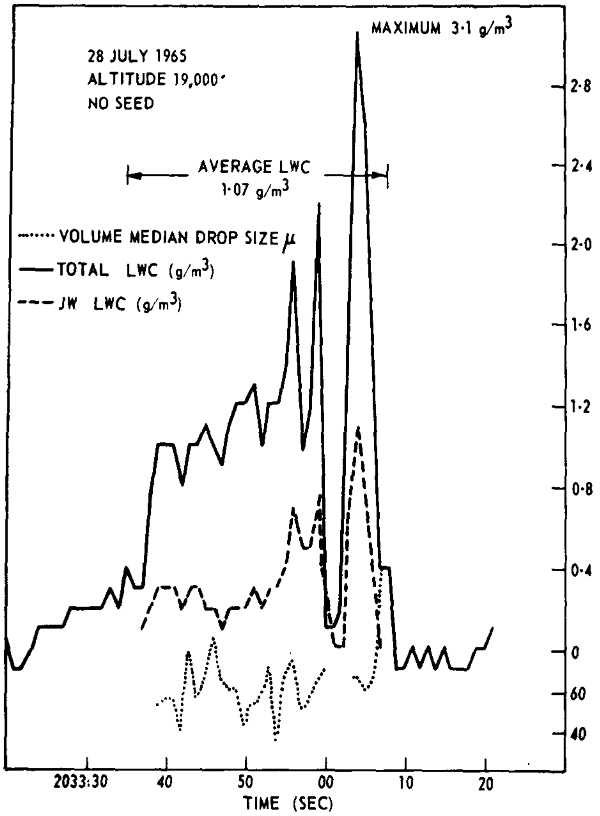

FIG. 2. Physical profile at the 19,000 ft level; 28 July control cloud.

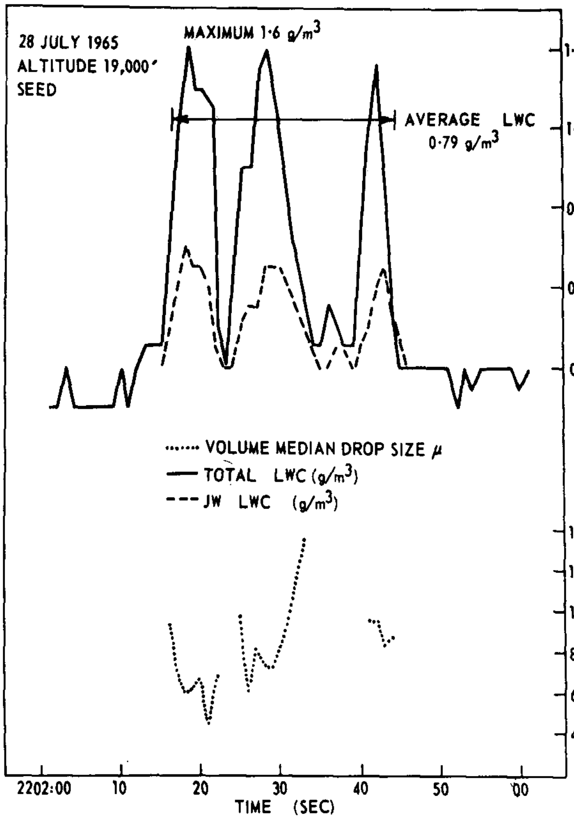

FIG. 3. Physical profile at the 19,000-ft level; 28 July seeded cloud (before seeding).

a. 28 July

Good physical measurements were obtained for both a seeded and a control cloud on this day, the control cloud's 19,000-ft physical profile being shown in Fig. 2. This cloud was observed to exist with its upper level at a temperature < −6C for 23 min prior to penetration, and a further 7 min after penetration, but the cloud could grow no higher than to the 24,000-ft level (−18C). The steadiness of the temperature profile (Fig. 1) indicates the absence of a strong warm updraft in the upper portion of the cloud. Assuming that a few "primary" ice particles (1 m^{-3}) were able to form early in the cloud's existence as it approached the −10C isotherm, the splintering calculations predict that about 9 min would be sufficient time for this cloud to achieve 95% glaciation. If such glaciation actually did occur in this short time interval in the control cloud, then 24,000 ft should represent an upper limit to the growth of a seeded cloud possessing similar physical characteristics

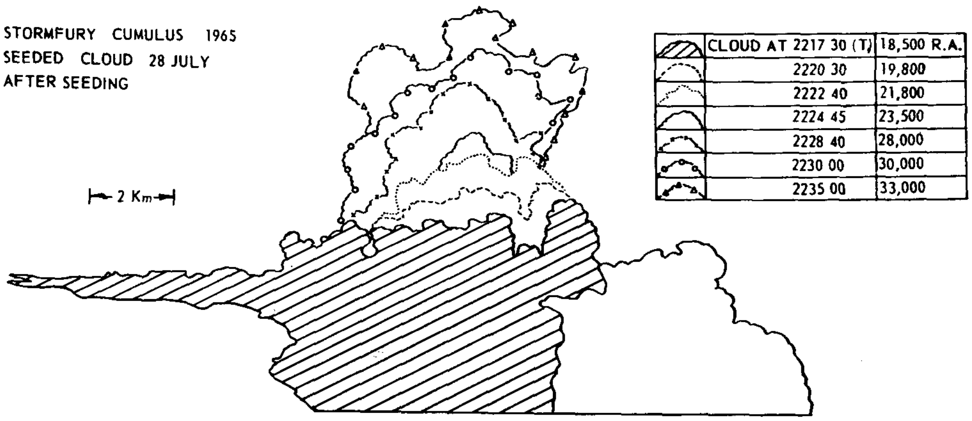

FIG. 4. Growth of the 28 July seeded cloud.

and existing in nearly the same time and place as the control.

Fig. 3 shows the profile of the seeded cloud which developed 2 hr after the control and in an area approximately 100 n mi distant. The cloud top was in an active state with new turrets forming and old ones collapsing. Although the cloud top pushed above 19,000 ft (−7C) when it was first sighted, by seeding time, 15 min later, no part of the cloud was above 17,500 ft (−5C). Upon seeding, however, the cloud grew explosively to 35,000 ft in the next 18 min as illustrated by Fig. 4.

Because apparently a large amount of fusion heat was released by the silver iodide, such dynamical behavior suggests that the organized updraft area of the cloud was essentially liquid at the time of seeding. Although the splintering calculations predict that the seeded cloud should have been 95% glaciated some 5 min before it was seeded (clearly an impossibility if seeding caused the growth), it is quite possible that, since the cloud top never became colder than −7C prior to seeding, primary ice particles may not have been present in sufficient quantities to initiate the chain-reaction multiplication mechanism.

A comparison of the dynamical behavior of the two clouds studied on this day strongly indicates that the updraft areas of the control cloud could not glaciate naturally as efficiently as could the updraft areas of the cloud which was artificially seeded. The seeded cloud's 11,000 ft height gain relative to the control points out the effectiveness of silver iodide seeding in tropical maritime cumuli. Apparently, the splintering calculations resulted in far too short a glaciation time for this day's control cloud, since 95% glaciation in 9 min should have permitted such efficient release of fusion heat as to give growth compatible with that of the seeded cloud.

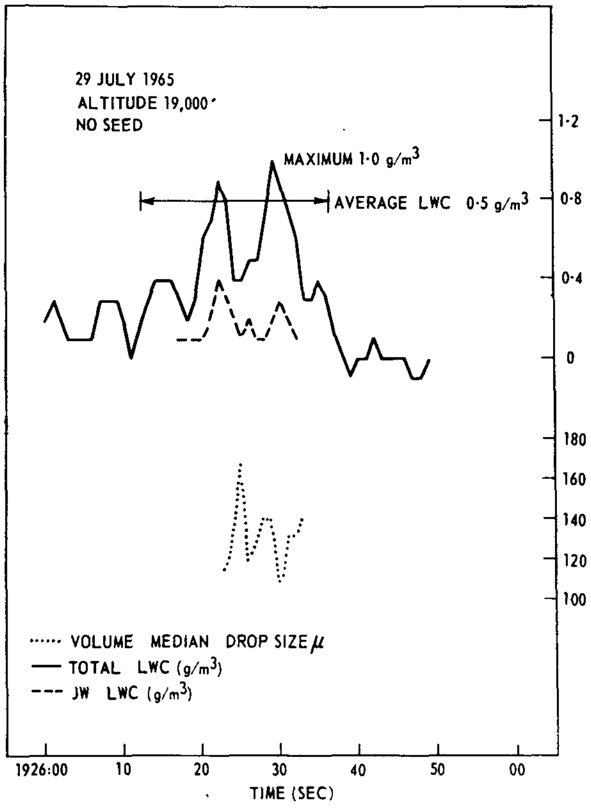

Fig. 5. Physical profile at the 19,000-ft level; 29 July control cloud.

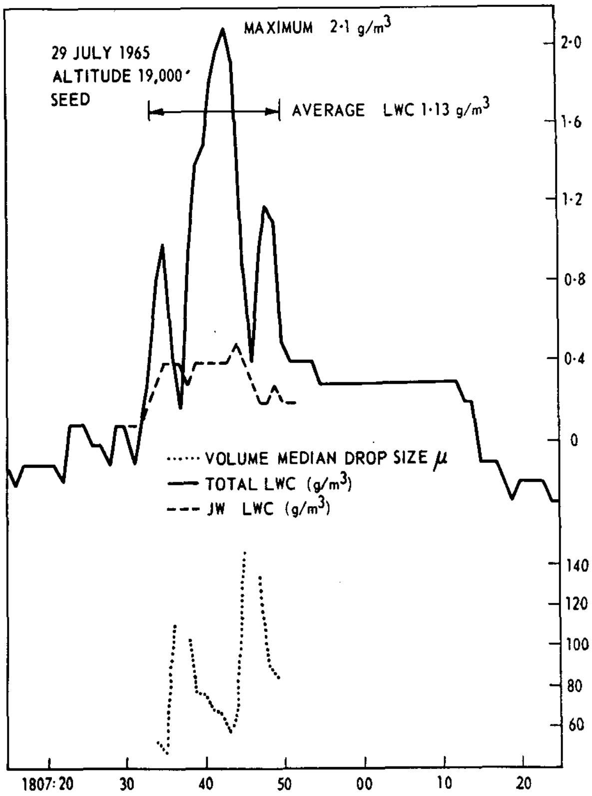

Fig. 6. Physical profile at the 19,000-ft level; 29 July seeded cloud (before seeding).

b. 29 July

The control cloud for this day was first observed to have a height of 20,000 ft (−9C), but it could grow no higher than 22,500 ft (−15C) before it began to decay 15 min later. From the cloud's physical profile, shown in Fig. 5, it can be calculated from Table 1 that 95% natural glaciation should have occurred in about 14 min; the cloud, however, failed to exhibit any buoyancy gain.

In contrast, the seeded cloud for this day, initially observed at 20,000 ft (−9C), had grown to 24,000 ft (−19C) 15 min later, at which time it was seeded. During the following 18 min, the seeded turret grew spectacularly to 38,000 ft, shearing off from the main body of the cloud which died without further growth. Although the seeded cloud existed in the same environmental conditions as the control, it was considerably wetter than the control cloud, as can be seen from the profile in Fig. 6. An examination of the 19,000-ft temperature profile (Fig. 1) reveals a strong increase in temperature in the seeded cloud's interior, thus indicating an actively growing turret with a substantially warm updraft. Evidence of such activity could not be found in the control cloud.

The dynamical behavior of the two clouds on this day does not lend itself to an easy single explanation. The San Juan radiosonde data indicated the presence of a weak stable layer between 21,000 and 23,000 ft. It appears that the seeded cloud, being wetter and more active than the control, was just able to penetrate this layer prior to seeding, while the control could not. It is therefore possible that the seeded cloud would have grown independently of seeding, particularly since its top temperature just prior to seeding was near -20C. Because the seeded cloud was able to grow 4000 ft prior to seeding, it might be argued that the additional growth after seeding was just an acceleration of an already established process of natural fusion heat release.

Koenig's splintering calculations predict that 10 min should have been sufficient time for 95% of the seeded cloud to have glaciated naturally before seeding. Even allowing for the warm updraft, droplets in this cloud were supercooled at -10C or colder for at least 10 min before seeding, but substantial, almost explosive, growth did not commence until after the cloud was seeded. Such dynamical behavior suggests a liberal release of fusion heat upon seeding, thus requiring an essentially liquid updraft region at the time of seeding. By a similar analysis, this day's control cloud should have completely glaciated according to the splintering model, but its failure to grow indicates ineffective fusion heat release in its updraft region. Calculations similar to those described by Wexler and Donaldson (1966) predict that 3% of all drops >2.5 mm radius should freeze at -10C in 25 sec, and 50% of such drops should freeze in the same time at -14.5C. The large volume-median drop sizes in both the seeded and control cases (Fig. 5 and Fig. 6) would seem to indicate that such large droplets should have been present in these clouds to provide an adequate source of primary ice particles for ice-multiplication initiation. This would be particularly true in the case of the seeded cloud with its strong supporting updraft.

The failure of the seeded cloud on this day to exhibit much growth prior to seeding, and the failure of the control cloud to grow at all, even though both clouds were supercooled at temperatures <-10C for a sufficient amount of time to completely glaciate according to the splintering model, indicates that the model calculations greatly overpredicted the extent and/or rate of natural glaciation in these clouds. The 15,500-ft growth increase in the seeded turret indicates that natural glaciation does not proceed efficiently enough to interfere with the effectiveness of the artificial seeding of tropical maritime cumuli.

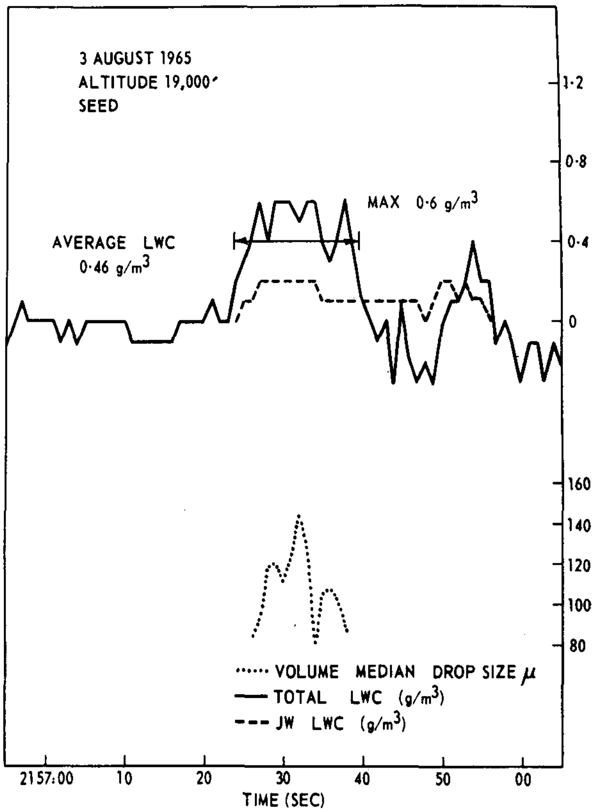

FIG. 7. Physical profile at the 19,000 ft level; 3 August seeded cloud (before seeding).

c. 3 August

The only case available for this day was a seeded cloud which had its upper 4000 ft supercooled well below -15C for $16\frac{1}{2}$ min prior to seeding, but managed to grow only 2500 ft during that time. After seeding, however, the seeded turret grew 10,500 ft in 14 min and separated from the main cloud mass. Comparing the cloud's physical profile shown in Fig. 7 with the splintering criteria in Table 1, it can be seen that this cloud should have been 95% glaciated at least a full 3 min before it was seeded. The dynamical behavior of the cloud, however, strongly refutes the idea that it had completely glaciated before seeding. The sudden increase in cloud buoyancy shortly after seeding can reasonably be attributed to warming caused by a mass amount of fusion heat release, an impossible condition for a cloud already fully glaciated. The cloud's long supercooling time at such a low temperature should theoretically insure a primary ice concentration of 1 m^{-3}, but the ice apparently could not propagate throughout the cloud as rapidly as predicted by the splintering model. The extent of natural glaciation in this cloud was apparently not sufficient to interfere with the effectiveness of the silver iodide seeding.

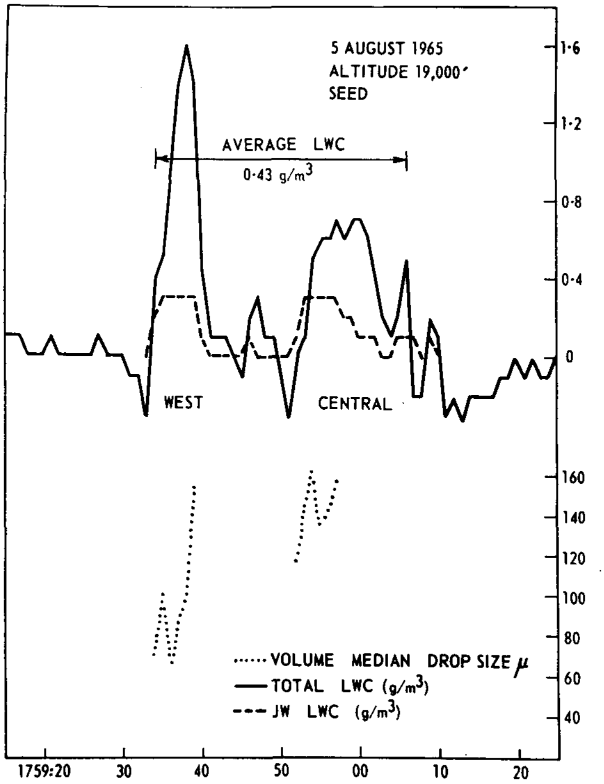

Fig. 8. Physical profile at the 19,000 ft level; 5 August seeded cloud (before seeding).

d. 5 August

The control cloud for this day topped at 26,000 ft (−14C) and was supercooled below −9C for at least 21 min. Unfortunately, the DC-6 penetration of this cloud was incorrectly made through an extremely dry edge instead of through the center, thus making it impossible to compare the physical characteristics of this cloud with the splintering criteria presented in Table 1.

In contrast, a great deal of work has already been published about the seeded cloud for this day (Ruskin, 1967; Simpson 1967). As can be seen from Fig. 8, this cloud possessed two distinct turrets, a rather wet western turret and a dry central turret. The central turret was the oldest part of the cloud and had existed above the 21,000 ft level (−12C) for at least 18 min before beginning to dissipate near the time of seeding. As can be seen from Fig. 9, the western turret was a young, growing area which had existed above 19,000 ft (−7C) for 6 min at the time of seeding. The splintering calculations (Table 1) predict that, at the time of seeding, the central turret should have been 95% glaciated while the western turret should have been about 10% glaciated.

Formvar replication data were available for the western turret at the 17,000 ft level (−4C) shortly before the time of seeding. Using a method similar to Averitt and Ruskin (1967), a detailed ice-to-water percentage area analysis was made from the Formvar sections which did not contain large graupel pellets or shattered liquid droplets. As Fig. 10 indicates, the average concentration of ice in the western turret just before seeding time was 20%, but a localized pocket of up to 50% ice existed in a small area near the cloud edge. This is roughly in agreement with a similar analysis on the same cloud performed by Ruskin (1967). The low water content of the central turret made a quantitative estimate of ice impossible for that portion, but, in small areas where good data were available, the central turret appeared somewhat more glaciated than the western.

The presence of significant quantities of ice in the young western turret lends support to a multiplication mechanism since the number of natural freezing nuclei active at −8C cannot account for the large amount of ice throughout the turret. However, the old central

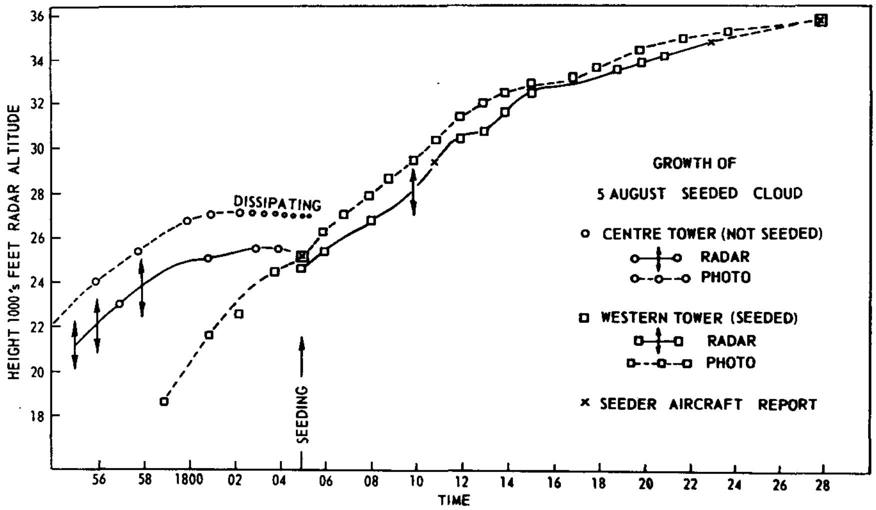

Fig. 9. Growth of the 5 August seeded cloud.

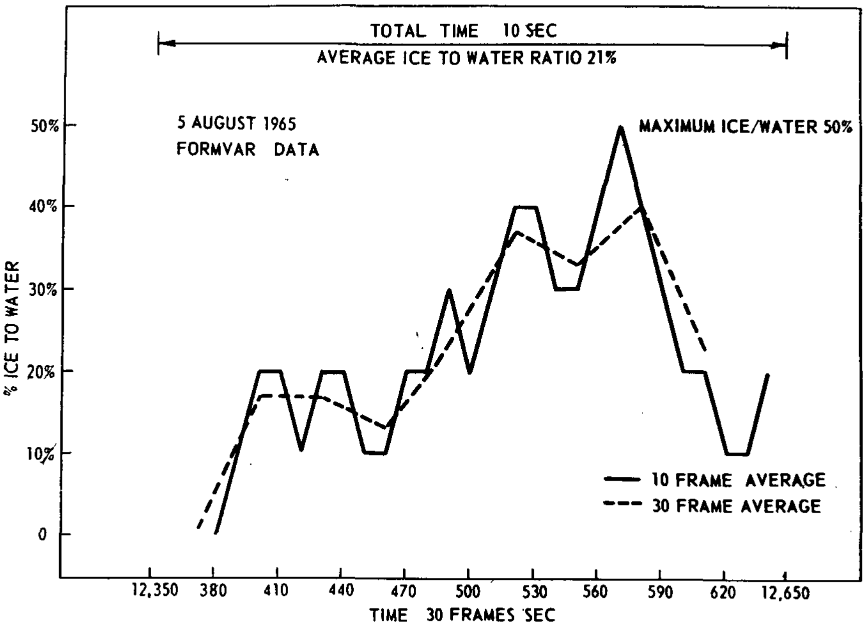

FIG. 10. Ice-to-water area percentage from Formvar data for 5 August seeded cloud. Abscissa is in frame number, 30 frames being equivalent to 1 sec or 100 m.

turret had reached the −18C level by the time of the Formvar sampling, and there is a possibility that the western turret was contaminated by ice particles filtering down from above. It is also not clear just how much of the observed ice was actually liquid freezing on impact with the cold Formvar. Although not conclusive, the presence of small pockets of up to 50% ice concentration in this cloud at −4C may be indicative of a multiplication mechanism working on a localized scale near the edges of the cloud, but not necessarily spreading throughout the entire cloud.

In any event the dynamical behavior of the two turrets works against an efficient *large scale* natural glaciation theory. According to the formvar evidence from a penetration just after seeding, the western turret was able to completely glaciate within 5 min after the silver iodide was released, and it managed to grow 10,500 ft higher than the unseeded central turret. If natural glaciation proceeded as rapidly and as extensively through tropical maritime cumuli as envisaged by the splintering model, it would be very difficult to explain the failure of the central core to grow in a similar manner as the seeded turret.

It is interesting to observe that arguments for some kind of an ice-multiplication process working on a less extensive scale and proceeding less rapidly than envisioned by Koenig can be advanced from a study of this cloud. This is especially significant in view of the fact that this was the only Stormfury case that had good Formvar replication data at the required temperature.

e. 10 August

Although the only two Stormfury clouds randomly selected for intensive study on this day were both seeded, excellent physical data were obtained on a penetration through a non-seeded cloud. Particularly noticeable in this control cloud's physical profile shown in Fig. 11 is the large volume-median size of the drops. This is consistent with observations of rain falling from cloud base during the entire 5 min it was under observation. Although the cloud topped at −11C (about −7C in the active, warm updraft core) when first observed, it quickly rained out and began to dissipate. Unfortunately, the cloud's history prior to the first observation is not known, thus making it impossible to determine the total time of supercooling and relating its behavior to the splintering hypothesis.

Good physical data were not obtained on penetrations of this day's first seeded cloud, but the second seeded case provided the profile shown in Fig. 12. First observed topping near −8C, this cloud grew 4000 ft to the −17C level in the 18 min leading up to the time of seeding. In 30 min following seeding, the cloud's growth rate accelerated as it grew an additional 14,000 ft.

The splintering calculations predict that this seeded cloud should have been 95% glaciated some 8 min before the time of seeding. However, the cloud's dynamical behavior is not consistent with such a prediction. The pronounced acceleration of cloud growth after seeding strongly implies fusion heat release through silver iodide nucleation, a condition requiring an essentially supercooled liquid state in the seeded area at the time of seeding. The large height increase of the seeded cloud again serves to point out the effectiveness of artificial glaciation under the right conditions in tropical maritime cumuli.

5. Discussion of the dynamical modeling

Although it is both useful and interesting to try to evaluate the efficiency of ice multiplication by physically and dynamically examining a cloud's life history in retrospect, a much more effective way of determining the importance of natural glaciation on cumulus modification is to predict beforehand the behavior of a certain size cloud in a given environment assuming the complete absence of natural glaciation and then testing the predictions on actual clouds. Likewise, from a suitable numerical model of cumulus dynamics it should be possible to predict the effects of seeding before the actual seeding experiment is conducted. If the clouds, after seeding, behaved as predicted by a model that assumes no natural glaciation at a temperature warmer than −15C, and if the unseeded clouds also behaved as predicted by such a model, it would be very hard to understand how natural glaciation at temperatures warmer than −15C could be a significant process in altering the dynamics of cumuli.

Two such independently developed numerical models were used to predict the behavior of all 23 clouds studied in the 1965 Project Stormfury experiments. The model used by the Experimental Meteorology Branch (EMB) of ESSA has been described by Simpson *et al.* (1965). The model used at The Pennsylvania State University (PSU) is a steady-state modification of a time-dependent model developed and described by Weinstein and Davis (1968).

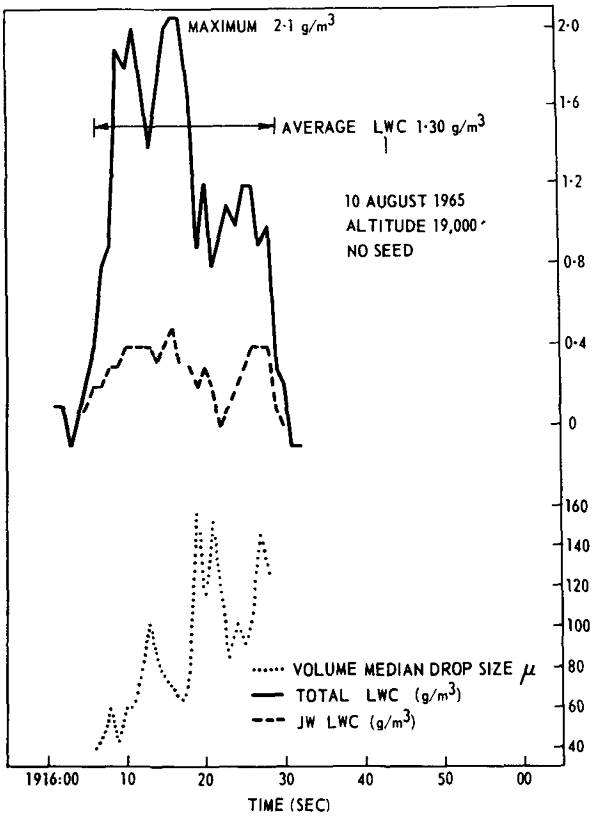

Fig. 11. Physical profile at the 19,000 ft level; 10 August control cloud.

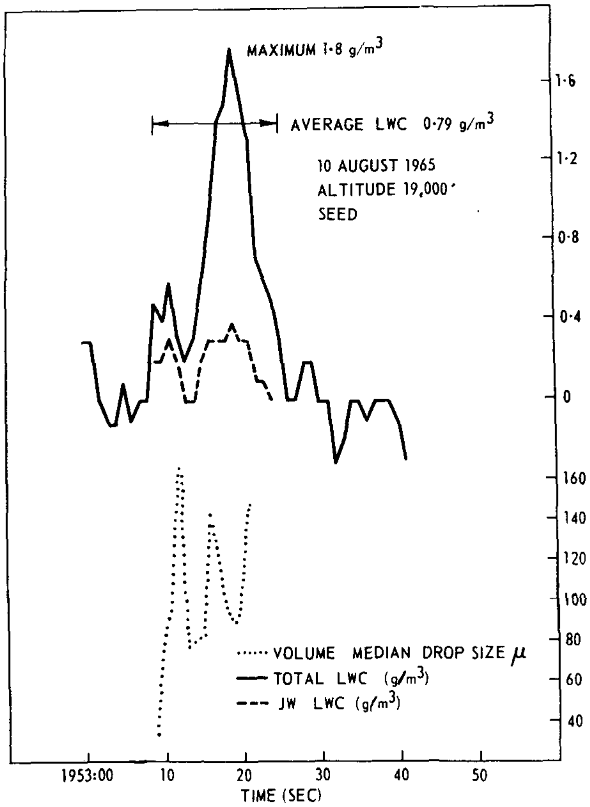

Fig. 12. Physical profile at the 19,000-ft level; 10 August seeded cloud (before seeding).

Essentially, the EMB model calculation consisted of integrating the vertical equation of motion for the rising cloud tower, which is assumed to behave as a rising plume with a vortically circulating cap, entraining environmental air at a rate inversely proportional to its horizontal dimension. The vertical acceleration of the center of the cloud tower is expressed as the difference between buoyancy and drag forces. The buoyancy force is a function of the temperature excess of the cloud over the environmental air, and is reduced by entrainment and by the weight of the condensed water within the cloud. The drag forces consist of momentum exchange from entrainment and a small aerodynamic effect. One-half of the cloud's liquid water was assumed to fall out of the cloud at each integration step. The model has recently been modified to include microphysical interactions (Simpson *et al.*, 1968).

The PSU model does not deal directly with the vertical acceleration of a cloud turret, but rather with conversion of kinetic energy to updraft velocity. The production of energy is again a function of the temperature excess of the cloud over the environmental air, the drag of the cloud's liquid water, and an entrainment parameter. A constant vertical mass flux through the cloud is assumed, thus allowing the updraft radius to be a function of the vertical velocity. The cloud's liquid water is partitioned into cloud water and hydrometeor water by assuming autoconversion and accretion rates, and all of the hydrometeor water is carried until the cloud reaches its maximum height, at which time it is released.

Although the two models approach the energetics of cloud growth from slightly different directions, the thermodynamic and entrainment calculations are handled in roughly the same manner. Both models require an environmental sounding, cloud base height, and the appropriate cloud radius as input data, and both compute cloud temperature excess, liquid water content, vertical velocity profiles, and maximum cloud height as output.

In practice, neither model assumes glaciation to occur naturally at temperatures >-15C. If the cloud were seeded, a subroutine was introduced which allowed the latent heat of fusion to be released linearly between -4 and -8C (EMB model), or completely at -6C (PSU model). Both models then assumed ice saturated conditions, thus accounting for additional warming as water vapor sublimed onto the ice instead of condensing into water.

Given an environmental sounding and the cloud base height, it was thus possible to predict cloud top heights of both the seeded and the non-seeded Stormfury clouds on both models if an in-cloud updraft radius could be chosen for the PSU model corresponding to the turret radius used in the EMB model.

6. Results of the dynamical modeling

A composite summary of the modeling results is given in Table 4. The chosen PSU model radius is an extrapolation into the cloud body of the turret radius

TABLE 4. Comparison of the EMB cumulus model with the PSU model: Results from the 1965 Project Stormfury experiments.

Time	Cloud	Action	Cld Radius		EMB Model Predict		PSU Model Predict		Obs Max Top (Km)	EMB Diff (km)	PSU Diff (km)
			EMB	(m)PSU	Unfroz Cld Ht	Seed (Km)	Unfroz Cld Ht	Seed (Km)			
28 July											
2058	1	Contr	500	1400	6·4	9·8	14·2	14·4	6·3	+0·1	+7·9
2217:30	2	Seed	550	2850	6·7	10·5	15·6	15·7	10·5	0	+5·2
2033	3	Contr	650	2000	7·8	11·9	14·9	15·1	7·4	−0·4	+7·5
29 July											
1810:30	1	Seed	1150	1700	7·6	12·4	6·6	12·1	11·6	+0·8	+0·5
1929:30	2	Contr	1100	1700	7·0	11·9	6·6	12·1	6·8	+0·2	−0·2
2044:30	3	Contr	1150	2000	7·6	12·4	8·2	12·9	7·8	−0·2	+0·4
2126:30	4	Seed	800	1350	5·4	5·4	5·2	5·2	5·4	0	−0·2
2205:30	5	Seed	800	1350	5·4	5·4	5·2	5·2	5·0	+0·4	+0·2
1 August											
2013:30	1	Seed	800	1500	6·0	6·0	5·7	5·9	6·2	−0·2	−0·3
3 August											
2158:30	1	Seed	1000	1800	9·4	11·1	10·0	11·2	11·2	−0·1	0
4 August*											
1825:30	1	Contr	950	1500	8·5	10·4	8·2	10·2	9·9	−1·4	−1·7
2144:30	2	Seed	650	1100	6·3	7·1	6·7	7·5	7·4	−0·3	+0·1
5 August											
1657:30	1	Contr	1000	1500	8·4	12·9	7·5	12·9	8·4	0	−0·9
1805:30	2	Seed	850	1250	7·0	11·9	6·3	11·9	11·0	+0·9	+0·9
8 August											
1636:30	1	Contr	1200	2300	7·2	8·6	6·1	7·0	7·0	+0·2	−0·9
1703:30	2	Seed	900	2100	6·4	6·5	5·9	6·4	6·4	+0·1	0
9 August											
1727:30	1	Contr	700	1200	8·4	9·8	8·7	11·1	8·3	+0·1	+0·4
1740:30	2	Seed	850	1250	9·5	11·2	9·2	11·4	11·2	0	+0·2
1847:30	3	Contr	1200	1400	6·8	7·5	5·3	5·3	6·5	+0·3	−1·2
1944:30	4	Seed	700	2100	8·4	9·8	13·7	13·9	10·2	−0·4	+3·7
2022:30	5	Seed	1300	2000	7·1	9·2	5·8	6·8	8·7	+0·5	−1·9
10 August											
1813:30	1	Seed	900	1300	8·6	10·6	7·9	10·2	10·2	+0·4	0
1957:30	2	Seed	1100	1500	9·7	12·0	8·3	11·2	11·4	+0·6	−0·2

* The apparent discrepancies in both models in predicting the 4 August control case could be resolved if the cloud naturally glaciated at -15C; in that case the EMB model predicts a top height of 10.0 km, while the PSU model predicts a top height of 9.8 km. The cloud grew to 9.9 km. This is the only case for modeling support for natural glaciation at temperatures >-15C.

used by the EMB model. Although admittedly this is a very subjective technique, it was performed prior to the model calculations to eliminate bias.

As can be seen from Table 4, the PSU model cloud top heights were generally in good agreement both with those predicted by the EMB model and with the actual observed cloud heights, with the notable exception of the three clouds on 28 July. A careful re-examination of the cloud photographs for this day revealed that the radii chosen for the PSU model were almost a factor of 2 too large, and this error was compounded by an unstable environment above 20,000 ft which allowed very buoyant clouds at that level to grow naturally all the way to the tropopause. Because the cloud's buoyancy, computations are a function of entrainment, which in turn is a function of the cloud's horizontal dimension, the error in choosing the cloud radii on this day was critical and caused the PSU model to overpredict cloud growth by an embarrassing 50%.

The statistical results of the modeling are graphically portrayed in Figs. 13 and 14. If the EMB model predictions are compared with the observed maximum heights of all 23 Stormfury clouds, a correlation coefficient of 0.98 is established by the results. Excluding the three clouds on 28 July from the analysis, the correlation coefficient between the PSU model predictions and the observed maximum height of 20 Stormfury clouds is 0.92.

Such results strongly imply that natural glaciation does not affect the dynamical behavior of tropical maritime cumuli, at least at temperatures >−15C. Only for one cloud (control case of 4 August) do both models predict cloud heights better if natural glaciation is assumed at −15C. Using a slightly different technique of analyzing the results of the model predictions, Simpson *et al.* (1967) demonstrate a very good correlation between seeding and growth which strongly indicates that natural glaciation is not nearly as efficient as artificial seeding by silver iodide in modifying the dynamical behavior of tropical maritime cumuli.

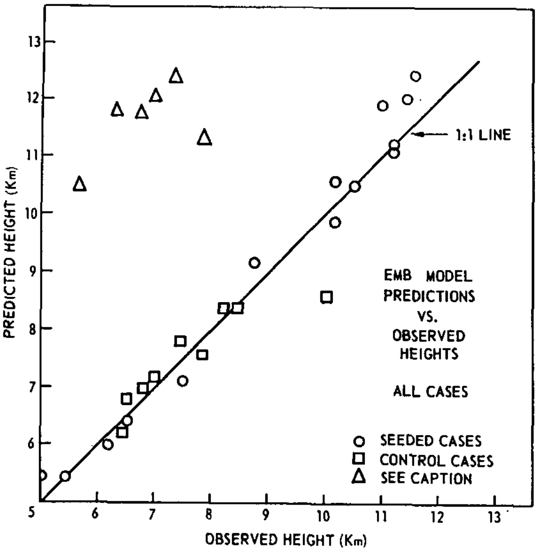

Fig. 13. Experimental Meteorology Branch (EMB) model predicted cloud top heights vs observed cloud top heights for all 23 Stormfury clouds. The correlation coefficient is 0.98. The triangular symbols give the EMB model predicted cloud top heights for natural glaciation at −8C (of the extent predicted by the splintering model) vs the observed cloud top heights. Only the six Stormfury clouds with long, documented life histories and good microphysical data cloud were used in this particular analysis. The correlation coefficient between predicted heights and observed heights for these six cases is a rather poor 0.43, indicating that the splintering model glaciated these clouds too rapidly.

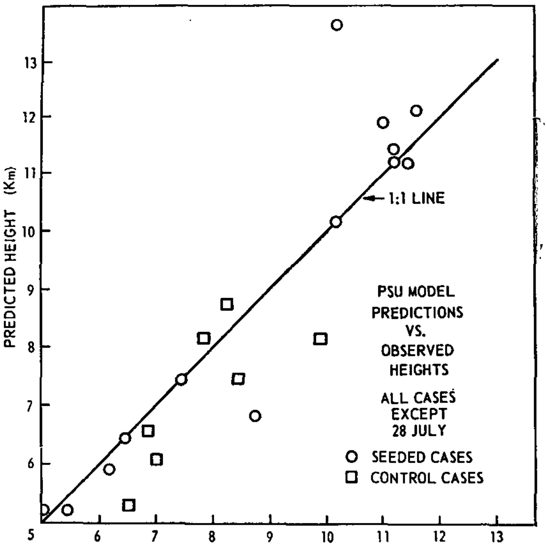

Fig. 14. Pennsylvania State University (PSU) model predicted cloud top heights vs observed cloud top heights; three cases on 28 July excluded from analysis. The correlation coefficient for these 20 clouds is 0.92.

7. Summary and conclusions

In order to test the validity of Koenig's (1966) ice splintering model, and in order to determine if natural glaciation is important enough in tropical maritime cumuli to influence modification attempts by silver iodide seeding, a detailed study was made of cumuli observed during the 1965 Project Stormfury experiments. Physical data involving the water and temperature profiles within the clouds were analyzed, and dynamical studies were initiated on two independently developed numerical cumulus models.

In the physical analysis it was found that all of the seeded clouds studied grew at least 10,000 ft higher than a paired control cloud in the same environment, thus indicating a strong cause-and-effect relationship between seeding and growth. A very strong correlation between seeding and growth was later confirmed in the dynamical analysis. Some direct evidence of partial glaciation in a cloud topping at no colder than −5C was found, but all of the clouds behaved dynamically in a manner indicating that their vital updraft areas did not glaciate as rapidly as predicted by the splintering model. The evidence suggested that the updraft core of a typical tropical maritime cumulus cloud can remain in a supercooled liquid state at temperatures of −10C and colder for periods ≥ 20 min, and natural glaciation in such a cloud is not extensive enough to significantly influence its dynamical behavior. On the other hand, the results of the study indicate that artificial glaciation induced by silver iodide seeding is an effective means of modifying the dynamical behavior of such clouds by converting the cumulus updraft areas from supercooled water to ice at temperatures ≲ −5C.

The primary conclusion to be drawn from this study is that natural glaciation does not proceed rapidly and/or extensively enough in the critical cloud updraft areas to alter the effectiveness of modifying tropical maritime cumuli by causing artificial glaciation with silver iodide.

8. Future studies

Evidence now suggests that the occurrence of ice in clouds topping at temperatures near −10C is far more prolific than can be explained by assuming a one-to-one relationship with active freezing nuclei. From the results of this study, however, apparently the ice is not evenly distributed throughout the cloud body, as the vital updraft areas remain essentially supercooled liquid for long periods of time. It is possible that some kind of an ice-multiplication mechanism may be able to work near the cloud edge to glaciate local pockets, but cannot work effectively in the wetter updraft core.

A better physical understanding of the behavior of freely-falling freezing water droplets in realistic atmospheric conditions is essential to the interpretation of an ice-multiplication mechanism. It now seems likely that the original laboratory work on splintering performed by Mason and Maybank (1960) may have greatly overestimated the efficiency of such a mechanism in the free atmosphere. Both Dye and Hobbs (1968) and Johnson and Hallett (1968) have failed to find copious splintering under more reasonable atmospheric conditions using rather large (1 mm) suspended drops, but more work now needs to be concentrated on both the freezing of small droplets in free fall and the importance of a riming mechanism on ice multiplication.

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REFERENCES

Averitt, J. M., and R. E. Ruskin, 1967: Cloud particle replication in Stormfury tropical cumulus. *J. Appl. Meteor.*, **6**, 88–94.

Dye, J. E., and P. V. Hobbs, 1968: The influence of environmental parameters on the freezing and fragmentation of suspended water drops. *J. Atmos. Sci.*, **25**, 82–96.

Gokhale, N. R., 1965: Dependence of freezing temperature of supercooled water drops on rate of cooling. *J. Atmos. Sci.*, **22**, 212–216.

Johnson, D. A., and J. Hallett, 1968: Freezing and shattering of supercooled water drops. *Quart. J. Roy. Meteor. Soc.*, **94**, 468–482.

Koenig, L. R., 1963: The glaciating behavior of small cumulonimbus clouds. *J. Atmos. Sci.*, **20**, 29–47.

——, 1966: Numerical test of the validity of the drop-freezing/splintering hypothesis of cloud glaciation. *J. Atmos. Sci.*, **23**, 726–740.

——, 1968: Some observations suggesting ice multiplication in the atmosphere. *J. Atmos. Sci.*, **25**, 460–463.

Latham, J., and B. J. Mason, 1961: Generation of electric charge associated with the formation of soft hail in thunderclouds. *Proc. Roy. Soc.* (*London*), **A260**, 537–549.

Levine, J., 1965: The dynamics of cumulus convection in the trades: A combined observational and theoretical study. Woods Hole Oceanographic Institution, Ref. No. 65-43, 129 pp.

Mason, B. J., and J. Maybank, 1960: The fragmentation and electrification of freezing water drops. *Quart. J. Roy. Meteor. Soc.*, **86**, 176–186.

Mossop, S. C., R. E. Ruskin and K. J. Heffernan, 1968: Glaciation of a cumulus at approximately −4C. *J. Atmos. Sci.*, **25** 889–899.

Murgatroyd, R. J., and M. P. Garrod, 1960: Observations of precipitation elements in cumulus clouds. *Quart. J. Roy. Meteor. Soc.*, **86**, 167–175.

Ruskin, R. E., 1967: Measurements of water-ice budget changes at −5C in AgI-seeded tropical cumulus. *J. Appl. Meteor.*, **6**, 72–81.

Sax, R. I., 1967: Natural and artificial glaciation of tropical cumuli. NSF Rept. No. 9, Dept. of Meteorology, The Pennsylvania State University, 85 pp.

Simpson, J., 1967: Photographic and radar study of the Stormfury 5 August 1965 seeded cloud. *J. Appl. Meteor.*, **6**, 82–87.

——, G. W. Brier and R. H. Simpson, 1967: Stormfury cumulus seeding experiment 1965: Statistical analysis and main results. *J. Atmos. Sci.*, **24**, 508–521.

——, R. H. Simpson, D. A. Andrews and M. A. Eaton, 1965: Experimental cumulus dynamics. *Rev. Geophys.*, **3**, 387–431.

——, V. Wiggert and T. Mee, 1968: Models of seeding experiments on supercooled and warm cumulus clouds. *Proc. First Natl. Conf. Weather Modification*, Amer. Meteor. Soc., Albany, N. Y., 251–269.

Weinstein, A. I., and L. G. Davis, 1968: A parametrized numerical model of cumulus convection. NSF Rept. No. 11, Dept. of Meteorology, The Pennsylvania State University, 44 pp.

Wexler, R., and R. J. Donaldson, Jr., 1966: The spread of ice in cumulus clouds. *J. Atmos. Sci.*, **23**, 753–756.