Measurements of Water-Ice Budget Changes at -5°C in AgI-Seeded Tropical Cumulus

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ABSTRACT

During the 1965 Project Stormfury experiments a combination of six cloud physics aircraft instruments were used to measure the changes in the water-ice budget in a large tropical cumulus which had been seeded. Pyrotechnic "Alectos" were used to produce an estimated 180 AgI nuclei per liter effective at -5°C in the seeded area. Measurements showed an 80 per cent conversion to ice at the -5°C level (17,000-ft pressure altitude) in a 1 km region of the cloud 5 min after seeding, together with a 1.5°C rise in temperature. At the same time the adjacent unseeded region of the same cloud decreased in percentage ice at that level, but increased about the same amount in temperature, probably because of increased updraft induced by the heat of fusion energy released in the seeded region.

On two passes 10 min apart a 300-m length of "wisp" visible outside the main cloud produced many 10–20 μ replicas of ice particles in air which had a measured 75 to 90 per cent relative humidity, including the moisture from the cloud particles which were vaporized in an instrument which measures the cloud total water content.

1. Introduction

For several years one important phase of the hurricane modification project Stormfury (Malkus and Simpson, 1964; Simpson *et al.*, 1965) has been an attempt to increase the state of knowledge of the dynamics and cloud physics of tropical cumulus clouds, particularly as they may relate to the understanding of hurricane processes. Toward this end a series of experiments was conducted to study the effects of seeding the supercooled tops of tropical cumuli during the summer of 1965. Comparison of all of the clouds studied in the 1965 project, the randomization methods used, and the resultant observations are reported by Simpson *et al.* (1966).

Publications will be made by other investigators who are making detailed analyses of many aspects of the 1965 Stormfury cumulus experiments and by the Naval Research Laboratory (NRL) group concerning other phases of tropical cloud physics. In one of two accompanying papers in this issue, cloud ice replication is discussed by Averitt and Ruskin (1967); in the other, Simpson (1967) presents the cloud-growth data and preliminary analysis of the related cloud dynamics of the 5 August 1965 seeded cloud. The present paper discusses the changes in ice, water, and precipitation which were measured before and after seeding of the 5 August cloud.

2. General experimental procedure

The general flight procedures followed were essentially the same as those of the 1963 cumulus experiments described in the references cited above. The August 1965 experiments were conducted over the open ocean about 300 mi south of Puerto Rico. Aircraft of the U. S.

Weather Bureau and U. S. Navy made observations by radar and photography from outside the chosen cloud and measurements inside the cloud at several altitudes, at cloud base, and above the cloud top. The U. S. Air Force made dropsonde soundings of the clear environment as shown in Fig. 1. (An aircraft sounding made near a cloud is superimposed on the same tephigram.)

The cloud of interest is shown in the center of Fig. 2. At the time of this photo (6 min before seeding) the vertical "pack" of four cloud-penetration aircraft had just completed its first monitoring pass from west to east (right to left in the photo) through the line of cloud cells.

An A3B jet seeding aircraft of the Naval Ordnance Test Station, China Lake, Calif., crossed near the cloud top at 23,500 ft pressure altitude on a south-to-north pass and dropped 16 burning "Alecto" pyrotechnic silver iodide generators into the west cell of the cloud at 100-m intervals. Five minutes later the monitoring aircraft "pack" made an east-to-west pass and repeated the penetrations for a total of 7 passes at 7–8 min intervals until about 40 min after seeding.

One of the NRL aircraft participated as a cloud-monitoring plane. Several cloud physics instruments which had been under development were operated in combination for the first time. By inter-comparison of the data from the various instruments, information was deduced to describe the cloud water budget in terms of the amount of water in small cloud droplets, large precipitation drops, and small and large ice crystals.

The altitude of the NRL aircraft flights was chosen to provide maximum detail in the region slightly colder than freezing in order to determine as much as possible about the microphysical changes which might relate

FIG. 1. Tephigram showing 5 August 1965 USAF dropsonde sounding in clear (probably subsiding) area 300 mi south of Puerto Rico and an aircraft sounding near a cloud 100 mi farther north.

to the effects of silver iodide seeding, and which could not be measured by the instrumentation available on the other participating aircraft.

In the case of the cloud seeded on 5 August the changes in water-ice budget at 17,000 ft altitude (-3 to -5°C) were determined in a line of cloud cells before and after the seeding of one cell of the line. These data, when combined with photos, radar records, and data from several aircraft flying simultaneously at higher and lower altitudes, provide a relatively complete documentation of the cloud changes.

In contrast to the growth of the seeded cloud to 35,000 ft, no others observed on this day grew much above 27,000 ft, and few reached that high. Most of the clouds which were penetrated exhibited a tendency similar to the seeded cloud to have considerable variability in the amount of ice present at the 17,000-ft level, this variability persisting throughout the life of the cloud.

3. Characteristics of "Alteco" AgI generators

Detailed investigation of the "Alteco" pyrotechnic AgI generators and their nucleating efficiencies have been under way for several years. Results of these studies will be published by the various investigators as soon as possible. However, in order to permit better evaluation of the findings reported in this paper in line with the comments by Vonnegut (1966) and others, a summary of the "Alteco" characteristics is included here, based on personal communications regarding the incomplete studies by Dr. Pierre St.-Amand of Naval Ordnance Test Station, China Lake, and Dr. Lewis Grant, Colorado State University.

The "Alteco" configuration is shown by St.-Amand and Donnan (1963) in their Fig. 3. Its basic dimensions are 7.5 cm diameter and 20 cm long; its weight is 3.2 kg including 2 kg of pyrotechnic propellant mix. Several units are mounted aboard an aircraft in a standard

FIG. 2. The tropical cumulus cloud after the first aircraft monitoring pass, 6 min before seeding. The top was at 27,000 ft; the cell to be seeded (at the right side in this view) was at about 24,500 ft. An unsaturated "wisp" is at the upper left of the main cloud.

photoflash flare launcher, from which they can be launched in rapid sequence. When the propellant is ignited it forces the unit out of the launcher and propels it in an erratic "zig-zag" trajectory as it falls. It continues to burn for about 40 sec, while falling about 20,000 ft.

The pyrotechnic propellant material is compounded so that about 3/4 of its original weight is contained in the resultant AgI smoke. The basic ingredients are silver iodate and aluminum in a "synthetic rubber" binder of polybutadiene cross-linked with acrylic acid. In the combustion process the silver iodate is decomposed to iodine, free oxygen, and small liquid droplets of silver. Part of the free oxygen combines with the aluminum to form an oxide and the remainder combines with the binder to form water vapor and other combustion products. The relative amounts of combustion taking place in the metals and in the binder control the burning temperature, hence the particle size of the AgI smoke which is formed by recombination of the free silver and iodine. The molecular ratio of the latter is optimized to achieve an essentially complete conversion.

Effectiveness of the AgI particles in acting as freezing nuclei for supercooled water droplets at various temperatures from freezing to -20°C has been investigated using the recently developed calibrating equipment at Colorado State University. In this equipment temperature and water vapor are controlled to produce a supercooled cloud in a refrigerated chamber which is in the form of a cylinder of about 3 m^3 volume. Known amounts of various ice-nucleating materials are in-

troduced into the chamber and the resulting ice crystals are collected on sampling slides and counted.

For the "CY21 Alecto" used in the seeding experiment of 5 August 1965, the still incomplete tests at Colorado State University with the present best estimate of the correction for coagulation in the test system indicate that the numbers of freezing nuclei per gm of AgI are 1.5×10^{15} effective at -20°C , 5.3×10^{13} at -10°C , and 6.5×10^{10} at -5°C .

If the smoke were distributed uniformly through 6 km of fall, 1.7 kg of AgI would provide 0.3 gm m^{-1} of altitude, or about 180 nuclei liter $^{-1}$ for those nuclei which are effective at -5°C , assuming each "Alecto" covered uniformly $100 \times 1000\text{ m}^2$ of horizontal area. For the upper portion of the cloud with a cloud-top temperature of -18°C , the nuclei concentration would be about four orders of magnitude higher.

4. NRL aircraft instrumentation

The primary instruments providing the data which have been combined to obtain the water-ice budget changes are as follows:

Total water content instrument. The total water content instrument consists of a water (and ice) evaporator coupled to an ultraviolet (Lyman alpha) spectral-absorption water-vapor-density sensor (Ruskin, 1965). This instrument and the others requiring cloud droplet sampling were mounted one meter below the wing and sufficiently removed from the fuselage to reduce the effects of aerodynamic sorting of the drops.

FIG. 3. Schematic view of cloud total water evaporator and Lyman-alpha spectral sensor to measure the resultant total water vapor density with an overall time resolution of 30 msec.

A schematic view of this instrument is shown in Fig. 3.

The evaporator has been developed to provide a minimum of air flow restriction, and to provide a maximum collection efficiency for droplets in a loose maze of fine screens intermixed with a heating element which is distributed throughout the evaporator housing. The heating element is maintained somewhat below the boiling temperature of water in order to avoid "bouncing" and to obtain maximum spreading of the water over the hot surfaces. The resulting fast evaporation combined with the low restriction to the air flow permits passage of a given parcel of air through the evaporator in about 0.01 sec while providing about 98 per cent–99.5 per cent evaporation. The aerodynamic characteristics of the probe are such that the pressure in the entry is approximately equal to free-stream static pressure. This geometry provides an essentially isokinetic entry of small and large particles of both water and ice with a minimum of modification of their natural size distribution ahead of the entry. An entry diameter of 1 cm was chosen in order to provide a sufficiently large sample volume to approach being statistically representative for the larger hydrometeors. A knowledge of the flow rate is needed only if numbers of large drops per unit volume is desired.

After passing through the evaporator, the cloud sample passes through the beam of a glow discharge tube producing the Lyman-alpha line in the hydrogen ultraviolet at 1215.6 Å. This spectral line is so highly absorbed by water vapor that the light is reduced to $1/e$ in 0.5 cm of path length by water vapor density equivalent to a dew point of 0°C (Tillman, 1965). Measurement of the absorption of the Lyman-alpha radiation provides a record of the water vapor density (which is now the total water of the original cloud sample). The response time of the Lyman-alpha sensor is about 3 msec.

For the overall instrument, distance resolution of cloud water changes along the flight path is about 3 m at an aircraft speed of 100 m sec⁻¹. The fast-response characteristic of the instrument is demonstrated by the fact that individual precipitation particles larger than about 300 μ radius can be identified on the record from the instrument. Fig. 4 shows an example of a flight

record with a chart speed of 0.5 sec per chart division. The right hand event mark indicates large precipitation drops on the windshield and generally agrees with the bursts of "spikes" on the Lyman-alpha record. The vapor density increase resulting from the evaporation of a drop as large as 1–2 mm usually reaches a maximum in about 0.03 sec and is evident for a total time of only about 0.1 sec. Since about 10 liters of sample air pass through the instrument per second, individual spikes from large drops with concentrations up to 1000 m⁻³ can be measured when superimposed on the "steady" level of water content contributed by the cloud droplets.

Thermoelectric dew-point hygrometer. The Lyman-alpha measurement of water vapor density is affected by the sample air density, which varies with altitude pressure and sample temperature. In order to determine easily the absolute vapor density, the spectral absorption detector is calibrated during clear-air portions of the flight in terms of dew point as recorded from a thermoelectrically cooled automatic dew-point hygrometer (Ruskin, 1965).

During this series of flights the hygrometer sample was admitted through a "reverse-flow" entry at the rear of the airfoil with the aim of measuring the dew point of the water-free air in clouds. It was later determined that the liquid water was only partially rejected; therefore, only the dew-point hygrometer data taken in clear air could be used. In clouds the readings indicated that part of the cloud water was being measured, thus precluding use of those data for either a "dry" or total water calibration at those times. A more satisfactory arrangement used on some other flights introduces a portion of the evaporated sample into the dew-point sensor to provide continuous total-water calibration.

Axial-flow vortex thermometer. In order to deduce liquid water content from a record of the total of water vapor and liquid, the saturation water vapor density of the cloud must be known. The assumption is made that the cloud air is usually saturated (or that the cloud air dew point equals the cloud temperature). Cloud temperature is measured by the NRL-developed axial-flow vortex thermometer (Ruskin *et al.*, 1952). Insofar as has been determined, these temperature

FIG. 4. Flight record at 17,000 ft; chart speed of 0.5 sec per division to permit resolution of the individual raindrops in the left hand trace of the Lyman-alpha measurement of cloud total water. Cloud entry is at the bottom; exit near top of record.

measurements are reliable except under prolonged icing conditions and for a short time after entering the unsaturated air upon leaving rain or a cloud cell. In the fast-response model used on the flights discussed here, evaporation of water which had been condensed on the thermometer element while in the cloud causes up to 3C cooling for only 5–10 sec after leaving a cloud. This error will be referred to as the wet-bulb error. Cross-checking the times of leaving a cloud cell by reference to the total water record provides a means of identifying the 5–10 sec intervals that this wet-bulb error affects the temperature record. For the standard model vortex thermometer a longer time interval is required to recover from the wet-bulb error.

Ultraviolet optical extinction recorder. A further cross-check of cloud entry and exit times is provided by a 30-msec response optical-extinction recorder utilizing a 20-m path length between a mercury light on a wing tip and a photomultiplier type of detector mounted in the upper radome on the fuselage. In order to reduce the effect of sunlight entering the detector at certain flight attitudes with respect to the sun, the light is modulated and the detector is tuned to the modulation frequency. Also, the 2537-Å UV line of the mercury spectrum

(essentially outside the solar spectrum) is used with a “solar blind” optical filter at the detector. This wavelength is short enough so that the Mie extinction efficiency factor is essentially constant for all cloud droplets which are larger than about 1μ radius. The extinction is related to droplet radius r and droplet number per unit volume n by the relationship

$$I = I_0 \exp(-Q_{\text{ext}} \pi r^2 n L), \quad (1)$$

where

I = light intensity at the detector in cloud,

I_0 = light intensity at the source (equal to that at the detector in clear air), I/I_0 being the fractional transmission and $(1 - I/I_0)$ the fractional extinction,

Q_{ext} = Mie extinction efficiency factor (approaches the value 2 for droplets with radius larger than about 4 times the light wavelength), and

L = path length from source to detector.

The liquid water content W per unit volume of air is given by

$$W = (4/3) \pi r^3 n. \quad (2)$$

By combining the extinction measurement and liquid water content data one can calculate roughly the number of droplets per unit volume and the radius that each would have if they were in an imaginary homogeneous cloud having the same water content and total surface area as the actual heterogeneous cloud. This value of radius is often referred to as the "volume-surface mean radius" or "Sauter mean radius." Random fluctuations of light level cause an uncertainty of about ± 3 per cent extinction.

Hot-wire liquid water recorder. A Johnson-Williams hot-wire type liquid water content meter (Neel, 1955) provides a continuous direct-reading record of water content of the small cloud droplets. The larger drops contribute little to the indicated water content, the error increasing with increasing drop size, as concluded by Barrett (1958). Ice particles are essentially non-detectable; and continued flight through heavy precipitation appears to cause a small negative indication. However, an instrument of this type is valuable as a simple means of providing immediately usable data. Its size-discriminating characteristic can be useful when used in conjunction with other instruments.

Cloud particle replicator. An NRL version of the continuous cloud particle replicator described by MacCready and Todd (1964) is discussed in the accompanying article by Averitt and Ruskin (1967). This instrument provides information as to types of ice crystals present in the cloud and a semi-quantitative estimate of the relative amounts of ice and water with a distance resolution of about 1 m at 200 mph. Reliable quantitative data is restricted in this instrument because of the uncertainties of collection efficiency, coalescence on the film, and shattering at the edges of the entry port impact with the film. However, the information on ice processes obtainable with this instrument provided the key answers for much of the present study.

5. Flight measurements

In the case of the Stormfury seeded cloud of 5 August 1965 the "pack" of four monitoring aircraft flew with one plane at the cloud base, and one each at 10,000, 17,000 and 19,000 ft (pressure altitude). They made seven cloud penetration passes at about 7-min intervals.

The flight data for the first two penetrations of the NRL plane at the 17,000-ft level are shown in Fig. 5 as a composite of the pertinent recorder traces together with data deduced from analysis of the cloud particle replicator plotted on the same time scale. The first cloud pass (before seeding) which started at 1759 GMT is shown at the bottom of the chart. This pass was made from west to east. The first (bottom) 12 sec on the chart is labeled to show the west cell. Six minutes later (at a time labeled 1805:30 near the center of Fig. 5) this west cell was seeded, with the seeding plane crossing south to north on a line perpendicular to the line of cells. At that time the original west cell appeared

on the photos to have expanded horizontally from its original 1.25 km to about 1.6 km (Simpson, 1967). During the time of the seeding run the monitoring aircraft were completing a circle east of the cloud preparatory to the after-seeding penetration.

Near the top of the chart is shown the first pass after seeding, labeled "Second Monitor Penetration." Since this pass was made from east to west, data for the seeded region are at the top of the record labeled "West 1.25 km." At this time the boundaries of the original cells had become indistinguishable, but the aircraft data indicate that the west 1 km was different in several respects from the rest of the cloud.

Referring to the various traces of Fig. 5, trace (a) indicates that visual observation of heavy precipitation on the windshield (event mark traces) correlates quite well with regions of the cloud evaporator Lyman-alpha trace (c) showing large drops.

In order to facilitate reduction of the data on evaporated total water and ice, the temperature trace (b) is shown superimposed over the cloud evaporator record (c). An indication of a reduced temperature resulting from the wet-bulb error is apparent only between the two west cells during the first pass and again when leaving the cloud after the second pass. A warming occurs throughout much of the second pass, 1–2.5°C in the central 2 km and 1–2°C in the west 1 km.

The total water content record, trace (c), extends beyond the recorder calibration lines when in clear air. The equivalent dew-point values for the vapor densities measured are shown below the chart. The water content values are tabulated in the first line of Table 1. This record indicates a maximum of 2.4 gm m^{-3} and average of 2 gm m^{-3} in the west 1.25 km on the pass before seeding and 2.8 and 2.4 gm m^{-3} , respectively, on the pass after seeding. The central 2 km on the first pass shows 1.4 maximum and 0.6 gm m^{-3} average (including two intervals of 100 m each unsaturated), and on the second pass 1.8 maximum and 1.7 gm m^{-3} average with less variation. The western 3 km exhibited increased numbers of large drops or graupel on the pass after seeding.

The Johnson-Williams liquid water content instrument, curve (d), responds primarily to the small droplets. Its water content values are tabulated in the second line of Table 1. This instrument in the west 1.25 km showed on the first pass an average value of about one-third of that indicated by the total-water instrument, and only one-twentieth on the second pass (when more of the total water was in large drops and ice.) In the central region of the cloud the Johnson-Williams meter on the first pass shows an average equal to about half that of the total-water instrument and one-eighth on the second pass, indicating an increase in large drops. The reduced response of the Johnson-Williams instrument with larger drops is demonstrated when, on the first pass through the west cell, it shows a dip for 3 or 4 sec coinciding with a burst

of large drops as indicated by the cockpit event marker and the total-water instrument.

The percentage of extinction in a 20-m path is shown in trace (e). As can be deduced from Eqs. (1) and (2), the ratio of cross-sectional area of water droplets to volume of the droplets increases with decreased droplet size; therefore, the extinction of the light beam also increases with decreased droplet size for a given liquid water content.

The small number of 0.5–1 mm radius hydrometeors appearing in the total-water record (about 3 to 10 sec⁻¹ or 300–1000 m⁻³) results in an extinction of 0.5–5 per cent in the 20-m path extinction instrument during the “heavy precip” portions of the clouds in which these hydrometeors constitute as much as 50 per cent of the total liquid water and ice.

The similarity of the extinction record and the Johnson-Williams record further indicates that the

TABLE 1. Changes in water-ice budget (all quantities in gm m⁻³).

	Seeded (west) portion (1-1.25 km)				Central 2 km			
	1759 GMT pass		1810 GMT pass		1759 GMT pass		1810 GMT pass	
	Average	Maximum	Average	Maximum	Average	Maximum	Average	Maximum
Total water and ice	2.0	2.4	2.4	2.8	0.6	1.4	1.6	1.8
20-35 μ average radius droplets	0.6	0.8	0.1	0.15	0.3	0.75	0.2	0.3
Large drops and graupel	1.3	1.5	1.3	1.6	0.2	0.35	1.35	1.4
Large drops liquid water	1.3	1.5	0.8	1	0.1	0.15	1.3	1.3
Graupel ice	~ 0	~ 0	0.5	0.6	0.1	0.2	0.05	0.1
Small ice	0.1	0.1	1.0	1.05	0.1	0.3	0.05	0.1

latter instrument also responds primarily to the small droplet portion of the size spectrum in these clouds. Therefore, the Johnson-Williams record can be used as a quite good representation of the small droplet portion of the water budget.

The particle replicator films have been analyzed primarily for relative changes in the total area covered by replicas of liquid water and ice, curve (f), and ice images only, curve (g). Numbers for three size classes of graupel or large water drops have been estimated in curves (h) within the rather large limits of error inherent in the instrument due to shattering. These curves are shown in terms of number per liter of air (assuming 100 per cent collection efficiency) for images larger than 2.5 mm diameter, larger than 1.2 mm, and larger than 0.6 mm. Uncertainty remains as to whether the smaller images resulted from smaller drops or from large drops which shattered on impact on the film or during entry by overlapping the edge of the entry port. The sizes of the large drops have been estimated from the evaporative total water instrument and from windshield observations to be approximately 0.6-2 mm diameter. The number of drops in this size range, about 300-1000 m⁻³, roughly follows the dotted curve in (h) of the number of images greater than 2.5 mm diameter.

While not bearing directly on determination of the water budget, curve (i) of Fig. 5 is presented as an aid in hypothesizing the overall conditions of the upper portion of the cloud. Most of the small ice in the cloud appeared as round images, 8-15 μ in diameter, or irregular shapes somewhat larger, as shown in Fig. 6. These irregular shapes may have all resulted from shattering of larger crystals, including thin-wall hexagonal columns 150 μ across. Because of the shattering problem, no data are plotted for numbers of ice particles; instead, curve (i) is a plot of totalized lengths per liter of air for identifiable fragments which appear to have originally been parts of round needles (usually 5-20 μ diameter) or round and hexagonal columns, some of which were hollow (usually 40 to 60 μ across). Examples of these replicas are shown in the accompanying article (Averitt and Ruskin, 1967). Near the bottom of the upper section of curve (i) increased amount of ice in large crystals in the region of the east (oldest) cell includes many hollow columns which may have formed at the colder temperature of higher altitudes (Kobay-

ashi, 1958), or at -4 to -6C as suggested by Hallett (1965).

Data indicating an unsaturated condition were recorded in a 300-m length of the cloud which appeared visually to be a "glaciated wisp," visible in Fig. 2 just outside and at the upper left of the main cloud. At the end of the first cloud pass and again just prior to penetration on the second pass the total water record, trace (c) shows a "hump" in which the equivalent dew point of the evaporated sample is about 5C above the dew point of the clear-air environment, but 1-4C below saturation temperature in the cloud (corresponding to 75 to 90 per cent relative humidity including the vaporized cloud). These regions coincide with areas appearing on the particle replicator film in which appreciable water and/or ice are indicated. The per cent ice in trace (g) may be underestimated in this region since considerable uncertainty exists in distinguishing between ice and water because almost no "blush" was present on the film as it usually is in saturated clouds (Averitt and Ruskin, 1967). In the unsaturated wisp the per cent ice may have been anywhere between the solid and dashed curves of trace (g). On both passes the temperature in this unsaturated cloud was about 0.5C below that of the environment,

FIG. 6. Replicas from the seeded west 1 km on the first pass after seeding, showing nearly all ice. The small ice particles are the same size and appearance as most had been in the older portions of the cloud before seeding. The larger particles are probably shattered parts of larger crystals.

probably indicating a cooling of the cloud by evaporation of the hydrometeors.

In addition to the two cloud transits shown in Fig. 5, five more data passes were made at 7–8 min intervals. Throughout most of the second pass after seeding the cloud was more than 90 per cent ice. On later passes the ice changes at this altitude were more erratic with random patches of ice and supercooled water throughout the interval of 40 min after seeding. On all of these passes the cloud temperature was 0–0.5°C colder than the environment air.

6. Summary of water budget changes

The principal data discussed are summarized in Table 1 in terms of a water and ice budget for the (west) seeded region before and after seeding as compared to the adjacent (central) 2 km of the cloud for the same times. In Table 1 the “Total water and ice” values are deduced from the NRL total-water instrument, column (c) of Fig. 5. The size estimate of the “20–35 μ average radius droplets” covers the range of volume-surface mean radii in the various cloud regions as deduced from the Johnson-Williams vs. 20-m extinction measurements; their tabulated liquid water values are from the Johnson-Williams instrument, column (d) of Fig. 5.

The values of “Large drops and graupel” are estimated from a cross-comparison of the “spikes” on the evaporator record, the 2.5 mm image curve of Fig. 5, column (h), and the difference between the liquid water contents from the Johnson-Williams hot-wire instrument and those from the NRL total-water instrument. The values of “Large drop liquid water” and “Graupel ice” are deduced from estimates of the fractions of the graupel images which are ice and water, respectively.

The values of “Small ice” were deduced from the totalized area of ice images on the “Formvar” replicator exclusive of the ice in graupel and in round or hexagonal columns.

7. Discussion

The data presented herein provide at least semi-quantitative information as to some of the physical and microphysical changes which occurred at the –3 to –5°C altitude after seeding one cell of a large tropical cumulus cloud consisting of a row of several cells. While conditions are never identical in any “matched pair” of convective clouds, this condition was approached in the present case by comparing measurements in two adjacent cells of the same cloud. This cloud proved to be unusually suitable for comparison of cell developments since the line of cells had considerable crosswise (north-to-south) slope due to vertical wind shear as can be seen in Fig. 8 of Simpson (1967); therefore, the effect of precipitation “washing out” the

lower portion of the cloud as discussed by Saunders (1965) was minimal and roughly equal for all cells. This “washout,” which limits the life of most large tropical cumuli, was sufficiently reduced in this cloud (due to the slope) so that moisture feeding into the base on the upwind side permitted continued cloud growth even while all cells were raining out. Therefore, data was obtainable for a longer time than is possible for most similar clouds.

Measurements by Simpson (1967) of the radar and cloud photos show close agreement with cloud top observations made by the seeding aircraft on several passes at the altitude of the top. These measurements indicate that the seeded cell of the cloud maintained a growth rate of about 1000 ft min⁻¹ from 4 min before seeding to 7 min after, with a momentary decrease in rate at about the time of seeding. During the 40-min interval of monitoring aircraft penetrations, this portion of the cloud grew from about 24,000 to 36,000 ft before dissipating to an altitude below freezing level.

The NRL measurements indicated more complete freezing of the west 1 km of the seeded compared to the unseeded region for this cloud. The temperature of the central 2-km region warmed 1–2.5°C between the pre-seeding pass and the pass 5 min after seeding. The west 1 km of the seeded portion also warmed, but about 0.5°C less, even though it had nearly all (80 per cent) converted to ice; whereas the central 2 km had reduced in ice content at the 17,000-ft (–3 to –5°C) altitude. During the next 8 min the entire length of the cloud at 17,000 ft converted to 90 per cent or more of ice. No warming was present at 17,000 ft on any later pass. The before-to-after-seeding increase in precipitation-size (partially frozen) drops was greater in other cells than in the western 1.25 km of the cloud.

The central-and-west 3 km appeared in the photos to be growing at the time of the second pass. The temperature rise suggests the same. The reduced amount of ice in the central 2 km on the second pass probably resulted from the ice present during the first pass having risen to a higher altitude. Little new ice had formed, probably because of a combination of insufficient time below OC and the temperature being only –2.5 to –4°C instead of the –5°C of the previous pass. A few large ice crystals, one of which is shown in Fig. 7 were present, probably due to their higher terminal velocity preventing their being swept upward.

The fact that the west 1 km was also –3 to –4°C at this time, yet largely frozen, provides further evidence (at least circumstantial) of the effectiveness of the seeding in promoting the freezing process in this case.

A question which is not directly answered by the data is why the temperature in the frozen west 1 km had increased less than that in the adjacent unfrozen portion. One explanation (Simpson, 1967) is that the frozen region probably had a reduced rate of updraft at this time and location (near the outer edge of the

FIG. 7. "Formvar"-film droplet replicas made in the first after-seeding pass in the unseeded central 2 km. The appearance is also generally typical of the seeded cell on the pass before seeding except no large ice was present and the water drops were closer together and overlapping.

cloud). If so, then its temperature would have been still lower if it had not received the latent heat of fusion. This energy probably was the cause of the west 3 km being more vigorous than would otherwise have been expected. A reduction in growth rate at the time of seeding and the rapid later growth is substantiated by the photos and radar data presented by Simpson (1967).

8. Conclusions

1) Measurements herein presented seem to leave little doubt that the seeding of one cell of this particular tropical cumulus cloud by AgI pyrotechnic smoke was effective in enhancing glaciation at about -5°C .

2) Without taking into account the overall dynamics of the cloud processes, the aircraft data do not directly prove that the accelerated release of latent heat of fusion produced the observed acceleration of growth, since, at the -3 to -5°C level, the maximum increase of ice after seeding was not in the region of maximum warming.

3) While precipitation increased throughout the length of this cloud, the increase was less in the seeded portion than in the rest of the cloud.

4) Direct evidence showed a glaciated region existing in unsaturated air for at least 10 min in a 300-m length of "wisp" visible outside the main cloud.

5) More experiments with more complete instrumentation on aircraft at several levels, particularly at altitudes a few degrees colder than -5°C , will be required to prove directly the extent to which the increased rate of heat of fusion release is the causal factor in rapid cloud growth observed in several seeding experiments, as well as sometimes in natural clouds.

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