An Airborne Continuous Cloud Particle Replicator[1]

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(Manuscript received 21 August 1967)

ABSTRACT

An instrument for collecting cloud particles from an airplane has been developed. Cloud particles are captured and permanently replicated using the well known Formvar technique. From the continuous record of hydrometeor replicas, the forms, sizes and frequency distributions can be established. Description of the instrument and examples of data collected from natural clouds are presented. Problems of calibration are discussed.

1. Introduction

A continuous cloud particle replicator for measuring the size, concentration and structural properties of hydrometeors from an airplane has been developed and used during field operations of the University of Chicago Cloud Physics Laboratory. Work on a continuous replicator began at Chicago in 1960 as part of the Ph.D. thesis research of Koenig (1962a, 1962b, 1963) and has been carried out by the authors since 1962.

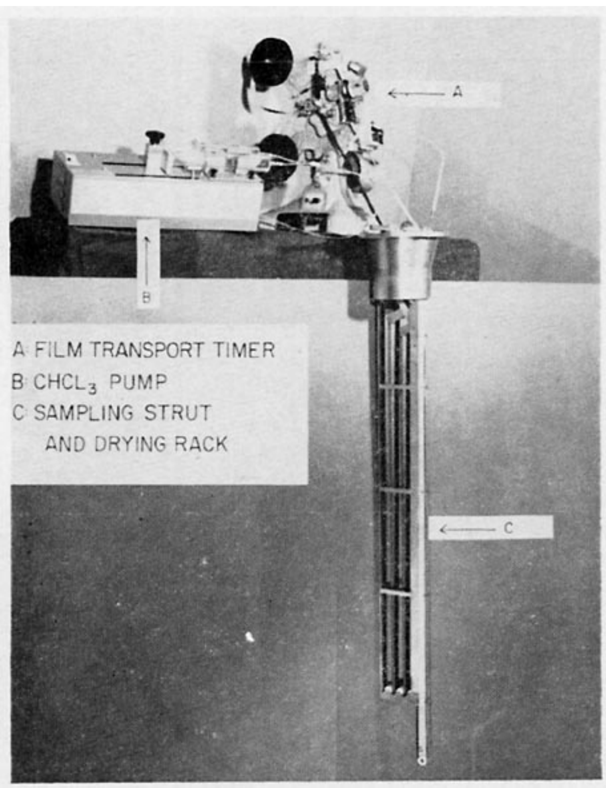

FIG. 1. Replicator and accessories.

Although developed completely independently, in principle of operation the Cloud Physics Laboratory replicator is similar to the device previously reported by MacCready and Todd (1964). The principal difference between the two replicating devices is that the Cloud Physics Laboratory unit uses a continuous tape precoated with Formvar which is resoftened in flight. The MacCready and Todd unit applies fresh plastic solution to a backing tape just before sampling exposure. Some of the advantages and disadvantages of the latter method have already been discussed by MacCready and Todd (1964) and by Averitt and Ruskin (1967). The purpose of this paper is to report on the design, and calibration of, and to give examples of data from, a unit using precoated collection tapes.

2. Design of the Cloud Physics Laboratory replicator

The replicator and its accessories are shown in Fig. 1. Part A is the film transport mechanism, a modified movie projector which has been adapted so that the film stock moves at a uniform speed that can be varied from 50 to 250 mm sec^{-1}. A timer device marks the film at 1-sec intervals and provides a timer pulse to the oscillograph recorder to permit synchronization with other types of measurements. Part B is a pump for the chloroform used to resoften the precoated Formvar ribbon. Chloroform flow can be regulated over 5 orders of magnitude with this pump. That part of the replicator (without cover) which is extended into the airstream is shown as part C.

During the 1964-1966 flight operations the replicator was mounted on a Twin Beech D-18 airplane. Since the nose area ahead of the prop-line was completely filled with radar, it was necessary to locate the replicator in the waist section from which it could be extended below the lower fuselage surface, as shown in Fig. 2. When

[1] The research reported herein was supported by the National Science Foundation under Grants G8214 and GP-3779.

extended, the sampling slit was 88 cm below the skin line. To achieve this it was necessary to extend the unit after the aircraft was airborne and retract it before landing.

Additional details of the replicator unit are shown in Fig. 3. The identified components are: I front cover, II frame supporting sampling slit and drying rack, III end cover, which contains the sampling aperture, and IV the back cover. The precoated Formvar ribbon is resoftened at point V where it is sprayed with pure chloroform. A heater element has been added just downstream of this point to help overcome the local cooling produced by the initial evaporation of excess chloroform. The entire front chamber is padded with felt for the purpose of keeping this volume saturated with chloroform.

The softened plastic is exposed to the airstream by means of the exposure slit, width of 4 mm. On either side of the slit is a 50-W de-icing heater element.

An important feature of the Cloud Physics Laboratory replicator is the shape of the backing plate behind the exposure slit. At the point of exposure the film is supported by a shallow trough, sloping 5° to center from either side. This modification improved the quality of the replicas considerably over those of earlier models because wind pressure keeps the film snugged back against the trough, thus confining the soft Formvar so that it is less easily blown off by the airstream. It also seems to minimize the cross-film flow which occurred in earlier models in which the film was backed by a cylindrical support. This cross-film flow resulted in a non-uniform distribution of the replicating material and motion of droplets after impaction. Another advantage of the trough-shaped backing plate is that it tends to insure an air cushion behind the collector tape. This air cushion allows the tape to flex, thus reducing break-up of large particles.

The back side of the sampler, detail VI, is the drying chamber which is capable of storing 5.8 m of exposed film across six Teflon rollers. This is enough to store an average cloud pass. The film then passes into the fuselage where it traverses additional drying storage before

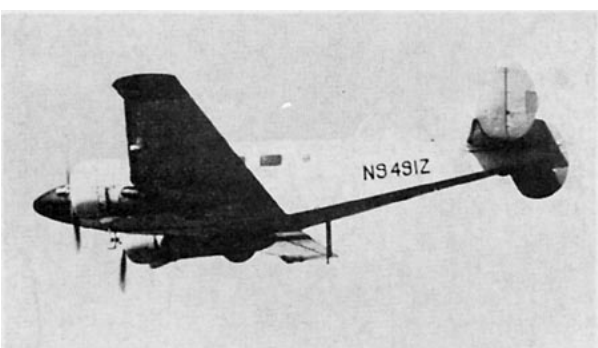

FIG. 2. The instrumented project aircraft showing CPL replicator located under the middle of the fuselage.

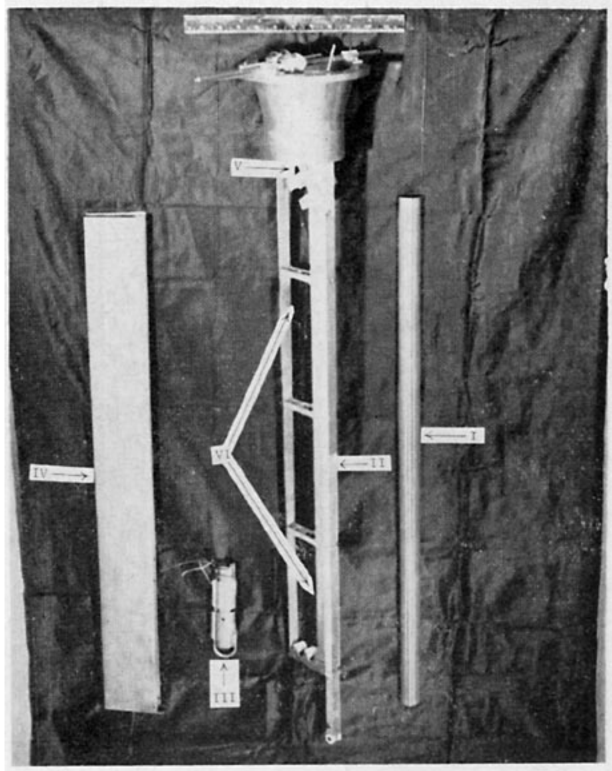

FIG. 3. Replicator in detail (see text).

it is fed to the take-up reel. The total travel length is 8.38 m between exposure slit and storage roll.

3. The Precoated Formvar tape

A standard motion-film leader[2] is used as the supporting surface for the Formvar ribbon. This polyester film is completely inert to chloroform. The film stock is precoated in the laboratory with a 7.5% solution of Formvar, using a semi-automatic device which continuously feeds a regulated flow of solution to the leader film and carries the film through a drying chamber to a roll-up reel. When completely dry the Formvar ribbon is about 70 μ thick. Field experience has shown that properly prepared tapes could be stored for weeks without deterioration of their replicating quality. To use this ribbon to replicate cloud particles it is resoftened by a chloroform spray immediately prior to exposure to the airstream. It is at this point that the advantages of a precoated plastic ribbon become evident. Precoating permits a much thicker coat than we have been able to apply successfully in the solution method. Softening this thick coat from the top then gives a bed of plastic increasing in viscosity toward the supporting tape. Thus, an incoming particle tends to be decelerated with less chance of break-up and distortion as it is captured. The disadvantages of the precoated method, as seen in

[2] Kronar leader stock P40A, 0.004 inch thick, transparent, DuPont, Wilmington, Delaware.

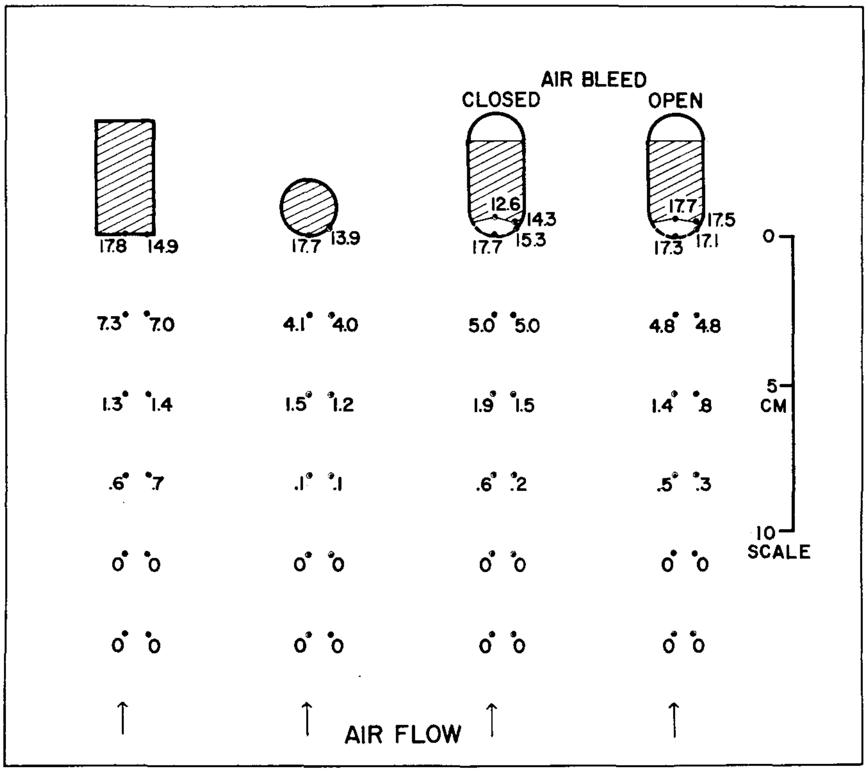

FIG. 4. Static pressure profiles ahead of 16-mm replicator head.

the Cloud Physics Laboratory operation, are longer drying time, more mechanical cracking in the plastic during the drying and roll-up, and the necessity for using somewhat larger quantities of chloroform. The latter is important because evaporation and local cooling of the chloroform can result in condensation of water on the Formvar and consequent "blushing" as discussed by MacCready and Todd (1964) and Averitt and Ruskin (1967). We have attempted to minimize this effect by careful design of the chloroform spray chamber.

4. Calibration for collection efficiency

During the course of evolution of the CPL replicator we have used both 16 and 35 mm collector tapes. From general principles (Langmuir and Blodgett, 1946) we have preferred the 16-mm version since it would be expected to have higher collection efficiencies for small drops. However, as was pointed out by Averitt and Ruskin, there are uncertainties about the applicability of Langmuir-Blodgett (L-B) collection efficiencies to replicators because of the effect of the slit upon the air flow.

During the past winter we made a study of the air conditions ahead of our replicator heads to compare them with similar measurements ahead of shapes used by Langmuir and Blodgett. These measurements were carried out in the CPL wind tunnel. We placed a small pitot-static tube at various positions ahead of full scale models of the 16- and 35-mm collector heads, and ahead of a cylinder, a ribbon and a rectangular block, each having widths equal to the corresponding collector heads.

In order to simulate as closely as possible the heads as they were used on the CPL airplane, it was necessary to test two different versions of each head—with and without an internal air bleed. In the construction of our replicator, the strut carrying the slit was connected to the interior of the plane's fuselage by two small holes through which the collector tapes passed. From earlier studies we knew that the static pressure within the fuselage was less than outside, free-stream, static. Therefore, we suspect that there was a continuous flow of air through the slit and into the fuselage. To study this flow in the wind-tunnel tests, each head was equipped with an internal air bleed of appropriate size which allowed air to exhaust from inside the replicator into a region of appropriately lower pressure.

Measurements in front of the 16-mm collecting head were compared with those in front of a cylinder and a rectangular block (Fig. 4). We note that the upstream region of static pressure increase is quite similar for the semi-streamlined head and the cylinder of same width, but that it is less in magnitude than for the flat block of same width. Static pressure P_s at the center of the slit is almost identical to that at the center of the cylinder; toward the edge of the slit P_s is somewhat higher than

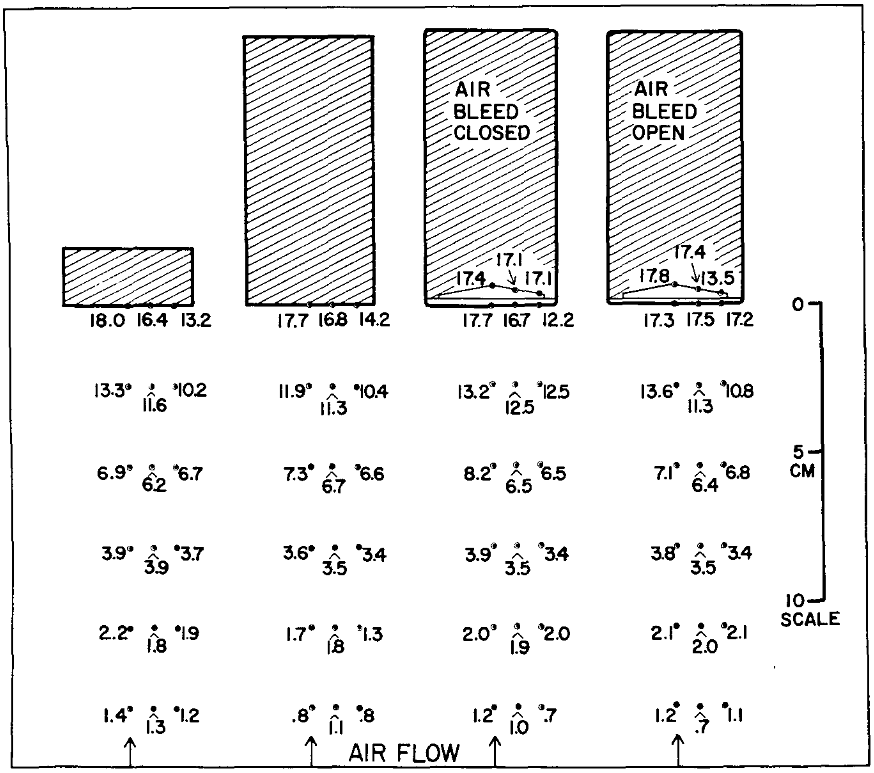

FIG. 5. Static pressure profiles ahead of 35-mm replicator head.

we find for corresponding positions on the cylinder. With the air bleed closed, measurements of P_s directly behind the slit, on the surface of the collector plate, revealed a serious problem. Values of P_s at that location were found to average several cm of water less than those in the slit itself. Moreover, we found rapid and irregular fluctuations of P_s at the collector plate. Changes of several cm of water over periods of 1-2 sec were observed. Undoubtedly these measurements were markedly affected by properties of the manometer system, but it is clear that there is a high level of turbulence between the slit and the collector plate. When the air bleed was opened, P_s at the collector plate immediately smoothed out and rose to a value almost equal to that in the slit. The amount of air flowing through the slit was measured by inserting a flow meter into the bleed line. This flow was found to be 170 cm^3 sec^{-1}, compared with 4.2 liter sec^{-1} swept out by the projected slit area. The question of turbulence behind the slit was discussed by Averitt and Ruskin (1967). It undoubtedly has a serious effect upon the replication process and upon drop break-up. Thus, our measurements suggest that we were fortunate to have had the air bleed as it probably improved overall quality of the data.

Measurements using the 35-mm collecting head showed no essential difference between the upstream profiles ahead of the ribbon, the smooth rectangular block, and the model of the collector head (Fig. 5). Opening the air bleed had negligible effect upon the P_s values. The measured flow through the slit on the 35-mm head was 250 cm^3 sec^{-1} compared with 7.4 liters sec^{-1} swept out by the projected slit area.

On the basis of the wind tunnel studies we conclude the L-B collection efficiencies can be applied with fair confidence to obtain drop spectra entering the slit. However, it is very obvious that additional careful work has to go into proper design criteria for the region between the slit and the collector tape.

Additional insight into the validity of using L-B collection efficiencies is provided by comparing drop spectra obtained with the 35-mm replicator and with a slide sampler adapted from the design of Clague (1965). The Clague sampler uses 3-mm slides coated with MgO smoke (May, 1950). These slides are spring propelled from a magazine, across the sampling slit, around a curved track and returned to the magazine. Use of the narrow slide should provide a large collection efficiency for all drop sizes and should make calculation of collection efficiencies more certain.

The slide sampler was clamped out the co-pilot's window of the Beech D-18, pointing upward about on a 45° angle. In this position the sampling slit was about 38 cm from the upper front corner of the window and and outside of the propwash.

We encountered great difficulty in preventing the MgO coatings from being destroyed as the slides were fired. However, we succeeded in obtaining five slide samples simultaneously

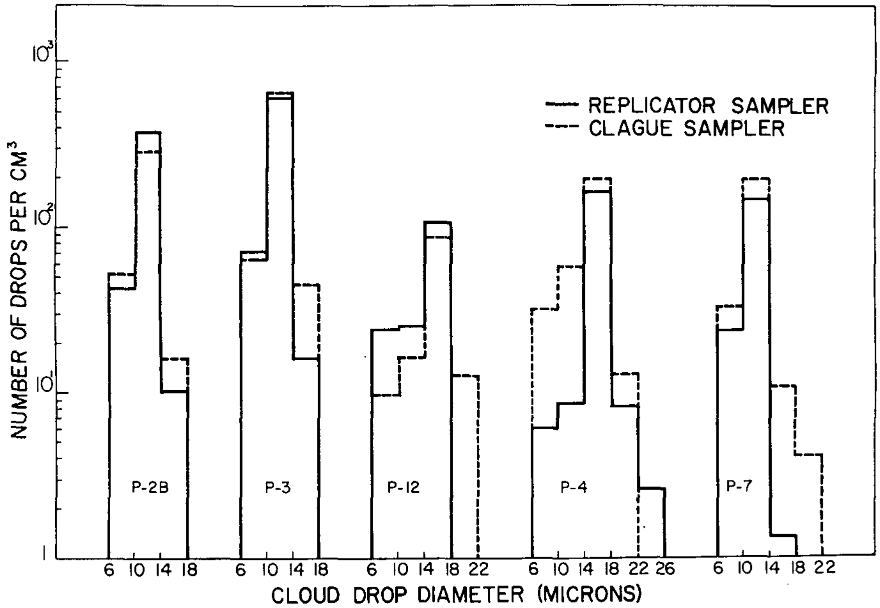

FIG. 6. Comparison of droplet spectra obtained with the CPL replicator and Clague slide sampler.

showing that the slides had been exposed in regions of uniform drop spectra. The latter condition permits us to compare spectra taken at two different points on the plane and reduces the uncertainty in drawing conclusions from a single sampling slide. All five samples were obtained a few hundred feet above the bases of small cumulus congestus clouds in the dissipating stage.

Data from the slides were corrected using L-B collection efficiencies for a 3-mm ribbon. The relative wind in the vicinity of the sampling point had previously been measured and found to be about 130% of aircraft true speed.

Data from the replicator were corrected using L-B efficiencies for a 35-mm ribbon and aircraft true air speed which previous measurements had shown applicable at the replicator sampling point. Data for these samples are given in Fig. 6. Four of the slide samples (P-2B, P-3, P-12, P-4) are based upon a sampled volume of a little over 0.5 cm³, the other (P-7) upon a volume of about 1 cm³. All replicator samples are based upon a sample volume of 1 cm³, representing a sampling time of 2×10^{-2} sec (32 cm of flight path) and were checked against a similar sample 1 sec earlier and 1 sec later.

The similarity between the samples obtained from the two devices is very encouraging, especially in view of the small sample volumes available from the slide device; it lends credence to the opinion that L-B efficiencies can be used with fair confidence with the 35-mm replicator. No similar comparison is available for the 16-mm device.

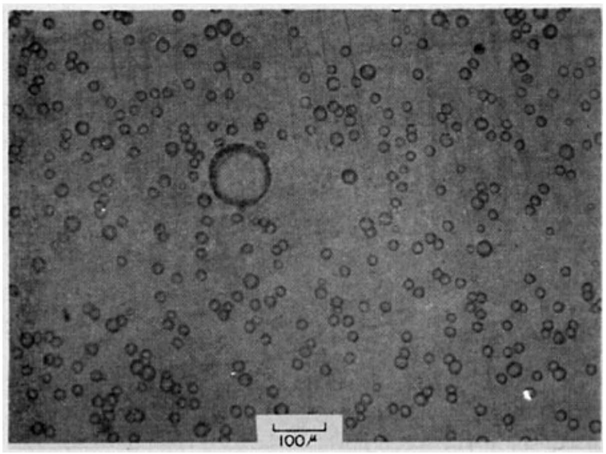

FIG. 7. Cloud droplet replicas from cumulus congestus cloud, Flight 663, altitude 10,000 ft MSL, liquid water content 3.3 gm m^{-3}, temperature 1C. The median drop diameter is 20 μ. The large drop in the middle is distorted; the apparent diameter is 100 μ.

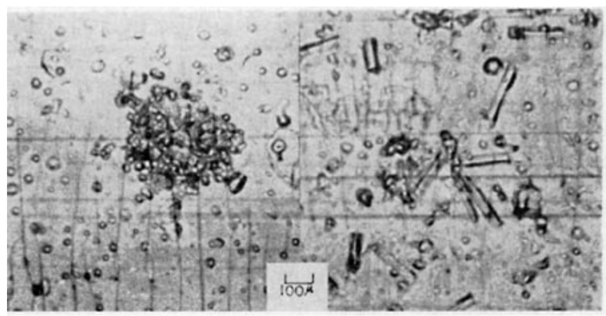

FIG. 8. Replicas of soft snow pellet (400 μ diameter) surrounded by supercooled cloud droplets and needles and columnar ice crystals having substantial depth. Collected on Flight 662 in Cb calvus. Altitude 16,000 ft MSL, temperature −7C.

5. Discussion and examples of data

Figs. 7, 8, 9 and 10 are selected examples to illustrate the kinds of data that can be obtained with the CPL continuous replicator.

The CPL replicator has obtained useful data in clouds from −20 to +20C, with water contents between 0.1 and 3.5 gm m^{-3}. It gives the best data in clouds that are either all ice or all liquid; our poorest replicas come from mixed phase clouds. In general, our experiences verify those reported by MacCready and Todd (1964) and Averitt and Ruskin (1967). Ice crystals are reliably replicated. Snow flakes are broken, but recognizable. Snow pellets are clearly recognizable, while ice pellets bounce off leaving only a skid mark. Small cloud drops are faithfully replicated but large drops, of a size comparable to the thickness of the film (70 μ), seen to be flattened in the drying process.

Since much of our research involves sampling solid hydrometeors close to the freezing level, we have not used artificially heated drying chambers for fear of melting small ice crystals. As a consequence, one of our major problems has been the time required for drying of the Formvar. Premature rollup results in mechanical distortion of the samples and possible melting of ice particles. In extreme cases it can result in the Formvar sticking to the back side of an adjacent layer on the take-up roll, and consequently, the complete loss of record. With only 8 m of tape in the drying racks, we found that our most reliable operation was to use the sampler in short bursts of 20-30 sec separated by 2–5 min. This would insure drying of the tapes before roll-up.

In its present form the CPL replicator must be regarded as a laboratory device mounted on an airplane.

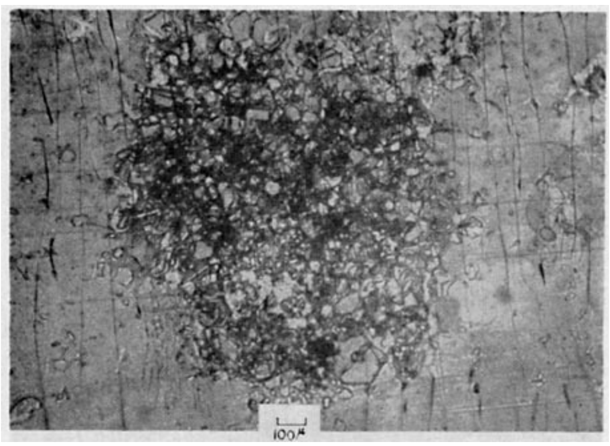

FIG. 9. Replica of crushed snowflake, 1.4 mm in diameter. This illustrates breaking and crushing which occurs when solid hydrometeors are replicated at air speeds of about 70 m sec^{-1}.

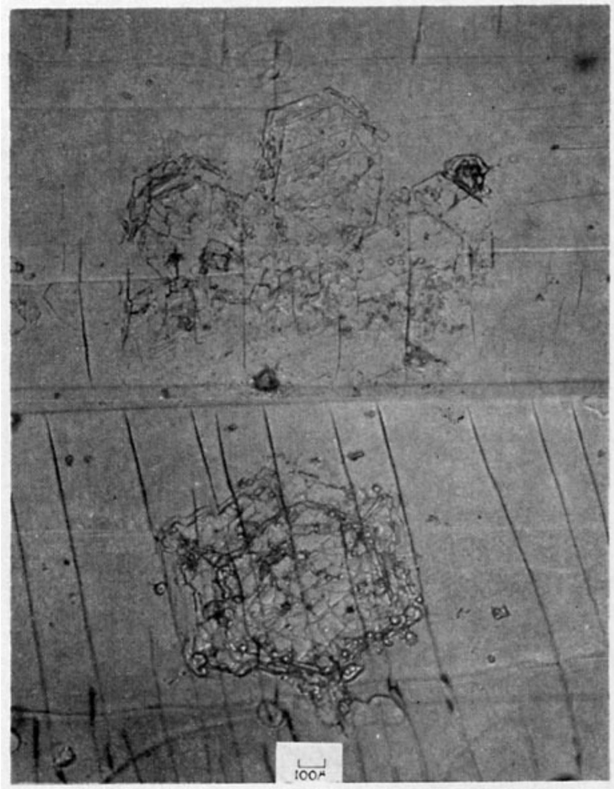

FIG. 10. Replica of sector type snow crystals with a few rimed cloud droplets. Collected in a thunderstorm anvil at 17,500 ft MSL, temperature −10C.

It requires the same "personal" attention required of any laboratory set-up. In the hands of a skilled and patient operator it becomes an essential tool for studying cloud microstructure.

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