"REVIEWED"

ATMOSPHERIC TESTS OF AN ORGANIC NUCLEANT IN A SUPERCOOLED FOG

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Abstract: An organic artificial ice nucleant (Pseudomonas syringae) was dispersed as a fine powder from an aircraft within a supercooled fog over Mono Lake, California on 2 December 1989. The dispersal took place about 30 m below fog top at a temperature of -8°C. Two test runs about 3 to 4 km in length were made; 10 gm and 100 gm of nucleant were distributed over the test track during the first and second runs, respectively. Following each test run, a highly instrumented cloud physics aircraft flew tracks within the fog that were orthogonal to the original test track. Particle measuring probes (FSSP, 1D-C and 2D-C) were used to determine fog characteristics and to quantify a seeding signature.

The light seeding rate (10 gm over the test track) of P. syringae produced no detectable seeding signature, probably because the monitoring aircraft missed the treated plume. The heavier rate (100 gm over the test track), however, produced an obvious seeding signature that was first detected about 5 minutes after release of the nucleant. The signature began with high concentrations of relatively small (50 to 100 μm) particles, and the ice crystal concentration decreased with time as their size increased. The mean, median and modal particle sizes at a particular time are virtually equal in the plume, suggesting a common origin for the ice crystals.

P. syringae clearly produced glaciation of a supercooled fog at temperatures of about -8°C in agreement with laboratory test results. Additional atmospheric tests are planned at warmer temperatures.

1. INTRODUCTION

For the past 40 years, modern cloud seeding technology has been largely focused on the ice nucleation processes which are central to the natural production of snow and rain over much of the earth's surface. Within these atmospheric processes, the ration of ice particles to supercooled liquid water often establishes the efficiency of clouds and storm systems to produce precipitation at ground level. In many cases, the concentration of naturally occurring ice nuclei (IN) is lower than required for the most efficient precipitation process, even at temperatures as cold as -20°C. (Pruppacher and Kleth, 1980). For this reason, a number of substances such as silver iodide (Vonnegut, 1947) have been selected to act as supplementary IN within a broad range of cloud seeding programs throughout the world.

Because most naturally occurring IN found in clouds are not particularly active at temperatures warmer than about -10°C, there has been a continuing search for a source of IN, either natural or artificial, which have the ability to convert supercooled cloud droplets to ice crystals at the warmest possible temperature. Solid carbon dioxide (dry ice) is an excellent candidate and, since its early demonstrated use in 1946 (Schaefer, 1948), has been used in many cloud seeding programs. However, dry ice suffers from availability in remote areas, storage problems, quantities required for airborne dispersal, and its effective dispersal is restricted to altitude where the temperature is colder than 0°C.

The presence of microorganisms in precipitation has received a number of investigations dating back more than 20 years (Gregory, 1967; Schnell and Vali, 1972, 1973; Maki, et al, 1974; Schnell and Vali, 1976; Vali, et al, 1976; Lindow, et al, 1978; Maki, et al, 1978; Yankofsky, et al, 1981; Lindow, et al, 1982; and Levin, et al, 1987, 1988). The value of these investigations is noteworthy because of the ice nucleation properties of some naturally occurring microorganisms at temperatures near 0°C. P. syringae was one of the major candidates for investigation within many of these research programs.

In more recent years, the Eastman Kodak Company developed the expertise and production facilities necessary to produce large quantities of beneficial bacteria, principally P. syringae. The material has found its way to Snowmax™ Snow Inducer, a product of Kodak's Bio-Products Division useful in snowguns installed at many ski resort areas throughout the world. Snowmax™ is a freeze-dried preparation of the natural bacterium P. syringae which is grown in large fermenters, frozen in a manner similar to that used in freeze-dried food, and then sterilized by electron beam radiation. Snowmax™ is not a product of engineering, it is a natural bacterium selected solely for its ice nucleation ability.

In November 1987, representatives from Kodak came to Fresno, California, where some preliminary tests of Snowmax™ material as a potential ice nucleus for weather resources management programs were conducted in the facility at Atmospherics Incorporated. Ice crystals were artificially produced in a three-compartment freezer chest, and these crystals were captured on Formvar coated slides. The qualitative experiments were conducted in the temperature range of -4°C to -20°C, with crystal habit and temperature relationships noted (Henderson, 1987).

The results from these preliminary laboratory tests were encouraging enough to warrant more sophisticated characterization tests in the isothermal and dynamic cloud chambers at Colorado State University. These more quantitative tests were conducted in March 1988. The results (Ward and DeMott, 1989) were so dramatic that plans were organized for a field test of P. syringae. These airborne tests were conducted by Atmospherics Incorporated near Hawthorne, Nevada. During the two day tests in September, 1988, it was demonstrated that Snowmax™ dry powder can be dispensed from aircraft and significant visual glaciation effects can be produced at in-cloud temperatures as warm as -5°C. (Rogers, 1988).

Because of the constantly changing characteristics of even small cumulus clouds, and the difficulty in dealing with their dynamic properties, further tests were planned for areas where fog decks provided a more stable outdoor laboratory.

2. DESIGN OF THE TESTS OF PSEUDOMONAS SYRINGAE

The subsequent tests of the P. syringae organic nucleant were made in super-cooled fog over Mono Lake, California (see Figure 1). These tests were make in the context of a larger study of Aircraft-Produced Ice Particles (APIPs), called MOLAS (Mono Lake APIPs Study).

Mono Lake is 1968 m MSL and has a surface area of about 250 km^2. It has no outlet and is completely surrounded by higher terrain rising to 3,500 m MSL nearby to the west. During winter weather when a high pressure system is well-established over California, the surface air east of the Sierra range is cold and supercooled fog occurs over Mono Lake and Mono Valley to the east. A temperature inversion of a few degrees may persist for periods of 3 to 5 days and the fog, which forms beneath the inversion, is stabilized by condensation rates from the lake surface being equal to the droplet evaporation/sublimation at the top of the fog layer.

The flight tests were simple in design and execution. A set amount of P. syringae was released as a fine powder from a Cessna 421 test aircraft flying about 30 m below fog top. The King Air 200T cloud physics aircraft of the University of Wyoming followed closely behind the seeder aircraft until it entered the fog and began its release of nucleant. The scientist aboard the King Air set its pointer to the position where the seeder aircraft initially entered the fog and the pilot then flew tracks that were orthogonal to the track of the seeder aircraft (see Figure 1). The

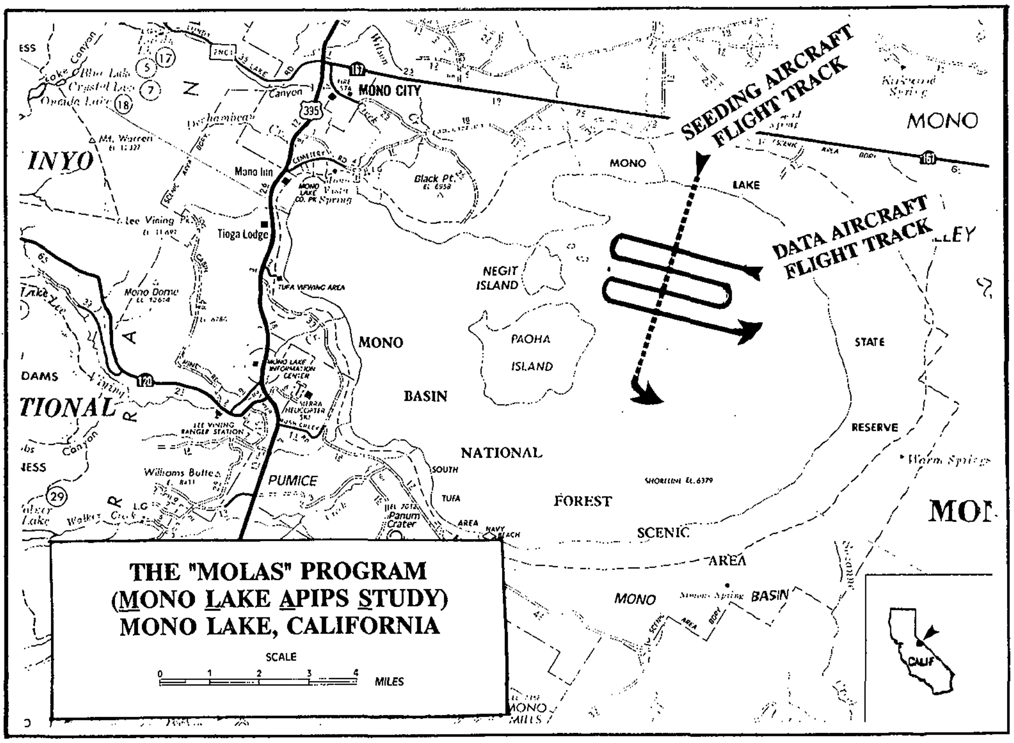

Figure 1 Map showing the geographic context for the MOLAS (Mona Lake APIPs Study) Program. The aircraft flight patterns have been superimposed.

seeding track was normally 3 to 4 km and the flight legs of the cloud physics aircraft within the fog averaged about 1 km either side of the track of the seeder aircraft.

Since the MOLAS effort has demonstrated the reality of APIPs (reports in preparation), both the seeder and monitoring aircraft were flown at relatively low power settings to minimize any possibility that the aircraft themselves would produce ice crystals that might be ascribed erroneously to the organic nucleant. This potential problem is something that must be considered in all future cloud physics studies that make use of aircraft platforms.

The hydrometer concentrations, sizes and habits were determined using three probes manufactured by Particle Measuring Systems, Inc. of Boulder, Colorado, that are flown routinely aboard the University of Wyoming King Air 200T aircraft. These include: a Forward Scattering Spectrometer Probe (FSSP), and OAP-200X (1D-C) and OAP-2D-C (2D-C) probes. The FSSP detects particles up to 30 μm in size in increments of 2 μm, the 1D-C detects particles up to 187 μm in diameter in increments of 12.5 μm, and the 2D-C detects particles up to 500 μm in intervals of 25 μm. Water contents within the fog were estimated using Johnson-Williams instrumentation. More information on the University of Wyoming King Air data system can be obtained by referring to Endsley et al., (1986).

3. TEST RESULTS

On the day (2 December 1989) of the P. syringae test flights, supercooled fog covered the lake surface and the valley to the east and was banked against the Sierra range to the immediate west (Figure 2). Fog top was 2060 m MSL at a temperature of about -8°C. The temperature rose to over +8°C only 500 m above the fog. A partial plot of temperature versus height is provided in Figure 3.

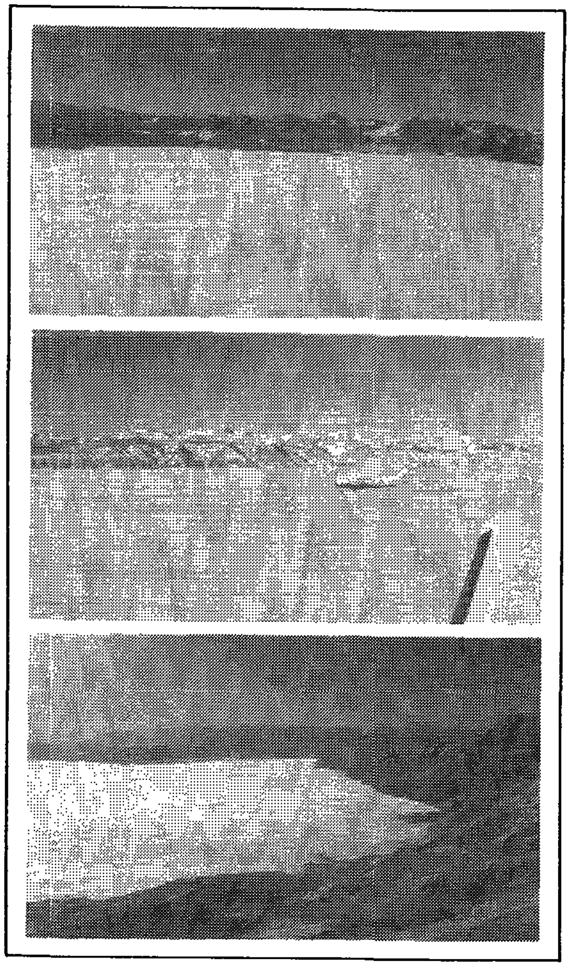

Figure 2 Photograph above the supercooled fog over Mono Lake on 1 December 1989.

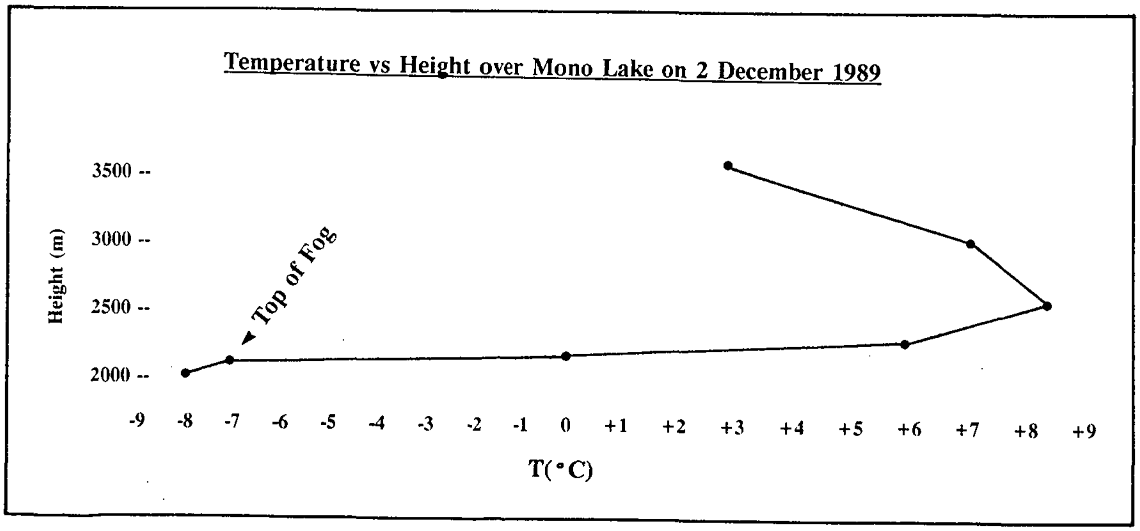

Figure 3 Plot of temperature (°C) vs height (m) over Mono Lake on 2 December 1989.

The P. syringae nucleant was dispersed as a fine powder from the front window of a Cessna 421 aircraft °n two test runs of 3 to 4 km in length. On the first run, 10 gms of nucleant were distributed, while on the second, about 100 gms were released. Following each test run, the King Air 200T cloud physics aircraft flew tracks within the fog that were orthogonal to the original seeding track. The flight track for the second case is shown in Figure 4. The tracks of the seeder and monitoring aircraft, moving from north to south, coincided until 102450 PST, when the Cessna aircraft entered the fog for commencement of seeding and the King Air aircraft began a turn to the east to setup its monitoring runs. The rest of the track is that of the King Air, as it crossed the seeding track five times for measurements.

A summary of the pass measurements is provided in Table 1. Note that fog water contents averaged 0.20 to 0.25 gm/m^3, the mean (averages over 6 sec.) maximum droplet concentrations ranged between 100 and 150 drops/cm^3 and the mean (6 sec averages) droplet size ranged between 10 and 17 μm. Natural ice in concentrations of 1 to 2 crystals per liter were encountered in the undisturbed fog near the time of the test runs.

Examination of the 2D-C entries in Table 1 suggest that the light seeding rate (10 gm over the test track) of P. syringae produced no detectable seeding signature. There is no evidence of increased ice crystal concentrations during the four monitoring passes that began about 1 minute after the release of the nucleant at 100833 PST. Ice is present with mean (5 sec averages) sizes 50 to 100 μm during all passes, but the concentrations are low. If there was a seeding signature, it was missed by the monitoring aircraft.

The entries in Table 1 suggest a different circumstance for the heavier seeding rate. About 5 minutes after release of the nucleant at 102450 PST, maximum ice crystal concentrations of 155 crystals per liter were detected as the monitoring aircraft traversed the test track. Mean particle size at first penetration of the plume was 85 μm. Six minutes later the maximum particle concentration had decreased to 40 per liter but the mean ice crystal size had increased to 166 μm. This appears to be a seeding signature that warrants closer examination.

A visual inspection of the 2D-C particle images during portions of the five monitoring passes is possible in Figure 5. The vertical lines in each panel are 800 μm long and the particles can be scaled by using this line as a reference. The times (in secs) in the left margin of each panel are the elapsed times between the passage of the seeder aircraft and the times that the monitoring aircraft intercepted the seeding track. If the times are short, the nucleated particles might be too small to be detected by the 2D-C probe.

Nothing is evident in the images during the first two passes. Note the two large ice particles during the latter portion of pass 1 (panel 2). Such particles, although low in concentration, were common during the MOLAS program. They had an origin that was independent of the aircraft and the nucleant releases.

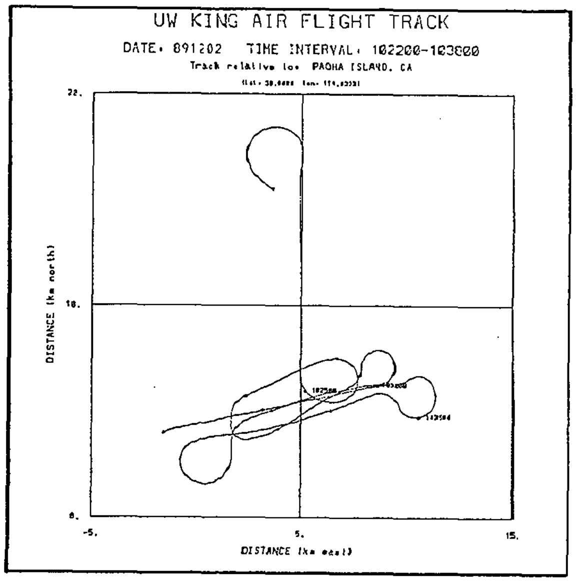

Figure 4 Flight track of the University of Wyoming King Air during the second test of the P. syringae nucleant on 2 December 1989.

Table 1. Pass Data Summary for MOLAS

Date	Begin Time (PST)	Avg TAS (m/sec)	PASS #	TRF °C	Avg. Max JW LWC (gm/m^3)[1]	FSSP CON MIN (#/cm^3) (6 sec. avgs.)	FSSP CON MAX (#/cm^3) (6 sec. avgs.)	FSSP d MIN (microns) (6 sec. avgs.)	FSSP d MAX (microns) (6 sec. avgs.)	2D-C MAX CON (#/l) (1 sec value)	2D-C d (5 sec mean size)	Comments
12/2	100833	-	0	-	-	-	-	-	-	-	-	drop of 10 gm of Pseudomonas Syringae from Cessna 421
12/2	100948	96	1	-8.0	0.25	10	102	11	13	1	54	no evidence of plume
12/2	101142	95	2	-7.6	0.20	9	135	11	14	1	59	no evidence of plume
12/2	101436	96	3	-7.8	0.20	27	126	11	12	2	65	no evidence of plume
12/2	101700	100	4	-7.5	0.20	2	104	10	17	2	107	no evidence of plume
12/2	102450	-	0	-	-	-	-	-	-	-	-	drop of 100 gm of Pseudononas Syringae
12/2	102554	87	1	-7.7	0.20	62	109	10	11	2	148	no evidence of plume
12/2	102748	85	2	-7.6	0.20	19	146	11	12	1	60	no evidence of plume
12/2	103012	93	3	-7.6	0.20	2	87	10	17	155	85	obvious penetration of plume
12/2	103248	96	4	-7.2	0.20	18	125	10	12	9	134	still in plume
12/2	103606	97	5	-7.5	0.25	7	140	10	15	40	166	still in plume

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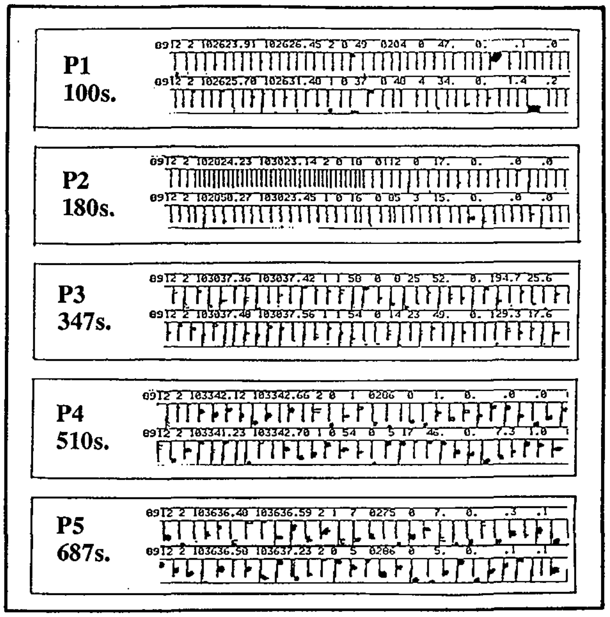

Figure 5. 2D-C images of the ice crystals on 2 December 1989 during the testing of the P. syringae nucleant. The multiple vertical lines in each panel are 800 μm in length and can be used to size the particles. The elapsed time between the imaging of the particles and the time of their generation appears at the left margin of each panel.

The images for passes 3, 4 and 5 suggest a different story. Many small ice crystals are evident during pass 3 and these particles grow larger with time while maintaining their relative uniformity in size. This appears to be a seeding signature.

Further quantification of the apparent signature is made in Figures 6 and 7 in which particle totals and mean, median and modal particle sizes are presented, respectively. The plots are for the 5 secs of each pass that is centered on the time that maximum 2D-C ice crystal concentrations were observed.

Plots of the total number of particles in each bin over the 5 secs centered on the peak crystal concentration show nothing noteworthy for the first two passes following release of 100 gms of P. syringae. The third pass at 103037 PST shows a dramatic increase in the number of ice crystals, especially in the size range of 75-100 μm. The fourth and fifth passes show a lesser number of particles but those that remain have grown larger with time. With the exception of the first two passes in which no signature was noted, the plots resemble a normal distribution.

Plots of the mean, median and modal ice crystal sizes in Figure 7 show that these measures are nearly equal within each of the last three monitoring passes. This near uniformity in particle size suggests a common temporal origin for these ice crystals --- in this case, nucleation by the organic nucleant when it was released from the seeder aircraft.

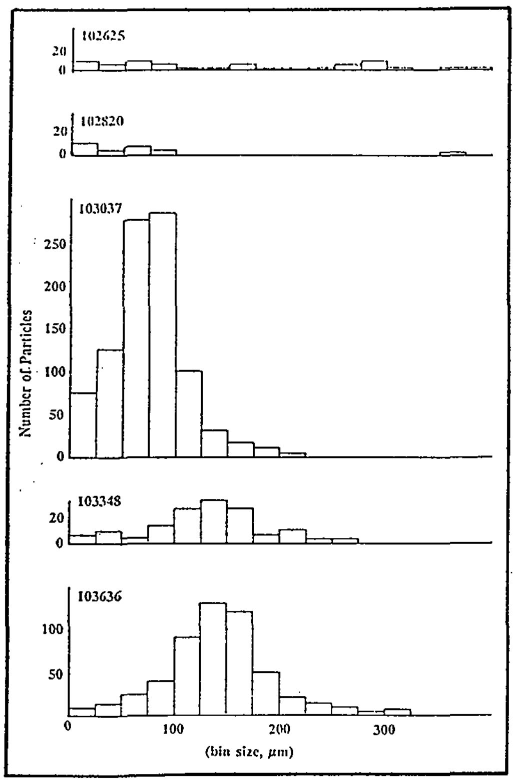

Figure 6 The total number of particles in each bin on each pass during the second test of the P. syringae nucleant. The totals are over the 5 secs centered on the time of maximum measured crystal concentrations.

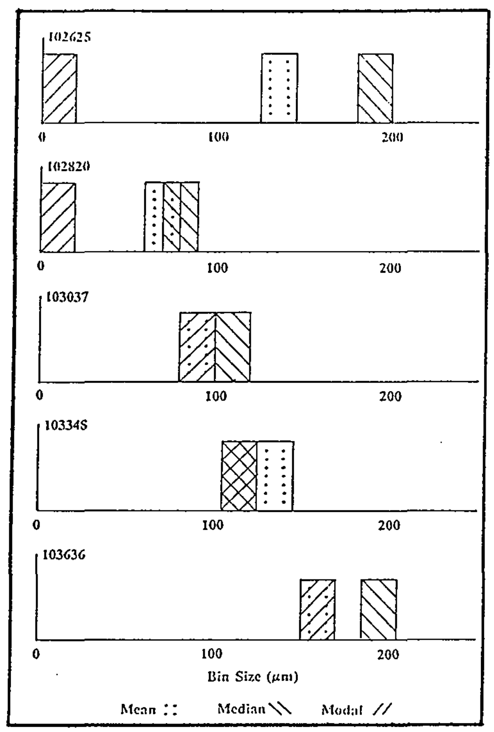

Figure 7 Mean, median and modal particle sizes for each monitoring pass. These statistical measures are for the 5 secs centered on the time of maximum measured crystal concentrations.

4. CONCLUSIONS

There is little doubt that the P. syringae particles nucleated ice crystals in a supercooled fog at -8°C, since the aircraft were flown at power settings during the nucleation tests that should have eliminated the generation of Aircraft Produced Ice Particles (APIPs). To our knowledge this is the first test of this nucleant in the atmosphere for which quantitative confirmation of its nucleating capabilities has been possible. The seeding signature begins as high concentrations of small particles which grow with time. The mean, median and modal particle sizes are nearly equal in the plume, suggesting a common origin for the ice crystals. The primary initial crystal habit appears to be columns or needles, which rime during the growth process.

Our failure to detect a seeding signature for the release of the 10 gm of nucleant must be interpreted as a failure to penetrate the plume by the measuring aircraft due to the limited dispersion and resultant areal extent of the plume. Passage of the measurement aircraft just a few meters above or below the track of the seeder aircraft could account for missing the plume in the light seeding case.

Additional atmospheric tests of the P. syringae nucleant at warmer temperatures are desirable to learn its true nucleation capabilities in a temperature zone that is not serviced well by conventional nucleants, such as silver iodide. These initial quantitative atmospheric tests indicate that P. syringae may prove to be a valuable tool for artificial nucleation in the atmosphere.

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