An Experimental Study of the Production of Ice Crystals by a Twin-Turboprop Aircraft

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ABSTRACT

The University of Wyoming King Air (KA) research aircraft was used in controlled, in situ experiments to determine whether or not, and under what cloud and aircraft operating conditions, a twin-turboprop aircraft would itself produce ice crystals during passage through clouds containing supercooled liquid water. Such crystals are termed "Aircraft Produced Ice Particles" (APIPs). Computer-aided, air-relative navigation was used to pilot the KA back through the diffusion volumes of earlier flight segments. To protect against false-positive and false-negative conclusions, large concentrations of artificially nucleated ice crystals were used as tracers at one or two points along each flight segment. These tracers should have the same diffusion and sedimentation characteristics as the APIPs, and their detection should indicate that any APIPs, if present, would also be detected.

The results of 15 experiments in which the cloud volume affected by the aircraft was subsequently sampled suggest that the KA produces APIPs only in a limited range of cloud and operating conditions. The range of experimental conditions included temperatures from −3° to −25°C, liquid-water contents up to 0.5 g m^{-3}, mean drop diameters 7–20 μm, maximum drop diameters up to 30 μm, true airspeeds 80–110 m s^{-1}, engine speeds 1700–1900 rpm, and low to heavy airframe icing. For the single case in which APIPs were detected, the conditions were −12°C temperature, 0.5 g m^{-3} liquid-water content, 20-μm mean diameter, 27-μm maximum diameter and heavy airframe icing. An experiment with very similar conditions, but with little or no airframe ice, generated no APIPs. The two most plausible APIP generation mechanisms consistent with these results are splinter production during airframe icing and/or enhanced ice nucleation rates due to adiabatic cooling in propeller tip or wing tip vortices.

1. Introduction

Progress in cloud and precipitation physics research has been critically dependent on the availability of in situ observations of the thermodynamics, air motions, and hydrometeor populations of clouds. Many different types of research aircraft, as well as sounding devices, have been used for obtaining observations within clouds. Remote sensing also is providing an increasingly detailed view of cloud parameters. Much of our knowledge about cloud processes is anchored in those observations, through the continuing process of comparison and reconciliation with theory, laboratory measurements, and numerical models.

One area where in situ observations has been especially valuable is the study of the origins and development of ice particles. The key role of these particles in precipitation development, and in other cloud processes and cloud characteristics (such as radiative properties), coupled with the lack of usable laboratory or theoretical approaches, gives ice observations a very high priority. In fact, data collected from aircraft have led to the identification of various processes of secondary ice generation, and to the clarification of at least three distinct pathways of precipitation development involving different ice origins.

As with any measurement system, there is a concern associated with the use of aircraft for cloud studies. To what extent does the aircraft disturb the cloud that is being observed? Because of its large size and weight, engine exhaust, etc., a number of cloud properties are clearly influenced by the aircraft during its passage through clouds. For clouds of the order of kilometers in size, the dynamic effects can be shown to be negligible in a global sense, although local effects, for example, at the top of a stratus layer, can be of some consequence. Hence, it is generally advisable to avoid observations in cloud regions that were previously disturbed, even though this requirement is in conflict with the need to obtain observations in a Lagrangian frame of reference.

Of the various effects of aircraft on clouds, perhaps the most potent one is the generation of ice particles in supercooled clouds. Such an effect has been postulated by many investigators (Vonnegut 1948; Ludlam 1956), and strong evidence for the phenomenon was presented by Rangno and Hobbs (1983, 1984), who termed the resulting particles "Aircraft Produced Ice Particles (APIP)." Their reports engendered a number of other studies, whose results were less clear cut, leav-

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ing the question open for further examination. The experiments to be reported here were designed to provide a controlled test of the phenomenon. Our results show that APIPs are indeed generated under certain conditions, but not always. The available data are insufficient to delineate the ranges of conditions leading to APIPs, and it can only be suggested, based on the data, what the mechanism of ice generation might be.

It should be noted that the term "APIPs," since its specific use by Rangno and Hobbs (1983), has become associated with the phenomenon of ice particle generation by aircraft within clouds containing supercooled liquid water. The more widespread phenomenon of "contrails" refers to ice (or water) condensing in the wake of aircraft in clear air; the most important element of that process is the addition of water vapor to air that is already near the saturation point. Whether there is some commonality between the processes leading to contrails and APIPs is not yet known for certain, but it appears doubtful on a number of grounds.

2. Previous studies

Based on repeated penetrations of cumulus turrets, Rangno and Hobbs (1983) showed that their research aircraft (B-23) generated copious numbers of ice crystals in clouds containing supercooled liquid water. The sampling of previously traversed cloud volumes was achieved by visual navigation. In addition, they showed the same results from retrospective analyses of flights in which the B-23 had crossed its own path.

The evidence found by Rangno and Hobbs (1983) for the generation of ice crystals by the penetrating aircraft was that ice crystal concentrations increased by 1 to 4 orders of magnitude between the initial and repeat penetrations. The crystals were found to have uniformly small sizes, corresponding to growth during the lapse of time between penetrations. The range of cloud conditions in which Rangno and Hobbs (1983) detected APIPs, for the retrospective and dedicated experiments taken together, included various species of cumulus, altocumulus, and stratocumulus, with temperatures from $-4°$ to $-24°$C. Maximum cloud-droplet concentrations ranged from 15–730 $\mathrm{cm^{-3}}$ for diameters $< 13\ \mu$m and from 0–200 $\mathrm{cm^{-3}}$ for diameters $> 25\ \mu$m. Liquid-water contents were not reported. In 9 of the 13 dedicated experiments, the degree and nature of airframe icing was reported. In these nine cases the largest reported increase in maximum crystal concentration was a factor of 1200, for a flight with "heavy, clear" airframe ice accumulation. In some cases APIPs were not found, but this was attributed to the aircraft not having intersected an earlier path.

In another study, Rangno and Hobbs (1984) attributed elevated concentrations of crystals to the earlier passage of another, commercial aircraft. Since the commercial plane was equipped with turboprop engines and the research B-23 was piston-driven, they concluded that both types could produce APIPs.

In considering the mechanism involved in the generation of APIPs, Rangno and Hobbs (1983, 1984) rejected the possibility that nucleation of ice by lead compounds from the aircraft exhaust was involved because turboprop engines that use unleaded kerosene were also observed to generate APIPs. Other possible mechanisms discussed by Rangno and Hobbs were 1) the production of ice splinters associated with icing of the aircraft, 2) adiabatic cooling due to rapid expansion of air disturbed by the aircraft, and 3) other aerodynamic effects, such as cooling of droplets by evaporation in aircraft-induced downdrafts. The observations of Rangno and Hobbs did not lead to a decision regarding the most likely mechanism of APIP generation.

Mossop (1984), in comments on the observations of Rangno and Hobbs (1983), pointed out that aerodynamic heating and latent heat release during airframe icing could warm the rimed surface by at least 2°–3°C, extending the range of temperatures over which the process of splinter production demonstrated in the laboratory by Hallett and Mossop (1974) might explain the APIP observations. However, Mossop (1985b) showed new evidence that the temperature of the air (and supercooled droplets) appears to be more important than the rimed surface temperature in setting limits to the range of conditions for splinter production.

Vonnegut (1948, 1986) proposed that APIPs might result from homogeneous nucleation of ice if adiabatic expansion in propeller tip and wing tip vortices caused cooling to temperatures below $-40°$C.

In further field experiments aimed at studying the APIP phenomenon, Gordon and Marwitz (1986) used a tracer to identify the path of the penetrating aircraft. A turboprop-driven lead aircraft made a cloud penetration and released SF_6 gas as a tracer. The sampling aircraft (Wyoming King Air) followed in the path of the first aircraft with an SF_6 detector. Cloud temperature was $-10°$C, the maximum liquid-water content was 0.37 g $\mathrm{m^{-3}}$, maximum droplet concentration reached 700 $\mathrm{cm^{-3}}$ and only a few spots had ice crystals ($\leq 25\ \mathrm{L^{-1}}$). The SF_6 tracer was detected by the sampling aircraft, but no evidence of APIPs was found.

Gordon and Rodi (1990) used air-relative, onboard navigation to direct the King Air back through cloud volumes that were previously penetrated by the same aircraft. Three clouds were penetrated in the experiment, all at about $-10°$C with droplet concentrations ranging from 300–800 $\mathrm{cm^{-3}}$ and liquid-water content ranging from 0.4–0.7 g $\mathrm{m^{-3}}$. Engine rpm was alternated between "normal" (1700 rpm) or "high" (2000 rpm) during the initial penetration of a cloud in order to change the degree of cooling behind the propellers. APIPs were found in one case with high and one with normal rpm, while APIPs were not detected in another case with high rpm. The APIPs generated in the high rpm case appeared as a 16-fold increase in peak crystal concentration; the increase in the normal rpm case was 3-fold.

In total, prior evidence regarding ice particle production by aircraft in supercooled clouds can be summarized as follows: cases in which large increases in ice concentration were demonstrated constitute fairly conclusive evidence for the possibility of APIP generation. However, experiments with no increases in ice concentration remain ambiguous; such results were due either to a lack of APIP generation under prevailing conditions, or to a failure to find the affected cloud region during sampling. This problem, and the paucity of data in general, left unresolved the questions of how APIP generation depends on aircraft type, airspeed, cloud characteristics and other conditions.

The purpose of these experiments was to carry out repeated cloud penetrations with the Wyoming King Air, and to ascertain successful sampling of potentially influenced cloud volumes with computer-directed navigation and with the use of small pockets of artificially generated ice crystals as tracers. The use of ice crystal tracers assured that false positive and false negative results could be identified, as detailed later on. In addition, we intended to quantify APIP generation as a function of cloud and flight parameters. Some preliminary results from this research were presented by Serrano (1988) and by Vali et al. (1988).

3. Experimental design

The detection of APIPs in an experiment involving only one aircraft depends directly on the ability to retrace part of an earlier flight segment. A crucial part of the experimental design, then, was to have one or more tests, independent of the APIPs themselves, to ascertain whether or not the aircraft had successfully sampled a volume of air affected by the earlier presence of the aircraft. The method included two such tests: 1) in-flight, air-relative navigation of the aircraft back along a portion of the earlier flight path, with postflight calculation to see if the retraced path fell within the diffusion volume of the original path, and 2) detection of crystal "tracers" that had been artificially nucleated at one or two points along the original path.

a. Air-relative navigation

The computer system on the University of Wyoming King Air aircraft (KA) has been used for many years as a tool for air-relative navigation of the aircraft back through previously sampled air parcels. The primary application of this technique has been in cloud seeding studies, to assess the effects of the seeding material.

The method assumes a uniform horizontal and vertical wind field in the region of the flight for the duration of each experiment. At a time or position chosen by the pilot or the on-board scientist, a reference point is established by initiation of the navigation algorithm. Integration of the air-relative displacement vector is started, and for the remainder of the experiment the pilot is given continually updated heading and distance information back to the reference point ("pointer"). The aircraft is piloted to return to the pointer after appropriate turns and with the desired lapse of time.

The simplest use of pointer technique in these studies was the "single-pointer" experiment. In these cases, in order to resample a few kilometers of the previous flight path, rather than just a single point, the pilot navigated the aircraft back through the pointer either along the original heading or along the reverse of the original heading. Crossing the pointer with <2° deviation in heading from the original (or +180°) yields a sampling of the potentially affected cloud volume along a 5.7 km distance, if the cross-path spread (by diffusion) of the aircraft's effect is assumed to be 0.2 km. The 2° accuracy in heading is readily achieved, and the pointer is readily intercepted with about 0.1-km precision.

In order to ease the task of navigating back along a flight segment, the method described above was extended to include two points along the original path. For such "double-pointer" experiments the headings and distances back to both pointers were calculated simultaneously. Two additional parameters were also calculated: 1) the displacement of the aircraft normal to the baseline determined by the two pointers, and 2) the difference between the aircraft heading and the baseline heading. This allowed navigation through the pointers and along the baseline in a manner similar to that used for Instrumented Landing Systems (ILS) and other cockpit navigation devices. A schematic flight path for a double-pointer experiment is shown in Fig. 1. Typical pointer-to-pointer separation was 3–7 km. As illustrated in Fig. 1, the turn was carried out so that there would be time for baseline alignment before retracing the segment of interest. Naturally, the sequence could be repeated more than once.

Thus, both the single- and double-pointer methods can be used to define a line, or segment, to be retraced by the aircraft. In fact, by the time the aircraft actually returns to the segment to be retraced, a finite volume of air has been affected by the aircraft. This volume was assumed to be cylindrical, with its axis along the original flight segment and its radius determined by the diffusion distance from the original path. Passage through this cylindrical volume then constitutes sampling of air or cloud previously affected by the aircraft. In other words, this would be the volume in which APIPs, if present, should be detected. For the remainder of this discussion that volume will be termed the "volume of influence" (VOI).

In postflight analyses, the radius, r, of the VOI was calculated by assuming homogeneous turbulent diffusion, after Batchelor (1950):

$$r = (et^3)^{1/2} + r_0.$$

Here r is the radius of the diffusion plume at a concentration of one standard deviation below the mean

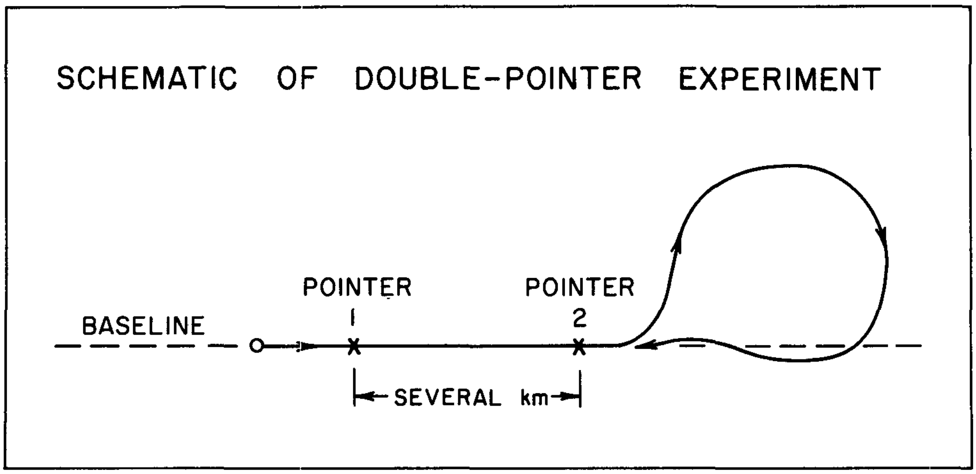

FIG. 1. Schematic air-relative flight path for a double-pointer experiment.

plume concentration, e is the measured eddy dissipation rate, and r_0 is the radius of the initial disturbance due to the aircraft structure. For the KA we have assumed $r_0 = 50$ m. For the experiments described below, a particular retrace was judged successful if the aircraft remained within the VOI for more than 80% of the segment between the pointers. The calculated lengths of the retraces ranged from 3.2 to 11.5 km.

b. Tracers

While the pointer methods are capable of providing the accuracy of retracing necessary for this study, they work reliably only in completely homogeneous wind fields. Since that condition is never fully satisfied, and, certainly, some cases are worse than others, it was felt desirable to have an independent indication of success or failure in resampling the VOI. A variety of tracer methods could be considered for this purpose. It was elected to use a high concentration of artificially nucleated ice crystals at each pointer location. Previous studies have shown that sprays of liquid propane (boiling point = −42.1°C) successfully initiated homogeneous nucleation of supercooled water (Hicks and Vali 1973). Because of safety concerns on the aircraft, Freon 22 was used instead, since it is practically incombustible and has a boiling point close to that of propane (−40.6°C).

The use of ice crystals as tracers in this experiment has two strong advantages over the use of chemical tracers, such as SF_6: 1) the tracer crystals should diffuse (and fall) in the same manner as the APIPs, and 2) detection of the tracer crystals would give a very strong indication that the cloud conditions and growth times should permit ice crystals to be observed on the resampling pass. Detection of the tracers, then, was taken as independent evidence that the aircraft had resampled the VOI *and* that the cloud conditions were appropriate for the growth of the APIPs to detectable sizes.

The ice crystal tracer also protected the experiments from both false-positive and false-negative conclusions; that is, encountering high ice concentrations, but not detecting the tracer pulses, could be ascribed to missing the VOI while some natural ice generation process was active (limited regions of locally high ice concentrations are occasionally encountered in many clouds). On the other hand, detecting tracer pulses, but finding no increase in ice concentration in the region between them, could be clearly ascribed to the absence of APIPs, without the suspicion that the VOI was missed. Not detecting the tracer pulses, either because of unsuitable growth conditions or insufficient growth time, or because the VOI was missed, then constituted a failed experiment. Detection of the tracers, along with an increase in ice concentration along the sampling path between them, was considered an unequivocal indication of APIPs.

In all the experiments described below, the pointer(s) and crystal tracers were used together. However, there were cases when the tracer release equipment malfunctioned, and others where the cloud failed to persist at the location of one of the releases. Therefore the usable experiments have been classified into three categories of successively increasing confidence: category 1—successful interception of the pointer(s) without detection of the tracer(s); category 2—interception of the pointer(s) *and* detection of one set of tracer crystals (from a single-pointer release or from one of the two double-pointer releases); and category 3—interception of the pointer(s) *and* detecting both sets of tracer crystals (double-pointer). Category 3 is listed here for completeness only, as there are no cases of that kind in the present dataset. Note that in all the experiments of category 2, the tracer crystals were detected within or very close to the VOI; this gives added confidence in the navigation method and in the calculation of VOI, and justifies inclusion of the category 1 cases in the analyses to follow, even though those cases taken alone would be subject to criticism for lack of independent confirmation of resampling the VOI.

c. Cloud selection

Selection of clouds in each case was governed by two general requirements: 1) the need to conduct the experiment in as wide a range of temperatures, liquid-water contents, droplet concentrations and drop sizes as possible, and 2) the need for relatively homogeneous wind fields while using the pointer tracking technique. The second requirement thus limited our choice to clouds with relatively small updraft speeds, as would be found in stratiform and shallow cumulus or altocumulus clouds.

Table 1 lists the cloud type, base temperature, base altitude and thickness for each of the experimental periods. The low droplet concentrations observed in all cases (Table 2) are consistent with what one would expect in these clouds, which formed in midtropospheric air with low vertical velocities.

4. Results

In all, some 23 experiments were performed, on 8 different days, in stratiform clouds of different varieties. Eight experiments did not yield usable data, either because of high winds moving the experimental line out of stationary wave clouds (3 cases), or because of equipment and/or navigation problems (5 cases). Details of the 15 successful experiments are given in Table 2.

The experiments are grouped by category in Table 2, and are identified by date and by the sequence on that date. Four experiments were run in north-central California (CA), all as single-pointer tests. The other experiments were carried out in southeast Wyoming (WY), all using double pointers. The tabulated experimental conditions are those encountered during the initial flight segments; i.e., along the axis of the VOI. The data include temperature (average for the flight leg; variability was <0.5°C for all cases), range of droplet concentrations measured with a light-scattering probe (Particle Measuring Systems, Boulder, Colorado; Model FSSP), mean liquid-water content and droplet sizes from the FSSP, range of 1-s average crystal concentrations measured by a one-dimensional optical array device (Particle Measuring Systems, Boulder, Colorado; Model 1D-C), engine torque, true airspeed, and relative amount of airframe ice load. Engine torque is included since higher torque for a given airspeed and for level flight indicates greater drag due to the presence of heavier airframe ice loading. The last three columns all refer to resampling the VOI, giving the maximum 1-s average crystal concentration found in the VOI of the tracer pulse ("nd" indicates no tracer crystals were detected), the length of the flight segment within the VOI, and whether or not APIPs were detected. As shown in Table 2, 9 of the 15 experiments are of category 1, with the remaining 6 in category 2. Tracer crystals were detected in 2 of the 4 single-pointer experiments and in 4 out of 9 double-pointer experiments. In only one case was there evidence for APIPs, using the criterion that the concentration of ice crystals on the repeat penetration exceeds the average of the initial penetration by two standard deviations.

As shown in Table 2, the range of cloud conditions included temperatures of −3° to −25°C, liquid-water contents up to 0.5 g m^{-3}, droplet concentrations of 10–280 cm^{-3}, mean droplet sizes of 7–20 μm, and background ice concentrations of 0–800 L^{-1}. Aircraft operating parameters ranged over true airspeeds of 80–110 m s^{-1}, engine torques of 1000–1500 ft lb, and low to heavy airframe icing.

On two of the experimental days (20 November 1986 and 31 May 1989), the background ice crystal concentrations given by the 1D-C probe seem high for the temperatures that were present. This overestimate may have been due to instrument characteristics. The 1D-C probe has a particle diameter resolution of 12.5 μm, and thus may detect some of the larger cloud droplets in addition to ice crystals. An imaging probe of 25-μm resolution (Particle Measuring Systems, Boulder, Colorado; Model 2D-C) was also flown in these experiments. Data from this probe are surer indications of ice crystal concentrations. On 20 November 1986 and 31 May 1989 the 2D-C concentrations were 1–2 orders of magnitude less than the 1D-C concentrations, confirming that the 1D-C values included large cloud droplets. In contrast, the other four sets of experiments had 1D-C and 2D-C concentrations within an order of magnitude of each other. Still, for the evaluation of the APIP experiments we relied on the 1D-C concentrations because of the ability of the probe to detect the small ice crystals generated as tracers or APIPs. When looking at the absolute values of the reported crystal concentrations, the lack of discrimination in the 1D-C probe must be borne in mind.

The experimental results given in Table 2 are also

TABLE 1. Cloud types and cloud conditions for APIPs experiments.

Date	Cloud type	Base T (°C)	Base alt (m)	Thickness (m)
20 Nov 1986	As	−11.1	4600	Not avail.
21 May 1987	Ac	−8.0	4400	500
12 Dec 1988	Ac len	−9.0	3900	400
13 Dec 1988	Ac len*	−8.4	3600	2800
21 Dec 1988	Ac len*	−11.9	3800	1100
31 May 1989	As	−2.7	2700	900

* Multilevel altocumulus lenticularis, so base conditions are for the lowest level and thickness is the difference between the lowest and highest levels.

TABLE 2. Successful experiments.

		Initial flight segment									Resampling		
Expt	Locn	T (°C)	FSSP (cm)	lwc (g m^{-1})	dbar (μm)	dmax (μm)	1*DC* (L^{-1})	Torq (ft lb)	TAS (m s^{-1})	Icing	1*DC-T* (L^{-1})	Trace (km)	APIP
Category 1													
20 Nov 1986, 3	CA	−12	20–60	.04	15	21	30–300	1520	96	low	nd	11.5	no
20 Nov 1986, 4	CA	−14	10–100	.05	14	33	50–800	1500	100	low	nd	7.5	no
13 Dec 1988, 1	WY	−19	20–40	.01	11	14	0.0	1260	104	low	nd	7.8	no
13 Dec 1988, 4	WY	−25	60–80	.01	7	12	1–6	1330	109	low	nd	7.6	no
13 Dec 1988, 5	WY	−8	30–280	.02	7	14	0.0	1310	104	low	nd	4.2	no
21 Dec 1988, 1	WY	−14	100–120	.02	10	18	<.4	1190	107	low	nd	4.8	no
31 May 1989, 1	WY	−3	40–50	.1	17	28	10–50	1210	92	low	nd	5.5	no
31 May 1989, 3	WY	−3	40–50	.1	17	30	10–300	1325	81	low	nd	4.1	no
31 May 1989, 5	WY	−4	40–60	.1	17	28	10–70	1550	87	low	nd	5.1	no
Category 2													
20 Nov 1986, 1	CA	−12	30–70	.5	20	27	14	1540	95	heavy	4000	9.0	yes
20 Nov 1986, 2	CA	−12	30–70	.3	18	30	0–90	1325	100	low	>3000	7.5	no
21 May 1987, 1	WY	−10	20–30	.03	8	15	<10	1160	96	low	1000	7.7	no
12 Dec 1988, 1	WY	−9	45–60	.02	11	18	5	980	88	low	190	4.4	no
13 Dec 1988, 2	WY	−18	40–70	.01	9	14	0.0	1290	105	low	330	3.2	no
21 Dec 1988, 2	WY	−13	100–140	.01	9	15	<.2	1410	105	low	42	3.7	no

presented in Fig. 2, where each individual experiment is located as a function of mean liquid-water content and mean temperature. A darkened circle is used for the experiment that involved heavy airframe ice loading. The "Y" or "N" beside each circle denotes the presence or absence of APIPs, respectively.

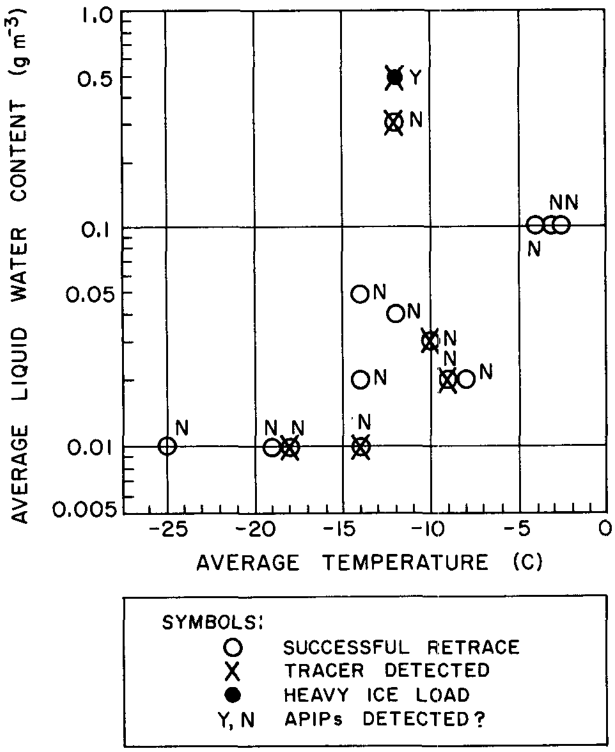

FIG. 2. Summary of the APIPs experiments listed in Table 1, as seen in the 2-D parameter space of average liquid-water content and temperature. Symbols are defined in the figure; further details are given in the text.

As Fig. 2 reveals, the production of APIPs by the King Air is not a simple function of either temperature or liquid-water content. The no-APIP cases spread over the entire temperature range of −3° to −25°C, and up to all but the highest liquid-water contents (0.01 to 0.3 g m^{-3}). The one case with APIPs occurred during a combination of heavy airframe ice load (accumulated during an extensive in-cloud period prior to the actual experiment) *and* high liquid-water content (0.5 g m^{-3}). These results suggest that APIPs generation is linked to the presence of an ice load on the aircraft. Of course, heavy ice loads are most likely to occur in clouds with high liquid-water contents, so the two conditions may be linked.

The following sections describe four of the experiments from Table 2 and Fig. 2 in greater detail. They are all from category 2, and include two single-pointer cases (20 November 1986, 1 and 20 November 1986, 2), and two double-pointer cases (21 May 1987, 1 and 21 December 1988, 2).

a. Experiment 1, 20 November 1986

Figure 3 contains a plot of the air-relative flight track, and plots of 1-s average FSSP droplet concentration, FSSP liquid-water content, and 1D-C particle concentration for the experiment. The flight track is shown as a thin line; the large diamond shows the center of the freon release. The thick line and the "VA" label on the retrace path denote times when the aircraft was within the calculated VOI of the previous pass. The open box and the "VF" label shows the calculated VOI of the freon release segment. The flight path symbols (thin line, thick line, box, and diamond) and labels

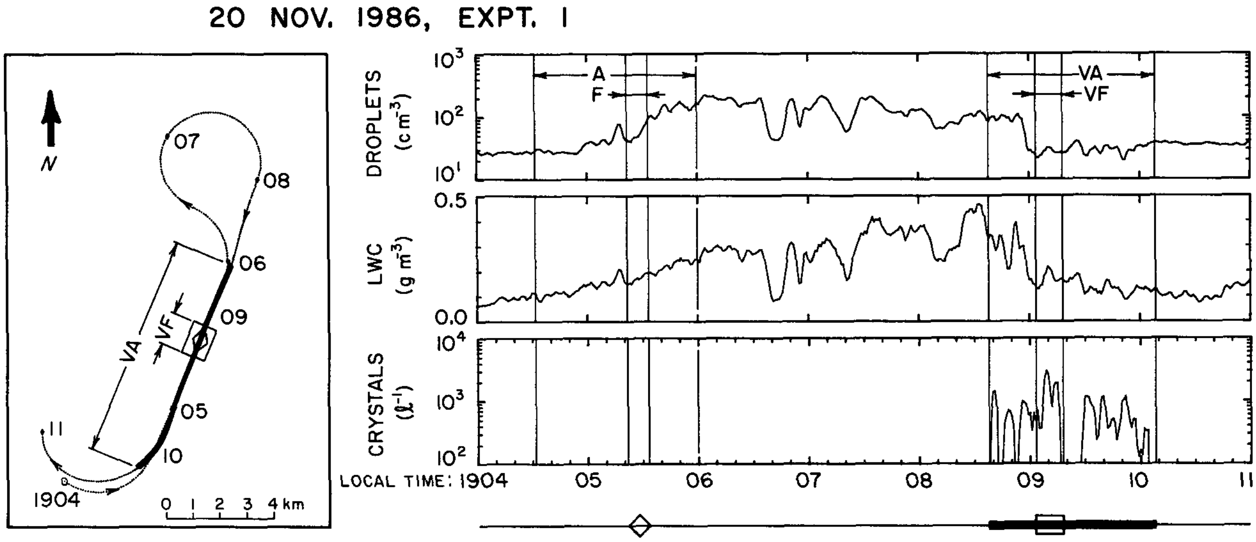

FIG. 3. Air-relative flight path and time traces of droplet concentration, liquid-water content, and ice crystal concentration for Experiment 1, 20 November 1986. Details of symbols and notation are given in the text.

are repeated in the right-hand diagram for reference. Other designations included in the diagram are "A" for the flight segment that was later approached within less than the diffusion distance; i.e., the segment whose VOI is later resampled, and "F" for the period of freon release corresponding to the expected detection period "VF."

During segment A of the initial pass, the range of 1D-C particle concentrations was 0–80 L^{-1} (average about 14 L^{-1}). The tracer crystals are clearly evident, in good correspondence with the expected location, at 1909:10 LST. Maximum crystal concentration reached 4000 L^{-1} in this pulse. During the remainder of retrace path, crystal concentrations ranged from 0 to 2000 L^{-1}, with values exceeding 100 L^{-1} most of the time. These ice crystal concentrations are coincident with the VA segment, and are distinctly different from those observed during the initial A segment. For those reasons it appears justified to conclude that the crystals detected during the retrace segment VA were APIPs. Peak concentrations of the APIPs were about 25 times greater than the original or background levels. The large variability in crystal concentrations has no ready explanation; it may be speculated that they are associated with turbulence and with fluctuations in cloud parameters during the initial penetration. In agreement with the observer's notes for this flight, the high engine torque (Table 2) is indicative of the presence of heavy airframe ice load during the experiment. Immediately after completion of the experiment, a descent to warmer temperatures was executed to deice the airplane.

b. *Experiment 2, 20 November 1986*

This experiment was performed once altitude was regained, which followed the descent for deicing mentioned above. Even though the KA was now flying at the same altitude (−12°C) and at a higher airspeed (100 m s^{-1}) than in the first experiment, the engine torque was over 200 ft lb smaller. Thus, the airframe was nearly free of ice load during this second experiment, and the ice accumulation rate was also lower due to the lower liquid-water content encountered. Figure 4 shows the air-relative flight track and the plots of cloud parameters for this experiment, using the same conventions as Fig. 3. Most of segment A had crystal concentrations less than 100 L^{-1}. Except for the 5000 L^{-1} burst corresponding to the tracer (VF), segment VA had concentrations similar to those of A, ranging 0–150 L^{-1}. Thus, no evidence for APIPs was found in this case.

c. *Experiment 1, 21 May 1987*

Figure 5 contains the flight track and time plots of various cloud parameters for a double-pointer experiment. The figure notation includes one segment (A) with two freon releases (F1 and F2) and the corresponding VOIs (VA, VF1, and VF2). Segment A had droplet concentrations of 20–30 cm^{-3} and only 2 or 3 small spots of ice at concentrations less than 10 L^{-1}. Other than the burst of crystal concentration for the second tracer (VF2 maximum about 1000 L^{-1}), the retrace VA still contained only a few spots of crystals at less than 10 L^{-1}. No tracer crystals were detected at VF1, possibly because of vertical displacement of the small plume. The evidence from this experiment, in the vicinity of VF2 and throughout VA, indicates the absence of APIPs.

d. *Experiment 2, 21 December 1988*

Figure 6 shows data obtained during a double-pointer experiment in altocumulus lenticularis at a temperature of −13°C. The results are quite similar to

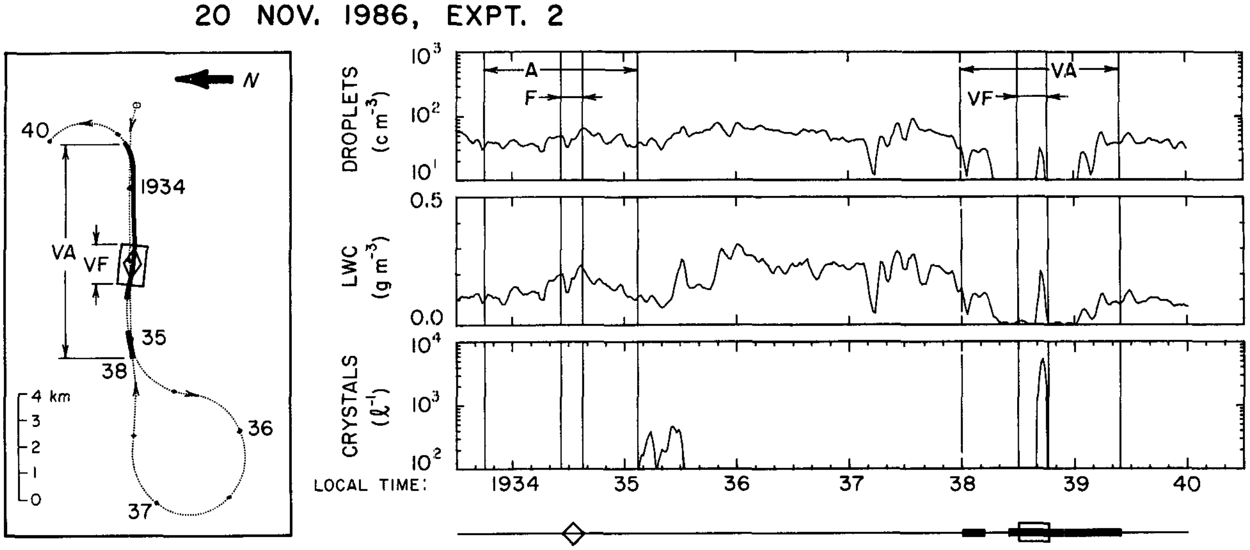

FIG. 4. As in Fig. 3, for Experiment 2, 20 November 1986.

the preceding case: only one spot of ice, at about 2 L^{-1}, was seen in segment A, and the only evidence of ice in VA was the burst of crystals to 40 L^{-1} corresponding to the second pointer (VF2). The lack of tracer crystals at VF1 is explained by the fact that the release F1 took place just at the edge of the cloud, partly in clear air. Data from this experiment also indicate an absence of APIPs.

5. Conclusions

It has been shown that air-relative navigation of the King Air (KA) can be used successfully to sample cloud air within the volume of influence (VOI) of an earlier flight segment. Evidence for this statement is provided by the detection of crystal tracers at the expected locations along the original flight path. It has also been demonstrated that artificially nucleated ice crystals can be used effectively as tracers, for independent confirmation of resampling VOIs and for proof of conditions amenable to the growth of the ice crystals during the experimental interval.

The experimental results demonstrate that the KA produces APIPs only in a limited range of cloud and aircraft operating conditions. Evidence for the absence of APIPs was obtained in experiments carried out over a wide range of temperatures (−3° to −25°C), liquid-water contents (up to 0.3 g m^{-3}), and droplet sizes (7–

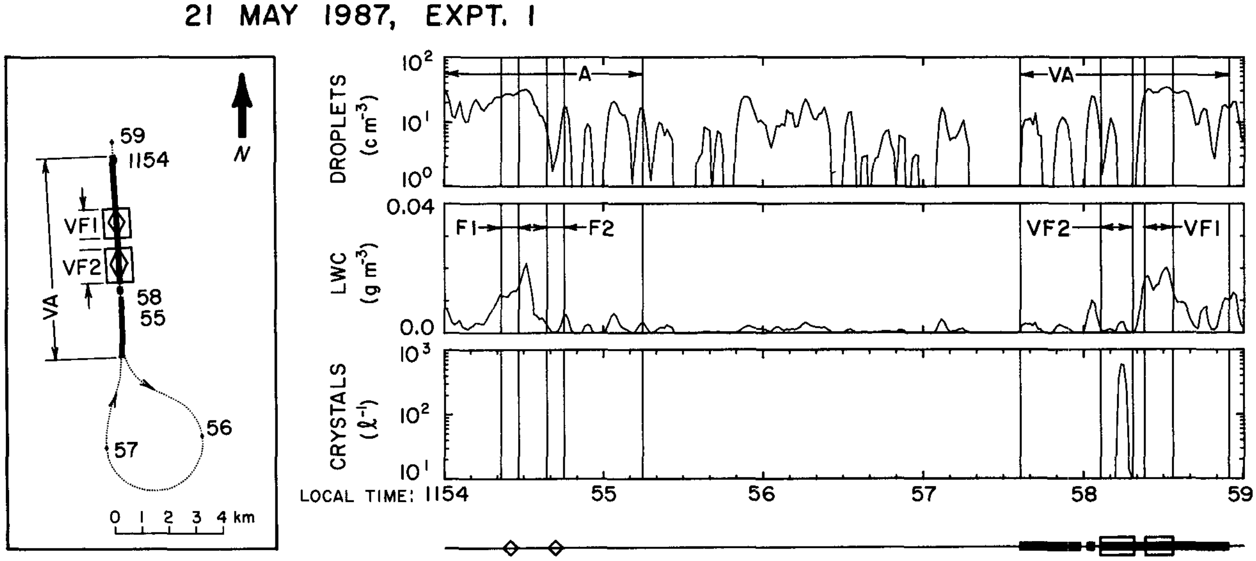

FIG. 5. As in Fig. 3, for Experiment 1, 21 May 1987.

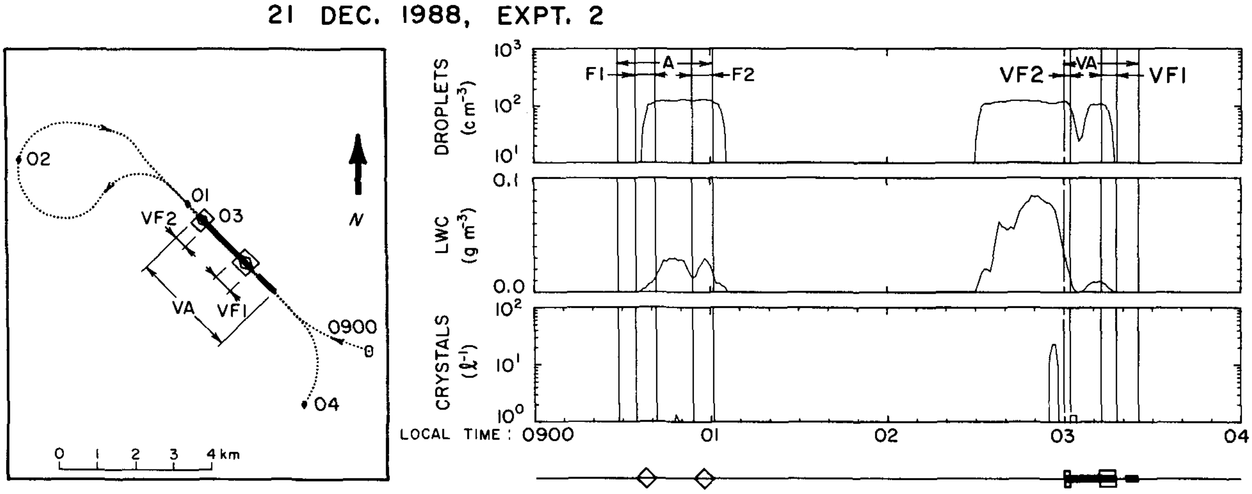

FIG. 6. As in Fig. 3, for Experiment 2, 21 December 1988.

20 μm mean diameter). Operating conditions of the aircraft varied over a limited range (airspeeds of 80 to 100 m s^{-1} and engine speeds of 1700 to 1900 rpm).

In only one of the 15 successful experiments in this project was there positive evidence for APIPs. This experiment was carried out in a combination of relatively warm temperature (−12°C), relatively high liquid-water content (0.5 g m^{-3}), large droplet sizes (20-μm mean diameter, 27-μm maximum diameter) *and* with a heavy load of airframe ice. Another experiment with similar cloud conditions (−12°C, 0.3 g m^{-3}, 19 μm, 30 μm), but with little or no airframe ice, had no evidence of APIPs. In general, the case with APIPs fits within the range of conditions covered by the other experiments. Two distinguishing factors for the case with APIPs are higher liquid-water content (0.5 g m^{-3} versus 0.3 g m^{-3} for no APIPs) and heavy airframe icing.

It is impossible to deduce from just one case with APIPs what mechanism of crystal generation was at work, yet examination of these results in light of the various hypotheses seems worthwhile for aiding further research. Of the two distinguishing features mentioned above, heavy airframe icing appears to be the most unique in comparison with the other experiments. Differences in liquid-water contents can be expected to lead to proportionate differences in the generation of APIPs; the existence of a threshold value separating positive and negative cases would be surprising. Thus, the indication is that airframe ice might be a prerequisite for the generation of APIPs. Whether the specific structure of the airframe ice is a factor, or just the amount of coverage, is unknown.

In many ways, the conditions indicated to be required for the generation of APIPs by the KA are reminiscent of the Hallett–Mossop mechanism for secondary ice production (Mossop 1985a,b). This possibility was also suggested by Rangno and Hobbs (1983). However, extrapolation of the laboratory results of Mossop to aircraft conditions is far from reliable, since droplet impact speeds with the aircraft are 20–30 times higher than those used in the laboratory, and aerodynamic heating will establish a large thermal gradient between the air and the riming aircraft surface. Clearly, laboratory tests will be necessary to examine splinter production at aircraft velocities.

Whether airframe icing was a factor in the experiments of other investigators is unclear. Rangno and Hobbs (1983) reported airframe icing for six of the eight cases that had evidence of APIPs, but a correlation between APIPs production and amount of airframe icing did not emerge. For their two experiments with the greatest APIPs production, the degree of icing was not known.

The experiments appear to be inconsistent with expectations based on the explanation (Vonnegut 1986) that cooling by expansion, behind the propellers or behind the wings, leads to increased ice formation by nucleation. The propeller tips on the King Air have tangential velocities in the range of 200 to 250 m s^{-1}, which result in calculated coolings of 17° to 22°C. For the temperatures prevailing in our tests, additional temperature drops of those magnitudes would have led to the activation of large concentrations of heterogeneous ice nuclei in all cases, and even to homogeneous nucleation in three of the tests. We cannot provide quantitative estimates for the concentrations that would have resulted, primarily because of the uncertainties in ice nucleus concentrations, and because the volumes of air affected by cooling are unknown. Thus, while some ice production by this mechanism might have taken place and remained undetected in our tests, the relatively large number of tests in which no APIPs were detected argues against the effectiveness of cooling as a source of APIPs. Because of the null results, we cannot check on the prediction of the expansion theory that the concentrations of ice crystals generated should increase with decreasing cloud temperatures.

In conclusion, it appears that a turboprop-driven aircraft can generate APIPs in supercooled clouds, but only in a limited combination of cloud conditions and aircraft operating parameters. It is suggested that airframe icing might be one prerequisite for APIPs. At present, the most plausible mechanisms for generating APIPs are ice splinter production during airframe icing and enhanced ice nucleation in propeller tip vortices. Further research will be needed to determine which of these processes, if either, or another, generate APIPs in clouds, and to quantify those processes.

The impact of our finding of limited occurrence of APIPs is that during many types of investigations with the King Air or similar aircraft, valid measurements of ice crystal populations can be obtained even if the same parcel is sampled several times. However, within clouds of high liquid-water content, and after longer periods of cloud penetrations when large amounts of airframe icing accumulate, passage of the aircraft may add high concentrations of ice particles to the cloud volume. The consequences of the generation of such ice crystals can be appreciable in the development of precipitation, radiative properties, and other characteristics of the clouds. It seems important to obtain further definitions of the dependence of ice crystal production by aircraft on cloud and aircraft characteristics.

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