Aircraft-Produced Ice Particles (APIPs): Additional Results and Further Insights

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ABSTRACT

This paper presents new results from studies of aircraft-produced ice particles (APIPs) in supercooled fog and clouds. Nine aircraft, including a Beech King Air 200T cloud physics aircraft, a Piper Aztec, a Cessna 421-C, two North American T-28s, an Aero Commander, a Piper Navajo, a Beech Turbo Baron, and a second four-bladed King Air were involved in the tests. The instrumented King Air served as the monitoring aircraft for trails of ice particles created, or not created, when the other aircraft were flown through clouds at various temperatures and served as both the test and monitoring aircraft when it itself was tested. In some cases sulfur hexafluoride (SF_6) gas was released by the test aircraft during its test run and was detected by the King Air during its monitoring passes to confirm the location of the test aircraft wake. Ambient temperatures for the tests ranged between $-5°$ and $-12°C$. The results confirm earlier published results and provide further insights into the APIPs phenomenon. The King Air at ambient temperatures less than $-8°C$ can produce APIPs readily. The Piper Aztec and the Aero Commander also produced APIPs under the test conditions in which they were flown. The Cessna 421, Piper Navajo, and Beech Turbo Baron did not. The APIPs production potential of a T-28 is still indeterminate because a limited range of conditions was tested. Homogeneous nucleation in the adiabatically cooled regions where air is expanding around the rapidly rotating propeller tips is the cause of APIPs. An equation involving the propeller efficiency, engine thrust, and true airspeed of the aircraft is used along with the published thrust characteristics of the propellers to predict when the aircraft will produce APIPs. In most cases the predictions agree well with the field tests. Of all of the aircraft tested, the Piper Aztec, despite its small size and low horsepower, was predicted to be the most prolific producer of APIPs, and this was confirmed in field tests. The APIPs, when they are created, appear in aircraft wakes in concentrations up to several hundred per liter, which are initially very small and almost uniform in size but grow to larger nearly uniform sizes with time. APIPs production is most likely at low ambient temperatures when an aircraft is flown at maximum power with the gear and flaps extended, resulting in a relatively low airspeed under high-drag conditions. It is predicted that APIPs production of an aircraft can be decreased or eliminated altogether by using a propeller with a larger number of propeller blades, such that the engine thrust is distributed over more blades, thereby decreasing the cooling on each blade. Plans to test this hypothesis using three- and four-bladed King Airs as the test aircraft never came to fruition because of unsatisfactory weather conditions. It is likely that APIPs have confounded the results of some past cloud microphysical investigations, especially those in which repeat passes were made through individual clouds under heavy icing conditions by aircraft known now to be APIPs producers. Aircraft flying under such conditions are forced to use high power settings to overcome the drag of a heavy ice load. These are the conditions that field tests demonstrate are most conducive to the production of APIPs. In these situations, APIPs may have led investigators to conclude that there was more rapid development of ice, and higher concentrations of ice particles in clouds, than actually was the case.

1. Introduction

Considerable progress has been made in documenting and explaining the existence of aircraft-produced ice particles (APIPs) since they were first brought to the attention of the scientific community by Rangno and Hobbs (1983, 1984). These particles appear in the cylindrical wakes of propeller-driven aircraft. Rangno and Hobbs observed them produced by the University of Washington B-23 in turrets of cumulus clouds, at temperatures equal to or less than $-8°C$, and in wintertime stratus by a commercial turboprop aircraft at temperatures equal to or less than $-9°C$. They hypothesized that APIPs were caused either by nucleation on combustion nuclei containing lead compounds, splintering of rime formed as aircraft surfaces iced, or adiabatic

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cooling in the wakes of the propeller tips. Vonnegut (1986), commenting on their observations, pointed out that adiabatic expansion in the flow around the propeller tips was sufficient to cool cloud droplets to $-39°C$ if cloud temperatures were only a few degrees below $0°C$, and that when cloudy air is cooled below $-39°C$, large concentrations of ice particles likely result from homogeneous condensation followed by freezing. That the expansion of air can produce cooling sufficient enough to produce ice crystals by homogeneous nucleation was verified by Weinstein and Hicks (1976), who generated ice crystals for supercooled fog dispersal through the expansion of compressed air.

Kelley and Vali (1991) determined that the University of Wyoming Beech King Air 200T left large concentrations of ice particles in its wake when penetrating supercooled clouds at temperatures equal to or less than $-8°C$. They hypothesized that ice splinters were dispersed during the process of ice riming onto the leading edges of the aircraft while flying through supercooled clouds.

Sassen (1991) observed a trail of APIPs with a ground-based lidar after a Beech King Air 200T penetrated altocumulus clouds at $-30°C$, demonstrating that APIPs can be produced at very low temperatures in regions with low concentrations of supercooled water.

Woodley et al. (1991) investigated the APIPs phenomenon in a field project named the Mono Lake APIPs Studies (MOLAS). They found APIPs could be produced readily by the Wyoming Beech King Air 200T in supercooled fog over Mono Lake in California at temperatures equal to or less than $-8°C$. The production of APIPs was determined to be a function of the ambient temperature, the power setting of the aircraft (i.e., propeller torque and revolutions per minute), and its configuration (i.e., aerodynamically "clean" or with gear and flaps extended). The colder the ambient temperature and the higher the power setting, the more readily the aircraft produced APIPs. In addition, at a given temperature, the aircraft more readily produced APIPs if its gear and flaps were extended. The APIPs, initially in concentrations of several hundred per liter, were of nearly uniform size, as documented by hydrometeor imaging probes, and the ice crystals grew at a rate of 0.4 μm s^{-1} to larger and nearly uniform sizes, as was observed by Rangno and Hobbs and other early observers of APIPs. They concluded that the mechanism for production of APIPs is homogeneous nucleation from the vapor in the adiabatically cooled region near the propeller tips. Neither heterogeneous nucleation nor direct freezing of the fog droplets can explain the estimated high concentrations ($>10^5$ crystals cm^{-3}) of ice crystals in the generating zone behind each blade tip. Only a homogeneous nucleation process in which large concentrations of tiny water droplets nucleate from the vapor and then rapidly freeze can produce ice crystals in such high initial concentrations. Foster and Hallett (1993) later describe experimental laboratory and theoretical work leading them also to the conclusion that APIPs must be produced by homogeneous nucleation from the vapor during adiabatic expansion in the airflow around propeller tips.

Other aircraft (e.g., a Cessna 421, an Aero Commander, and a T-28) were tested for APIPs production during MOLAS but none were detected. The release of sulfur hexafluoride (SF_6) tracer gas by the test aircraft and detection by the monitoring aircraft facilitated these tests. In some cases the ambient temperature was too warm for the King Air 200T to produce APIPs; in others it was cold enough for the King Air to make APIPs, but the other test aircraft did not.

The MOLAS work continued over a period of several additional years. In this later work,

- additional aircraft were tested;
- a method was developed to assess, without actual field testing, which aircraft are most at risk for the production of APIPs;
- procedures were developed that can be implemented to avoid APIPs during the course of cloud physics investigations in the supercooled portions of clouds;
- structural modifications of the aircraft propeller system were suggested that might mitigate the APIPs problem, but field tests were inconclusive because of unsatisfactory weather conditions; and
- the probable impact of APIPs on prior cloud physics studies was estimated.

These additional results are presented here.

2. Overview of the MOLAS APIPS studies

The additional studies of APIPs were conducted for most of their duration in supercooled fog over Mono Lake, California. Mono Lake was also the site of the initial work in MOLAS, because of its unique geographical and meteorological setting and episodes of supercooled fog.

The MOLAS research has been limited to suitable supercooled fog, because the natural microphysical variability in fog is small relative to the expected APIPs signal. In the context of MOLAS, a suitable fog was one that covered most of Mono Lake and had a depth that would allow safe passage of the aircraft over nearby obstructions. The fog-top temperatures had to be equal to or less than $-5°C$, with equal to or less than $-7°C$ being more desirable, and it had to have low natural ice crystal concentrations (ICC). Such low natural ice crystal concentrations are not readily achieved on a reproducible basis in the supercooled regions of convective clouds. In addition, there is a higher probability of sampling the volume that has been disturbed by passage of the test aircraft in fog than in convective clouds in which strong vertical motions may carry the aircraft wake away from its flight level on subsequent cloud passes.

The flight tests were simple in design and execution. The King Air 200T cloud physics aircraft of the Uni-

versity of Wyoming followed close behind the test air-craft until it entered the fog. The scientist aboard the King Air set its air parcel navigation pointer (Gordon and Marwitz 1986) to the position where the test aircraft initially entered the fog and the pilot of the King Air then flew across the track of the test aircraft. The aircraft radar altimeters were intercompared in side-by-side flight before the experiments began, in order to facilitate finding the wake of the test aircraft. In December 1991 and 1993, the test aircraft released SF_6 gas during its trial runs, and the King Air attempted to detect this tracer gas during its monitoring runs, as an unambiguous in-dicator that it had entered the wake of the test aircraft. For the entire experiment, the SF_6 tracer gas was de-tected by the monitoring aircraft on 57% of its passes after release of the gas by the test aircraft. This process was not possible in January 1991, because the SF_6 de-tector had to be removed from the King Air for use in other projects.

When the King Air aircraft was both the test and monitoring aircraft, it made an initial test run into the fog, setting a navigational point about 1 km prior to the end of the test track. The King Air was then flown successively across its own test track. In most cases, the King Air made its intercepts progressively down the track of the test aircraft in order to avoid its wake from previous monitoring runs. In a few instances, however, the King Air returned intentionally to the same point along the test track in order to reexamine something of interest. The key to these experiments was the air-rel-ative navigation system aboard the King Air, which al-lowed it to be flown back through previously sampled or disturbed air parcels.

Each initial test of every aircraft involved a pass into supercooled fog at a maximum power setting. When the monitoring for this test was completed, subsequent tests were made at lower power settings, if the initial tests produced APIPs. Based on the earlier work in MOLAS, it was expected that the high-power tests with aircraft landing gear and flaps extended would be most likely to produce APIPs. This high-drag configuration was used to simulate the flight conditions that might be en-countered when the aircraft was flown under heavy icing conditions, requiring maximum power to stay aloft.

In order to minimize the possibility of ice crystal contamination by APIPs generated by the instrumented observing aircraft, this King Air aircraft was flown at relatively low power settings during the monitoring runs. For all passes, the elapsed time between the time that the test aircraft first traversed a point and the time that the monitoring aircraft traversed it again was cal-culated.

The hydrometeor concentrations, sizes, and habits were determined using three probes manufactured by Particle Measuring Systems (PMS), Inc., of Boulder, Colorado. These probes are flown routinely aboard the University of Wyoming King Air 200T aircraft. These include a forward scattering spectrometer probe (FSSP), particle measuring system OAP-200X (1D-C), and two-dimensional optical array OAP-2D-C (2D-C) probes. Water contents within the fog were estimated by inte-grating the output of the FSSP. A Johnson–Williams (JW)-type hot wire also was used to infer cloud liquid water contents, but its readings were low relative to the FSSP readings of MOLAS-2 and to the JW readings of MOLAS-1.

3. Experimental results

Overall, 17 experiments for the detection of APIPs signatures were conducted during the 1991/92 season, with a total of 89 monitoring passes, where an initial APIPs signature is defined as a narrow linear plume of small ice crystals in a supercooled water cloud in which the concentration of ice crystals is much higher than that of the surroundings, and the plume width is less than 500 m. Crystals in the plume are very uniform in size, indicating that they nucleated at the same time.

There were two productive flight days in December 1991. The first was a "dry run" without supercooled fog on 12 December. The second flight took place on 13 December, during which time SF_6 was released and detected in thin, patchy supercooled fog. There were four flight days in January 1992. The fog depth and temperature were suitable for APIPs on 19, 20, and 21 January 1992. During flights on these days APIPs sig-natures were detected for the King Air and Aero Com-mander aircraft. Because the SF_6 detector was not avail-able during this period, the absence of an APIPs sig-nature, following fog penetrations by a Cessna 421 and a Beech Baron aircraft, did not prove unequivocally that none had been produced. The monitoring aircraft may have missed the plume of the test aircraft.

Successful flights to study APIPs were conducted in supercooled fog over Mono Lake on 18 and 19 Decem-ber 1993. Seven experiments were conducted on the 2 days with a total of 36 monitoring passes. The SF_6 gas was released by a Piper Navajo and an Aztec test aircraft and detected by sensors aboard the King Air on 27 of the 36 monitoring passes.

Typically, the fog water contents averaged 0.20–0.25 g m^{-3}, although they ranged as low as 0.10 g m^{-3} at temperatures between $-9°$ and $-11°C$. Within the un-disturbed fog, the mean (averages over 6 s) maximum droplet concentration was 290 drops per cubic centi-meter (std dev of 76 drops per cubic centimeter), and the mean (6-s averages) droplet size ranged between 7 and 12 μm for the test runs. The natural ice crystal concentrations from the 2D-C probe in the undisturbed fog near the time of the test runs averaged 8 crystals per liter (std dev of 12 crystals per liter).

Documentation of an APIPs case produced by a test aircraft in fog over Mono Lake on 12 December 1993 is presented in Fig. 1. The observations were made by the monitoring King Air. The abscissa in all panels is time [Pacific standard time (PST)]. Working from top
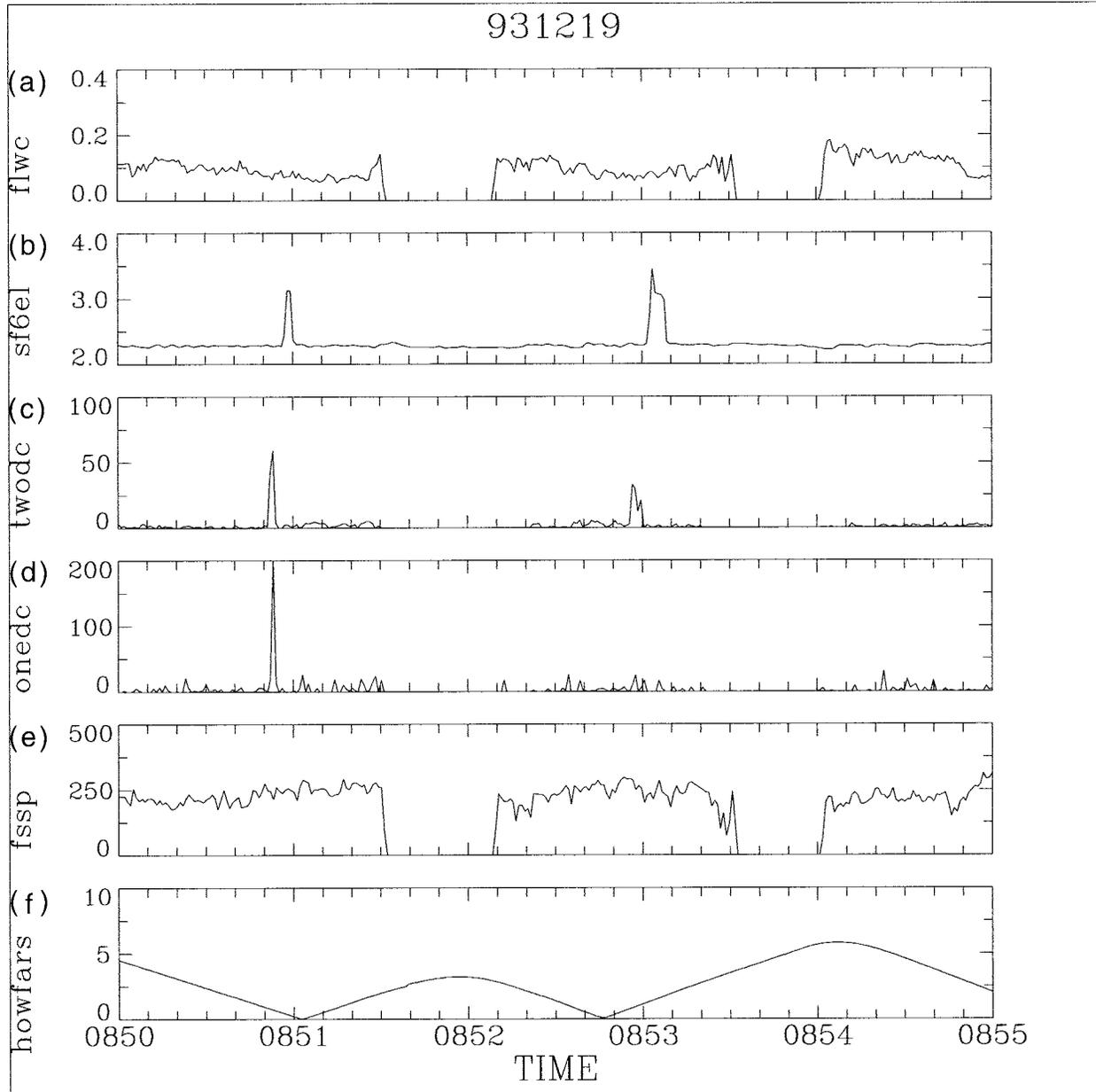
FIG. 1. Line plots of selected aircraft measurements. The total time represented on the abscissa is 5 min and each "tick" mark is 10 s. (a) Fog liquid water content (g m^{-3}) obtained by integration of the output from the FSSP. (b) Detected SF$_6$ in units of detector output voltage. (c),(d) Detected ice crystal concentrations (L^{-1}) for the 2D-C and 1D-C probes, respectively. (e) Droplet concentration (cm^{-3}) from the FSSP. (f) Distance (howfar plot) of the aircraft from the navigation point that was set along the test track. When the distance from the point is "0," the aircraft has returned exactly to the set point.

to bottom, the first panel gives FSSP liquid water content (g m^{-3}), the second gives the detector output voltage for the SF$_6$ gas, which was released by the test aircraft, and the third and fourth panels give the 2D-C and 1D-C ice crystal concentrations, respectively. Figure 1e gives the FSSP droplet concentrations and Fig. 1f labeled "howfar" gives the distance in nautical miles for the King Air from the point that it set at the onset of the run of the test aircraft.

Two obvious APIPs signatures appear in Fig. 1. Note that the spikes of 2D-C and 1D-C ice crystal concentrations are aligned in time with the small spikes of SF$_6$ concentration. The small temporal lag is due to the processing time of the gas detector. The ice crystal and gas spikes in each signature occur quite close to the reference point set by the King Air flying just above and behind the test aircraft during the first run. In both cases the spikes occur within 10 s of this point of reference.

Because the results of MOLAS through December 1993/January 1994 suggested that it might be possible to mitigate or eliminate the APIPs signature of some aircraft if they used a propeller with a larger number of blades, the MOLAS research was extended to investigate this possibility. The extension also made it possible to conduct more tests of a T-28, which had not been tested successfully to this point. Prospective tests were planned for the Fargo, North Dakota, region during the 1996/97 winter season and for the Denver, Colorado, region for the 1997/98 season. It was not until February and March 1998, however, that suitable conditions occurred, equipment and personnel were available, and additional flight tests were actually conducted.

On 16 February 1998 two tests of the T-28 were made at a temperature of $-9°C$ in upslope stratus along the Colorado–Wyoming border. The King Air detected small concentrations of SF6 tracer gas during the monitoring passes, but no APIPs were detected. The third test of the day involved the King Air at maximum power with gear and flaps down and a strong APIPs signature was detected.

On 19 March 1998 an attempt was made to test three- and four-bladed versions of the King Air 200 aircraft. Again, there was supercooled upslope stratus with top temperatures ranging between $-8°$ and $-9°C$. The University of Wyoming King Air, when flown at maximum power and in a ''dirty'' configuration, produced an obvious APIPs signature. By the time the four-bladed King Air was in position for its test, however, the clouds had thinned and the top temperatures had warmed to $-7°C$. A small SF_6 spike was detected along with a small spike of 1D-C counts on the first monitoring pass, but it was well within the natural variability evident in the clouds of the day. A navigational mix-up subsequent to the first pass made it doubtful that the wake of the test aircraft was traversed on the following monitoring passes. Thus, the result is indeterminate with respect to differences in APIPs production by a four-bladed propeller King Air as compared with a three-bladed one.

4. The physical basis of the APIPs results

The observations during this program and in previously reported programs show that APIPs can be produced readily in supercooled clouds by several aircraft at temperatures equal to or less than $-8°C$. The physical processes responsible for their generation are now considered using a rather simple approach. Foster and Hallett (1993) have addressed this problem in considerable detail previously. Woodley et al. (1991) concluded that homogeneous nucleation from the vapor of high concentrations of small water droplets, which then freeze in the cooled region near the prop tips, is the likely cause of APIPs, but how this cooling is produced was not addressed. During and following the field observations presented above, the aerodynamics of propellers were investigated. A propeller is a moving airfoil and its movement through the air generates thrust that moves the aircraft. The air moving over the forward convex surface of a propeller generates the equivalent of the lift generated as air moves over a wing. In the case of the propeller, however, this lift generates thrust. The more rapid motion of air over the forward surface of a propeller blade in comparison with the rear surface generates a pressure drop that is greatest at the blade tips and along the trailing edges. This pressure drop is responsible for propulsion, as well as a sudden adiabatic decrease in temperature. If this cooling is strong enough, it can cause cloud droplets to freeze, or possibly cause homogeneous nucleation of additional large numbers of droplets, which then freeze and generate APIPs. After consulting with engineers at the Beech Aircraft Company, manufacturer of the King Air 200, and the Hartzell Propeller Company, manufacturer of the three-bladed propellers on each turboprop engine on the King Air, we were provided with the following relationship for an aircraft in forward flight from Lan and Roskam (1980, p. 262), relating power (P; kW) to thrust (TR; N):

$$TR = (EP)V^{-1} \tag{1}$$

where E is (nondimensional) propeller efficiency and V is true airspeed (TAS) in meters per second (not the air velocity coming off the props). Most books about aircraft performance (e.g., Lan and Roskam 1980; Roskam and Lan 1997) simply assume that the propeller efficiency (E) is some constant. Commonly cited are E values between 0.80 and 0.85. There are procedures, however, for its calculation by relating the power coefficient to the advance ratio (see, Lan and Roskam 1980). Such detail is not needed here.

To demonstrate the above relationship a calculation is presented for the King Air, assuming a constant propeller efficiency of 0.80. The maximum possible shaft power of the King Air is 634 kW. Tests of this aircraft at 780 hPa and maximum power, and in an aerodynamically clean configuration, produced a TAS of 103 m s^{-1}. Substituting these values into the above equation gives a thrust of 4924 N. When this thrust is distributed over the three blades of the propeller system, it gives 1641 N of thrust per blade.

This thrust (equivalently, lift) is not uniformly distributed along each blade. The variation of thrust along a blade is expressed by a thrust coefficient. The variation of the thrust coefficient over each propeller blade (radius = 125 cm) of the King Air is shown in Fig. 2. The inner 20% of the blade produces no thrust at all. This means the 1641 N of thrust is distributed over the remaining 80% of the blade or over the outer 100 cm. The blade has a width of 17.78 cm, so the area of the blade producing thrust is approximately 1.778×10^3 cm^2.

In this example, the thrust produced by each blade (1641 N), is assumed to be uniformly distributed over the outer portion of the blade, and the resulting force
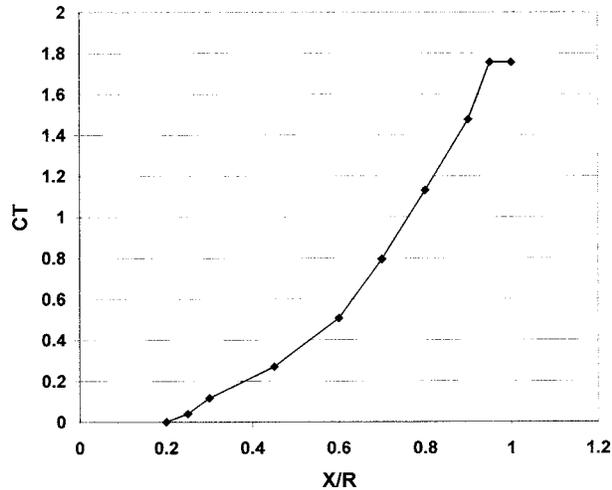
FIG. 2. The propeller thrust coefficient (CT) vs normalized distance (x/R) from the propeller hub for the University of Wyoming King Air, where R is the propeller radius. The data were provided by the Hartzell Propeller Company.

per unit area is 92.3 hPa. This is equivalent to a uniform drop of 92.3 hPa distributed over the outer 80% of the blade surface. If the aircraft is assumed to be flying at 780 hPa where the temperature is −10°C, a pressure drop of 92.3 hPa will result in a moist adiabatic cooling of 7°C, if indeed this process is moist adiabatic. The temperature behind the propeller would then be −17°C, which is too warm by at least 21°C for the production of ice crystals by homogeneous nucleation, but may cause a few cloud droplets to freeze. It is more likely, however, that the process is dry adiabatic because there is not enough time for adjustment to moist conditions during the explosive expansion at the propeller tips. In any case, the additional cooling would only amount to about 1°C.

It is instructive to repeat the above calculation for the King Air when it is flown in a dirty configuration with gear and flaps down. All that changes for this calculation, assuming that the propeller efficiency is held constant at 0.80, is the TAS, which was measured to be 82 m s^{-1} under the experimental conditions of MOLAS. Repeating the mathematical exercise above, it is found that the temperature drop is about 2°C more than when the aircraft was flown in a clean condition with the landing gear and flaps retracted.

The calculated temperature drops are insufficient to produce homogeneous nucleation, but the relative temperature difference between the aerodynamically clean and dirty results agrees rather well with the results of MOLAS in which it was noted that APIPs are produced by the King Air at an ambient temperature of about −8°C when flown at maximum power with the gear and flaps extended and at −10°C at the same power but with the gear and flaps retracted.

These calculations were repeated for a number of other aircraft and the aircraft were then ordered in terms of their propensity to produce APIPs (Table 1). As with the King Air, it was assumed the propeller efficiency was 0.80 and that only the outer 80% of the blade produces thrust. The input data include the 1) aircraft type, 2) true airspeed when the aircraft is flown at maximum power with its gear and flaps extended to simulate icing conditions, 3) shaft horsepower, 4) number of blades per propeller, 5) area of each propeller blade, 6) estimated pressure drop over the propeller blade, and 7) an indication as to whether the aircraft produced an APIPs signature during field tests.

The results of Table 1 provide some surprises, especially for the Piper Aztec, which is ranked first in predicted APIPs production. Intuitively, the Aztec would appear to be the least likely to produce APIPs because of its small size and relatively small engines. It is ranked higher than the King Air in terms of APIPs production because 1) its thrust is distributed over two propeller blades and not three; 2) its propeller blade is small, giving more thrust per unit area of propeller blade and, therefore, more cooling; and 3) its airspeed is low when it is flown in a dirty configuration, giving more time for the propeller blades to act upon the moving air.

TABLE 1. Estimated cooling over the propeller blades of several aircraft operated at maximum power with gear and flaps extended (calculations assume propeller efficiency of 0.80).

Aircraft	P (kW, max)	TAS[a] (m s^{-1})	No. blades	Propeller area (cm^2 × 10^3)[b]	Pressure drop (hPa)	Temperature[c] drop (°C)	Percent thrust over 5% of propeller	APIPs signature?
Piper Aztec	186	130	2	1.200	118	9.2	25.0	Yes
T-28	1063	155	3	4.113	110	8.5	—	?
King Air	634	160	3	2.223	105	8.0	16.3	Yes
Aero Commander	534	160	3	2.154	97	7.3	17.7	Yes
B-23	1193	150	3	5.756	91	7.0	—	Yes
Piper Navajo	231	141	3	1.352	80	6.0	22.5	No
Beach Turbo Baron	231	141	3	1.383	79	5.8	17.0	No
C-421	280	147	3	1.732	74	5.2	13.7	No

[a] The TAS (true airspeed) is at max power with gear and flaps down.
[b] 80% of the total propeller was used in the calculations.
[c] The temperature drop was calculated from a skew-T thermodynamic diagram assuming a moist adiabatic process.

Upon actual testing in 1993, these predictions were verified. The Piper Aztec is a prolific producer of APIPs.

The calculations indicate that the Cessna 421 should be the least likely to produce APIPs. Indeed, we have not been able to get an APIPs signature from this aircraft at temperatures as low as $-12°C$.

It is still not known whether the T-28 produces APIPs. The predictions in Table 1 suggest that it should be even more prolific than the King Air, but this has not been verified. The attempt to verify the prediction during tests in March 1998 failed mainly because the cloud-top temperatures warmed to $-7°C$ before the tests could be conducted. In addition, the pilot found it difficult to fly the aircraft at maximum power in a dirty configuration without exceeding the speed restrictions when the gear and flaps were extended.

We have duplicated, with our simplified model of adiabatic expansion around propeller blades, the relative differences in APIPs production among the aircraft tested in MOLAS, but we have not yet demonstrated that the temperature drop at the propeller of any aircraft is great enough to produce homogeneous nucleation of ice crystals, thought to occur at temperatures equal to or less than $-39°C$. Examination of Fig. 2, showing the overall thrust coefficient distribution on the propeller blade of the King Air, reveals that the thrust is not distributed uniformly over the blade, as was assumed in the example above, but rather increases to near the propeller tip, and so only the outer reaches of the prop likely produce APIPs. This agrees with Fig. 15 of Woodley et al. (1991), which shows a condensation helix, having a width of only 5%–10% of the total prop length, emanating from near the propeller tips.

The area under the curve of Fig. 2 is proportional to the total thrust of the King Air as calculated from Eq. (1), when the aircraft is operated at various configurations and power settings. By integrating under the curve it was determined that about 16% of the overall thrust produced by the King Air engines is concentrated in the region between $X/R = 0.90$ and 0.95. Generation of this thrust over this small region results in a pressure drop of 300 hPa and a corresponding moist-adiabatic temperature drop of 29.7°C, when the aircraft is operated at maximum power with the gear and flaps down. A cooling at the propeller tips of this magnitude, starting from an environmental temperature of $-10°C$, is enough to produce homogeneous nucleation of ice particles.

Additional information provided by the Hartzell Company permitted an improved estimate of propeller efficiency for the King Air operating at 780 hPa and $-10°C$. Look-up tables yield a propeller efficiency of 0.84. This is 5% greater than the assumed value of 0.80 used in the calculations of thrust above. Using this calculated value of E in Eq. (1) for the cases in which 16% of the thrust is distributed over the 5% of the propeller blade, providing the most lift, gives a pressure drop of an additional 15 hPa. This is equivalent to further cooling of about 1°C for an overall temperature of about

$31°C$ below the ambient temperature. These results support the observation that the Beech King Air 200 aircraft is a producer of APIPs and the hypothesis that the mechanism is homogeneous nucleation from the vapor.

5. Combination of observations and predictions

A listing of the results of the MOLAS experiments is provided in Table 2. Each table entry represents a single experiment, involving four or more traverses across the track of the test aircraft. Typically, the first traverse of the monitoring aircraft is the one reported in the table. The ambient temperature for each test is provided. The maximum ice crystal concentration is the maximum observed in each experiment. A value with an asterisk indicates that it represents an APIPs signature according to the criterion set forth earlier. For those cases in which SF_6 gas was released by the test aircraft the maximum ice crystal reading and asterisk (when warranted) are followed by either $++$ or $+-$, where the first $+$ indicates that gas was released and the following $+$ or $-$ means that the gas was or was not detected during the monitoring runs, respectively. Thus, a $+-$ means that the monitoring aircraft missed the gas plume.

The estimated pressure drops and the corresponding decreases in temperature, assuming moist-adiabatic expansion, are listed for uniform distribution of the engine thrust over 80% of the prop length and for distribution of the thrust appropriate to 5% of the prop area near its tip. The resulting total temperatures (i.e., $T +$ delta T) follow. The total temperature after dry- (rather than moist) adiabatic expansion near the 5% of the prop area providing the most lift is tabulated for comparison with the results based on moist-adiabatic expansion.

A cursory examination of the tabulations indicates a relationship between the total temperatures after expansion for each experiment and the observed maximum ice crystal concentrations; that is, the lower the total temperature following expansion is, the greater are the ice crystal concentrations. There are, however, some notable exceptions, especially the test results for the Piper Navajo during which only background ice crystal concentrations were observed despite a large predicted temperature drop behind its prop tips. Note in Table 2 that this aircraft is predicted to produce only a modest temperature drop when the thrust of its engines is distributed over 80% of each propeller blade. Only when 22.5% of the total thrust is apportioned to 5% of the lifting area of the prop, as required by its published propeller thrust profile, is this aircraft predicted to become a producer of APIPs. Only the Piper Aztec has a larger fraction (25%) of its overall thrust apportioned to 5% of its lifting propeller area, resulting in a large predicted temperature drop. In the case of the Aztec, however, the predictions and observations of its APIPs tendencies agree, whereas with the Navajo aircraft they do not.

TABLE 2. Summary of APIPs cases during MOLAS. See text for meaning of pluses and minuses in last column.

Aircraft type	T (°C)	Delta pressure (hPa) (TR over 80% of prop)	Delta T (°C)	T + delta T (moist)	Delta pressure (hPa) (partial TR over 5% of prop)	Delta T (°C)	T + delta T (moist)	T + delta T (dry)	Max ICC (No. L⁻¹) * = APIPs signature
King Air	−8	98	−7.4	−15.4	256	−23.8	−31.8	−34.9	76*
King Air	−8	44	−3.2	−11.2	116	−9.2	−17.2	−19.2	1
King Air	−8	70	−5.5	−13.5	182	−15.6	−23.6	−25.6	18
King Air	−8	98	−7.4	−15.4	256	−23.8	−31.8	−37	133*
King Air	−7	69	−5.4	−12.4	180	−15.5	−22.5	−26	3
King Air	−8	93	−7.2	−15.2	242	−22.6	−30.6	−35.1	60*
King Air	−8	85	−6.5	−14.5	223	−20.5	−28.5	−32.9	53*
King Air	−8	63	−4.8	−12.8	164	−13.9	−21.9	−25.5	10
King Air	−5	79	−5.8	−10.8	207	−18.5	−23.5	−27.7	12
King Air	−5	90	−7	−12	234	−21.2	−26.2	−30.8	5
King Air	−11	72	−5.6	−16.6	188	−16.2	−27.2	−30.7	287*
King Air	−11	60	−4.6	−15.6	157	−13.2	−24.2	−27.6	17
King Air	−11	67	−5	−16	174	−14.8	−25.8	−29.3	6
King Air	−10	101	−8.1	−18.1	263	−25	−35	−40	38*
King Air	−9	80	−5.9	−14.9	209	−18.7	−27.7	−31.9	22
King Air	−9	99	−7.8	−16.8	259	−24.2	−33.2	−38.2	126*
King Air	−10	110	−8.8	−18.8	286	−27.8	−37.8	−43.1	95*
King Air	−12	91	−7.1	−19.1	237	−22	−34	−38.8	40*
King Air	−11	92	−7.2	−18.2	240	−22.2	−33.2	−38	73*
King Air	−12	85	−6.5	−18.5	221	−20.1	−32.1	−36.5	73*
King Air	−8	115	−9.3	−17.3	300	−29.7	−37.7	−43	109*
C-421	−8	71	−5.5	−13.5	156	−13	−21	−24.4	22
T-28	−6	108	−8.7	−14.7	?	?	?	?	11++
T-28	−9	108	−8.7	−17.7	?	?	?	?	<10++
T-28	−9	108	−8.7	−17.7	?	?	?	?	<10++
C-421	−8	71	−5.5	−13.5	156	−13	−21	−24.4	11
C-421	−5	71	−5.5	−10.5	156	−13	−18	−21.4	3
C-421	−5	71	−5.5	−10.5	156	−13	−18	−21.4	5
Aero Commander	−10	101	−8.1	−18.1	286	−27.8	−37.8	−43.1	11+−
Aero Commander	−9	101	−8.1	−17.1	286	−27.8	−36.8	−42.1	95*++
Beech Turbo Baron	−8	75	−5.6	−13.6	203	−18	−26	−30	8
Beech Turbo Baron	−9	75	−5.6	−14.6	203	−18	−27	−31	3
Piper Navajo	−10	79	−5.8	−15.8	283	−27.5	−37.5	−42.8	5++
Piper Navajo	−10	79	−5.8	−15.8	283	−27.5	−37.5	−42.8	2++
Piper Navajo	−10	79	−5.8	−15.8	283	−27.5	−37.5	−42.8	5++
Piper Aztec	−10	116	−9.3	−19.3	465	−55.9	−65.9	−70.2	263*++
Piper Aztec	−10	94	−7.4	−17.4	378	−40.7	−50.7	−55.8	69*++
Piper Aztec	−10	84	−6.4	−16.4	336	−432	−44.2	−49.5	11+−
King Air	−9	99	−7.8	−16.8	259	−24.2	−33.2	−38.2	105*++
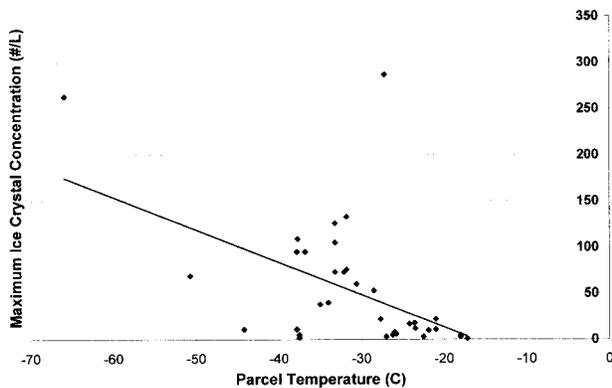
FIG. 3. Maximum ice crystal concentration vs total temperature after moist-adiabatic expansion. The linear correlation is −0.501.

A scatterplot of maximum of ice crystal concentrations versus the total temperature after moist-adiabatic expansion from the 5% of the prop producing the most lift is shown in Fig. 3. Although there is considerable scatter (correlation − 0.501), there is an obvious relationship. All of the cases with maximum ice crystal concentrations greater than 38 crystals per liter were identified as APIPs signatures based on the criterion as to what constitutes an APIPs signature. Note that most of the APIPs cases have predicted total temperatures somewhat greater than −39°C, the generally accepted threshold for homogeneous condensation and subsequent freezing.

Some of the other results are worthy of note, including the results of the three tests of the Piper Navajo discussed above (two of three points near the abscissa
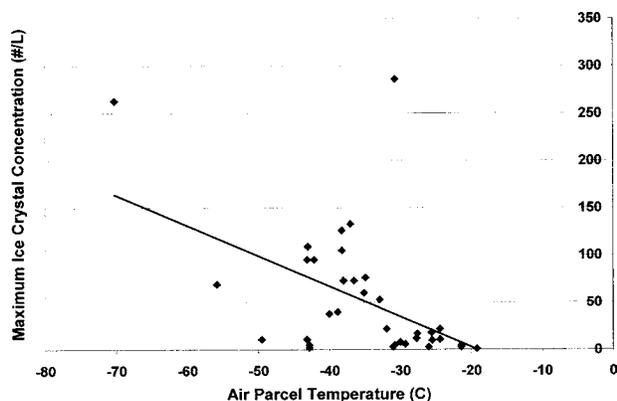
FIG. 4. Maximum ice crystal concentrations vs total temperature after dry-adiabatic expansion. The linear correlation is -0.487.

near $-38°C$). Also of some interest is one of the tests of the Piper Aztec, during which time a maximum ICC of 11 crystals per liter was observed despite an estimated total temperature of $-44°C$ after expansion. One of the tests of the Aero Commander also had a maximum ICC of only 11 crystals per liter despite a postexpansion temperature near $-38°C$. These cases should have produced APIPs signatures. Unlike the results for the Navajo, however, these apparent inconsistencies have an explanation; the cloud physics aircraft missed the plumes of the test aircraft during its monitoring runs, because no SF_6 was detected for these cases. Further, APIPs signatures were documented in other tests for these same aircraft at near the same total temperatures. A third surprise is the strong apparent APIPs signature at a temperature greater than $-30°C$ that was documented for the King Air. Because the signature is real, an error may have been made in recording the flight configuration and/or power of the test aircraft for this experiment.

It is interesting that in most cases the predicted temperatures of the APIPs cases fall a few degrees Celsius short of the threshold for homogeneous nucleation. As a sensitivity test, the predictions of expansion temperature were revised under the assumption as stated earlier that the expansion at the prop tips was dry adiabatic. The total temperatures after dry-adiabatic expansion for the test cases are listed in Table 2. This brings the predictions of expansion temperatures into better agreement with the measurements of maximum ice crystal concentrations, as can be seen in Fig. 4, although, the linear correlation (-0.487) is slightly less than for the moist-adiabatic expansion.

6. Discussion

The MOLAS program indicates that APIPs may have been a problem for cloud physics investigations conducted in supercooled regions at temperatures lower than $-7°C$, as suggested by Rangno and Hobbs (1983, 1984). Some might consider the problem of little im-

portance and claim that no one flies aircraft in clouds at high power, high drag, and low airspeed, which are the conditions most conducive to APIPs production. In fact, however, aircraft often are flown in clouds in this condition when high power is needed to overcome the drag of heavy icing. (In the APIPs tests the landing gear and flaps were lowered to simulate the drag from heavy icing.) Single cloud passes are not a problem because the sampled cloud volume is contaminated behind the measurement probes. Multiple passes in the same cloud at the same level, however, pose a challenge, because of the risk the development of ice may have been initiated by the passage of the aircraft. Even the conduct of randomized cloud seeding experiments may have been compromised if the clouds in the unit receiving simulated treatment received steady doses of APIPs. It is suggested, therefore, that scientists involved with past cloud physics investigations and seeding experiments reexamine their experiments to determine whether APIPs may have compromised their data and confounded their interpretation. It may be that the inferred rates of production and ultimate concentrations of ice observed in presumably natural supercooled clouds were artificially high due to the production of APIPs in some of these studies.

In assessing whether APIPs might have been a problem for a particular experiment, one might use a checklist that poses the following questions: 1) Were the measurements made from an aircraft known to produce APIPs? 2) If not, do estimates of cooling at the propeller tips, using the methodology described herein, suggest that APIPs are likely with the aircraft in use? 3) Was the flight temperature during measurements equal to or less than $-9°C$? 4) Was heavy aircraft icing encountered during the measurements such that high power settings and low airspeeds were involved in the measurements? 5) Were the subject clouds penetrated more than once? 6) Is it possible that an APIPs signature could have gone undetected by the instrumentation on the aircraft? 7) Are the results of the studies sensitive to the unknown presence of APIPs? For example, if a past study focused on the formation of the initial ice, APIPs could invalidate its findings. If the answers to most of these questions are in the affirmative, it is likely that APIPs confounded the cloud microphysical measurements.

We have followed our own advice, beginning with the Florida Area Cumulus Experiment (FACE) project, which was under the direction of the first author. FACE began with microphysical measurements in and the randomized seeding of individual supercooled convective clouds and it transitioned to exploratory (Woodley et al. 1982) and confirmatory area experiments (Woodley et al. 1983). A variety of aircraft were involved in FACE, including a Piper Navajo, a Cessna 421, an Aero Commander 690, the King Air 200 of the University of Wyoming, a DC-6, a B-57, and a C-130 turboprop aircraft. Most of the microphysical measurements, in addition to observations of cloud liquid water and infer-

ences of draft speed made on all aircraft, were made by the King Air and focused on the natural evolution of ice in the clouds and its alteration by glaciogenic seeding using ejectable silver iodide flares. This was done through repetitive cloud passes through the same cloud tower, some at the same level as the initial pass and others at successively higher levels as the aircraft followed the rising cloud top. Knowing the proclivity for APIPs of the King Air, it is likely that some of the measurements were contaminated by APIPs. This would have minimized the microphysical differences between the seeded and nonseeded clouds. Even so, seed versus nonseed microphysical differences were still evident despite the probable APIPs contamination.

The two FACE experiments involved single passes through suitable cloud towers with seeding or simulated seeding, depending on the randomized treatment decision. During the actual or simulated seeding operations the seeder aircraft always became laden with ice, and it often was necessary to go to maximum power in order to stay aloft at a constant altitude. Sometimes the ice load was so heavy that the aircraft was forced to descend to a lower altitude and warmer temperatures in order to rid itself of the ice load. Under such conditions, aircraft prone to APIPs would be most likely to produce them. This would have reduced the seeded versus nonseeded microphysical and rainfall differences. It is doubtful, however, that this was a major problem for the FACE effort because the seeding was usually done at temperatures greater than $-10°C$ by aircraft not prone to the production of APIPs.

Following FACE, the first and fifth authors were involved with randomized experimentation and cloud physics measurements in west Texas (Rosenfeld and Woodley 1997, 2000 and Woodley and Rosenfeld 2000) and Thailand (Rosenfeld et al. 1999). APIPs probably were not much of a problem, because the seeding or simulated seeding was done typically at temperatures greater than $-9°C$. The cloud physics aircraft used in Texas and Thailand were the turboprop Piper Cheyenne and King Air 350 aircraft, respectively. Neither aircraft is particularly susceptible to APIPs, because the thrust is distributed over four blades.

Besides the cloud microphysical studies in Florida, Texas, and Thailand, the basic investigative procedure of seeding with one aircraft then using the same or a second aircraft to monitor cloud microphysical characteristics by performing repeated passes at a suitable level in the mixed-phase region has been used in many other projects. Examples include the High Plains Experiment (HIPLEX) (Smith et al. 1984), the Sierra Cooperative Pilot Project (SCPP) (Marwitz and Stewart 1981; Stewart and Marwitz 1982; Rodi 1982), work in Alberta, Canada (English and Marwitz 1981), the Bethlehem Precipitation Research Experiment (BPRE) (Krauss et al. 1987), and the Precipitation Augmentation for Crops Experiment (PACE) (Czys et al. 1992; Czys et al. 1993). Different aircraft were involved in the different projects. For example, the Wyoming King Air was involved in HIPLEX and SCPP as a cloud physics aircraft, a Queen Air and a Cessna 441 twin turboprop in later years were used in the Alberta work, and the South Dakota School of Mines and Technology T-28 was used in PACE (but for only for two cases). In general, the possibility of APIPs was not factored into the analysis in these experiments, although in the case of the South African work, the data were scrutinized for APIPs and no influence of them was identified (Krauss et al. 1987). The extreme temperature sensitivity for APIPs production, as well as the sensitivity to aircraft performance settings, makes assessment of the possible impact of APIPs difficult. Detailed pass-by-pass temperatures and aircraft performance settings generally are not included in the published work. In HIPLEX publications some temperature information is provided and it is clear that many of the cloud physics passes were at temperatures too warm for APIPs production. Except in the case of PACE, a clear distinction in microphysical properties between seeded and nonseeded populations was found. (There were not enough cases in PACE to do such an analysis.) Although the distinction may have been clearer in the absence of APIPs, if they occurred they did not prevent the microphysical distinction between seed and nonseed cases.

The second author was involved in the SCPP. This was a winter precipitation enhancement research project over the American River Basin east of Sacramento, California, sponsored by the Bureau of Reclamation. Randomized airborne cloud seeding was performed using an Aero Commander (for much of SCPP a Cessna Citation jet, which has not been considered in the current research, was used for seeding) by dropping lines of either silver iodide flares, dry ice pellets, or nonseeding agent (placebo cases) in liquid water regions at about the $-8°C$ level of orographic and areawide storms. The University of Wyoming King Air 200T would then set a navigation pointer on the seeded line and make multiple passes through the line in order to document the effects of seeding. On many occasions the King Air and/or the Aero Commander would encounter moderate to severe airframe icing, making it necessary for the aircraft to break off the pattern in order to descend and deice. During these icing events on the King Air, the engine torque would be gradually increased in order to keep the aircraft at altitude with little change in true airspeed until deicing was necessary. This is an ideal situation for the production of APIPs by either aircraft because both were found to produce APIPs during the MOLAS project. Results from these studies in the SCPP should be reexamined for the possible effects of APIPs.

Simultaneous with the APIPs fields investigations reported in Woodley et al. (1991), Foster and Hallett (1993) focused on the production of ice crystals resulting from the expansion and cooling of moist air in a laboratory setting. Their results fit the standard theory of homogeneous nucleation of water droplets as long as

the droplets remained at a low enough temperature long enough to freeze by homogeneous nucleation. In applying their results to the production of APIPs they concluded "situations that require large thrust from the propellers (e.g., climbing, icing, or flying at very slow speed with flaps down) are most likely to produce ice particles and should be avoided in all cloud passes made when re-penetration is intended." This is the same conclusion reached by Woodley et al. (1991) based on their initial MOLAS field studies. The subsequent MOLAS results described above reemphasize this conclusion.

The MOLAS findings suggest that it may be possible to mitigate and/or eliminate the APIPs signature of some aircraft by switching to propellers with a larger number of propeller blades. This would be especially critical for aircraft such as the three-bladed University of Wyoming King Air, which often has been used in studies of supercooled cloud microphysical structure. Fortunately, the King Air 200 is available in four-bladed propeller models. Upon changing to a four-bladed propeller, the same total engine thrust would be distributed over four blades rather than three, meaning that there would be less force per unit area on each blade and, therefore, less cooling on each blade. We attempted to validate this conclusion but were unable to do so because of unsuitable weather conditions by the time the four-bladed King Air 200 arrived on station. Until there is evidence to the contrary, an obvious way of avoiding APIPs altogether would be the use of a jet aircraft for the cloud physics measurements.

It is unfortunate also that suitable conditions for the testing of the armored T-28 of the South Dakota School of Mines and Technology were not obtained in MOLAS. Its primary use has been for microphysical measurements in clouds that are too vigorous for penetration by other aircraft. Although APIPs by this aircraft have not yet been documented by anyone, our calculations suggest that its APIPs production should be similar to that of the University of Wyoming King Air.

7. Conclusions

Nine aircraft, including a Beech King Air 200T cloud physics aircraft, a Piper Aztec, a Cessna 421-C, two North American T-28s, an Aero Commander, a Piper Navajo, a Beech Turbo Baron, and a second four-bladed King Air were tested in continuing studies of APIPs. The instrumented King Air served as the monitoring aircraft for trails of ice particles created, or not created, when the other aircraft were flown through clouds at various temperatures, and as both the test and monitoring aircraft when it itself was tested. In many cases SF_6 was released by the test aircraft during its test run and detected by the King Air during its monitoring passes in order to confirm the location of the test aircraft wake. Ambient temperatures for the tests ranged between $-5°$ and $-12°C$.

The results confirm earlier published results and pro-

vide further insights into the APIPs phenomenon. The King Air at ambient temperatures less than $-8°C$ can produce APIPs readily. The Piper Aztec and the Aero Commander also produced APIPs under the test conditions in which they were flown. The Cessna 421, Piper Navajo, and Beech Turbo Baron did not. The APIPs production potential of a T-28 is still indeterminate because a limited range of conditions was tested.

Homogeneous nucleation in the adiabatically cooled regions where air is expanding around the rapidly rotating propeller tips is the cause of APIPs. An equation involving the propeller efficiency, the engine thrust, and the true airspeed of the aircraft is used along with the published thrust characteristics of the propellers to predict when aircraft will produce APIPs. In most cases the predictions agree well with the field tests. The major exception, involving the Piper Navajo, remains unexplained. Of all the aircraft tested, the Piper Aztec, despite its small size and low horsepower, was predicted to be the most prolific producer of APIPs, and this was confirmed in the field.

The APIPs, when they are created, appear in aircraft wakes in concentrations up to several hundred per liter, are initially quite small and almost uniform in size, and they grow to larger nearly uniform sizes with time. APIPs production is most likely at low ambient temperatures when an aircraft is flown at maximum power with the gear and flaps extended, resulting in a relatively low airspeed under high-drag conditions.

It is predicted that APIPs production of an aircraft can be decreased or eliminated altogether by using a propeller with a larger number of propeller blades, such that the engine thrust is distributed over more blades thereby decreasing the cooling on each blade. Plans to test this hypothesis using three- and four-bladed King Airs as the test aircraft never came to fruition because of unsatisfactory weather conditions.

It is likely that APIPs have confounded the results of some past cloud microphysical investigations, especially those in which repeat passes were made through individual clouds under heavy icing conditions by aircraft known now to be APIPs producers. Aircraft flying under such conditions are forced to use high power settings to overcome the drag of a heavy ice load. These are the conditions that field tests demonstrate are most conducive to the production of APIPs. In these situations APIPs will generally lead investigators to conclude there was a more rapid development of ice, and higher concentrations of ice particles in clouds, than actually was the case.

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