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Response of a Research Aircraft to Icing and Evaluation of Severity Indices

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The relationship between four atmospheric parameters and three measures of flight degradation are investigated using data from an instrumented research aircraft. Data from flights that took place in wintertime stratus clouds over northeastern Colorado are emphasized; additional data points from encounters with large supercooled droplets over northern California and northern Arizona are included. The maximum decrease in coefficient of lift due to icing was 35%, with 68% of cases within 10% of the uniced aircraft value. Coefficient of drag increased by up to 230% as a result of icing and climb capability was reduced by up to 6.9 m/s. Greater performance loss was related to higher liquid water content, median volume diameter, and potential accumulation of ice. A combination of liquid water content > 0.2 g/m^3, median volume diameter > 30 μm, and temperature > −10°C was responsible for the largest performance decreases. Severity indices that were dependent on liquid water content, median droplet volume diameter, and temperature were tested. An index that takes into account the effects of large droplet icing provided the best relation between higher severity level and increased performance degradation.

Introduction

FROM both theory and experience it has long been known that icing, the accretion of supercooled liquid water on an airframe, can have adverse effects on flight. The amount, distribution, and nature of the accreted ice play roles in determining how the aircraft responds. Icing can reduce the coefficient of lift for an aircraft or airfoil, increase the coefficient of drag, increase stall speed, and create stability and control problems.[1] A recently studied phenomenon regarding stability arises with tailplane icing in which the tail surface ices up and stalls prior to wing stall, forcing the aircraft to pitch suddenly downward.[2]

Numerical models and wind-tunnel tests have been used extensively to study the quantitative effects of icing on flight. However, few results of actual flight tests by aircraft in natural icing conditions are found in the literature. Cooper et al.[3] studied icing encountered by a Super King Air research aircraft and concluded that the primary effect of icing was to increase the coefficient of drag by as much as a factor of 2, while the effect on lift was minimal. Sand et al.[4] used the same data set to demonstrate a relationship between the total accumulated amount of liquid water encountered by the aircraft and the decline in climb capability. These data were not examined further to determine individual effects of liquid water content (LWC), temperature, and droplet size, although it was noted that performance declined both to a greater degree and more rapidly when droplets with diameters larger than ~30 μm were present. Politovich[5] expanded this study to include more cases of large droplet icing and found consistently greater effects on flight in cases with similar LWC and large droplets present than when droplets were confined to smaller sizes. Ratvasky and Ranaudo[6] studied effects of icing on the stability of a DeHavilland Twin Otter using simulated ice shapes constructed of styrofoam, rather than ice resulting from natural conditions. Telford[7] reported on performance and cloud physics measurements in an analysis of the fatal crash of the Desert Research Institute's B-26 research aircraft. Hoffman and Demmel[8] presented data from severe icing encounters in Germany, including reports of decreases in airspeed resulting from icing, but did not quantify the degradation in terms of the meteorological quantities.

From these and other studies there is general agreement that for in-flight icing three quantities have the most important influences on flight: 1) LWC, 2) temperature, and 3) droplet size. However, there is still not a general consensus as to the proper quantification of these meteorological parameters as they affect flight, such as thresholds to describe expected severity. There are several reasons for this. First, data sets of both meteorological and aircraft response parameters are relatively scarce and available for only a few aircraft such as the University of Wyoming King Air and NASA Twin Otter. Meteorological data sets exist, including the climatological studies of Lewis,[9] Jeck,[10] and Sand et al.,[4] and case studies of icing environments are found in the literature, such as those of Guttman and Jeck,[11] and Cober et al.[12] These studies have no corresponding information on aircraft response to the environments encountered.

One of the goals of the winter icing and storms project (WISP), from Rasmussen et al.,[13] is to develop improved methods for aircraft icing forecasting. Quantification of the icing hazard in terms of expected effect on an aircraft is an important component of WISP. Research aircraft were deployed for field experiments to provide in situ measurements of atmospheric conditions. In addition to the meteorological data collected, flight performance parameters were recorded that provide useful information on the response of the aircraft to icing environments.

The purpose of this article is to explore details of the relation of meteorological parameters to flight degradation. Contributions to degradation from various parameters are considered both separately and in combination and the results are quantified and placed in the context of previous studies of aircraft performance and cloud climatology. A method for quantifying the performance decline expected for a range of icing conditions, a severity index, is presented that is consistent with this data set.

Data Sets

Data from the University of Wyoming's King Air research aircraft, obtained in eastern Colorado during two WISP field

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Table 1 Wyoming King Air instrumentation[a]

Measurement	Instrument	Manufacturer	Response	Accuracy	Resolution
		State parameters			
Temperature	Platinum resistance	Rosemount model 102	<1 s	±0.5°C	<0.1°C
Temperature	Reverse-flow, platinum resistance	NCAR design, minco element	<0.5 s	±0.5°C	<0.1°C
Dew point	Cooled mirror	Cambridge model 137C3	3°C/s (slew rate)	±0.5°C (>0°C), ±1.0°C (<0°C)	0.3°C
Pressure		Rosemount 1201FA1B1A	15 ms	±4 mb	0.3 mb
		Cloud variables			
Liquid water	Hot wire (CSIRO)	University of Wyoming	~10 ms	0.1 g/m³	0.05 g/m³
Liquid water	Ice accretion on a vibrating rod	Rosemount 831			
Droplet size	FSSP	PMS	0.1 s	2 μm	2 μm
Hydrometeor size	1D-C	PMS	0.1 s	12.5 μm	12.5 μm
Hydrometeor size and shape	2D-C	PMS	μs	25 μm	25 μm
		Performance			
IAS	Differential pressure	Rosemount 831 CPX	25 ms	±1 mb	0.1 mb
Rate of climb	Differential altitude	Rosemount 1241-A-4BCDE	50 ms	1% to 4.5 km, 2% to 8 km	0.25 m/s
Rate of climb	INS	Litton LTN51	<1 s	1%	50 ft/min
Vertical acceleration	Stabilized accelerometer	Humphrey SA-09-0502-1	10 μs	0.2 deg	
Pitch, roll	Stabilized accelerometer	Humphrey SA-09-0502-1	10 μs	0.2 deg	
Yaw, attack angles	Differential pressure	Rosemount 858AJ28	0.1 s	0.2 deg	<0.1 deg

[a]Only instruments relevant to these analyses and used during the WISP or P89[5] flights are listed.

seasons (February–March 1990 and January–March 1991) are used for these analyses. Seven flights were selected from the two field efforts that correspond to those used by Pobanz et al.[14] in their study of large supercooled droplet regions. These flights were chosen because they provide a variety of conditions encountered during WISP. To extend the measurements to even larger droplets than typically encountered in eastern Colorado, data from 10 encounters with large droplets from Politovich[5] were included in the analyses. These flights took place over the Sierra Nevada mountains in northern California and over the mountainous area of northern Arizona. The cases from this study will be referred to as P89 cases for the remainder of this article. For either data set, only encounters with supercooled liquid in clouds were considered; flights in freezing precipitation below visible cloud were not included. Cloud was generally defined as a forward scattering spectrometer probe (FSSP) or Commonwealth Scientific and Industrial Research Organization (CSIRO) probe-measured LWC > 0.01 g/m³ and FSSP-measured droplet concentration > 5/cm³.

The Wyoming Beechcraft King Air 200T is fully equipped for cloud physics measurements and is certified for flight into known icing conditions. Characteristics of the aircraft and its instrumentation package are listed in Table 1. For this study, 1-s recorded values were used. Performance data, including pitch and attack angles, airspeed, and engine torque, were filtered to 1 min to eliminate higher frequency variations. Temperature measurements were from a reverse-flow probe that eliminates effects from wetting of the sensing element.[15] Cloud droplet size distributions were measured using a particle measuring systems (PMS) FSSP, which was operated on the 2–30- or 3–45-μm range during the flights. A PMS 1D-C probe was used for measurements of hydrometeors in the 12.5–187.5-μm-diam range. Because of uncertainties in the sample areas for the first four channels (12.5–50 μm) of the 1D-C probe, they were not used in the calculations. The 1D-C probe cannot discriminate between droplets or ice particles and liquid/ice discrimination must be determined from images of cloud particles recorded by a PMS 2D-C probe.

The median volume diameter (MVD) is often used to characterize the droplet size distribution. Finstad et al.[16] demonstrated that for a variety of droplet spectrum measurements the collection efficiency of the entire spectrum is well characterized by the collection efficiency of the MVD. The MVD was determined from size distributions recorded from the FSSP, using airspeed-dependent corrections to the bin sizing as described by Cerni.[17] When 2D probe records indicated that hydrometeors in the size range measured by the 1D-C probe were water droplets, these measurements were included in the determination of LWC and MVD. When no large droplets were present, LWC from the FSSP was used for the 1991 segments, and from a King-type liquid water detector (King et al.[18]) for the 1990 segments. Data from the P89 cases use LWC from the FSSP, except for one day during which the FSSP was not operating. For that flight, LWC calculated from a Rosemount icing probe was used.

The calculated potential accumulation (PA) was used to describe the total ice on the airframe. Potential accumulation is the amount of ice that could have been accumulated on the airframe, given the measured LWC and a collection efficiency of unity, and is the accumulated product of LWC and distance flown. The PA is expressed as mass per unit area (g/cm²) of exposed airframe. Only FSSP or CSIRO liquid water measurements were included in these calculations. Thus, in some cases the PA may have been underestimated, but this is probably a very minor effect. The PA was zeroed when the air temperature exceeded 0°C, to account for melting. However, it was not zeroed to account for the activation of de-icing mechanisms, since the times of activation were not recorded during flight, and the mechanisms do not de-ice the entire aircraft.

Analysis of Performance Degradation

Three parameters were used for the analysis of aircraft performance: coefficients of lift and drag, and climb capability. Although these do not address stability and control issues, they have been previously documented for the Wyoming King Air.

A complicating factor in these analyses is the application of de-icing mechanisms. The Wyoming King Air is equipped with pneumatic boots on the leading edges of the wings and vertical and horizontal stabilizers. Some of the measurement probes are de-iced, and the propellers are anti-iced. However, not all airframe surfaces are de/anti-iced, and when de/anti-icing equipment is activated, not all airframe ice is removed. A further factor is pilot response to icing conditions. During WISP, one pilot flew all flights; three pilots flew during the P89 flights. The aircraft was not in autopilot mode during any of the flight segments used in this study. Typically, during a level flight segment in icing, the pilot would maintain constant altitude by a combination of increased power to the engines and increased angle of attack. Through experience, the pilots knew to keep up the airspeed, especially if they suspected large droplet situations, since these can dramatically increase stall speed.[3]

Coefficients of Lift and Drag

The coefficients of lift C_L and drag C_D during flight were derived using the method described by Cooper et al.[3] To obtain accurate values, it is necessary for the aircraft to cover a wide range of attack angles. This can be accomplished through porpoising maneuvers, whereby the aircraft makes consecutive ascents and descents of 100–200 m. These were often performed after significant icing encounters. In cases where porpoising maneuvers were not conducted, calculations were applied to recorded data after ascending or descending out of cloud.

Twenty-one WISP flight segments were analyzed for the calculation of C_L and C_D. Standard error analysis techniques were used to estimate uncertainties in the coefficients, using instrumental accuracies provided in Table 1. The average error in C_L was 10.4%, in C_D it was 4.6%. Errors were not calculated for the P89 data points, but Cooper et al.[3] cited errors in C_L and C_D of ~5% for these data.

Calculation of the coefficients allows direct examination of the effect of ice accretion on lift and drag. The disadvantage of this measure of performance is that it cannot be done continuously; only discrete measurements are available. After an icing encounter the aircraft often ascended to above cloud top to sublimate the accreted ice, during which time the porpoising maneuvers were completed. Also during this time, enough sublimation often took place that the surface was smoothed and performance increased so that the coefficients may not be truly representative of the alterations resulting from the encounter.

Coefficients of lift are plotted against LWC, temperature, MVD, and PA in Fig. 1. Uncertainties in the coefficients are shown as vertical bars on the WISP data points. The horizontal bars on the WISP data points represent the standard deviations of values measured during the icing encounters preceding the coefficient calculations. The P89 points represent the means of LWC, temperature, and MVD measured during the encounters, and the PAs at the ends of the encounters. Four P89 data points from one flight have neither MVD nor PA; the FSSP was not working on this flight and so LWC was calculated from a Rosemount Icing detector and the presence of large droplets was inferred from 2D-C images. For the un-iced aircraft C_L is 0.59 (LWC = MVD = PA = 0). This value is plotted as a gray square on the LWC, MVD, and PA figures and is represented as a dotted line across the range of temperatures shown in the figure. Following icing encounters C_L ranged from 65–108% of the un-iced value, with 21 of the 31 points (68%) within 10% of the un-iced C_L (recall that the average calculated error was 10.4%). No single cloud parameter nor combination of parameters were good predictors of C_L decrease. None of the P89 points had low C_L, which is consistent with Cooper et al.[3] who found the primary effect of large droplets was to increase drag rather than decrease lift. The only WISP point having MVD > 30 μm and low C_L had a relatively warm temperature of −6.6°C; there is a suggestion of lower C_L with higher temperature, but any trends in these data are weak.

Figure 2 shows C_D plotted against the same cloud-related parameters. For the un-iced aircraft C_D is 0.036 and always increased as a result of icing in these encounters, by as much as 230%. Temperature alone is not a good predictor or C_D increase, but C_D tends to increase with increasing LWC, MVD, or PA. Highest C_D are for the P89 points, which generally have a combination of LWC > ~0.2 g/m³, MVD > 50 μm, and temperature > −10°C. Two highlighted WISP points with MVD > 30 μm have only small increases in C_D, but also had LWC < 0.1 g/m³ and nearly zero PA. The third highlighted WISP point, with higher C_D, had a LWC of 0.23 g/m³ and higher PA.

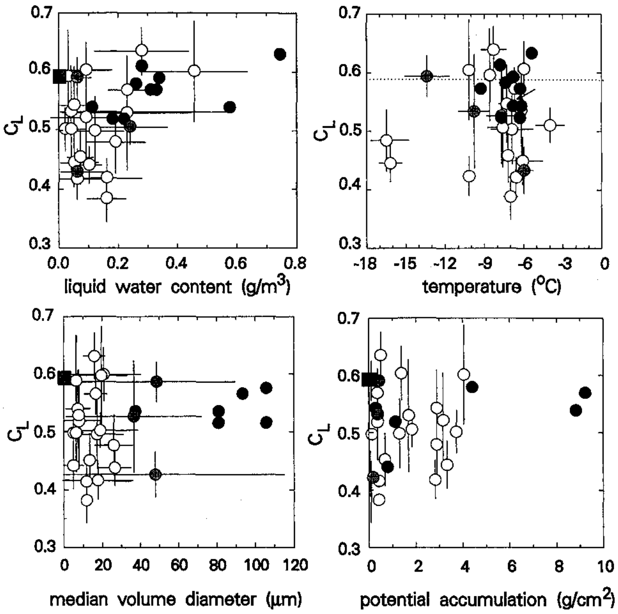

Fig. 1 Coefficient of lift plotted against liquid water content, temperature, median volume diameter, and potential accumulation for King Air data. Twenty-one WISP values are shown: unfilled dots have MVD < 30 μm, gray dots have MVD > 30 μm. Black dots are the P89 cases. The gray square and the dotted horizontal line are C_L for the clean aircraft. Vertical bars on the WISP data points are standard deviations in C_L; horizontal bars are the standard deviations of the parameters indicated. Analysis methods are described in the text.

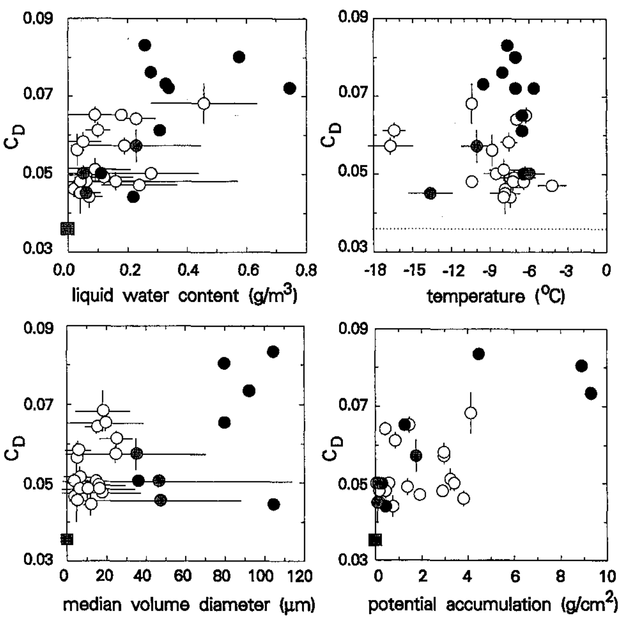

Fig. 2 Same as Fig. 1, for the coefficient of drag C_D.

Difference in Rate of Climb Capability

The aircraft's ability to climb was evaluated by comparing the actual rate of climb (ROC) with that expected for a clean aircraft.[3] The resulting difference in climb capability is referred to as ΔROC, where negative values indicate declines in performance. Sand et al.[4] found that this parameter has an accuracy of ~1.2 m/s. The quantity ΔROC can be calculated continuously along the flight track and provides a means of monitoring aircraft performance capability. Higher negative ΔROC indicates greater loss in climb capability.

Data from the seven WISP flights were examined and times with local minima in ΔROC were chosen as critical points for analysis. These minima may either represent temporary losses in climb capability or instances when de-icing boots were deployed. However, in general, the pilot did not deploy the boots during cloud penetrations unless absolutely necessary. These minimum ΔROC values were compared to simultaneous 1-min averages of cloud values to examine momentary changes rather than long-term effects directly. Eighty-two data points were isolated. The 10 P89 data points were included in these analyses; in these cases the minimum calculated ΔROC values listed in the reference were used. As was the case for coefficients of lift and drag, this parameter may reflect the effect of the total ice accumulation as well as current conditions.

Figure 3 shows the effects of LWC, temperature, MVD, and PA on ΔROC. The relation between ΔROC and PA from Sand et al.[4] is plotted; most of the data in the figure are consistent with that relation. For the cluster of data points with MVD < 30 μm, there is little relation between MVD and ΔROC. For those data, ΔROC is most strongly related to LWC and PA, and the addition of WISP data points with MVD > 30 μm and the P89 points strengthens those relationships. Temperature is again not a good predictor of performance loss; while greatest ΔROC were for temperatures between −6 and −10°C, there are also many data points in that temperature range with low ΔROC. As was the case for the C_D results, a combination of high MVD, LWC > 0.2 g/m^3, and warm temperatures results in the greatest reduction in climb capability. The WISP points with MVD > 30 μm all have low LWC, <0.1 g/m^3, and low ΔROC. Their relations to cloud parameters, especially PA, tend to resemble the small droplet (MVD < 30 μm) data points more than the P89 points.

To further isolate the immediate effects of cloud parameters on performance the rate of decline in climb capability d(ΔROC)/dt was derived. Flight segments in cloud (LWC > 0.01 g/m^3) for which ΔROC showed a steady decrease were isolated. Since Sand et al.[4] reported an accuracy of 1.2 m/s for ROC calculations, that was used as a threshold. One-hundred sixty-two periods for which ΔROC was more than 1.2 m/s for at least 10 s were identified. The total decrease in ROC was divided by the time to get an average rate of decrease for the period. No relation between this measure of performance degradation and any of the four cloud parameters was found.

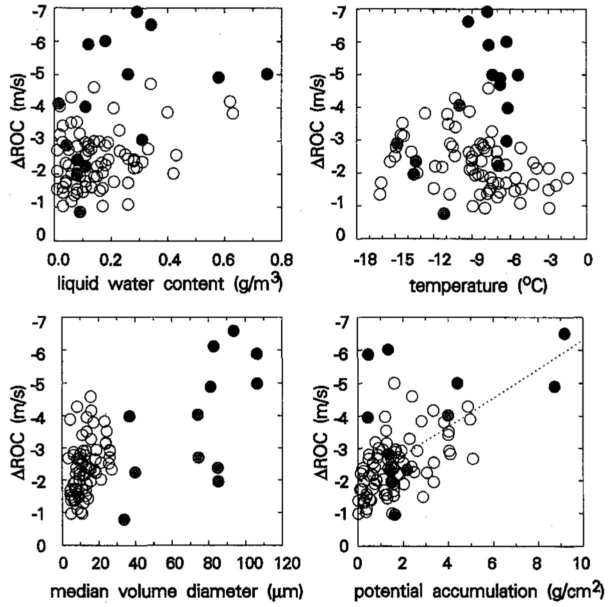

Fig. 3 Same as Fig. 1, for difference in rate of climb ΔROC. Eighty-one WISP (unfilled and gray) and 10 P89 (black) points are included. Gray dots are WISP data with MVD > 30 μm. The dotted line in the potential accumulation plot is the best-fit relation from Sand et al.[4]

Summary

For the King Air used in these studies, greatest performance loss tends to be associated with a combination of MVD greater than ~30 μm, LWC above ~0.2 g/m^3, and temperature warmer than −10°C. Considered separately, LWC, MVD, and PA have the strongest correlations with performance loss as measured by C_D increase and rate of climb decrease. Greatest performance losses tend to occur when temperatures are warm, but warm temperature alone does not guarantee performance loss. The presence of high MVD alone also does not ensure high performance loss; when MVD is greater than 30 μm and LWC is less than 0.2 g/m^3 there is little effect. Encounters with MVD above 30 μm can greatly increase drag, but have minimal effect on lift, even when LWC is more than 0.2 g/m^3. For MVD below ~30 μm, there is a poor relation between performance measures and MVD. Although C_L was decreased as a result of icing, no consistent relation between C_L and any of the separate or combined cloud parameters was observed.

Terminology for large droplets has proven to be confusing. Jones[19] defined large droplets as those with diameters 30–100 μm, and freezing rain or drizzle as those from 100–1000 μm, based on where ice accretes on an airframe. However, in the recent work of Cober et al.,[12] droplets with diameters of 18 μm are referred to as large. The Glossary of Meteorology[20] defines cloud droplets as those with diameters to 200 μm and drizzle drops as those with diameters to 500 μm (there is an ambiguous overlap). The so-called icing envelopes included in FAR Part 25 Appendix C[21] are valid for mean effective (usually interpreted as median volume) droplet diameters to 40 μm (stratiform or continuous cloud) or 50 μm (cumuliform or intermittent cloud). In the studies of Cooper et al.[3] and Politovich[5] the term large implied diameters of ~30 μm and larger. Based on the results shown in Figs. 1–3, there is no compelling reason to change from a 30-μm threshold.

Comparison with Wind-Tunnel Icing Tests

Olsen et al.[22] performed wind-tunnel tests of a NACA 0012 airfoil under various combinations of LWC, temperature, and MVD. These tests were used to examine the effects of atmospheric parameters on drag. To compare the wind-tunnel results with this study, C_D for both data sets were compared with their respective un-iced values.

The relation of increasing C_D with higher LWC suggested by the King Air data in Fig. 4 is continued in the wind-tunnel tests. The lowest LWC tested in the wind tunnel was 1.0 g/m^3, which is far larger than the values encountered during either the WISP or P89 cases. Temperatures, MVDs, and PAs are similar, but the extremely high LWCs produced large increases in C_D, which differ from the tests in natural conditions. Trends are carried through from the King Air data, however, with higher drag resulting from higher temperatures, MVDs, and PAs.

The wind-tunnel MVDs and temperatures are well within the ranges of values in this data set and in the icing climatology undertaken by Sand et al.[4] However, LWCs are considerably higher than those found in clouds from either study. Only ~2% of icing encounters experienced by the King Air in flights over the continental U.S. (Ref. 4) had LWC > 1 g/m^3. In addition, the wind-tunnel tests in these high LWCs were conducted for periods of 6.2 and 8 min, which at the airspeeds used (94 and 58 m/s, respectively) represent 21 and 35 km of flight in these conditions. Paths of length > 20 km with LWCs

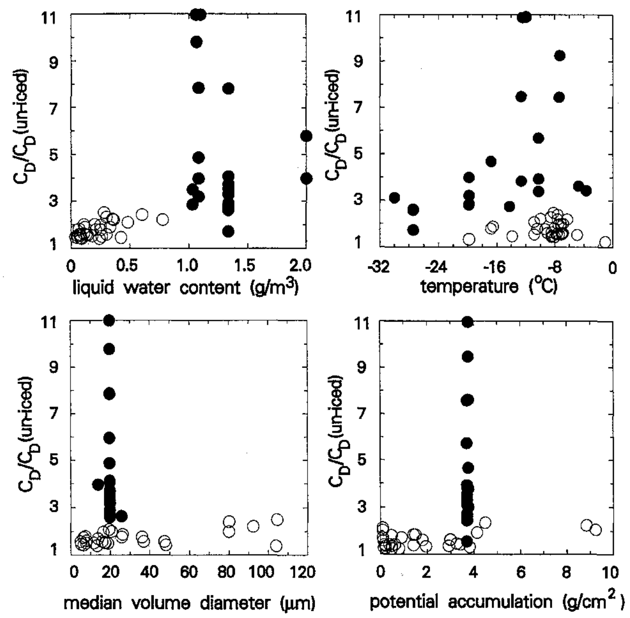

Fig. 4 Ratio of C_D to the un-iced aircraft or airfoil value, C_D/C_D (un-iced), plotted against liquid water content, temperature, median volume diameter, and potential accumulation. Black dots are data from the wind-tunnel tests described by Olsen.[22] Unfilled dots are WISP and P89 cases from Figs. 1 and 2.

exceeding 1 g/m^3 were not encountered in the Sand et al.[4] study.

The high liquid amounts used in the wind-tunnel tests, and later in numerical simulations of ice accretion using the LEWICE model, are not realistic but do confirm the relationships between atmospheric parameters and drag in this study. However, the amounts of drag increase could be misleading in overestimating what could be expected during flight. It is likely that the increases in drag observed in this study are closer to those expected as a result of icing in flight, although it must be noted that these results are valid only for this aircraft.

Icing Severity Index

The current definitions of icing severity, listed in Table 2, were adopted by the Subcommittee for Aviation Meteorological Services in 1968. They are meant to be used by pilots to report icing during flight and depend on a pilot's assessment of how well his or her aircraft is able to deal with the ice accreting on it. The categories, trace–light–moderate–severe, are somewhat subjective, and depend as much on aircraft type and pilot reaction as they do on meteorology. While such an index can be useful for pilots reporting icing during flight, it provides little guidance for forecasters who are called upon to predict such conditions. Lewis[23] proposed a severity index using the same terminology, based on theoretical accretion of ice on a 3-in.-diam cylinder traveling perpendicular to the airstream at 200 kn (89.5 m/s) for 1 h, for various LWCs and a droplet diameter of 15 μm. Newton[24] later verified that these calculated accretion amounts were within 15% of actual accretion measured during flight tests. Thresholds for severity categories are based on LWC. The Lewis index provides for adjustments to LWC to account for the difference in collection efficiencies of droplets that are not the standard 15 μm diameter. Jeck[25] later revisited this index and added an augmentation to account for the increased aerodynamic penalty resulting from clear icing at warmer temperatures (as suggested by Ranaudo et al.[1] and others). The Air Weather Service[26] recommended a simplified version of this index (AWSI) for use by forecasters to predict icing severity. A 14-μm droplet diameter is assumed for stratiform clouds and 17-μm diam for cumuliform clouds, with no temperature adjustment.

For this evaluation, the Lewis–Jeck Index (LJI) was further modified to account for the effects of large droplets suggested by the data presented previously. If the MVD is >30 μm, temperature is between -2 and -10°C, and LWC is >0.2 g/m^3, an adjustment to the w-corrected LWC is made that increases all severity levels by one category. If these conditions are not met, the MVD and temperature adjustments are as for the LJI, except that the size adjustment is applied prior to the temperature adjustment. This index will be referred to as the icing intensity index or III.

The data sets used in the previous analyses of aircraft performance based on lift and drag coefficients, as well as the decline in rate of climb capability, were used to compare the AWSI, LJI, and III. Details of the three indices are included in Table 2. The 14-μm (stratiform) droplet diameter was assumed for the AWSI, which is appropriate for the wintertime stratiform or orographic clouds these points represent. Figure 5 shows C_L, C_D, ΔROC, and C_D/C_D (un-iced) plotted against icing severity for the three indices. Figure 1 showed little dependence of C_L on atmospheric parameters and this is reflected by all three indices. The light category includes those points with lowest lift, to 65% of the clean aircraft value. The P89 points, which are in the moderate and severe categories, only have a C_L reduction of 10% at most. Comparison with C_D better highlights differences among the indices. The AWSI puts nearly all data points in the trace and light categories, even for high C_D increases. Temperature and MVD adjustments spread the LJI points into more categories and improve the relation between increasing index with increasing performance decline. However, these adjustments also move points into the none category when MVDs are small. The best relation is provided by the III, which has nearly all of the high C_D points in the severe category.

There is more scatter in the data for minimum ΔROC, but the III tends to reflect increasing severity with increasing performance loss better than the other indices. Those points with greatest degradation are labeled as light by the AWSI, as moderate by the LJI, and as severe by the III. Again, the LJI adjustment to LWC, and thus severity, by the w factor appears to overcompensate for small droplets. All of the high LWC wind-tunnel points are categorized as severe by the III and LJI, but not by the AWSI.

Are the severe category points in these evaluations truly severe, i.e., was the aircraft unable to sustain flight in the conditions encountered? In at least two of the P89 flights, the pilot felt it necessary to leave the icing areas as quickly as possible. During one, on Feb. 18, 1983, a turn was initiated and the pilot felt a buffet as though a wing stall was imminent. He then restored the airplane to a wings-level condition, and made a flat turn using only the rudder. This certainly could be considered a severe icing event and satisfies the reporting definition listed in Table 2. Based on comparable increases in C_D and decreases in climb capability, most of the other P89 encounters probably also belong in the severe category.

These severity indices reflect the icing environment in situ, and don't take into account the ice already accreted on the airframe. However, as the results shown in Figs. 1–3 indicate, that parameter is also a factor in performance degradation. To be used effectively, an index must be depicted spatially so that the flight path length through an icing environment as well as expected severity can be determined. The 2.6-nm and 17.4-nm intermittent and continuous designations in the FAR 25, Appendix C[21] certification envelopes attempt to address this. The LJI and III rely on knowledge of LWC, droplet size (as the MVD), and temperature. Currently, temperature estimates are available either in real time or as forecasts. Liquid water content fields are just now being added to numerical weather forecast models and their accuracy has not yet been robustly verified. Some research-quality numerical models include droplet size calculations, but these tend to simulate smaller

Table 2 Icing severity[a]

Category	LWC[b]	Pilot reporting definition
Trace	≤0.1 g/m^3	Ice becomes perceptible. Rate of accumulation is slightly greater than rate of sublimation. It is not hazardous even though de-icing/anti-icing equipment is not utilized, unless encountered for an extended period of time (over 1 h).
Light	0.11–0.6 g/m^3	The rate of accretion may create a problem if flight is prolonged in the environment (over 1 h). Occasional use of de-icing/anti-icing equipment removes/prevents accretion. It does not present a problem if the de-icing/anti-icing equipment is used.
Moderate	0.61–1.2 g/m^3	The rate of accretion is such that short encounters become potentially hazardous and use of de-icing/anti-icing equipment, or diversion, is necessary.
Severe	>1.2 g/m^3	The rate of accretion is such that de-icing/anti-icing equipment fails to reduce or control the hazard. Immediate diversion is necessary.

[a]Category names, LWC using the indices described in the text, and current pilot reporting definitions for each category are listed.
[b]LWC are adjusted by the following factors:
AWSI:

$LWC = 0.91\ LWC_m$, where LWC_m = measured or predicted LWC (no adjustments)

LJI:

$LWC = w \cdot (LWC_m + adj_T)$, where $adj_T = 0.1$ g/m^3 if $-2 > T > -8°C$
$adj_T = 0$ otherwise
$w = \varepsilon(MVD)/\varepsilon(15\ \mu m)$
ε is collection efficiency

III:

$LWC = w \cdot LWC_m + adj_T + adj_D$, where $adj_T = 0.1$ g/m^3 if $-2 > T > -10°C$
$adj_T = 0$ otherwise
$adj_D = 0.6$ g/m^3 if MVD > 30 μm and LWC > 0.2 g/m^3
$adj_D = 0$ otherwise

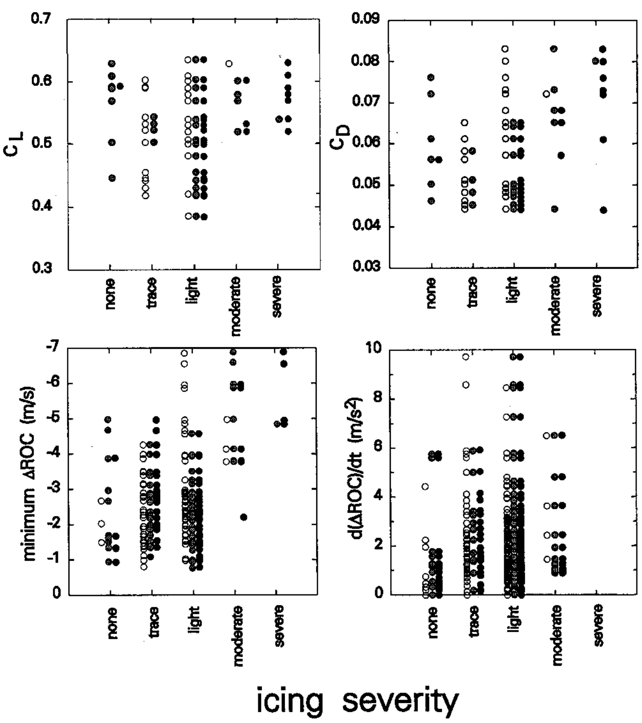

Fig. 5 C_L, C_D, ΔROC, and C_D/C_D (un-iced) plotted against three indices of icing severity. Severity is coded as trace (tr), light (lgt), moderate (mod), and severe (sev). Data are the same as for Figs. 1–4. Unfilled dots are for the AWSI, gray dots are for the LJI, and black dots are for the III.

scales (tens of kilometers) than are practical for an operational weather forecast.

Conclusions

Aircraft icing is a complex phenomenon and any exercise intended to isolate the specific effects of meteorological parameters on icing is difficult to interpret. Analysis of four aircraft response parameters reveals some useful trends. Loss of lift was not well correlated with any single atmospheric variable, nor with any combination. Drag increased and climb capability decreased with increasing LWC, MVD, and PA, and with warmer temperatures. A combination of MVD greater than 30 μm with LWC greater than 0.2 g/m^3 and temperature warmer than -10°C caused the greatest losses in performance. Cases with similarly high MVD, but LWC less than ~0.2 g/m^3, provided only modest performance decreases. Also, when MVD was less than ~30 μm, the increase in drag or decrease in climb capability had little relation to the MVD. The rate at which climb capability degraded was not strongly associated with any atmospheric variable tested. Inclusion of data from wind-tunnel tests confirmed the strong relation between liquid water content and drag increase, but the large liquid water contents used in those tests dominated any effects that may have been due to droplet size or temperature.

Severity indices that were dependent on LWC alone, and on LWC, MVD, and temperature were tested. An index that takes into account the effects of large droplet icing provided the best relation between higher severity level and greater performance degradation.

It must be emphasized that these results are probably valid only for the Wyoming Super King Air research aircraft, as configured during the research projects from which the data were obtained. An ideal severity index system would be one that would be valid for all aircraft types. To determine whether this is the case, more extensive flight testing, wind-tunnel, or numerical simulations are required.

The results of these studies should be useful for incorporating severity of icing into icing forecasts based on numerical weather model output. Thus, if LWC, temperature, and MVD are produced as model outputs, the expected effect on an aircraft could be predicted. These results may also be used to compare the response of different aircraft to similar atmospheric conditions, so that the severity index can be further tuned.

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