JOURNAL OF AIRCRAFT
Vol. 35, No. 6, November–December 1998

Characterizing the Supercooled Large Droplet Environment with Corresponding Turboprop Aircraft Response

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This continuing study evaluated turboprop aircraft performance response to various environmental conditions. These conditions included clear air, warm rain, ice only, mixed phase, and supercooled drops encountered during 19 separate flights. Supercooled droplets consisting of cloud, drizzle, and rain sizes were the main focus of this study. Aircraft response was quantified by rates of change in aircraft rate-of-climb capability, lift and drag coefficients and, lift over drag ratio. The aircraft performance parameters were compared to environmental hydrometeor parameters, such as 80% volumetric diameter (80VD)*liquid water content (LWC), quantifying the environmental conditions. Results show that encounters with supercooled drizzle drops, or ZL, resulted in maximum rates of performance degradation. These high rates of degradation forced the pilot to take evasive action within 5 min of entering these hazardous conditions. The Wyoming King Air experienced substantial increases in drag and stall speed, substantial decreases in climb capability, and significant lift degradations while encountering ZL. Encounters with supercooled cloud and rain-sized drops resulted in minor to low rates of performance degradation, whereas encounters with supercooled drops in low ice particle concentrations resulted in only minor rates of degradation. In addition, aircraft response to high ice particle concentrations and low liquid water, following a ZL encounter, resulted in rapid performance recovery, possibly because of erosion of ice on the airframe. Aggregates of needles and hexagonal plates led to the highest rates of recovery, whereas cold, clear air resulted in the lowest rates of recovery. Furthermore, flight analyses facilitated quantifying ZL horizontal extents and encounter frequencies. For example, ZL measured by a one-dimensional cloud probe during atmospheric research flights exceeded 0.05 g/m^3 twice per 10 flight hours over a horizontal length of 29 km. The results presented herein show a strong relationship between aircraft response and environmental parameters utilizing the largest drops in the hydrometeor distribution (80VD*LWC and ZL LWC). The results suggest that the most severe icing is actually caused by drizzle-sized drops as opposed to freezing rain. In addition, the results suggest that activating the de-icing boots (with typical chordwise coverage) after a ZL encounter may have little effect on aircraft performance recovery.

Nomenclature

C_D = aircraft drag coefficient
C_L = aircraft lift coefficient
D = aircraft drag
L = aircraft lift

Introduction

PROPER characterization and understanding of the natural environment responsible for aircraft icing is required to maintain aviation safety at its highest level. To this end, Ashenden and Marwitz[1] evaluated turboprop aircraft performance response to various environmental conditions. These conditions included clear air, warm rain, ice only, mixed phase, and supercooled drops. Supercooled droplets consisting of cloud, drizzle and rain sizes were the main focus. Ashenden and Marwitz[1] showed that encounters with supercooled drizzle drops (ZL) resulted in maximum rates of performance degradation, whereas encounters with supercooled cloud drops (ZC) and rain-sized drops (ZR) resulted in minor to low rates of performance degradation. In addition, Ashenden and Marwitz illustrated a strong relationship between turboprop aircraft response and the environmental parameter 80% volumetric diameter (80VD)*liquid water content (LWC). Aircraft response was quantified by rates of change in aircraft rate-of-climb capability, drag coefficient, and lift over drag ratio (L/D). Furthermore, the results suggested that the most severe icing is actually caused by freezing drizzle as opposed to freezing rain.

Current research is a continuation of and builds on the work of Refs. 1–5. The additional contributions herein include 1) additional freezing drizzle distributions, 2) horizontal extents of drizzle environment and frequency of encountering freezing drizzle during research flights, 3) an additional mixed-phase and drizzle encounter with de-icing boot activations, 4) an additional method to characterize the supercooled large droplet (SLD) environment, 5) aircraft recovery environments, and 6) a comparison of icing severity classifications.

The data sets evaluated for this research were obtained by the Wyoming Super King Air 200 during atmospheric research flights. The environmental measurements and aircraft performance calculations are discussed by Ashenden and Marwitz. The King Air data evaluated for this research consisted of 19 flights in various environments and two baseline flights in clear air. The data were obtained from field projects such as the Sierra Cooperative Pilot Project (SCPP),[6] the Winter Icing Storms Project (WISP),[7] the Small Cumulus Microphysics Study (SCMS),[8] and Storm Operational and Research Meteorology—Fronts Experiment Systems Tests (STORM–FEST).[9] In any particular flight (or case study), the environmental conditions, i.e., temperature, LWC, drop diameters, hydrometeor phase, varied, resulting in various aircraft responses. A flight segment during which the environmental conditions were quasihomogeneous and the aircraft state parameters were within the limitations of the performance model was considered a separate environmental encounter. For this reason, aircraft response to various icing environments could be evalu-

Received Feb. 1, 1998; revision received May 20, 1998; accepted for publication May 21, 1998.

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Table 1 PMS probes installed on Wyoming King Air

Probe	Size range, diameter in μm	Resolution, diameter in μm	Sample volume per 100 m of flight
FSSP	3–45	3	15 cm^3
OAP 1D-C	12.5–187.5	12.5	~0.5 l
OAP 2D-C	25–800	25	~5 l
OAP 2D-P	200–6400	200	168 l

ated from one particular flight.[1] The environments that were evaluated included freezing drizzle, mixed phase (with freezing drizzle), ice particles only, freezing rain, warm rain, ZC, and ZC with a high LWC.

Environment Characterization and Aircraft Response

The King Air carries a full suite of environmental instruments for the study of cloud microphysics. These instruments include four Particle Measuring Systems, Inc. (PMS) probes specified in Table 1, two hot-wire liquid water probes, temperature probes, and a Rosemount icing rate detector. The forward scattering spectrometer probe (FSSP), the one-dimensional cloud (1D-C), the two-dimensional cloud (2D-C), and the two-dimensional precipitation (2D-P) probes were used to measure drop sizes and LWC. PMS probe descriptions, processing techniques, and counting and sizing uncertainties are discussed by Ashenden.[10] The PMS probes are calibrated before and after each field project.

Freezing drizzle was frequently encountered with the Wyoming King Air over the Sierra Nevada during SCPP. Analyses of these data sets revealed, again, that periods of high aircraft performance degradation corresponded to regions with no to very low ice concentrations and high concentrations of drizzle drops. This ZL characteristic facilitated the processing of the SCPP hydrometeor distributions (phase classification algorithm not used), and examples of three ZL distributions corresponding to high performance degradations are shown in Fig. 1. This figure illustrates the drizzle environments over the Sierra Nevada measured in 1982, 1983, and 1985 with normalized hydrometeors for liquid mass ($g/m^3/\mu m$) vs hydrometeor diameters on a log/log scale. The cumulative mass was summed across the distribution to 100%, as depicted by the symbols not connected with a line. The hydrometeor diameter corresponding to the point at which 50% mass is achieved is defined as median volumetric diameter (MVD). The diameter corresponding to the point at which 80% mass is achieved is defined as 80VD. Note the high mass concentrations in the 1D-C probe and the differences between MVD and 80VD in Fig. 1. These are both strong indicators of a drizzle environment. 80VD emphasizes the larger drops in the distribution and is, therefore, more appropriate when characterizing the drizzle environment. The total liquid water content (TOTLWC) was calculated by integrating across the distribution, with the exception of the PMS probe overlap regions.

Drizzle Environment Frequency and Horizontal Extent

Knowing the frequency of encountering liquid water in flight, the level of liquid water content, and the horizontal extent of liquid water is helpful when designing aircraft ice protection systems. Sand et al.[3] reported the frequency of encountering cloud, or ZC, liquid water, and corresponding horizontal extents. Icing regions were selected where the LWC measured by the FSSP (measuring 3–45 μm diameters) exceeded 0.025 g/m^3, and where the temperature was <0°C. They reported about one encounter every 10 h of flight, which was characterized by LWC exceeding 0.1 g/m^3 continuously over a distance of 20 km, and the cloud liquid water contents exceeding 0.1 g/m^3 were found to extend continuously over distances as great as 80 km. In addition, these researchers noted about three encounters per hour with cloud LWCs as great as 0.5 g/m^3 and one encounter per hour with LWCs as great as 1 g/m^3.

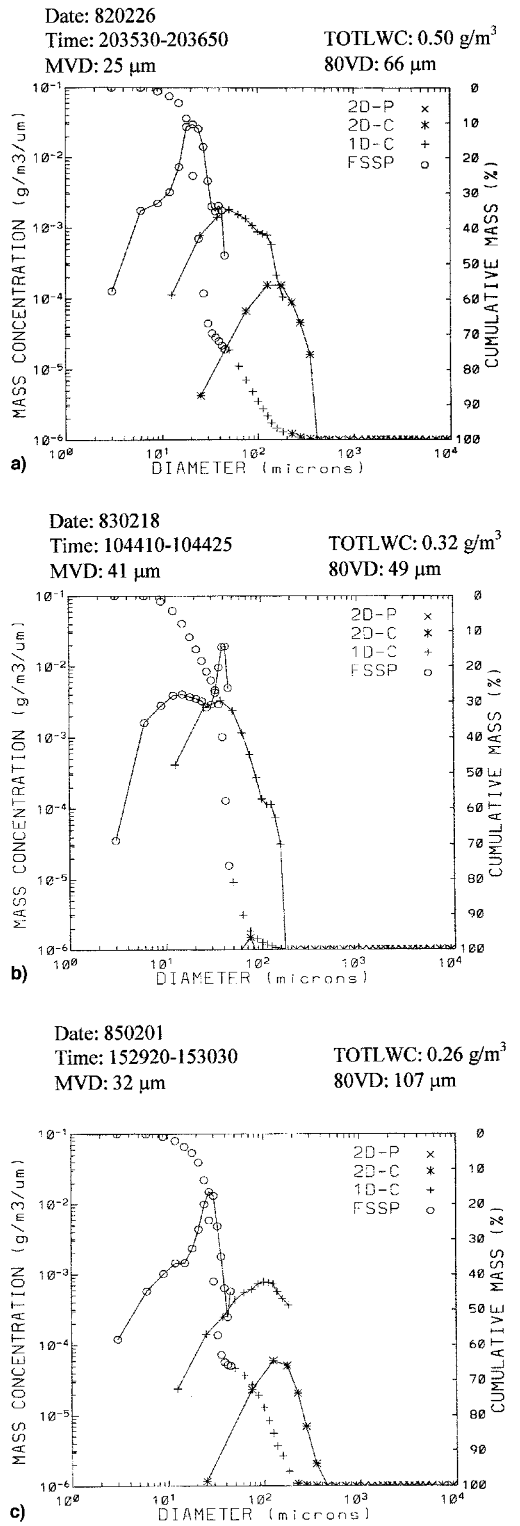

Fig. 1 Normalized drizzle distributions corresponding to high King Air performance degradations measured by the FSSP, 1D-C, 2D-C, and 2D-P on a) Feb. 26, 1982; b) Feb. 18, 1983; and c) Feb. 1, 1985. No 2D-P concentrations were detected for these three examples.

Similar procedures were used in the present work to determine the frequency of encountering drizzle, or ZL, liquid water and corresponding horizontal extents. The frequency of liquid encounters reported here and shown by Sand et al. should be considered an extreme mode because the mission emphasized flying through clouds for weather research (not exclusively icing research). The flight tracks are typically not straight lines between two points, rather, the tracks show several turns back to regions of interest (areas with liquid water). An aircraft not conducting atmospheric research therefore, such as a commuter aircraft, would undoubtedly experience less encounters per flight hour than shown here. The data presented here, however, can be considered the upper limit of horizontal extent and encounter frequency when flying in regions conducive to drizzle drop formation.

The drizzle LWC was measured by a PMS 1D-C probe (measuring 44–194 μm diameters) and a total flight time of 26 h were evaluated for this effort. First, the number of times drizzle liquid water continuously exceeded a threshold value was placed in a corresponding time segment or bin. This was done for each flight and the data were screened to filter out points where the temperature was warmer than -1°C and the PMS 2D-C probe measured >0.04 g/m^3 of liquid water. This eliminated possible freezing rain or ice-contaminated regions. The time segments were converted to distance using an average King Air true airspeed of 90 m/s. The values were normalized for total flight time, resulting in the number of drizzle encounters per flight hour with corresponding lengths shown in Fig. 2. This figure represents the number of supercooled drizzle encounters experienced per flight hour by the King Air during research flights, where the 1D-C LWC threshold of 0.05 g/m^3 was exceeded. The threshold values used and the selection of the 1D-C to characterize the drizzle environment were based on recent research.[10] The encounters per hour are plotted as a function of the length of the encounter where the 1D-C LWC remained continuously above the threshold values shown (0.05, 0.1, and 0.3 g/m^3). Three power curves were fitted to each of the data sets corresponding to the three threshold values. These encounters took place over the Sierra Nevada during SCPP and along the Front Range of the Rockies during WISP. As an example, these research flights encountered 0.05 g/m^3 or greater approximately once per flight hour over a length of 3 km or twice per 10 flight hours over a length of 29 km. The 0.05-g/m^3 regions were not found to extend beyond 29 km. By comparison, drizzle water contents $\geq$0.3 g/m^3 were encountered six times per 10 flight hours with an encounter length of 3 km. Continuous drizzle environments of 0.1 and 0.3 g/m^3 were not found to exceed 18 and 10 km, respectively.

A comparison of Fig. 2 to the work of Sand et al.[3] shows that the drizzle environments are not encountered as frequently as the cloud drop environments and the horizontal extents are shorter. The cloud water contents reported by Sand et al. reached values of 1 g/m^3 (FSSP) and the drizzle water contents (1D-C) evaluated here reached values of 0.4 g/m^3. Furthermore, the drizzle icing conditions are not uniform as illustrated by the varying lengths of encounter. Between these drizzle regions are gaps, where sublimation of the accumulated ice could occur if the gaps are also void of cloud drops. Sand et al. notes that the gaps between cloud LWC regions are less than 5 km, 50% of the flight time. Limited sublimation occurs in these short time scales, therefore, the cumulative effect of consecutive encounters, such as characterized by Fig. 2, should be considered.

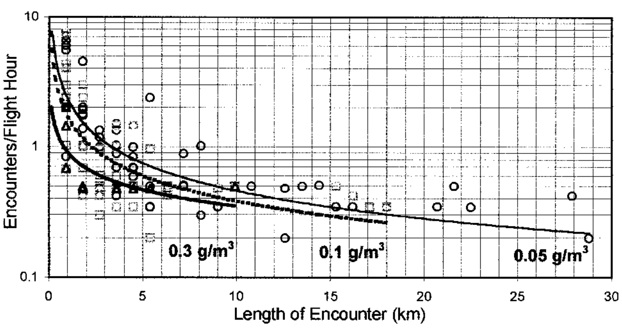

Fig. 2 Continuous drizzle encounters per King Air flight hour as function of encounter length, where 1D-C LWC remained above threshold values of 0.05 (○), 0.1 (□), and 0.3 g/m^3 (△). Power curves fitted to 0.05 (——), 0.1 (– – –), and 0.3 g/m^3 (▬▬) data.

Performance Response to Environmental Conditions

Two flights were detailed by Ashenden and Marwitz,[1] where the King Air encountered drizzle and mixed-phase environments. An additional drizzle and mixed-phase encounter that occurred on a SCPP research flight on Feb. 7, 1985 is detailed here. This case provides a closer look at lift loss associated with drizzle encounters and the effects of activating pneumatic de-icing boots after drizzle encounters. The aircraft equations of motion were incorporated into a performance model that was used to calculated aircraft C_L, C_D, L/D, and change in rate-of-climb (ΔROC).[1,10] The sum of the forces along the longitudinal axis was used to derive drag and the sum of the forces along the vertical axis was used to derive lift. The longitudinal acceleration was used to determine actual C_D throughout a

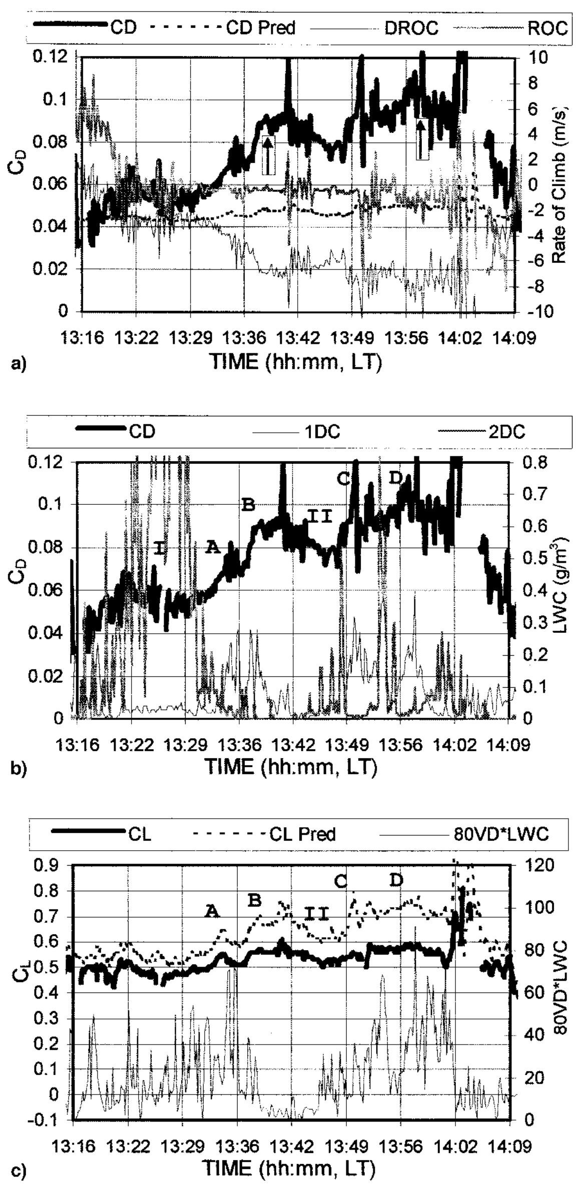

Fig. 3 Performance parameter 10 s average analog traces for freezing drizzle (ZL) and ice hydrometeor encounter on Feb. 7, 1985 over the Sierra Nevada with the heavy solid line representing aircraft C_D (or C_L) with a) ΔROC and ROC, b) 1D-C and 2D-C LWC, and c) predicted and actual C_L with 80VD∗LWC. De-icing boot activation noted with arrows.

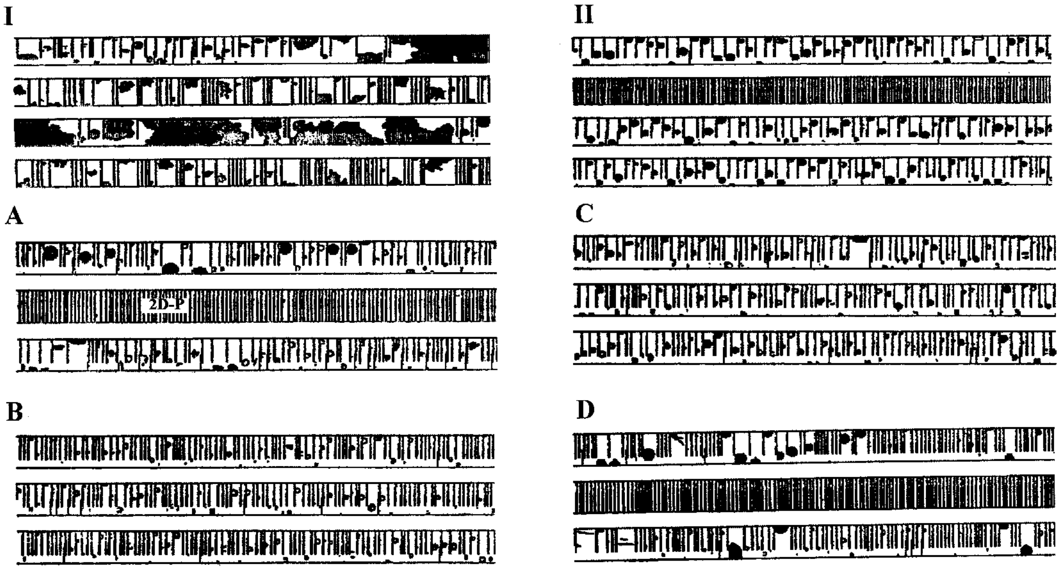

Fig. 4 Samples of two-dimensional images corresponding to the regions noted in Fig. 3. (I) mixed phase (aggregates), (A) mixed phase with ZL, (B) ZL and zero areas (small particles triggering two-dimensional probe), (II) ice (hexagonal plates), (C) mixed phase with ZL, and (D) ZL, zero areas and rimed ice particles. The height of the image bar represents 800 and 6400 µm for the 2D-C and 2D-P, respectively.

flight, and a drag polar (based on clean aircraft) was used to determine predicted C_D for the same angle of attack (AOA). The predicted and actual C_D analog traces are plotted in Fig. 3a to illustrate the regions of degradation. The beginning of the flight was uneventful with a majority of the encounters being with ice particle environments. The first two hours of the flight were not plotted in Fig. 3 to concentrate more on the regions where performance degradation occurred. The C_D traces in Fig. 3a show that the degradation was low in the ice aggregate region evident in the two-dimensional images in Fig. 4I. This region (I) also consisted of high ice particle concentrations measured by the 2D-C as shown by the LWC trace in Fig. 3b. For this flight, high 2D-C water contents were good indications of ice contamination. After 13:30 local time (LT), the ice particles decreased and the 1D-C LWC increased, coinciding with increasing performance degradation illustrated by the C_D traces (region A). Region A was a mixed-phase environment with drizzle drops as shown in Fig. 4A. As shown in Figure 4B (region B), the concentrations of drizzle drops increased as well as zero area images. Few ice particles, however, were observed and the temperature was -7.7°C. In this region, C_D increased 100%, ΔROC decreased to -6.5 m/s, L/D decreased to 6.5 (not shown) and, as shown in Fig. 3c, C_L decreased approximately 20%. The C_L decrease is determined by the difference between the actual and predicted C_L for the same AOA. This figure also shows that the corresponding 80VD*LWC value was approximately 25. In addition, the Rosemount icing rate detector was cycling at approximately five times a minute during this period, which is an additional indication of the severe icing environment caused by the drizzle-sized drops. Just beyond region B, at 13:39 LT, the pilot cycled the pneumatic de-icing boots to clean the leading edges, which, as shown by the C_D and C_L traces in Fig. 3, had no obvious benefit to aircraft performance. At approximately 13:40 LT, the pilot increased AOA to buffet (note the spike in the C_D trace), which corresponded to an airspeed of 138 kn compared with a clean aircraft buffet of approximately 100 kn. This high buffet speed was probably a result of the rough ice accretions visible to the flight crew on the upper surface of the wing. The high buffet speed also indicates a substantial increase in stall speed because aerodynamic buffet precedes stall by only a few knots of airspeed.

The aircraft degradation started to recover at 13:45 LT, when the environment changed to ice (hexagonal plates), as shown in the images in Fig. 4II and substantiated by the zero LWC measured by the FSSP (Table 2). Figure 3b also shows that the 1D-C LWC was low during this period, suggesting low ZL concentrations. The high concentration of ice (and low ZL) resulted in a drag decrease and a recovery in the lift degradation as shown in Fig. 3. At this point the aircraft was able to accelerate; however, at 13:48 LT, the ZL returned (note 1D-C increase and ZL images in Fig. 4C) and the aircraft started to slow again. Figure 3 shows the C_D and C_L traces diverging again in this drizzle environment (region C). The environment soon changed to ice, arresting the degradation; however, near 13:56 LT (region D), the ice concentrations decreased, the 1D-C LWC increased to 0.18 g/m^3, the 80VD increased to 93 µm, and the 80VD*LWC was 30. These environmental conditions are illustrated by the two-dimensional images in Fig. 4D. The two-dimensional images show rimed ice particles, which is an additional indication of the presence of liquid water. Even though this environment was classified mixed phase, the drizzle drops in Figure 4D probably led to the performance degradation. In this hazardous environmental condition, C_D increased by 120%, C_L decreased by 27%, ΔROC decreased to -8.4 m/s, and L/D decreased to 5.4. In addition, the Rosemount icing rate detector was cycling at approximately six times a minute, indicating the severe icing environment. Just beyond region D (Fig. 4) the ice particles returned, arresting the degradation again, and at 13:57 LT the pilot increased AOA to buffet, which corresponded to an airspeed of 144 kn (substantial stall speed increase). At 13:58 LT, the pilot cycled the pneumatic de-icing boots, which again, as shown by the C_D and C_L traces in Fig. 3, had no obvious benefit to aircraft performance. Previous wind-tunnel evaluations by Ashenden and Marwitz[10] have shown that residual drizzle ice remaining after a de-icing boot cycle (ice aft of the de-icing boots) can lead to substantial aerodynamic degradations; however, the de-icing boots are still a valuable protection against the smaller

Table 2 Environment classification

Parameter	Range, µm	FSSP	Bins	
			1D-C	2D-C
ZC	3–29	3–9	——	——
ZL	30–400	10–15	4–15	5–7
ZR	>400	——	——	8–20

hydrometeors, or ZC. The spikes in the traces near 14:02 LT in Fig. 3 were a result of porpoise maneuvers. After 14:02 LT, the aircraft performance completely recovered in ice particles, followed by warm ambient temperatures.

The analyses of the SCPP cases, such as that of Feb. 7, 1985 discussed here, and the Jan. 18, 1983 case discussed by Ashenden[10] offered several findings regarding the King Air response in ice particles only, mixed phase, and freezing drizzle environments. A brief summary of the SCPP analyses is offered:

1) Freezing drizzle results in high aircraft performance degradations, whereas mixed-phase environments results in only minor degradations. The performance degradation in ZL was in the form of drag increases, lift decreases, and stall speed increases.

2) Aircraft performance recovery is realized in ice particle environments (aggregates, plates) and sometimes in mixed-phase environments (needles) if the LWC is low.

3) Aircraft response (degradation and recovery) to the environmental conditions is on the order of 5 min or less. Several drizzle environments had to be exited within 5 min of entering the conditions.

4) Activating the de-icing boots *after* a ZL encounter had little effect on the aircraft performance recovery (King Air boots do not exceed 8.5% of wing chord).

Characterizing the Drizzle Environment

The amount, shape, and location of ice accumulated on the aircraft must be considered when comparing aircraft response to various environments. A clean aircraft encountering freezing drizzle for the first time in a flight may respond differently than if the aircraft had already accumulated ice on the airframe. Potential accumulation (PA) has been used by some researchers to normalize these situations. PA is defined as the mass of supercooled water that would accrete on a unit surface if the collection efficiency was 100%.[2] PA has typical units of g/cm^2 and represents the upper limit of the expected ice accretion because the droplet collection efficiencies can not exceed 100%. Potential accumulation is difficult to calculate (when considering all liquid water) in a mixed-phase environment without the use of a phase classification algorithm. In addition, ice can sublimate, melt, or shed off the airframe without decreasing PA, resulting in minimal correlation between potential accumulation and aircraft response.

The rates of change in C_D, ΔROC, and L/D were used in this research as opposed to the PA (and instantaneous values) technique to eliminate the dependence on the cumulative effect of airframe ice. The rates of change in C_D, ΔROC, and L/D were calculated over 60 s for each of the homogeneous regions. The rates of change in C_D were plotted against 80VD∗LWC for all encounters (19 flights) in Fig. 5. The advantages of using 80VD∗LWC compared to MVD, LWC, or 80VD in characterizing the supercooled large droplet environment was shown in Ashenden and Marwitz.[1] The 80VD emphasizes the larger drops in the distribution that seem to dictate the severity of the degradation (closer to the largest hydrometeor size, or D_{max}). To further delineate the various aircraft responses, 80VD was multiplied by total LWC, resulting in the 80VD*LWC parameter plotted in Fig. 5. The highest C_D and ΔROC (not shown) rates, or performance degradation, correspond to an 80VD*LWC between approximately 10 and 100.

The Jan. 18, 1983 region with an 80VD*LWC of 209 (arrows) indicates low rates of degradation, even though the instantaneous degradation parameters were very high (C_D = 0.108, ΔROC = −8 m/s). In this region, the aircraft had just entered a mixed-phase environment after accumulating substantial airframe ice in a freezing drizzle environment so that C_D was still high (region IV in Fig. 3b of Ashenden and Marwitz[1]). The C_D rate, however was low, illustrating the fact that the rate technique is independent of the accumulated ice. The freezing rain cases on March 8, 1994; Feb. 12, 1992; and Feb.

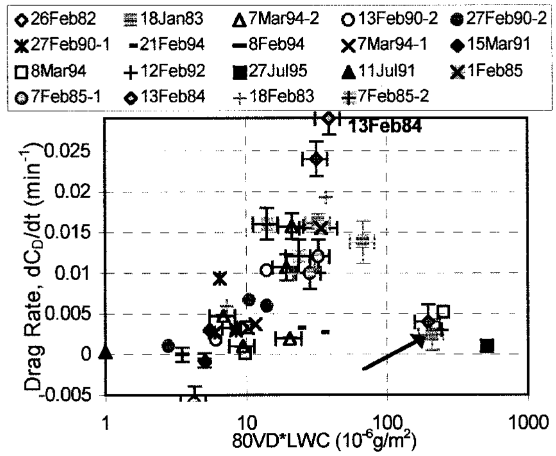

Fig. 5 Relationship between King Air C_D rate vs 80VD∗LWC. Arrows point to Jan. 18, 1983 encounter in a mixed-phase environment.

26, 1982 indicate low degradation rates, even though the 80VD∗LWC parameters were greater than 100 and regions of high LWC consisting of cloud drops (up to 1.2 g/m^3 on Feb. 21, 1994) indicate low to moderate degradation rates. Homogeneous regions with cloud drops (80VD∗LWC < 10), freezing drizzle (10 < 80VD∗LWC < 100), and freezing rain or ice (80VD∗LWC > 100) resulted in minor, maximum, and minor performance degradation rates, respectively. Figure 5, therefore, indicates that a single environmental parameter revealed by this research, which is related to performance degradation rates, is 80VD*LWC.

The corresponding rates for ZL and ZR were used to approximate how long before the King Air would exceed its reserve climb power. The climb reserve reached zero when the ΔROC reached approximately −10 m/s with a corresponding C_D of ~0.12. Using a reasonable ZL C_D rate of 0.015 min^{-1}, the time for the clean aircraft (C_D ~ 0.045) to reach zero reserve power was approximately 5 min. Similarly, using a reasonable ZR C_D rate of 0.003 min^{-1}, the time to reach zero reserve power was approximately 25 min. For comparison, the pilot was forced to exit the drizzle conditions on Jan. 18, 1983 after only 5 min in freezing drizzle. The peak C_D rate occurred on Feb. 13, 1984 (0.029 min^{-1}). At this rate the time to reach zero reserve power is approximately 2.5 min. Again, the drag rates are independent of the accumulated ice.

Aircraft Response to ZC, ZL, and ZR LWC

An additional method of characterizing the natural icing environment by utilizing the classification ZC, ZL, and ZR is proposed. The integrated LWC from the PMS probes were divided into the three bin categories ZC, ZL, and ZR, as shown in Table 2. Several variations of bin selections were evaluated by comparing the King Air response to the three LWC classifications. This mainly consisted of adjusting the dividing line between the ZC and ZL sizes by varying the FSSP and 1D-C bin ranges. The bin ranges shown in Table 2 were used in the integration to determine the ZC, ZL, and ZR LWCs. The bin selections shown provided the best relationship between King Air response and the LWC categories. Examples of this relationship are shown in Fig. 6 for the March 7, 1994 and Feb. 13, 1984 freezing drizzle encounters. The analog traces in Fig. 6a show a positive relationship between ZL LWC and C_D. The ZC trace, however, does not always show a positive relationship, specifically between 23:45 and 00:16 Greenwich Mean Time (GMT). The traces for the Feb. 13, 1984 case in Fig. 6b also show a positive relationship between ZL LWC and C_D. Note the large increase in ZL LWC and C_D near 14:16 LT. In addition, the ZR LWC is plotted, which shows a decrease in ZR LWC just prior to the substantial drag increase. The ZR LWC for this case, however, was because of mixed phase and ice conditions. The traces in Fig. 6b show the relationship between low ice concentrations, the existence of drizzle, and the subsequent performance degradation. The recovery in performance degradation beyond 14:18 LT occurred because the ambient temperatures were >0°C.

The ZC, ZL, and ZR LWCs were calculated for most of the King Air encounters evaluated. The ZC, ZL, and ZR LWC values were plotted against drag rate as shown in Fig. 7. Criteria were established to classify each encounter as cloud, drizzle, or rain-sized. An encounter was classified as cloud if the ZL LWC was <0.12 g/m^3 and the ZR LWC was <0.02 g/m^3, classified as drizzle if the ZL LWC was >0.12 g/m^3 and the ZR LWC was <0.02 g/m^3, or classified as rain if the ZR LWC was >0.02 g/m^3. The ZL C_D rates in Fig. 7 extend beyond 0.035 min^{-1}, even though the water contents are on the order of 0.2 g/m^3, whereas the ZC data extends beyond 1 g/m^3 with corresponding C_D rates < 0.004 min^{-1}. Figure 7 shows that the highest rates of performance degradation are because the drizzle-sized drops and that the cloud and rain-sized drops result in comparatively low rates of degradation. The ZC, ZL, and ZR LWC data provided in Figs. 6 and 7 suggest that drizzle

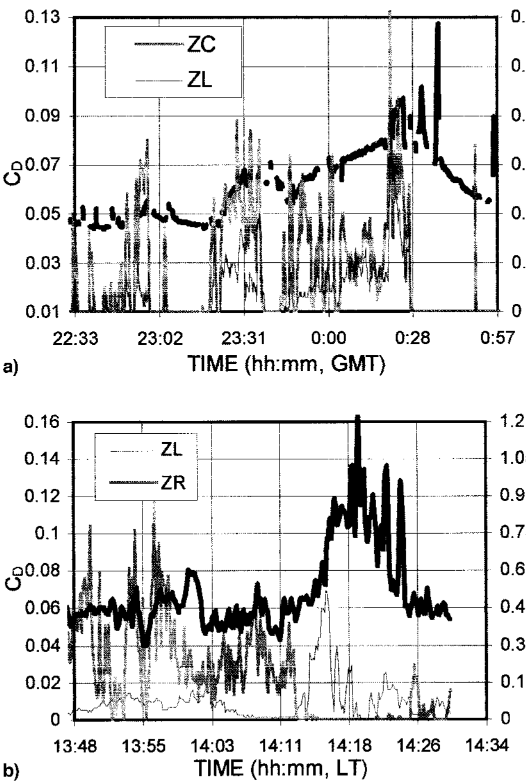

Fig. 6 C_D (▬▬) and ZL LWC analog traces for freezing drizzle encounter for a) March 7, 1994 with ZC LWC and b) Feb. 13, 1984 with ZR LWC.

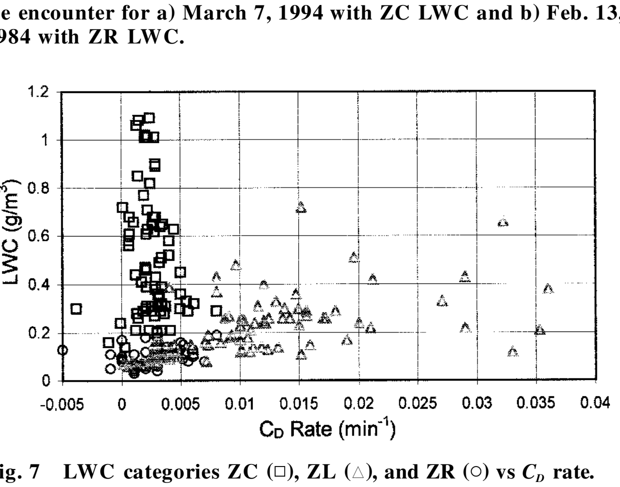

Fig. 7 LWC categories ZC (□), ZL (△), and ZR (○) vs C_D rate.

drops (30–400 μm) primarily dictate the type and rate of aircraft response. There seems to be little relationship between ZC LWC and ZR LWC and the corresponding aircraft response.

The ability of the environmental parameters (80VD∗LWC, ZC LWC, ZL LWC, ZR LWC, and temperature) to predict the response of the King Air was evaluated by means of multiple regression.[10] The results of the multiple regression analyses indicate that the explanatory variables 80VD∗LWC, ZL LWC, and temperature can explain about 50% of the aircraft degradation variance. Other variables that affect aircraft icing characteristics such as humidity, pressure, and aircraft collection efficiencies were not considered in this analysis. The results suggest that a second-order model incorporating 80VD∗LWC and temperature is the best evaluated model when considering all of the icing cases, and the linear model using 80VD∗LWC alone is the best evaluated model when not considering freezing rain. When considering all icing encounters, the second-order model incorporating ZL LWC and temperature is superior in predicting the aircraft degradation. The regression analyses show that the explanatory variable 80VD∗LWC explains 54% of the response variable (drag rate) when ZR LWC is omitted and 32% when ZR LWC is included. In addition, adding the variable temperature results in explaining 52% of the variability when ZR LWC is omitted and 42% when ZR LWC is included. Furthermore, the linear model with ZL LWC explains 42% of the variability and 43% of the variability when temperature is added. These results suggest that temperature is a valuable predictor only when ZR encounters are included. In addition, temperature only adds a 1% explanatory improvement when utilizing ZL LWC. To explain this, consider that the ZR encounters occurred at temperatures between −2 to −4°C and, therefore, exhibit temperature dependence. Considering the number and complexity of the dependent variables involved in the icing process, the selection of 80VD∗LWC and ZL LWC seem to explain a significant portion of the King Air degradation.

Aircraft Performance Recovery

Aircraft performance recovery in various environmental conditions is equally important when evaluating overall aircraft response. The rate of ice sublimation, melting, shedding, or erosion are directly related to the rate of aircraft performance recovery. The environments leading to aircraft recovery were evaluated in an attempt to classify the conditions (ice type, temperature, LWC) most favorable for performance recovery. Several King Air flights were analyzed and environmental encounters where the aircraft experienced negligible performance degradation or actual performance recovery were studied. Cases of King Air performance recoveries in cool, clear air (<0°C), mixed phase, ice only, and warm air (>0°C) are included in Table 3. The ambient temperature, FSSP LWC, rates of recovery, and ice types are included. Examples of two-dimensional images of hexagonal plates were provided earlier in Fig. 4II. A sample of aggregates of needles and riming dendrites encountered on two separate King Air flights are shown in Fig. 8. The environments listed in Table 3, with the exception of the warm air cases, were ranked in column two, based on the rates of recovery listed in columns 5–7. This ranking shows that the environment containing aggregates of needles had the highest recovery rates and cold, clear air had the lowest recovery rates. This finding agrees with the reports from the King Air flight crews that noted rapid performance recovery in large ice crystals. The rapid erosion of the sharp drizzle ice formations (smoothing) by large ice crystals may explain this observed phenomenon.[11] The recovery data listed in Table 3 may suggest a relationship between the amount of liquid water coexisting with the ice particles and the rates of recovery. As shown earlier in Fig. 4D, ice particles coexisted with liquid water (FSSP LWC = 0.2 g/m^3 and 1D-C LWC = 0.18 g/m^3) for the Feb. 7, 1985 encounter, and these ice particles were

Table 3 King Air performance recovery in various environments

Date	Ice type/rank[a]	Temperature °C	FSSP g/m^3	ΔROC rate[b]	L/D rate[c]	C_D rate[d]
26Feb82	None	1.2	0	1.13	2.7	−0.011
18Jan83 (III)	Needles/7	−5.6	0.21	0.1	−0.1	−0.002
18Jan83 (V)	Aggregates/1	−6.2	0.02	1.1	0.533	−0.014
7Feb85-1 (II)	Plates/2	−7.5	0	0.33	0.3	−0.006
7Feb85-2	Needles/3	−6	0.09	0.36	0.23	−0.004
7Feb85-2	Dendrites/4	−9.2	0.03	0.23	−0.03	−0.01
27Feb90-1	None	1	0	3.8	4.73	−0.05
8Feb94	None/8	−21.6	0	0	−0.1	0
7Mar94-1	None/9	−6.5	0	0.03	−0.1	0.0003
7Mar94-2 (III)	None/6	−7.3	0	0.1	0.2	0
8Mar94	Graupel like/5	−1.8	0.1	0.2	0.7	−0.001

[a]Ranked by rate of recovery. [b]ms^{-1} min^{-1} ("−" degradation). [c]min^{-1} ("−" degradation). [d]min^{-1} ("−" recovery).

a)

b)

Fig. 8 Two-dimensional images of a) rimed dendrites and b) aggregates of needles corresponding to the periods of performance recovery. Refer to Fig. 4 for image bar sizing.

heavily rimed. This environment led to substantial aircraft performance degradation, as discussed earlier. Again, the drizzle liquid water tended to dictate the aircraft response for this case and not the ice particles. Conversely, the environment leading to the highest recovery rate (<0°C) consisted of aggregates of needles with very little cloud LWC. This environment was encountered on Jan. 18, 1983 (Fig. 4V of Ashenden and Marwitz[1]) and the results suggested that the combination of aggregates with low LWCs led to the rapid recovery.

The results suggest a relationship between the type of ice environment (the amount of liquid water present) and the corresponding aircraft response. If the ice particles exist in low cloud liquid water, the particles will not stick to the accumulated airframe ice, but may actually erode and/or smooth the ice, possibly explaining the observed performance recovery. If the ice particles coexist with significant cloud water, the ice particles may actually stick to the accumulated ice, increasing the accumulation, and possibly increasing the performance degradation. This may have been the case for the Feb. 7, 1985 flight near 13:57 LT (Fig. 4D), where the performance was degrading, even though several ice particles were observed in the two-dimensional images.

In addition to the ice and cold, clear air environments, recoveries in warm air (>0°C) were evaluated. As expected, the recovery rates in the warm, clear air were the highest because of rapid melting of the accumulated airframe ice. A warning, however, is appropriate on applying the King Air response in mixed-phase and ice environments to other aircraft. As suggested by Bowden et al.,[12] the melting of ice crystals in a mixed-phase environment by thermal ice protection systems could present a problem because of runback freezing. The King Air was not prone to this problem because it uses pneumatic de-icing boots.

Comparison of Icing Severity Classifications

The King Air icing encounters were classified as hazardous or nonhazardous similar to the methods of Politovich.[5] Regions where the King Air pilot had to exit the icing conditions because of severe performance degradation were deemed hazardous icing regions. Regions where the King Air flew or could have flown for prolonged periods of time (over 1 h) were deemed nonhazardous. Using the pilot reporting definitions (trace, light, moderate, severe),[13] the nonhazardous and hazardous encounters would correspond to the trace/light and severe categories, respectively. These severity categories are based on the amount of ice accumulated on the aircraft over time and are dependent upon the type of aircraft. The individual encounters were classified in Table 4, based on the pilot action and the criteria discussed earlier. The same regions were also classified by the environmental parameters 80VD$*$LWC and ZL LWC. As illustrated in Fig. 5, regions with an 80VD$*$LWC between 10 and 100 resulted in the highest King Air performance degradation rates and were considered hazardous, as tabulated in Table 4. Regions were also defined as hazardous if the ZL LWC exceeded 0.12 g/m^3 and the ZR LWC remained below 0.02 g/m^3.

From the pilot reporting criteria, the icing encounter on Feb. 21, 1994 (high LWC cloud drop case) was determined to be a nonhazardous condition because the pilot did not have to divert from the icing conditions. This case resulted in only moderate degradation. However, this encounter was rated as hazardous using the 80VD$*$LWC and ZL LWC criteria. It was the high LWC that skewed 80VD$*$LWC and ZL LWC toward the hazardous rating. Table 4 also shows that this encounter was considered moderate in icing intensity utilizing the Air Weather Service (AWS) index provided in the Forecasters' Guide on Aircraft Icing,[14] and was rated severe utilizing the Lewis[15] index. These severity indices are not applicable to the larger drop environments because the collection efficiencies for cloud drops were utilized. In addition, these indices do not consider the type or airspeed of the aircraft when determining the icing severity. Unfortunately, there is no accepted icing severity index at this time that will account for freezing drizzle and rain. The limitations of the AWS and Lewis indices are apparent in Table 4 with the forecasts of trace, light, or moderate icing for all King Air encounters, with the exception of the Feb. 21, 1994 case. A review of Table 4 illustrates the advantage of the 80VD$*$LWC and ZL LWC parameters in characterizing the icing environments, particularly the freezing drizzle and rain environments.

The various icing environments were also classified as ZC, ZL, and ZR, based on their volumetric diameters. The ZC environment corresponded to low to moderate King Air performance degradation and is characterized with an MVD < 25 μm, an 80VD < 30 μm, and a D_{max} < 50 μm. The ZL environment corresponded to the highest King Air performance degradation and is characterized with an MVD between 25 and 150 μm, an 80VD between 30 and 200 μm, and a D_{max} < 500 μm. The ZR environment corresponded to low King Air performance degradation and is characterized with an MVD > 150 μm, an 80VD > 200 μm, and a D_{max} > 500 μm. The various

Table 4 King Air icing encounter environmental characterization

Date	Time, GMT	Temperature °C	TLWC g/m^3	ZL g/m^3	80VD, µm	80VD*LWC g/m^2	Severity AWS[a]	Severity Lewis[b]	Type[c] by size	Class[d] by Pilot	Class[e] by ZL	Class[f] by 80VD*LWC
26Feb82ZR	20:30	−6.6	0.4	0.09	478	196.5	Light	Light	ZR	No-hazard	No-hazard	No-hazard
26Feb82	20:36	−10.3	0.47	0.21	67	31.8	Light	Light	ZL	Hazard	Hazard	Hazard
18Jan83	0:14	−6	0.33	0.27	81	32.8	Light	Light	ZL	Hazard	Hazard	Hazard
18Jan83	0:24	−6.8	0.45	0.41	150	68.2	Light	Light	ZL	Hazard	Hazard	Hazard
18Feb83	10:55	−6.7	0.85	0.6	43	40	Moderate	Moderate	ZL	Hazard	Hazard	Hazard
13Feb84	14:17	−7	0.63	0.42	59	39	Light	Moderate	ZL	Hazard	Hazard	Hazard
7Feb85-1	13:38	−7.7	0.41	0.3	78	33	Light	Light	ZL	Hazard	Hazard	Hazard
7Feb85-2	18:20	−7	0.15	0.14	163	24	Light	Light	ZL	Hazard	Hazard	Hazard
13Feb90-2	18:57	−12.8	0.18	0.18	32	14.1	Light	Light	ZL	Hazard	Hazard	Hazard
27Feb90-2	23:42	−10.2	0.63	0.18	23	14	Light	Moderate	ZC	Hazard	Hazard	Hazard
7Mar94-2	0:22	−8.6	0.57	0.3	38	21.3	Light	Moderate	ZL	Hazard	Hazard	Hazard
21Feb94	20:57	−9.7	1.2	0.16	29	35	Moderate	Severe	ZC	No-hazard	Hazard	Hazard
27Feb90-1	14:35	−7.2	0.15	0	27	8.5	Light	Light	ZC	No-hazard	No-hazard	No-hazard
15Mar91	13:59	−9	0.32	0	17	5.5	Light	Light	ZC	No-hazard	No-hazard	No-hazard
12Feb92ZR	7:06	−2.1	0.16	0.01	1563	245	Light	Trace	ZR	No-hazard	No-hazard	No-hazard
8Feb94	22:41	−18	0.14	0	26	3.5	Light	Light	ZC	No-hazard	No-hazard	No-hazard
7Mar94-1	17:00	−9.3	0.36	0	29	10	Light	Light	ZC	No-hazard	No-hazard	No-hazard
8Mar94	21:14	−1.8	0.28	0.07	36	9.8	Light	Light	ZC	No-hazard	No-hazard	No-hazard
8Mar94ZR	22:40	−3.4	0.44	0.19	574	252	Light	Light	ZR	No-hazard	No-hazard	No-hazard

[a]AWS, Forecasters' Guide on Aircraft Icing.[12] [b]Lewis[13]. [c]ZL, ZR, and ZC, defined by MVD and 80VD. [d]Aircraft diversion was required for hazardous encounters. [e]ZL LWC > 0.12 g/m^3 and ZR < 0.02 g/m^3 were defined as hazardous. [f]80VD*LWC parameters between 10 and 100 were defined as hazardous regions.

Table 5 Liquid hydrometeor classifications

Parameter	Cloud drops	Freezing drizzle	Freezing rain
MVD, µm	<25	25–150	>150
80VD, µm	<30	30–200	>200
D_{max}, µm	<50	<500	>500
ZL LWC, g/m^3	<0.12	>0.12	——
ZR LWC, g/m^3	<0.02	<0.02	>0.02
80VD*LWC, 10^{-6} g/m^2	<10	10–100	>100

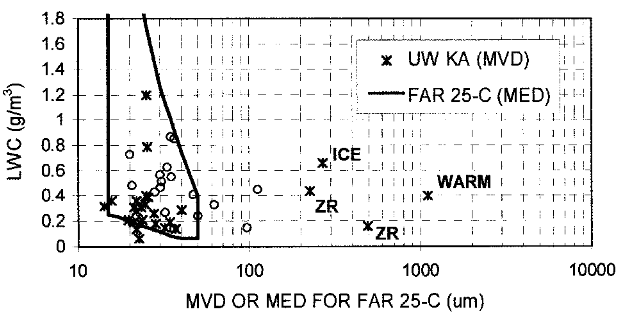

Fig. 9 King Air hydrometeor encounter (○, ∗) comparison with the FAA FAR 25-C, Intermittent Maximum Icing Conditions (▬▬). The (○) symbols represent those icing encounters that were hazardous. The encounters beyond 200-µm MVD were in a mixed-phase (ICE), rain drops (WARM), or freezing rain (ZR) environments.

icing environments were characterized and tabulated in Table 5 using the preceding ZC, ZL, and ZR criteria.

The Federal Aviation Administration (FAA) FAR Part 25 Appendix C (FAR 25-C) icing envelopes[16] were also used to evaluate the icing environments encountered by the Wyoming King Air. Figure 9 shows the comparison between the King Air encounters and the FAR 25-C Intermittent Maximum Icing; conditions typically utilized during FAA transport category aircraft certification. The King Air conditions were calculated using MVD and the FAR 25-C conditions are in terms of mean effective drop diameter (MED). These calculated volumetric diameters are not exact, but have been used in the literature interchangeably. Perpetuating the use of MVD is not desirable. However, utilizing MVD was required to compare the King Air icing encounters to those conditions typically established for icing certification. Both hazardous and nonhazardous conditions lie within and outside the borders of the FAR 25-C envelope as shown in Fig. 9. Differentiating between the hazardous and nonhazardous conditions within the 25-C envelope was impossible because of limitations of the MVD parameter. This was illustrated by Ashenden and Marwitz[1] in Fig. 5a, where a majority of the data points, including both hazardous and nonhazardous cases, occurred near 20-µm MVD. This comparison did show, however, that there were several natural conditions measured well outside the FAR 25-C. More importantly, several of these conditions encountered by the King Air were rated hazardous. Because the icing certification envelopes are utilized to screen aircraft for possible icing problems, the natural conditions most apt to cause performance degradations should be included in the FAR 25-C envelopes. Therefore, the FAR 25-C needs to be revised to include the ZL environment.

Summary

The results presented show that encounters with supercooled drizzle drops, or ZL, resulted in maximum rates of performance degradation. Encounters with supercooled cloud and rain-sized drops resulted in minor to low rates of performance degradation, whereas encounters with supercooled drops in low ice particle concentrations resulted in only minor rates of performance degradation. The results also show that the Wyoming King Air experiences substantial increases in drag, substantial increases in stall speed, and substantial decreases in climb capability when encountering freezing drizzle. However, the results presented herein show that the King Air also experiences significant lift degradation, contrary to the findings of the previous researchers.

The presented data also illustrated the advantage of using performance parameter rates as opposed to potential accumulation to facilitate correlation between aircraft response and environmental conditions. The effect of various amounts of accumulated airframe ice was eliminated when utilizing the performance parameter rates, thus facilitating the comparison of the data sets. The results demonstrate that the King Air performance degradation rates were highest in freezing drizzle. In the worst case the reserve performance capability of the King Air was consumed within 5 min. The rate of performance recovery was equally expeditious in warm air and in large ice crystals. Several case studies indicated rapid aircraft response to changing environmental conditions. That is, high rates of degradation were experienced within minutes of encountering regions of drizzle followed by high rates of recovery upon encountering regions containing large ice crystals and low LWC. These results suggest that the sharp ice feathers produced by freezing drizzle are the primary ice structures that are detrimental to the standard airflow characteristics, and are eroded, or smoothed, by large ice crystals. This erosion was only apparent when no or very low amounts of LWC coincided with the ice crystals, that is, low-density ice crystals. For temperatures colder than 0°C, aggregates of needles and hexagonal plates led to the highest rates of recovery, whereas cold, clear air resulted in the lowest rates of recovery.

The results show the limitations of MVD and the advantage of using 80VD to characterize the environment. Because of the statistical sampling limitations of the PMS probes, the largest size of the drop distributions, or D_{max}, was not used. 80VD appears to adequately characterize the distributions, is a reasonable compromise between MVD and D_{max}, and relates favorably to the aircraft performance response. In addition, total LWC did not favorably relate to aircraft response as severity indices would suggest. The Feb. 21, 1994 case with the highest LWC (1.2 g/m^3, 25-μm MVD, −9.7°C) did not correspond to high-performance degradation.

The advantages of the new environmental parameters, 80VD∗LWC and ZL LWC, over the standard MVD were demonstrated herein with favorable comparisons between 80VD∗LWC and ZL LWC, and the corresponding King Air response. The King Air performance degradation increased as the environmental parameter 80VD∗LWC increased up to 100; thereafter, the performance degradation was substantially less. These results clearly show that the King Air experiences high-performance degradation for an 80VD∗LWC between 10 and 100 or if ZL LWC exceeds 0.12 g/m^3. One exception to this trend occurred when high amounts of liquid water were contained in cloud drops, i.e., Feb. 21, 1994. In this case, the 80VD*LWC was 35 and ZL LWC was 0.16 g/m^3, yet the performance degradation calculated was moderate. It was the high LWC that skewed 80VD∗LWC and ZL toward the hazardous rating. In any case, it does not appear that this case was a severe icing condition as the current icing indices would suggest. However, the potential for severe icing because of runback was possible if the ambient temperatures increased from −9°C.

Evaluations, discussed herein, of ZC, ZL, and ZR LWC suggested that drizzle drops (30–400 μm) dictate the type and rate of turboprop aircraft response. There seems to be little relationship between ZC LWC and ZR LWC and the corresponding aircraft degradation. Multiple regression analyses showed that the selected parameters 80VD∗LWC or ZL LWC, with temperature, can explain approximately 50% of the aircraft degradation experienced in icing conditions. The contribution to the degradation prediction by temperature ranges from 1 to 10%, depending on the icing environment. Considering the number and complexity of the dependent variables involved in the icing process, however, the selection of 80VD∗LWC and ZL LWC seem to explain a significant portion of the King Air degradation. In addition, using 80VD∗LWC or ZL LWC is more advantageous when classifying the icing environments as hazardous or nonhazardous as compared to the current icing severity guidelines.

Based on past practices of the aviation community, the low King Air performance degradation in freezing rain was not expected. Freezing rain was believed to result in severe icing, whereas freezing drizzle was expected to result in moderate icing. The results of this research clearly show that for the King Air this was not the case, in fact, the opposite was true. For the King Air, encounters with freezing rain resulted in low-performance degradation, or light to moderate icing, and encounters with freezing drizzle resulted in high-performance degradation, or severe icing.

Acknowledgments

Research was funded by the Wyoming Planetary and Space Science Center, NASA Grant NGT 40050, and the Winter Icing and Storms Project, ATM-9523434. The Wyoming King Air was provided through a cooperative agreement between the University of Wyoming and the National Science Foundation, ATM-9319141. The authors thank Robert D. Kelly, William R. Lindberg, Alfred R. Rodi, and Dudley E. Smith for their guidance and assistance.

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