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Turboprop Aircraft Performance Response to Various Environmental Conditions

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This study evaluated aircraft performance response to various environmental conditions encountered during flight. These conditions included clear air, ice only, mixed phase, and supercooled drops. Supercooled drops consisting of cloud, drizzle, and rain sizes were the main focus of this study. Aircraft response was quantified by rates of change in aircraft climb capability, drag coefficient, and lift over drag ratio. The aircraft performance parameters were compared to an environmental hydrometeor parameter quantifying the environmental conditions. Results show that encounters with supercooled drizzle drops (SCDD) 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 degradation. In addition, aircraft response to high ice particle concentrations, in low liquid water, following an SCDD encounter, resulted in rapid performance recovery. The results presented herein show a strong relationship between aircraft response and an environmental parameter utilizing a weighted volume diameter and liquid water content. The results suggest that the most severe icing is actually caused by SCDD as opposed to freezing rain.

Nomenclature

D = aircraft drag force
g = acceleration because of gravity
L = aircraft lift force
M = aircraft mass, adjusted for fuel burn
S = gross wing area
T = aircraft total thrust, from two engines
$\dot{u}$ = acceleration along longitudinal axis
V = aircraft true airspeed
$\dot{w}$ = vertical acceleration
wt = aircraft weight, mg
α = aircraft angle of attack
θ = aircraft pitch angle
κ = propeller-induced flow velocity correction
ρ_0 = standard sea-level density
ϕ = aircraft roll angle

Introduction

THE aviation community has placed an increased emphasis on commuter-type aircraft within the last decade as a cost-effective means of fulfilling the needs of short-haul routes. The typical altitudes, airspeeds, and configurations of the commuter class not only results in an increase in icing encounters, but places the aircraft in regions more susceptible to hazardous in-flight icing such as freezing rain and freezing drizzle. In May of 1996, the Federal Aviation Administration (FAA) issued 18 airworthiness directives (ADs) requiring that aircraft manufacturers provide customer pilots with instructions for operating in freezing rain and freezing drizzle and offer instructions on how to safely exit these potentially hazardous conditions when encountered.[1] Considering the commuter aircraft flight profile and current usage, a research effort was undertaken to evaluate turboprop aircraft response to various environments encountered in flight.

The collection efficiencies and impingement limits of the airfoil and other aircraft components are directly dependent on the size of the liquid hydrometeors (drops).[2,3] The impingement limits increase in percent chord from the leading edge as the size of the drops increase. Because of their larger drop diameters, the ice shapes formed by freezing rain and freezing drizzle generally have increased impingement limits. Researchers have found that ice accretions between 5–15% of airfoil chord can result in substantial drag and stall speed increases.[4] Aircraft airfoils are typically protected to ~10% of chord by either hot bleed air or pneumatic boots sized for drops to ~40 μm in diameter. Encounters with drops larger than 40 μm, therefore, can result in hazardous ice accretions beyond the ice protection systems.

Liquid hydrometeors are categorized by diameter as cloud (<40 μm), drizzle (40–400 μm), or rain drops (>400 μm) as defined by Marwitz et al.[5] Freezing rain (ZR) is typically formed as melted aggregates of ice crystals collapse into large liquid drops and then supercool in a subfreezing layer below the melting layer.[6] The effect of freezing rain is considered extremely hazardous because of the rate of airframe ice accumulation, and at least one manufacturer states that their aircraft was not designed for freezing rain.[7] Freezing drizzle (ZL) is typically formed by enhanced growth of liquid drops by condensation and collision/coalescence without the need for a melting layer.[6] Freezing drizzle, used synonymously with supercooled drizzle drops (SCDD), has typically been considered a surface phenomenon and measured at the surface. The use of the term freezing drizzle herein means the presence of SCDD at the surface and/or aloft. A current aviation practice is to forecast severe icing in freezing rain and moderate icing in freezing drizzle.[3,8] This practice will be challenged in this paper.

Background

Experience based on Wyoming King Air encounters indicates that hazardous ice accretions are formed by freezing driz-

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zle and that this hazard diminishes for hydrometeor sizes that are either less than or greater than the diameter of drizzle drops (40–400 μm).[9] The University of Wyoming has operated the Beechcraft Super King Air 200T since 1977. The King Air was used frequently to conduct flights into icing conditions while studying precipitation development and cloud microstructure. A large data set has been archived over ~20 years of atmospheric research flying, which includes several severe icing encounters over different geographic locations. The importance and uniqueness of this data set comes from the fact that the research aircraft was instrumented to measure environmental microphysics and the corresponding aircraft response. Since 1982, the Wyoming King Air has encountered various icing environments consisting of liquid only, liquid with ice (mixed phase), or ice only. The liquid hydrometeors ranged from 3 to over 1000 μm in diameter, comprising the cloud, drizzle, or rain drop categories. Of these various encounters, roughly 30 have been in freezing drizzle. Observations by the King Air flight crew suggest that the drizzle drops freeze as sharp feathers or glaze nodules at or just beyond the de-icing equipment. Cooper et al.,[10] Sand et al.,[11] and Politovich[12,13] have shown that the Wyoming King Air experiences a substantial increase in drag, a substantial increase in stall speed, and an insignificant decrease in lift when encountering these drizzle drop conditions. These researchers determined the instantaneous drag, lift, rate of climb capability, and potential accumulation for the King Air in various icing environments. Potential accumulation was used to normalize the environments and was defined by Cooper et al.[10] as the mass of supercooled water that would accrete on a unit surface if the collection efficiency were 100%. Potential accumulation, however, is difficult to calculate in ice and mixed phase environments. For the current research, rate of change in certain performance parameters was utilized to eliminate the dependence on potential accumulation.

Politovich[12] relates aircraft performance parameters, such as drag coefficient, to environmental parameters such as liquid water content (LWC) and median volume diameter (MVD). Based on these relationships, Politovich suggests that high aircraft performance degradation is experienced when the LWC is >0.2 g/m^3, the MVD is >30 μm, and the temperature is warmer than −10°C. These criteria will be considered when evaluating the current icing cases. In addition, Politovich[12] states that when MVD is <~30 μm, the increase in drag or decrease in climb capability has little relation to the MVD. This finding suggests a limitation in using MVD as an environmental characterization parameter.

Cooper et al.[10] points out that some icing encounters are severe, not because of the nature of the mean diameters, but because of the presence of drops at the largest sizes (defined D_{max} herein), where they can accrete on unprotected surfaces such as the lower surfaces of the wings. They state that the MVD does not represent the effects of the spectrum in enough detail and may not be a reliable measure of the environment. Therefore, a more suitable parameter, which considers 80% of the hydrometeor spectrum, will be proposed herein.

The ice accretions in freezing rain reported by Bershinsky et al.[9] were like a glazed bathroom window, i.e., smooth and conformal compared to the sharp drizzle ice. The smooth, conformal ice may reduce the chance for airflow disruption, possibly explaining the minor performance degradation rate experienced by the King Air when encountering freezing rain. This phenomenon was evaluated in the Wyoming wind tunnel by testing the aerodynamic effects of simulated ice shapes on a two-dimensional NACA 23012 airfoil by Ashenden et al.[14] The ice shapes were predicted using an ice prediction code and hydrometeor distributions measured by the King Air in cloud drops, freezing drizzle, and freezing rain. The wind-tunnel results showed that the highest airfoil performance and aerodynamic degradation occurred with the ice shape formed by freezing drizzle. The ice shape formed by freezing rain resulted in only minor performance degradation, supporting the observations by Bershinsky et al.[9]

Anecdotal evidence suggests that other aircraft types may experience the same performance degradation trends in freezing drizzle and freezing rain.[5] For example, Stith et al.[15] states that the University of North Dakota's Cessna Citation II research aircraft experienced substantial ice accumulation during a freezing drizzle encounter on Jan 31, 1988. Aircraft performance parameters were not recorded, but they stated that additional power was required to maintain altitude and airspeed over that required for a clean aircraft, a clear indication of airframe ice-induced drag. Stith et al.[15] discuss five separate encounters with freezing rain with no mention of performance degradation in any of these cases. It could be assumed, therefore, that no significant degradation was observed with the Citation II in freezing rain. Another report states that the most severe icing condition during Lockheed P2V icing flight tests was in freezing rain.[16] This most severe icing condition, however, was encountered for 2 h, suggesting a slow rate in performance degradation in freezing rain.

Based on past King Air,[9] Citation II,[15] and P2V[16] in-flight icing encounter experiences, research in the Wyoming wind tunnel,[14] and research by Cooper et al.,[10] Sand et al.,[11] and Politovich,[12,13] we hypothesize that freezing drizzle results in maximum rates of aircraft performance degradation, whereas cloud drops, freezing rain, and mixed phase environments result in minor rates of performance degradation. To test this hypothesis, the Wyoming King Air response was evaluated in various environmental conditions encountered during flight. The aircraft response was quantified by rates of change in aircraft climb capability, drag coefficient, and lift over drag ratio. This research builds on the work of Cooper et al.,[10] Sand et al.,[11] and Politovich.[12,13] The additional contributions herein include the utilization of performance parameter rates to quantify the aircraft response in various homogeneous environmental regions, utilization of more representative environmental parameters, and refinements to aircraft performance calculations.

Research Aircraft Description

King Air 200T

The twin-turboprop Beechcraft Super King Air 200 light transport obtained certification FAR Part 23 plus icing requirements of FAR Part 25 on Dec. 14, 1973. The basic King Air 200 has undergone several modifications to allow for research instrumentation and structural support. The modifications include wing-tip instrumentation pylons, a 2-m particle decelerator (removable), an air velocity sensing nose boom, a millimeter radar wing housing (removable), and a Saunders Failsafe spar strap. The spar strap consists of a stainless-steel strap that connects the inboard segment of the outer wing panels along the lower wing surface. The faired spar strap protrudes roughly 6.4 cm below the wing between the two engine nacelles and may collect ice in large drop regions.[10,11] These modifications were considered during the performance degradation analyses; however, the effects of these modifications do preclude comparison to manufacturer baseline performance data.

Performance Monitoring

The Wyoming King Air was instrumented to monitor and record aircraft performance parameters. These parameters include aircraft accelerations, orientation angles, velocities, rate of climb, and left engine torque. These parameters are used in the calculations to determine lift, drag, lift over drag ratio, and expected rate of climb by methods described by Lenschow[17] and Perkins and Hage.[18] The King Air instrumentation utilized for this research has been well documented by past researchers.[10–12] A Honeywell Laseref Inertial Navigation System (INS) provides aircraft accelerations and velocities in aircraft longitudinal and vertical (normal) axes. Prior to the installation of the Honeywell INS, a Litton INS (LTN-51) was used to obtain similar information.

Environment Measurement

The King Air carries a full suite of environmental instruments for the study of cloud microphysics and a summary of those instruments was documented by past researchers.[10–12] These instruments include four Particle Measuring Systems, Inc. (PMS) probes and two hot-wire liquid water probes. The Forward Scattering Spectrometer Probe (FSSP: 3–45-μm-diam range), the One-Dimensional Cloud (1D-C: 44–194 μm), the Two-Dimensional Cloud (2D-C: 200 to over 6000 μm), and the Two-Dimensional Precipitation (2D-P: 200 to over 8000 μm) probes were used to measure drop sizes and LWC. PMS probe descriptions, processing techniques, and counting and sizing uncertainties are discussed by Ashenden.[19]

The concentrations measured by the 2D-P probe were plotted for analysis but were not used in the LWC and MVD calculations for this research. The liquid hydrometeor sizes encountered were within the measuring range of the 2D-C probe (including ZR) and both probes provided a large overlap region. The 2D-P probe was utilized, however, to indicate those areas with ice hydrometeor concentrations. Since the focus of this research was aircraft response in liquid, ice, and mixed phase environments, the 2D-P probe facilitated characterization of the icing environment (i.e., mixed phase or liquid).

The cloud spectra measured by the PMS probes were integrated to provide the total LWC for each icing encounter. This method was necessary because of the broad range of drop sizes and concentrations. For redundancy, an in-house CSIRO hot-wire probe was used to measure cloud liquid water.[20] The CSIRO probe, however, tends to underestimate the LWC for drops >30 μm.

Environmental characterization was required to facilitate comparison between environmental conditions and aircraft response. This was achieved by measuring ambient temperature, hydrometeor concentrations and sizes in the various environments encountered by the research aircraft. The raw data obtained by the PMS probes were processed postflight to obtain the environmental hydrometeor distributions for concentration and liquid mass. In addition, the integrated LWC and hydrometeor volume diameters were determined from the calculated distributions.

Representative hydrometeor distributions encountered by the King Air are shown in Fig. 1. This figure shows the normalized hydrometeors for liquid mass ($g/m^3/\mu m$) vs the hydrometeor diameters on a log/log scale. Figures 1a and 1b are examples of drizzle environments encountered on March 7, 1994 along the Front Range of the Colorado Rockies and Jan. 18, 1983 over the Sierra Nevada, respectively. These distributions correspond to the greatest King Air performance degradation for each flight. Each data point [○, +, ∗] represents the midpoint of each bin size for the respective PMS probes. Also note the apparent undercounting, or rolloff, for the smallest bins of each of the probes. If the smallest bins are ignored for each of the probes, fair agreement is obtained between each of the probes forming the hydrometeor distribution. The LWC was obtained by assuming each particle counted in each bin was spherical, that each particle has the diameter of the respective bin midpoint, and that each particle has a density of 1000 kg/m^3. With these assumptions, a mass for each bin was calculated and then summed over all of the bins, with the exception of the overlap regions, resulting in total integrated LWC (TOTLWC).

The cumulative mass was summed across the distribution to 100% as depicted in Figs. 1a and 1b by the symbols not connected with a line. The hydrometeor diameter corresponding to the point at which 50% mass is achieved is defined as MVD. The hydrometeor diameter corresponding to the point at which 80% mass is achieved is defined as 80VD (volume diameter). It will be shown that 80VD is a more appropriate measure of the hazardous hydrometeor diameters when considering aircraft icing as compared to the standard MVD. The 80VD parameter includes the drizzle-sized drops that cause dramatic aircraft performance degradation discussed herein. Additional normalized distributions of mass for supercooled cloud, freezing drizzle, and freezing rain encountered by the King Air are provided by Ashenden and Marwitz.[21]

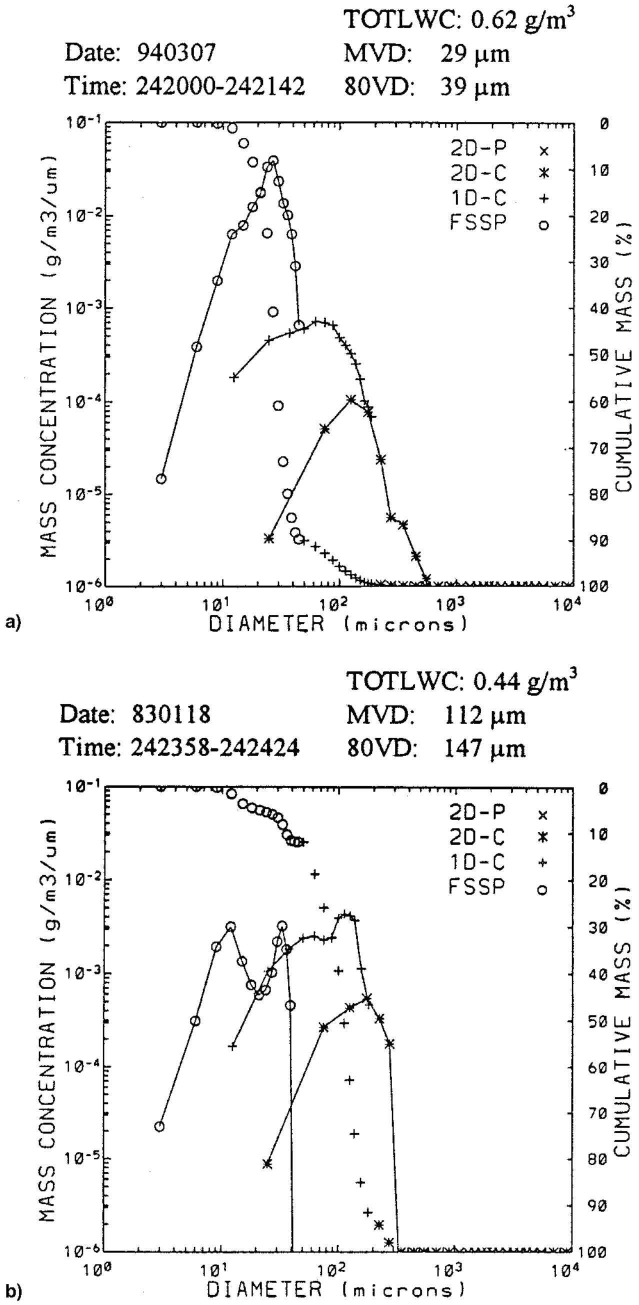

Fig. 1 Normalized hydrometeor distribution for mass measured by the FSSP, 1-DC, 2D-C, and 2D-P for a) Colorado ZL and b) California ZL. No 2D-P concentrations were detected for these two examples.

The spherical geometry and the density assumptions made earlier result in erroneous liquid water contents and volume diameters for mixed phase environments. Ice crystals cannot be assumed to be spherical and their density is usually far less than 1000 kg/m^3. Fortunately for this research, the periods of performance degradation generally corresponded to regions with no to very low ice concentrations (a microphysical characteristic of ZL). In addition, the concentration of ice particles is typically two to three orders of magnitude less than the concentration of liquid particles. This is particularly true for

Table 1 King Air 200T performance characteristics

Researchers	Configuration	C_{L_0}	C_{L_1}	C_{D_0}	C_{D_1}	$C_{D_{Av}}$
Rodi[23]	No INS	0.20	6.05	0.033	0.051	NR
Cooper et al.[10]	INS, no R-wing	0.22	6.16	0.024	0.033	0.036
Politovich[13]	INS, no R-wing	0.20	6.20	NR	NR	0.036
Ashenden 1996	IRS, no R-wing	0.30	6.20	0.033	0.025	0.040
Ashenden 1996	INS, no R-wing	0.30	6.20	0.034	0.026	0.041
Ashenden 1996	IRS, with R-wing	0.33	6.18	0.036	0.021	0.044

Note: NR = not reported, IRS = Honeywell, INS = Litton, R-wing = mm radar wing installed.

liquid and ice particles less than 200 μm in diameter. The sizing and LWC errors caused by ice contamination, therefore, were kept to a minimum in these regions.

Aircraft Performance Calculations

Theory

The aircraft horizontal and vertical equations of motion are used to derive expressions for coefficients of lift C_L and drag C_D. The principal aerodynamic forces were summed along their respective axis similar to the methods of Lenschow[17] to solve the horizontal and vertical equations of motion. Small angle approximations were made and the standard equations for lift and drag were substituted into the equations of motions obtaining the following expressions for aircraft lift and drag coefficients:

$$C_L = \frac{M(\dot{w} + g\cos\phi) - D\sin\alpha}{(1/2)\rho_0 S V_i^2 + \kappa T}$$

$$C_D = \frac{L\sin\alpha + T - M\dot{u} - wt\sin\theta}{(1/2)\rho_0 S V_i^2 + \kappa T}$$

These equations differ slightly from Lenschow's.[17] The previous equations include the effects of aircraft roll and are in aircraft coordinates, as opposed to Earth coordinates. As per Lenschow,[17] the effects of yaw angle (lateral deviations in the flight path) and aerodynamic damping were assumed to be negligible. In addition, since the Litton INS did not measure longitudinal acceleration, the earlier King Air data sets required differentiation of longitudinal airspeed to calculate the longitudinal acceleration. The longitudinal acceleration is dependent, therefore, on the type of INS installed.

Airfoil lift is dependent upon the angle of attack and airfoil drag is dependent upon lift caused by the induced drag, therefore, it is convenient to express C_L in terms of a lift-curve slope ($C_L = C_{L_0} + C_{L_1}\alpha$) and C_D as a drag polar ($C_D = C_{D_0} + C_{D_1}C_L^2$) when comparing baseline data. C_{D_0} is the parasite drag, incorporating the pressure and frictional drag and C_{D_1} encompasses the lift-induced drag.

The variable propeller efficiency η_p was calculated with an algorithm based on basic airfoil theory[22] and utilizing engine torque, rpm, aircraft true airspeed, ambient temperature, density, and propeller geometry (blade twist and chord distributions). The η_p algorithm incorporates a Prandtl–Glauert two-dimensional compressibility model and an iterative technique to match the measured and calculated torque by varying the geometric pitch angle. Once matched, η_p for various aircraft true airspeeds (with an implicit dependence on torque) was calculated. This approach assumes that the propeller was not affected by ice contamination.

A measure of performance degradation better suited for pilot use is rate of climb capability. When an aircraft enters an environment leading to airframe ice accretion, the aircraft may experience a negative climb capability where the aircraft is unable to maintain level flight and must descend. As described by Perkins and Hage,[18] expressions for rate of climb (ROC) and ROC degradation, ΔROC (modified by authors here), are given by

$$ROC = V\sin(\alpha - \theta) = (T - D)V/wt$$

$$\Delta ROC = (C_{D\text{clean}} - C_{D\text{actual}})(\rho V^3 S/2wt)$$

Baseline Aircraft Performance

Two clear air King Air flights were evaluated to obtain a baseline for the performance comparisons. The lift-curve slope and drag polar for the flights on July 11, 1991 and Nov. 13, 1992 were determined for the King Air. The millimeter radar wing was not installed for the July 11, 1991 flight. During this flight no icing occurred, special performance maneuvers were flown, and both the Litton and Honeywell INSs were installed. The Nov. 13, 1992 flight was also evaluated since no icing occurred, special maneuvers were flown, and the millimeter radar wing was installed.

Lift-curve slope and drag polar coefficients from other researchers and the two flights described earlier are included in Table 1. The lift and drag coefficients derived by Rodi[23] were obtained prior to installation of an INS. Cooper et al.[10] and Politovich[13] did not include a variable propeller efficiency algorithm and aircraft roll angle components. The millimeter radar wing appears to slightly increase aircraft C_{D_0} and C_{L_0}.

Performance Response to Environmental Conditions

Aircraft Encounter Case Studies

The Wyoming King Air data evaluated for this research consisted of 13 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) described by Reynolds and Dennis[24] and the Winter Icing Storms Project (WISP) described by Rasmussen et al.[25] The environments evaluated included freezing drizzle, freezing rain, warm rain, supercooled cloud drops, supercooled cloud drops with high LWC, mixed phase, and ice only. King Air responses to cloud drops, freezing drizzle, mixed phase with freezing drizzle, and ice only environments are detailed herein, the remaining encounters received the same treatment and are included in the overall aircraft response comparison.

Relationships between King Air performance and environmental parameters are illustrated in Figs. 2 and 3 with analog line traces. The aircraft response parameters (i.e., C_D, ΔROC) and environmental parameters (i.e., MVD, LWC) were calculated every second and then averaged every 10 s for the entire flight to generate the analog traces. Those portions of the flight where the aircraft roll angle was >5 deg, the ROC was >2 m/s, or there was a step change in engine torque, were deleted from C_D and ΔROC traces for figure clarity (i.e., removed roll-induced drag effects). An uncertainty analysis using the methods of Kline and McClintock[26] indicated that the performance parameters C_D, L/D, ROC, and ΔROC were within 14%, 15%, 1.2 m/s and 1.7 m/s, respectively.

Freezing Drizzle (March 7, 1994)

Freezing drizzle was encountered during the second WISP 94 research flight on March 7, 1994. Figure 2a shows that the

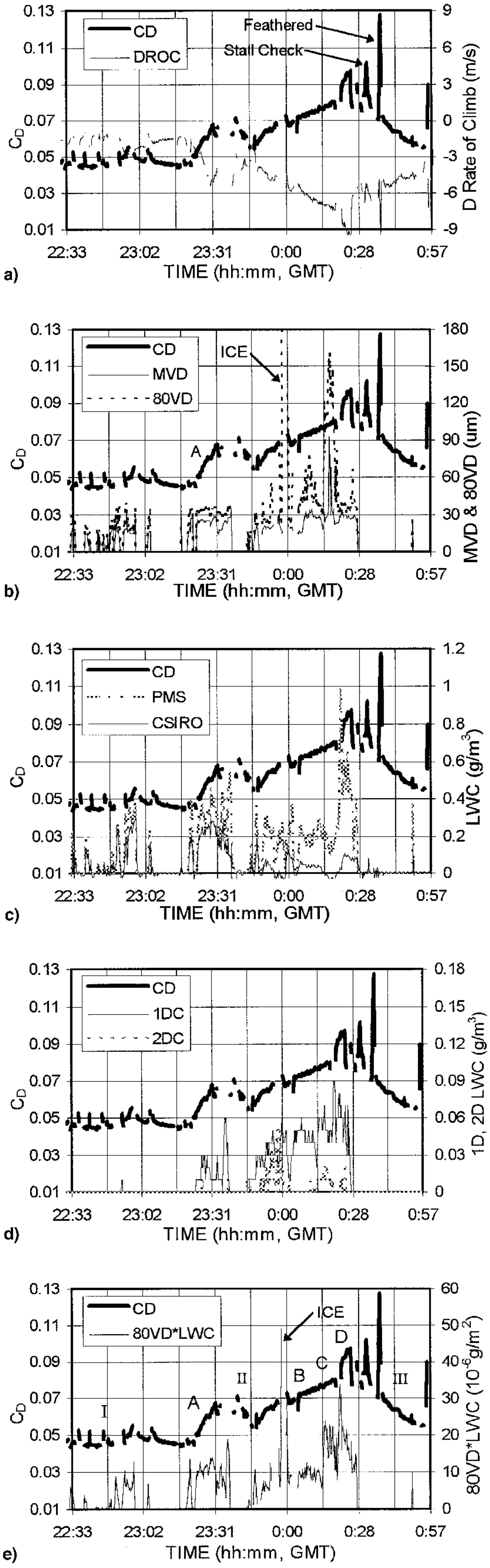

Fig. 2 Performance parameter 10-s average analog traces for ZL encounter on March 7, 1994 near Greeley, Colorado with the heavy-solid line representing aircraft C_D with a) ΔROC, b) MVD and 80VD, c) total integrated LWC from PMS and CSIRO probes, d) 1D-C, 2D-C LWC, and e) 80VD*LWC. Letters A, B, C, and D represent degradation regions and numerals (I, II, and III) represent performance recovery or no degradation regions.

aircraft C_D remained near 0.050 for the initial portion of this flight, indicating a marginal increase in drag based on a clean aircraft C_D of 0.040–0.044. Just past 23:17 Greenwich Mean Time (GMT) the aircraft performance started to degrade with a further increase in C_D and a decrease in climb capability (increasing ΔROC magnitude). The changes in C_D and ΔROC in Figs. 2 and 3 were determined to be because of airframe ice since the aircraft was in near-level, nonaccelerated flight.

Analog traces of MVD and LWC from the PMS probes are plotted with C_D in Figs. 2b–2d. The environmental conditions prior to 23:17 GMT consisted of only cloud drops indicated by the low MVD and the absence of LWC in the 1D-C and 2D-C PMS probes (Figs. 2b and 2d). From 23:17 to 23:30 GMT the aircraft experienced a significant degradation in performance even though the MVD was <30 μm (region A in Fig. 2b), illustrating the limitation of the MVD parameter. The increase in C_D corresponded to the presence of drizzle drops between 50–200 μm indicated by the 1D-C LWC. The 2D-C indicated very little LWC from drops bigger than 200 μm, except for the time around 23:55 GMT when there was a brief increase in 2D-C LWC to 0.04 g/m^3. The relation between total PMS and CSIRO probe LWC and the aircraft drag coefficient is indicated in Fig. 2c. The discrepancies between the integrated LWC from the PMS probes and the CSIRO hot-wire probe are evident after 23:17 GMT and are another indication of drizzle drops.

Illustrated in Fig. 2b, MVD does not adequately characterize the drizzle drop environments and, therefore, is not necessarily related to aircraft performance degradation. A trace of 80% volume diameter (80VD) is plotted in Fig. 2b for comparison. When 80VD $\cong$ MVD, indicating cloud drops, no drag increase is noted; however, when 80VD exceeds MVD, C_D does increase, illustrating the advantage of using 80VD in characterizing the environment. As discussed earlier, $D_{\max}$ is directly related to the droplet impingement limit and is assumed to control the performance degradation. However, the PMS probes cannot statistically resolve $D_{\max}$ because of the low counts measured in the tail of the hydrometeor distributions. For this reason, the 80th percentile mass-weighted diameter was utilized to reduce the statistical uncertainty in the particle counts.

A new environmental parameter is proposed considering the MVD limitations and the favorable environmental characterization using 80VD. The product of 80VD and TOTLWC (80VD*LWC with 10^{-6} g/m^2 units) was used to characterize the environment (units ignored hereafter for simplification). Incorporating LWC tended to normalize the various hydrometeor environments. For example, the initial flight region (I in Fig. 2e) consisted of small cloud drops (MVD $\lesssim$ 30 μm) and the LWC exceeded 0.3 g/m^3; however, the 80VD*LWC parameter remained low. 80VD*LWC was <8 prior to 23:17 GMT when there was negligible aircraft degradation. After 23:17 GMT, C_D increased with time in region A when 80VD*LWC exceeded 10. The LWC traces in Fig. 2d indicate that the increase in 80VD*LWC was from drizzle drops (measured by 1D-C). In addition, the flight crew noted that ice was accreting farther aft on the wing leading edges, indicating drizzle drops. In region II the icing conditions were exited, 80VD*LWC decreased to zero and C_D decreased. C_D began to increase in region B where drizzle drops were present (1D-C > 0.04 g/m^3). The increase in C_D corresponds to an increase in 80VD*LWC after 23:45 GMT. The 80VD*LWC was relatively homogeneous after this time except for a spike around 23:55 GMT during a missed approach. The spike resulted from some ZR and ice particles. After the missed approach, C_D continued to increase at a linear rate through regions B and C. A step increase in the volume diameters in region C caused 80VD*LWC to increase from 10 to 20, yet the C_D continued to increase linearly until 00:20 GMT. Upon entering region D the LWC increased to over 0.8 g/m^3, the 80VD increased to 39 μm, and the 80VD*LWC increased to approximately 30.

These conditions led to maximum aircraft degradation for this flight with C_D increasing to 0.102, ΔROC decreasing to -8 m/s, and lift over drag ratio (L/D) decreasing to 5.2 (not shown) near 00:22 GMT. At this time, the pilot increased engine RPM from 1700 to 1900, set maximum engine torque, and reversed heading. This degradation was substantial considering that the reserve ROC is only 8–10 m/s.[11] The cloud top was exited at approximately 00:28 GMT and the aircraft performance recovered in the cool clear air ($T < 0$°C, no visible moisture). At 00:32 GMT, the pilot performed a near stall check that resulted in aircraft buffet at approximately 125 kn compared to a clean aircraft buffet of approximately 100 kn (note C_D spike). The second spike in C_D (00:37 GMT) after exiting the cloud top was because of feathering the right propeller to facilitate photographing the ice-capped spinner. In the cool clear air, C_D decreased at roughly the same rate as it increased when in the supercooled hydrometeors. That is, comparing the slope of C_D at 00:14 (in icing) and at 00:43 GMT (in cool clear air), the slopes were similar in magnitude, but opposite in sign.

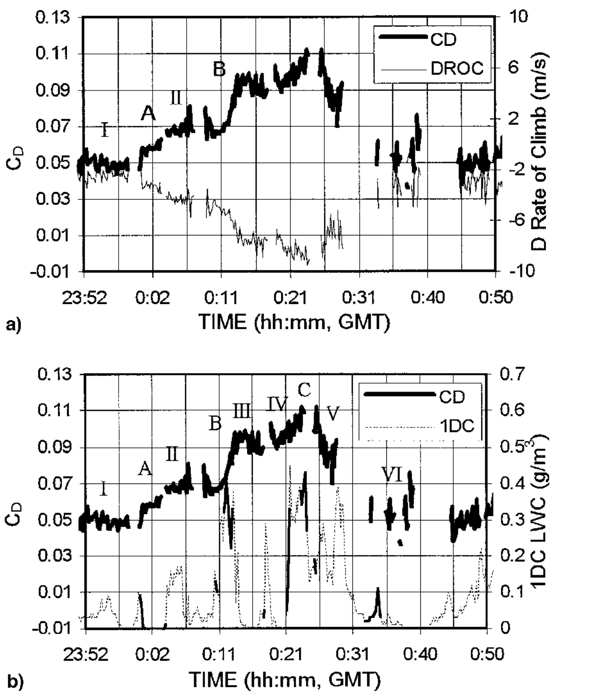

Fig. 3 Performance parameter 10-s average analog traces for ZL and ice hydrometeor encounter on Jan. 18, 1983 over the Sierra Nevada with the heavy solid line representing aircraft C_D with a) ΔROC and b) 1D-C probe LWC (heavier line indicates regions with no to low two-dimensional ice images). Refer to Fig. 2 for letter and numeral notation.

Mixed Phase with Freezing Drizzle (Jan. 18, 1983)

Freezing drizzle with and without ice crystals was encountered during the second SCPP research flight on Jan. 18, 1983. The beginning of the flight was uneventful with encounters with ice and mixed phase environments. Figure 3a shows that C_D remained near 0.050 in region I prior to 00:00 GMT. Figure 3b shows the initial portion of this flight consisted of low drizzle drop liquid water contents (1D-C < 0.1 g/m^3) and Fig. 4I shows that 2D-C ice images (aggregates) dominated the mixed phase environment. After 00:00 GMT the aircraft performance started to degrade with C_D increasing and ΔROC decreasing. Figure 4A shows 2D-C zero area images indicating that particles were just large enough to trigger the probe but were not large enough to register an image in region A. The hot-wire liquid water probes and the FSSP (not shown) indicated these particles were liquid, therefore, this environment consisted of cloud to drizzle-sized drops. The performance degradation leveled off near 00:05 GMT (region II) coinciding with a mixed phase environment of needles and zero area images shown in Fig. 4II. The C_D and ΔROC increased dramatically near 00:11 GMT (region B) when the 1D-C LWC increased to over 0.3 g/m^3 (Fig. 3b), the 2D-C recorded small circular images (Fig. 4B) indicating drizzle, and 80VD*LWC was near 50 (not shown). Note that the regions of performance degradation correspond to regions with no- to low-ice concentrations identified in Fig. 3b by the bold portions of the 1D-C trace.

In region III the C_D again leveled off, this time near 0.1. In this region the 1D-C LWC dropped to zero, the 80VD*LWC dropped to below 10, and the 2D-C probe revealed a transition to a mixed phase environment of small drizzle drops (zero area images) and needles (Fig. 4III). Only drizzle drops were encountered near 00:21 GMT, resulting in additional performance degradation. In region IV the King Air encountered a mixed phase environment, briefly arresting the degradation (images similar to Fig. 4III). The 1D-C showed erroneously high values because of the ice contamination at this time. At

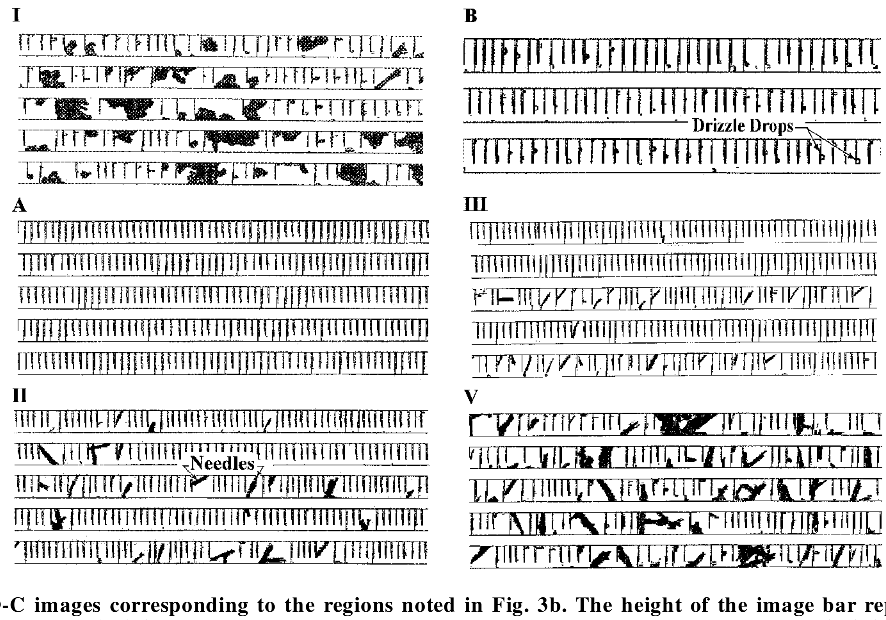

Fig. 4 Samples of 2D-C images corresponding to the regions noted in Fig. 3b. The height of the image bar represents a width of 800 μm. (I) mixed phase (aggregates), (A) mostly zero areas (small particles triggering two-dimensional probe), (II) needles and zero areas, (B) enlarged ZL image bars, (III) transition from zero areas to needles, and (V) mixed phase (needles and aggregates of needles).

Table 2 King Air performance response in various environmental conditions

Date (region)	Time GMT	Temperature, °C	TLWC, g/m^3	1D-C, g/m^3	MVD, μm	80VD, μm	80VDLWC, g/m^2	ΔROC, m/s	L/D	C_D	C_L	ΔROC rate[a]	L/D rate[b]	C_D rate[c]
Feb. 26, 1982	20:30	−6.6	0.40	0.02	25	478	197	−0.6	12.1	0.042	0.51	−0.4	−1.0	0.004
Feb. 26, 1982	20:36	−10.3	0.47	0.19	30	67	32	−7.7	6.4	0.105	0.66	−1.9	−1.5	0.024
Jan. 18, 1983 (A)	00:01	−5.3	0.12	0.08	61	100	12	−3.5	9.2	0.058	0.54	−0.4	−0.4	0.006
Jan. 18, 1983 (B)	00:14	−6.0	0.33	0.33	63	81	33	−7.1	6.5	0.096	0.62	−1.1	−0.6	0.016
Jan. 18, 1983 (IV)	00:22	−6.2	0.66	0.31	269	615	209	−8.0	5.7	0.108	0.61	−0.1	0.1	0.002
Jan. 18, 1983 (C)	00:24	−6.8	0.45	0.4	112	150	68	−9.0	5.0	0.127	0.63	−0.9	−0.4	0.014
Feb. 13, 1990	17:45	−15.6	0.18	0	28	33	6	−3.0	8.6	0.059	0.50	−0.2	−0.2	0.002
Feb. 27, 1990	23:42	−10.2	0.60	0.01	20	23	14	−5.2	7.2	0.078	0.56	−0.5	−0.6	0.006
Feb. 27, 1990	14:35	−6.4	0.21	0	24	29	6	−4.3	7.6	0.070	0.53	−0.2	−0.1	0.003
March 15, 1991	14:16	−9.0	0.20	0	21	27	5	−2.3	10.0	0.058	0.58	0.1	−0.6	−0.001
July 11, 1991[d]	15:51	12.3	0.00	0	0	0	0	−0.4	12.9	0.041	0.53	0.0	0.2	0.000
Feb. 12, 1992	07:06	−2.1	0.16	0	489	1563	245	−0.7	8.4	0.050	0.72	−0.2	0.3	0.003
Feb. 8, 1994	22:41	−18.0	0.14	0	22	26	4	−1.0	11.4	0.045	0.51	−0.1	−0.3	0.000
Feb. 21, 1994	20:57	−9.7	1.20	0	25	29	35	−4.1	7.6	0.070	0.53	−0.2	−0.2	0.003
March 7, 1994	17:31	−6.6	0.39	0.01	26	30	12	−3.2	8.9	0.064	0.58	−0.2	0.0	0.004
March 7, 1994 (A)	23:31	−6.1	0.31	0.01	21	33	10	−5.1	7.6	0.068	0.51	−0.1	0.1	0.004
March 7, 1994 (B)	00:13	−6.4	0.26	0.04	28	37	9	−3.5	6.6	0.076	0.50	−0.1	−0.1	0.002
March 7, 1994 (C)	00:18	−6.7	0.15	0.05	32	136	20	−4.6	5.7	0.090	0.51	−0.1	0.0	0.002
March 7, 1994 (D)	00:22	−8.6	0.57	0.06	30	38	21	−8.8	5.2	0.102	0.53	−1.4	−0.9	0.016
March 8, 1994	22:40	−3.6	0.44	0.02	225	574	252	−2.0	8.6	0.050	0.43	−0.4	−0.3	0.005
July 27, 1995[e]	17.05	15.7	0.40	0	1104	1262	511	−1.9	10.8	0.046	0.49	0.0	0.1	0.001
Recovery							Ice							
Feb. 27, 1990	15:09	2.0	0.00	——	0	0	None	−1.1	11.5	0.056	0.41	4.6	5.5	−0.061
Jan. 18, 1983 (III)	00:17	−5.6	0.02	0.01	22	74	Needles	−7.3	5.9	0.098	0.58	0.1	−0.1	−0.002
Jan. 18, 1983 (V)	00:27	−6.2	0.58	——	412	670	Aggregates	−6.8	6.2	0.100	0.62	1.1	0.6	−0.014
March 7, 1994 (III)	00:45	−7.2	0.00	——	0	0	None	−4.6	8.0	0.064	0.51	0.1	0.2	−0.002

[a]ms^{-1} min^{-1} ("−" degradation). [b]min^{-1} ("−" degradation). [c]min^{-1} ("−" recovery). [d]Clean aircraft baseline. [e]Warm rain.

approximately 00:24 GMT (region C), the 1D-C LWC increased to a peak of 0.44 g/m^3, the 80VD increased to 147 μm, and the 80VD*LWC was 65. The corresponding drizzle distribution was shown earlier in Fig. 1b and the two-dimensional images are similar to those shown in Fig. 4B. In this extremely hazardous environmental condition, the drag reached a maximum of 0.11 with a ΔROC of −9 m/s and a L/D of 5. Flight notes and video records substantiate the seriousness of this icing encounter by documenting the pilot's decision to begin turning and exiting the conditions within 5 min of entering the drizzle. The aircraft was at maximum power, with airspeed decreasing, and the wings indicating a near stall with an aircraft buffet at 140 kn. After the turn, the pilot mentioned that the performance recovery was quick in the visible presence of large ice crystals (region V), which, as suggested by Bain and Gayet,[27] may have eroded the accumulated airframe ice. Figure 4V shows this ice-only environment with a sample of the 2D-C images. The 1D-C LWC shown in Fig. 3b and the corresponding 80VD and 80VD*LWC are generally not valid after 00:25 GMT because of ice contamination. One exception to this appears in region VI when descent below the 0°C level resulted in raindrops and aircraft performance recovered completely, i.e., C_D returned to ~0.05.

Aircraft Response Comparison

Wyoming King Air data for 14 flights were evaluated in the same manner as discussed earlier for the March 7, 1994 and Jan. 18, 1983 cases. During any particular flight (or case study), the environmental conditions (i.e., temperature, LWC, drop diameters, phase) varied, resulting in various aircraft responses. A flight segment when the environmental conditions were homogeneous and the aircraft was in nonaccelerated flight was considered a separate environmental encounter. Individual aircraft responses to the various homogeneous environmental conditions were identified per specific criteria (e.g., regions A, B, I, and II in Figs. 2 and 3) and averaged over 30 s providing objective aircraft responses to the various environmental conditions. The aircraft state criteria specified that ROC was <2 m/s, roll angle was <5 deg, changes in true airspeed were <2 m/s over 10 s, and engine torque changes were <60 ft-lb over 10 s. The homogeneous environment criteria specified that changes in total LWC were <0.2 g/m^3 over 10 s and ambient temperature was <0°C. A subset of these encounters for aircraft performance degradation and recovery are tabulated in Table 2.

The King Air performance parameters (ΔROC and L/D) were plotted against several standard environmental parameters to explore for relationships between King Air response and environmental conditions in Fig. 5. The highest performance degradations correspond to the highest negative ΔROC and lowest L/D ratios. Figure 5a shows that the highest performance degradations occurred in ambient temperatures ranging between −5 and −14°C. The data points between 0 and −5°C correspond to freezing rain encounters that display lower performance degradations. The data points colder than −15°C correspond to cloud drops resulting in rime ice accretions and lower performance degradations. Figure 5b indicates little relation between aircraft response and TOTLWC from the PMS probes. It is noteworthy that the case with the highest LWC (1.2 g/m^3 encountered on Feb. 21, 1994 at −9.7°C and MVD < 30 μm) did not result in high performance degradation as suggested by current icing severity indices.[12] The relationship between performance degradation and LWC as measured by the 1D-C is shown in Fig. 5c for liquid-only environments. The 1D-C measures hydrometeor diameters ranging from 50 to 200 μm. Therefore, if the hydrometeors are liquid, the 1D-C is a good detector of drizzle drops. This figure shows that the highest degradation occurred when the 1D-C LWC was >0.05 g/m^3. The encounters with the highest performance degradation are noted with dates.

The rates of change in C_D, ΔROC, and L/D were used in this research as opposed to the potential accumulation technique[10–13] 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 all homogeneous regions. These rates are tabulated in Table 2 where a positive C_D rate, a negative ΔROC rate, and a negative L/D rate are indications of aircraft performance degradation. The rates of change in C_D were plotted against the environmental parameters MVD, 80VD, and 80VD*LWC for all encounters in Figs. 5d, 5e, and

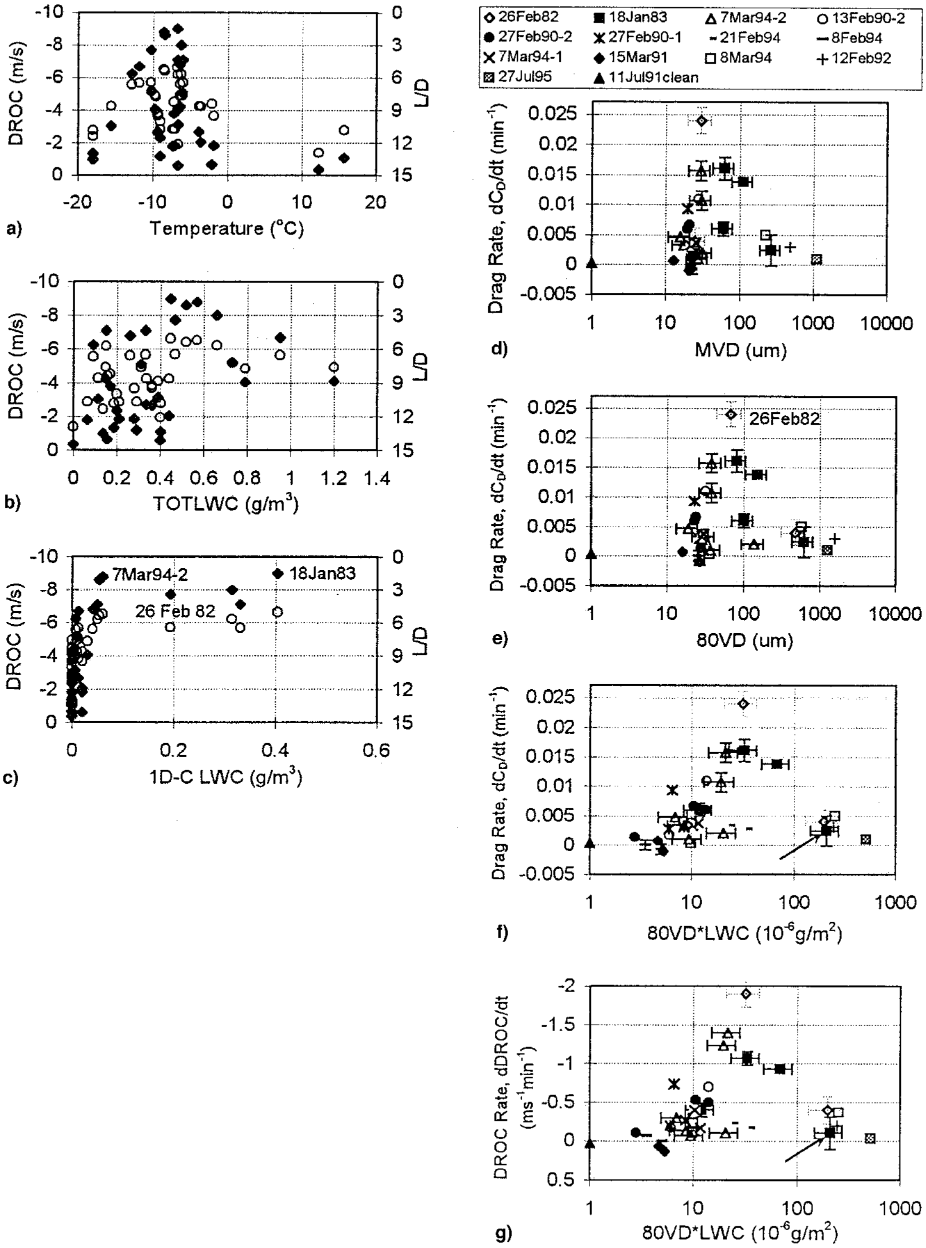

Fig. 5 Relationships between King Air performance and environmental parameters. a–c ΔROC (◆) and L/D (○) vs a) temperature, b) TOTLWC, and c) 1D-C LWC. d–f King Air drag rate for all flights evaluated (flight date key) vs d) MVD, e) 80VD, f) 80VD*LWC, and g) ΔROC rate vs 80VD*LWC. Arrows point to Jan. 18, 1983 encounter in a mixed phase environment.

5f, respectively. Figure 5d indicates aircraft performance degradation when MVD is between 20–200 μm. The MVD is limited in that it does not weigh the larger drops in the distribution and, therefore, causes the majority of the data points to stack around ~20 μm MVD. Figure 5e shows an improvement when using 80VD as the environmental parameter since the aircraft responses are not stacked around one value but, rather, are separated (note shift to right in Feb. 26, 1982 case). The 80VD emphasizes the larger drops in the distribution that seem to dictate the severity of the degradation (closer to D_{max}). To further separate the various aircraft responses, 80VD was multiplied by total LWC resulting in the 80VD*LWC parameter plotted in Fig. 5f. The ΔROC rates were also plotted against 80VD*LWC in Fig. 5g. The highest C_D and ΔROC rates, or performance degradation, correspond to an 80VD*LWC between approximately 10–100.

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, $\Delta ROC = -8$ m/s). In this region, recall that 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). The C_D rate, however, was low, illustrating the independence on the accumulated ice using the rate technique. The freezing rain cases on March 8, 1994, Feb. 12, 1992, and Feb. 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 performance degradation rates can be related to a single environmental parameter, 80VD*LWC.

The corresponding rates for ZL and ZR were used to approximate how long before the King Air would run out of reserve climb power. The climb reserve reached zero when the ΔROC reached approximately -10 m/s with a corresponding C_D of $\sim$0.12. Using a reasonable ZL C_D rate of 0.015 min^{-1}, the time for the clean aircraft ($C_D \sim 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 opted to exit the drizzle conditions on Jan. 18, 1983 after only 5 min in freezing drizzle.

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 2. The recovery rates in cool clear air (March 7, 1994) and mixed phase with low LWC (Jan. 18, 1983 at 00:17 GMT) were approximately equal; however, the recovery rate for the ice-only environment (Jan. 18, 1983 at 00:27 GMT) was substantially faster. This result 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 by large ice crystals may explain this observed phenomenon.[27] As expected, the recovery rates in the warm clear air were the highest because of rapid melting of the accumulated airframe ice.

Summary and Conclusions

This study evaluated aircraft performance response to various environmental conditions encountered during flight. These conditions included clear air, ice only, mixed phase, and supercooled drops. Supercooled drops consisting of cloud, drizzle, and rain sizes were the main focus of this study. Aircraft response was quantified by rates of change in aircraft *ROC* capability, C_D, and L/D. The aircraft performance parameters were compared to an environmental hydrometeor parameter quantifying the environmental conditions (80VD*LWC). Results show that encounters with SCDD 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. These results support the hypothesis stated earlier that freezing drizzle results in maximum rates of performance degradation, whereas cloud drops, freezing rain, and mixed phase environments result in minor rates of performance degradation.

The results demonstrate that the King Air performance degradation rates were the 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. Two case studies (March 7, 1994 and Jan. 18, 1983) indicated rapid aircraft response to changing environmental conditions. That is, high rates of degradation were experienced within minutes of encountering regions of SCDD followed by high rates of recovery upon encountering regions containing large ice crystals (low LWC). These results suggest that the sharp ice feathers produced by SCDD are the primary ice structures that are detrimental to the standard airflow characteristics and, as suggested by Bain and Gayet,[27] 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. These results suggest that the performance degradation and recovery are primarily dependent on the most recent environmental conditions (last 5 min) and the density of the ice crystals.

The results show the limitations of MVD and the advantage of using 80VD to characterize the environment. Because of the statistical limitations of the PMS probes, the largest sizes of the drop distributions, or D_{max}, were 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[12] would suggest. The case studied herein with the highest LWC (1.2 g/m^3, 25-μm MVD, -9.7°C) did not correspond to high performance degradation. Therefore, the type and rate of aircraft performance response is more clearly dependent on 80VD than on LWC or MVD.

The advantages of the new environmental parameter 80VD*LWC over the standard MVD were demonstrated herein with favorable comparisons between 80VD*LWC and King Air responses. In addition, the following approximate classifications of liquid hydrometeors were determined: cloud drops generally correspond to an 80VD*LWC < 10, MVD < 25 μm, and 80VD < 30 μm; freezing drizzle generally corresponds to an 80VD*LWC between 10–100, MVD between 25–150 μm, and 80VD between 30–200 μm; freezing rain generally corresponds to an 80VD*LWC > 100, MVD > 150 μm, and 80VD > 200 μm.

The minor King Air performance degradation rates in freezing rain were not expected based on current practices of the aviation community.[3,8] For the Wyoming King Air, encounters with freezing rain resulted in minor rates of performance degradation, or light to moderate icing,[8] and encounters with freezing drizzle resulted in maximum rates of performance degradation, or severe icing (flight diversion was necessary[8]). In other words, no climb reserve remained after approximately 5 min in ZL, whereas it would take approximately 25 min in ZR before degrading to the same condition. Flight in ZR should still be considered severe, especially after an extended period of time (on the order of 120 min for the Lockheed P2V[16]), but, as the presented data suggests, flight in ZL should be of greater concern. Though the results presented herein are for a King Air 200T turboprop aircraft, there is limited anecdotal evidence that the same performance trends may be experienced by other aircraft types.[5,15,16] Clearly, much more performance data are needed in freezing rain.

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