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Models and Characteristics of Freezing Rain and Freezing Drizzle for Aircraft Icing Applications

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16. Abstract

A large, new database of in-flight measurements of icing-related cloud and atmospheric variables in freezing rain and freezing drizzle conditions is used to help determine the range of temperatures, altitudes, exposure durations, icing intensities, precipitation drop sizes, and supercooled water concentrations to which aircraft could be exposed during flight in these conditions. In addition, three different models of cloud and precipitation drop size distributions are proposed for use in computing ice accretion rates and amounts on aircraft components or as a guide for designing water sprays to simulate freezing rain or freezing drizzle in icing wind tunnels or icing spray rigs.

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LIST OF ACRONYMS

AGL	Above ground level
AIRS	Alliance Icing Research Study
ASL	Above sea level
CFDE	Canadian Freezing Drizzle Experiment
CFR	Code of Federal Regulations
CWC	Cloud water concentration (g/m^3) in droplets from 1 to 50 µm diameter
DWC	Drizzle water concentration (g/m^3) in drops from 50 to 500 µm diameter
EURICE	European Research on Aircraft Ice Certification
FAA	Federal Aviation Administration
FSSP	Forward scattering spectrometer probe
FZDZ	Freezing drizzle
FZRA	Freezing rain
HE	Horizontal extent
IPHWG	Ice Protection Harmonization Working Group
LEWICE	NASA software for computing ice accretions on aircraft
LWC	Liquid water content (or concentration)
MSC	Meteorological Service of Canada
MVD	Median volume diameter
NASA	National Aeronautics and Space Administration
NASA GRC	NASA Glenn Research Center
NCAR	National Center for Atmospheric Research
nmi	nautical mile(s)
NRC	National Research Council
OAT	Outside air temperature
PMS	Particle Measuring Systems, Inc.
RWC	Rain water concentration (g/m^3) in drops larger than 500 µm diameter
SCPP	Sierra Cooperative Pilot Project
SLD	Supercooled large drops
SLDLWC	LWC in drops larger than 50 µm diameter (SLDLWC = DWC + RWC)
TAS	True airspeed
TLWC	Total LWC (TLWC = CWC + SLDLWC)
UND	University of North Dakota
WISP	Winter Icing and Storms Project

EXECUTIVE SUMMARY

This report describes the master database of supercooled large drop (SLD) measurements assembled at the Federal Aviation Administration (FAA) William J. Hughes Technical Center during the time period 1998-2004, various analyses of the data, and three practical SLD drop size distributions that are suitable for icing-related engineering applications. The database consists of 4800 nautical miles of in-flight measurements of icing-related variables in freezing drizzle (FZDZ) and freezing rain (FZRA). The data were collected from a variety of projects over North America, Europe, and the southern tip of South America. This large database was developed for use by the FAA in characterizing SLD conditions aloft, to complement Title 14 Code of Federal Regulations Part 25, Appendix C, for certification of airplanes for flight in icing conditions. The report explains and compares suggested models (characterizations) of FZRA and FZDZ. The appendices describe the original data, show supplementary analyses, and demonstrate some practical applications of the database.

1. BACKGROUND.

1.1 HISTORICAL PERSPECTIVE.

During the 1980s and 1990s, a number of tailplane icing incidents and accidents were reported on various turboprop airplanes [1]. This problem came to be known as ice-contaminated tailplane stall. These icing effects seemed to result from inadvertent encounters with freezing drizzle (FZDZ) or other so-called large drop icing conditions during flight. This raised questions about the occurrence, characteristics, and effects of supercooled large drops (SLD) and prompted research into these icing conditions. Meteorologically, SLD is simply either FZDZ or freezing rain (FZRA).

Evidence showed that elevated FZDZ existed, but seemed hard to find. It was known that on occasion, there were quite noticeable, possibly serious, effects on the performance of some aircraft if they encountered it and lingered in it. But these conditions had been found only after searching in upslope clouds along the Sierra Nevada Mountains in California, occasionally in the Denver, Colorado area, and perhaps more frequently, in the Canadian Atlantic provinces. The documented cases also appeared to be confined to relatively shallow layers and limited horizontal extents (HE). So the known cases were rare, remote, and locally confined. Therefore, it seemed unlikely that any aircraft simply transiting through an area of elevated FZDZ would be affected much by it.

On October 31, 1994, a twin turboprop commuter airplane crashed near Roselawn, Indiana, (USA) after holding for a period of time in icing conditions at about 10,000 feet. The accident report [2] determined that the fatal accident resulted from an uncommanded roll upset after the autopilot was automatically disengaged at the end of the holding period. The roll upset was blamed on probable ridge-like ice accretions running span-wise aft of the pneumatic deicing boots on the wings. These ice ridges have since been demonstrated to cause strong reversal forces on unpowered ailerons, such as those present on the accident airplane. Although, as is often the case, it is difficult or impossible to prove that any particular icing conditions were responsible, the chance that SLD was involved seemed too strong to ignore if the possibility of more mishaps were to be prevented in the future.

In response to the concern that ice protection certification may be inadequate for SLD conditions, the Federal Aviation Administration (FAA) called an International Conference on Aircraft In-flight Icing in May 1996 in Springfield, Virginia. Conference working groups provided the FAA with numerous recommendations for mitigating aircraft accidents due to in-flight icing [3]. These recommendations formed the basis for the FAA Inflight Aircraft Icing Plan [4], which contained 13 tasks for responding to the recommendations. Tasks 9 and 13 called for extensive research on SLD icing conditions.

An essential part of the research was to build a database of in-flight measurements of icing-related variables in FZDZ and FZRA conditions. These variables included drop size distributions, water concentrations, icing intensities (severities), temperatures, altitudes, and horizontal and vertical extents in FZDZ and FZRA and the clouds associated with them. The goal was to determine the range, mean, and limiting values of these variables for practical applications. These applications included establishing design and test criteria for flight in these conditions, estimating ice accretions on aircraft surfaces during flight through these conditions, and providing realistic droplet sprays for icing wind tunnels and guidance for icing weather forecasters. Some data from research flights into FZDZ or FZRA were already available from the Universities of Wyoming and North Dakota and from the Canadian Meteorological Service, but new research flights would still be needed. These eventually came from instrumented research planes operated by the National Aeronautics and Space Administration (NASA), the Canadian Meteorological Service, government laboratories in Europe, and an airplane manufacturer.

The task of collecting and compiling all these data into a single, computerized database for the FAA was assigned to the Flight Safety Team at the FAA William J. Hughes Technical Center. The Team had the required expertise and extensive experience in assembling and analyzing in-flight cloud measurements [5-7]. The principal investigator authored this report, which describes the FAA database and a variety of analyses that were performed. These analyses were performed in support of the Ice Protection Harmonization Working Group (IPHWG), which was formed as part of the FAA icing plan [4], to recommend new regulations, certification criteria, and guidance material for the safe operation of airplanes in SLD icing conditions.

1.2 OVERVIEW OF FREEZING RAIN AND FREEZING DRIZZLE METEOROLOGY.

For a good introduction to FZRA and FZDZ, the reader is referred to reference 8 from which this overview material is taken. A distinction is made between FZRA and FZDZ because of the differences in the formation mechanisms and the resulting differences in drop sizes and rain rates.

1.2.1 Freezing Rain.

Freezing rain results when snowflakes fall into a warm (T >0°C) layer aloft, melt into raindrops, and then fall through a subfreezing layer of air again before reaching the ground, as shown in figure 1. The only difference between freezing rain and ordinary stratiform (widespread, steady, nonfreezing) rain is the presence of a subfreezing layer from ground level up to perhaps a few thousand feet. Ordinarily, air temperatures rise steadily with decreasing altitude, and therefore, temperatures below the 0°C level aloft will be warmer than freezing. But freezing rain requires a reversal in the temperature profile somewhere below the melting layer such that subfreezing temperatures are again present at or above ground level. This can occur in connection with a warm front (figure 2) when warm air overruns a subfreezing layer of air already in place.

The warm layer aloft is a well-known feature that pilots are taught to use to escape inadvertent encounters with freezing rain in flight. The seemingly counter-intuitive rule of thumb is to climb to warmer temperatures.

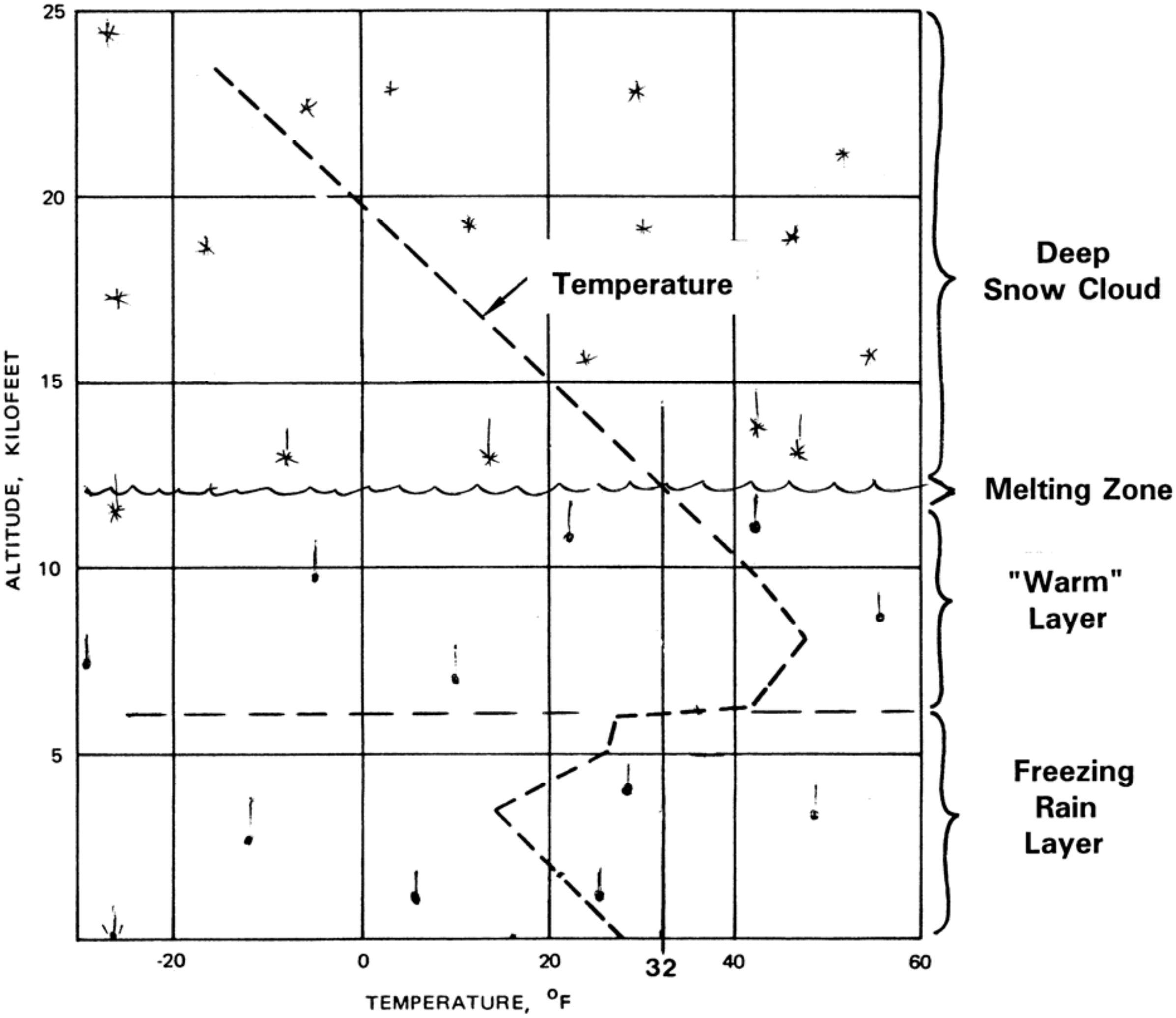

Figure 1. Schematic Representation of Freezing Rain Conditions

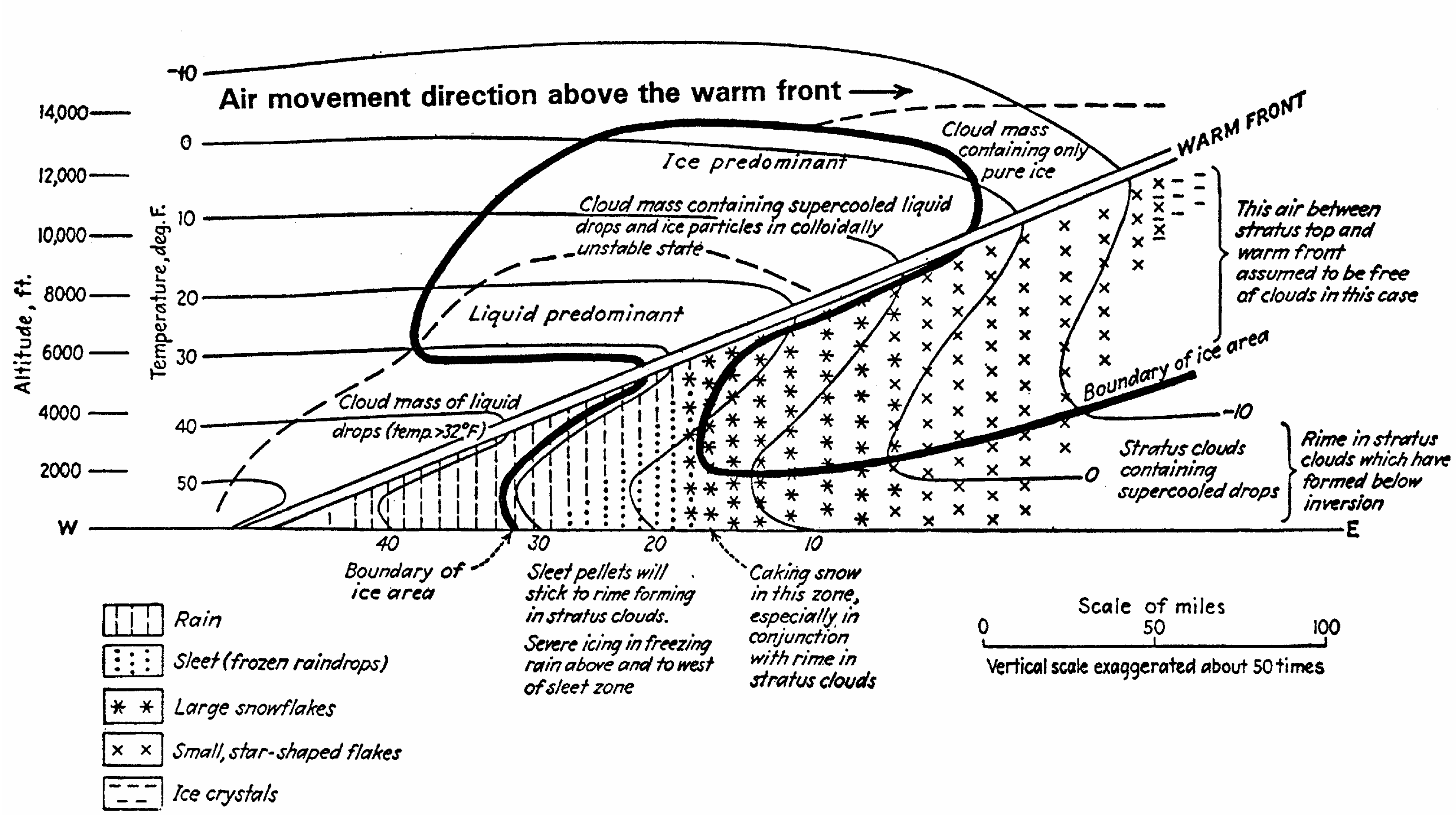

Figure 2. Schematic Representation of a Warm Front [9]

Raindrops are usually melted snowflakes or other ice particles, so raindrop size depends initially on the sizes (mass) of the melting snowflakes. Raindrops are defined as those drops larger than 500 µm (1/2 mm) in diameter. Drops from about 50 to 500 µm are drizzle drops, and drops smaller than 50 µm are ordinary cloud droplets. The raindrops may grow or shrink on their way to earth. They may grow somewhat by sweeping up additional cloud droplets if the raindrops fall through an intervening cloud layer. They may also shrink due to partial or total evaporation while falling through cloudless air. Any droplets that are several millimeters in diameter may also split in two due to aerodynamic forces during their fall. The rain rate depends mainly on the snowfall rate at the melting level and on any effects of evaporation. The resulting drop size distribution is generally a continuum from several millimeters down to tens of microns in diameter. Thus, the raindrop size distribution may also include droplets in the drizzle size range (50 to 500 µm). It is even possible that partial evaporation may sometimes reduce the rain drops to drizzle size before they reach the ground. In any case, most of the mass will be in the remaining larger sizes.

1.2.2 Freezing Drizzle.

Contrary to the rain process, drizzle develops totally within a liquid droplet cloud layer when the conditions are right. The melting snow process is not necessary and a "warm" layer is often absent. Drizzle is most familiar as experienced at ground level, where a "mist" of lightly falling droplets descends from low clouds above. But drizzle is not confined to the region below clouds—it continues throughout the vertical extent of the cloud layer where it is being formed. Drizzle droplets may even be somewhat larger and more numerous in the cloud than below, where partial or near total evaporation can reduce the sizes and numbers of the droplets on their way down.

The formation processes for drizzle are not well understood. Theoretically, if given enough time, some drizzle-sized droplets can eventually develop in any cloud that lasts long enough, is deep enough, and which contains enough condensed water. This process involves the gradual growth of some ordinary cloud droplets to a diameter of approximately 30 µm until they begin to settle. Then, they begin to collide and coalesce with other droplets on their way down through the cloud as they grow to drizzle droplet size (about 50 to 500 µm). This is found to be a slow and inefficient process, which is estimated to require at least 2 hours of uninterrupted cloud droplet growth after cloud formation just to get the process started [10]. Nevertheless, observations indicate that drizzle can form in layer clouds that meet the following requirements:

- The cloud layer lasts longer than 2 hours.
- The cloud layer is at least 1000 ft (0.3 km) deep.
- Temperatures everywhere within the cloud are warmer than about -12°C so that highly competitive ice crystals are less likely to be present.

The deeper the cloud, the larger and more numerous the settling drizzle droplets can become due to more time and more droplets with which they can collide. Politovich [11] and others have also pointed out that some kind of upslope motion (orographic or warm frontal) is needed to induce new condensation and to drive the continual cloud droplet formation and growth. This is necessary if the cloud layer is to be replenished or maintained against the gradual removal of cloud droplets and water by the drizzle falling out of the cloud.

Even so, the resulting amount of drizzle may be insignificant for aircraft icing unless something happens to greatly speed up the process.

It is known that two other mechanisms can enhance drizzle production by promoting the quick and continual growth of ordinary droplets into the 30-μm range where they can start the drizzle production process. One such mechanism is the presence of relatively large (approximately 10 μm) microscopic salt particles in the air where the cloud is forming. This happens frequently in oceanic coastal areas where whitecaps and surf spray inject saltwater droplets into the air. The smaller droplets evaporate and leave a residual aerosol of microscopic salt particles. This can be easily observed as a whitish haze along the beach zone. Cloud droplets always form on submicron hygroscopic particles (called cloud condensation nuclei) anyway, but the presence of unusually large nuclei is known to result in unusually large cloud droplets. This is why drizzle is more often observed under low cloud conditions in coastal areas than anywhere else. But large salt nuclei seldom reach very far inland or rise to the vicinity of the 10,000-ft (3-km) level where the elevated freezing drizzle clouds of interest occur. Therefore, some other mechanism must be at least occasionally active inland and at the altitudes of interest for large numbers and sizes of drizzle drops to be present. These unknowns make it difficult to predict the occurrence of FZDZ aloft.

1.3 TYPICAL SLD EXPOSURES.

1.3.1 Flying in Freezing Rain.

The most familiar and common type of freezing rain is that which occurs in the lowest few thousand feet above ground level (AGL) in winter. It normally occurs in warm frontal situations where a layer of warm air aloft, with snow above it, overrides a layer of subfreezing air in place at the surface (see figure 3).

If freezing rain is present, aircraft will be exposed to it during:

- descent and approach below the warm (melting) layer
- takeoff and ascent until the warm layer is reached
- low-altitude transit below the warm layer

Freezing rain usually causes conformal, widespread, glaze-like ice. In thin amounts, it may be clear, smooth, and difficult to see on the airframe. In larger amounts, it may become somewhat knobby and easier to recognize (see figure 4). Although the effects are not well documented, they may range from an iced-over windshield to a need for increasing power and angle of attack in order to overcome the accumulating weight and drag of the ice and the loss of propeller efficiency.

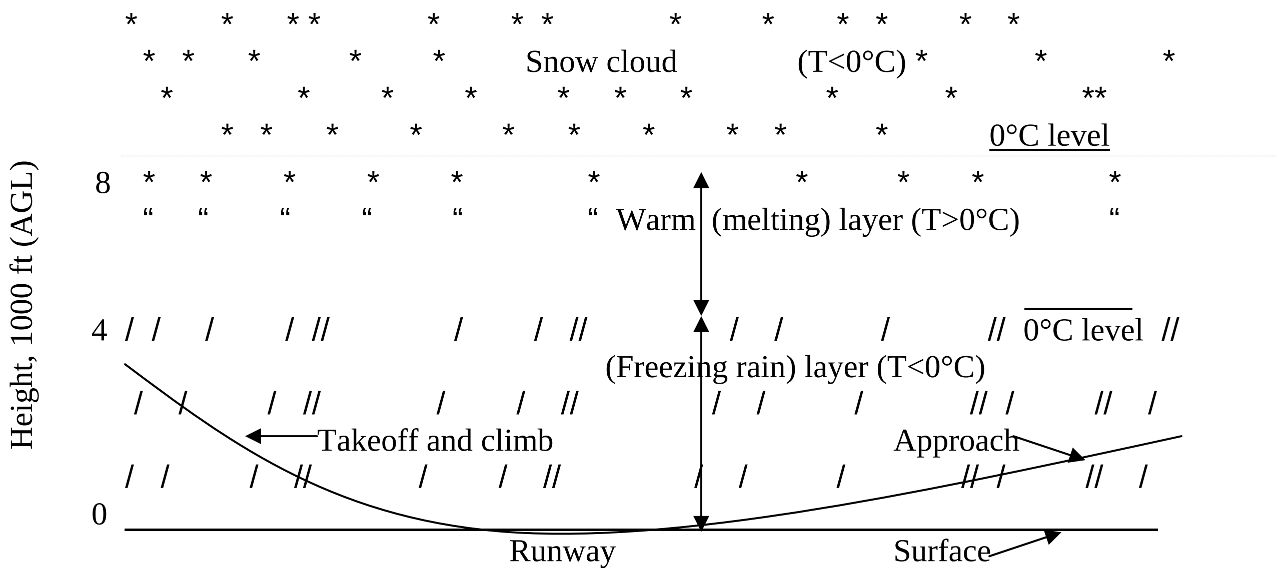

Figure 3. Vertical Profile of Temperature and Precipitation in Freezing Rain Conditions

Figure 4. Freezing Rain on a DH-6 Twin Otter
(photo courtesy of Porter Perkins, 1992)

1.3.1.1 Low-Lying Freezing Drizzle.

Low-lying freezing rain has a warm (T >0°C) layer above it and a usually deep snow cloud above that. Snow falling into the warm layer melts into the raindrops that continue down into an underlying frigid layer to become freezing rain.

The warm layer is the familiar escape route that is reached by climbing to warm temperatures from a freezing rain zone below. This is contrary to the normal situation where one descends to find warmer air. There is no escape at lower altitudes because the temperatures may get even colder there, and the freezing rain may continue all the way to the ground. The ground level temperatures may be only -1° or -2°C, but in the middle of the freezing rain layer above, temperatures can reach -9°C or below. Freezing rain layers may be up to 7000 ft deep.

1.3.1.2 Low Ceilings.

Freezing rain is often accompanied by a low ceiling—a stratiform cloud with a base around 1000 ft AGL or lower. These stratiform clouds may be a few hundred to a couple of thousand feet deep, and they lie in the cold (freezing rain) layer. This means that, in addition to icing from the freezing rain, an ascending or descending aircraft may pick up more ice in the low ceiling cloud.

1.3.1.3 The Warm Layer.

Although temperatures in the warm layer above can sometimes reach a comfortable, icing-free, +10°C, they may sometimes be barely warmer than 0°C. In this case, a cold-soaked aircraft may still accumulate slushy ice from partially melted snowflakes impacting the cold airframe. The warm layer may or may not be cloud free.

1.3.1.4 Elevated Freezing Rain.

Elevated freezing rain can occur in summer-like convective clouds that vigorously grow above the freezing level. Researchers have reported abundant amounts of freezing rain or freezing drizzle in strong updrafts at the -10°C level, for example. Except in unusual circumstances, these clouds normally would be avoided. Depending on the width of the cloud, the freezing rain encountered may be brief but intense. Effects may range from a rapid ice-over of the windshield to jet engine power loss.

1.3.2 Flying in Freezing Drizzle.

Most stratiform clouds do not seem to produce a significant amount of drizzle. But in certain conditions, including upslope clouds, warm front conditions, possibly in windy and turbulent cloud layers, and coastal maritime clouds, drizzle production can sometimes be unusually efficient.

Contrary to usual freezing rain conditions, where a “warm” (T >0°C) layer can be reached by climbing a few thousand feet, freezing drizzle often forms with no warm layer above it. In this case, the escape options are to turn back, climb above the cloud layer, or descend below the freezing level if it is high enough for ground obstacle clearance. Climbing above the drizzle-producing cloud layer may be preferable to descending below the freezing level. In flight, below the freezing level, a cold-soaked airplane may still accumulate ice from drizzle falling on the cold skin of the aircraft. This is especially true when the accessible warm temperatures are only 1° or 2°C above zero. On the other hand, climbing increases the angle of attack, which increases the rate at which freezing drizzle can accumulate as a thin but rough layer of ice far back on the underside of the wing. Five minutes of exposure is known to produce considerable drag penalties and reduced rate of climb capability on some airplanes. For this reason, climbing penetrations of drizzle clouds should be completed quickly.

1.3.2.1 Low-Lying Drizzle Clouds.

Low-lying drizzle clouds can extend from near ground level up to 13,000-ft AGL. This means that after takeoff, the aircraft may not break out of the drizzle until it passes 13,000 ft (4 km). If there is cloud and drizzle below 5000-ft AGL, then most likely there will be low ceiling conditions there as well. This means that on descent, the aircraft may be in freezing drizzle some or all the way to touchdown.

There may or may not be a warm (T >0°C) layer at some level in the cloud. The upper part of the drizzle cloud may be warm and the lower part may be cold (T <0°C) or vice versa. Or the cloud may be warm in the middle but cold in both the upper and lower parts.

1.3.2.2 Elevated Freezing Drizzle.

Elevated freezing drizzle may occur in separate, nonglaciated (i.e., supercooled liquid droplet) clouds between 5,000- and 20,000-ft above sea level (ASL). These cloud layers are usually less than 8000 ft deep, with a drier, cloud-free interval above and below. The temperature is below 0°C throughout the elevated drizzle cloud. The temperature decreases steadily with height, sometimes reaching as low as -20°C at cloud top. Drizzle appears to originate in the upper portion of stratiform clouds, as shown in figure 5. It may gradually extend some distance below the cloud layer until the slowly falling droplets evaporate in the drier air below.

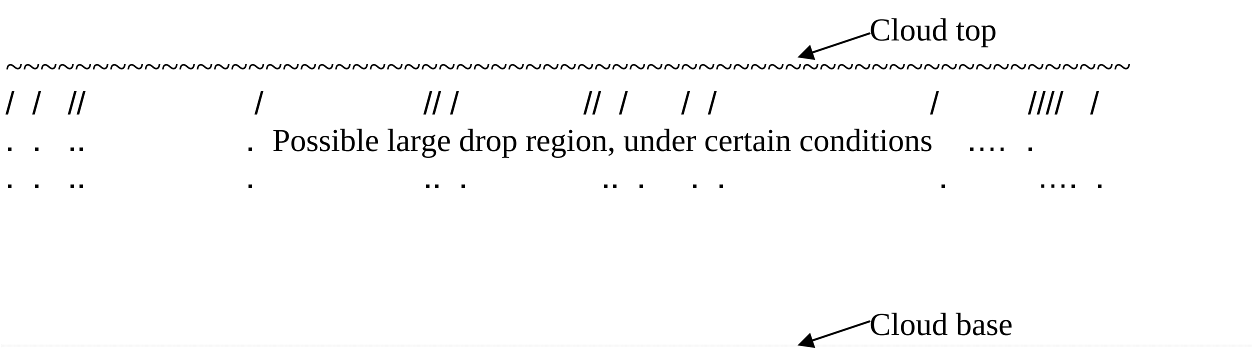

Figure 5. Schematic Representation of a Cloud Layer With Drizzle Forming Near the Top

Aircraft may encounter large droplet intervals for varying amounts of time, depending on whether the aircraft is ascending or descending through the cloud layer, or holding or cruising in the cloud layer, especially near cloud top.

Defining the SLD environment involves two aspects:

- collecting reliable airborne measurements of pertinent SLD variables
- devising an engineering model of SLD conditions for aviation purposes

Three workable models of SLD conditions are described in the next section. The measurements and data are described in appendices A through D.

2. NEW RESULTS.

2.1 GENERAL CHARACTERISTICS OF FREEZING DRIZZLE AND FREEZING RAIN.

The following characteristics apply to SLD conditions in general and are based on all the measurements in the Master SLD Database.

For freezing drizzle:

- Observed encounter distances = 1 to 90 nautical miles (nmi); average observed encounter = 11 nmi

- Maximum drizzle water concentration (DWC) = 0.5 g/m^3 over 1 nmi, decreasing with increasing averaging distance

- Maximum DWC = 0.3 g/m^3 (estimated) over standard reference distance of 17.4 nmi

- Altitude range = 0 to 22,000 ft (6.7 km) ASL

    - Maximum vertical extent = 12,000 ft (3.7 km)
    - Mean vertical extent = 3500 ft (1 km)

- Temperature range = 0° to -30°C (+32° to -22°F), with maximum DWC decreasing linearly below -15°C (+5°F) to zero at -30°C

- Average median volume diameter (MVD) = 120 µm

Note: Drizzle originates in clouds and therefore, for realistic estimates of ice accretions, freezing drizzle may need to be considered simultaneously with ordinary supercooled clouds, as described in Title 14 Code of Federal Regulations Part 25, Appendix C (hereafter, *Appendix C*) icing conditions. However, DWC develops at the expense of ordinary cloud water concentration (CWC), so the CWC should be reduced by the amount of DWC under consideration. That is, DWC + CWC <= CWC_{max}, where CWC_{max} is the probable maximum value obtained from *Appendix C*.

For freezing rain:

- Observed encounter distances = 1 to 80 nmi; average observed encounter = 13 nmi

- Maximum LWC in drops larger than 50 µm diameter (SLDLWC) = 0.5 g/m^3 over 1 nmi, decreasing with increasing averaging distance

- Maximum SLDLWC = 0.3 $g.m^3$ (estimated) over standard reference distance of 17.4 nmi

- Altitude range = 0 to 8000 ft (2.4 km) ASL or 7000 ft (2.1 km) AGL, whichever is less

  - Maximum vertical extent = 7000 ft (2.1 km) or 8000 ft minus surface elevation.
  - Mean vertical extent = 2900 ft (0.9 km)

- Temperature range = 0° to -12°C (+32° to +10°F), with no decrease in maximum SLDLWC

- Average MVD = 800 µm

Note: Freezing rain is often accompanied by low ceiling conditions, and therefore, for realistic estimates of ice accretions, freezing rain may need to be considered simultaneously with *Appendix C* stratiform icing clouds during approach and takeoff. However, the low ceiling clouds are no more than 3000 ft (0.9 km) thick, so their CWC will be limited to a maximum of about 0.3 g/m^3.

2.2 VARIATION OF TOTAL LWC WITH HE.

Figure 6 illustrates the gradual drop-off in total LWC (TLWC) with HE (averaging distance) for FZDZ events in the Master SLD Database.

As with ordinary clouds, the 99th percentile value of TLWC depends on the in-cloud path over which the LWC is averaged. The nature of clouds is such that the larger the LWC, the shorter the distance over which the high value of LWC can be maintained. Thus, the longer the averaging distances, the lower the possible maximum average value of LWC will be. In *Appendix C*, this variation has been accommodated by including curves for adjusting the LWC values as a function of HE. These are the “F-factor” curves in figures 3 and 6 in *Appendix C*. In the SLD case, too few averages have been obtained over long distances to reliably determine an SLD F-factor curve from the SLD data. It was found that the continuous maximum F-factor also appears to give a reasonable upper limit to the SLD TLWC (see figure 6). Lacking any better solution, the continuous maximum F-factor may be adopted for use with the SLD data. The details are given in appendix F of this report.

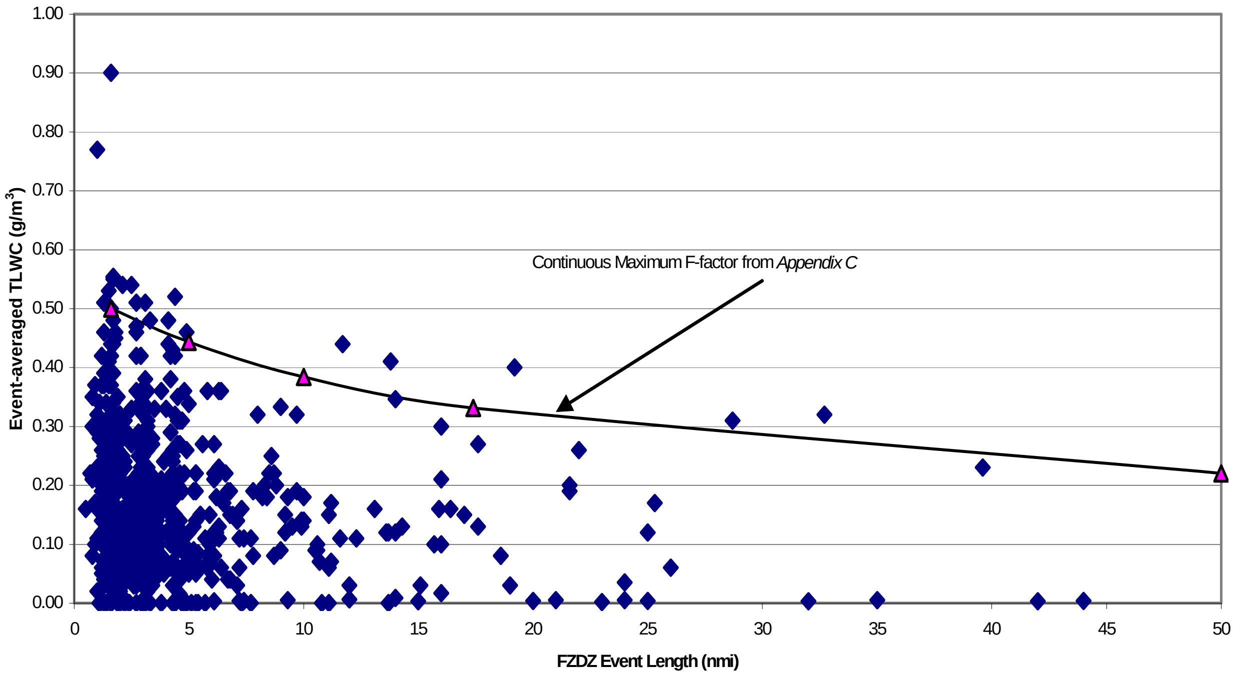

Figure 6. Total LWC for all FZDZ Events in the Master SLD Database

In the continuous maximum and intermittent maximum cases, the F-factor curves are set to unity at the reference distances of 17.4 and 2.6 nmi, respectively. The respective F-factor curves are used to adjust probable maximum LWCs for averaging distances both longer and shorter than these. In the SLD case, the reference distance has been chosen to be 1.6 nmi where the statistics for computing the 99th percentile TLWC are most reliable.

An F-factor for SLD conditions can be created from the continuous maximum F-factor as follows:

$$F_{SLD} = \frac{F_{Cont.\ Max.}}{1.725} = \frac{1.87 - 0.7\log(\text{distance})}{1.725} = 1.08 - 0.4\log(\text{distance}) \qquad (1)$$

where distance is in nautical miles (nmi) and the numerator is a numerical approximation to the continuous maximum F-factor curve in figure 3 of *Appendix C*. The denominator (1.725) causes F_{SLD} to have the value unity at 1.6 nmi.

The equation may then be used to estimate practical maximum values of SLD TLWCs for other exposure distances. For example, recorded one-way pass lengths through SLD conditions range from about 1.6 to occasionally 80 or 90 nmi, but 12 nmi is about the average one-way pass length in freezing drizzle or freezing rain conditions for the research flights in the Master SLD Database.

Maximum values of TLWC obtained by extrapolation beyond about 5 nmi may be termed estimated maximum values, due to their approximate nature beyond this distance.

2.3 VARIATION OF MAXIMUM TLWC WITH TEMPERATURE.

According to measurements in the Master SLD Database, maximum values of TLWC in FZDZ are practically independent of temperature from 0°C down to about -15°C. FZDZ is increasingly rare at lower temperatures, but it is occasionally found at temperatures down to about -25°C, at altitudes above 10,000 feet. Figure 7 shows the observed occurrences of TLWC versus temperature in FZDZ (and in drizzle that extended below the freezing level).

A linear drop-off was arbitrarily drawn to skirt the maximum TLWC values in figure 7. The line runs from the estimated 99th percentile value (0.52 g/m^3) at -15°C to 0 g/m^3 at -40°C.

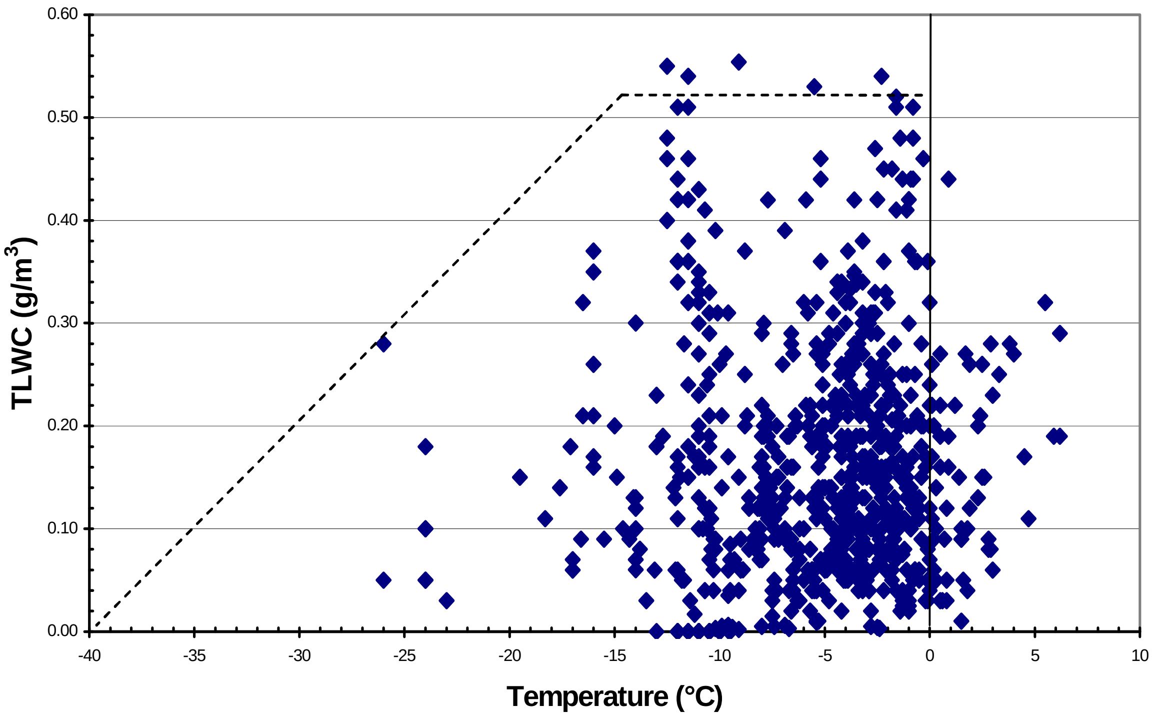

Figure 7. Total LWC for FZDZ Events Sorted by Temperature
(Dashed line represents a practical upper limit to TLWC for 1-5 nmi exposures.)

2.4 TEMPERATURE VERSUS ALTITUDE ENVELOPES.

Analogous to the continuous maximum and intermittent maximum temperature versus altitude envelopes (figures 2 and 5 in *Appendix C*), a pair of envelopes can be developed for FZDZ and FZRA conditions using the Master SLD Database. These are shown in figures 8 and 9. The scatterplots of measured temperature and altitude combinations are shown surrounded by lines (envelopes) that appear to be practical limits to the temperatures in which SLD conditions may be expected.

The two envelopes are different because the SLD formation mechanisms are different and FZDZ can occur over a greater altitude range than FZRA. The latter is confined to a surface layer of subfreezing air, which has never been found to be more than about 7000 feet deep.

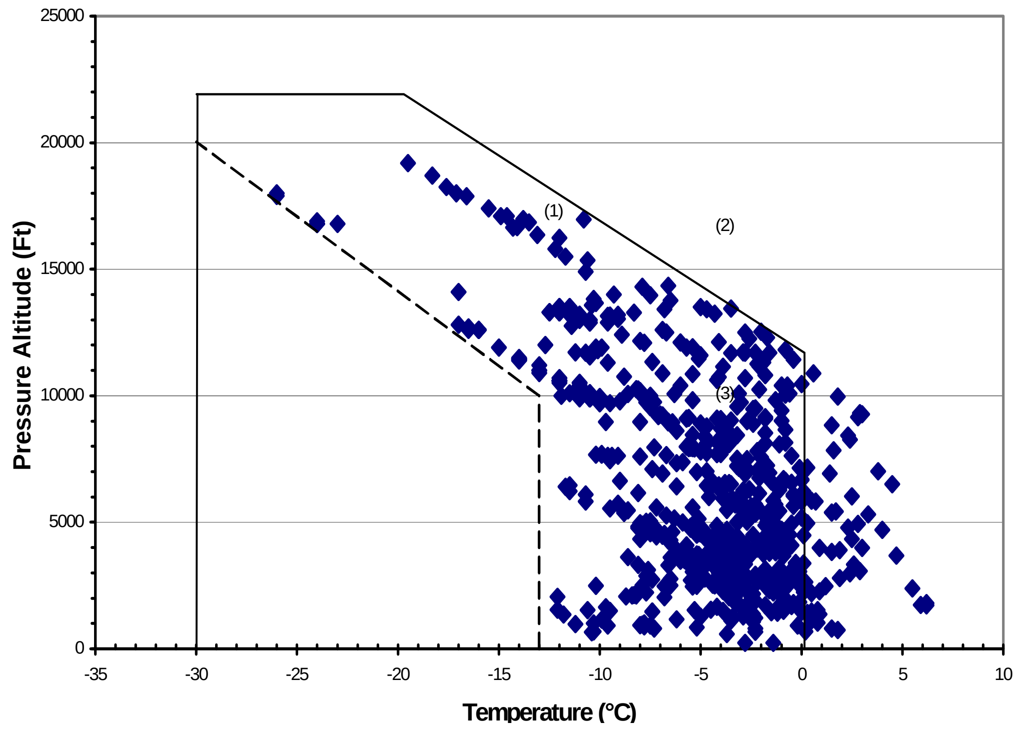

Figure 8. Measured Temperatures vs Altitude for Drizzle and FZDZ Events in the Master SLD Database

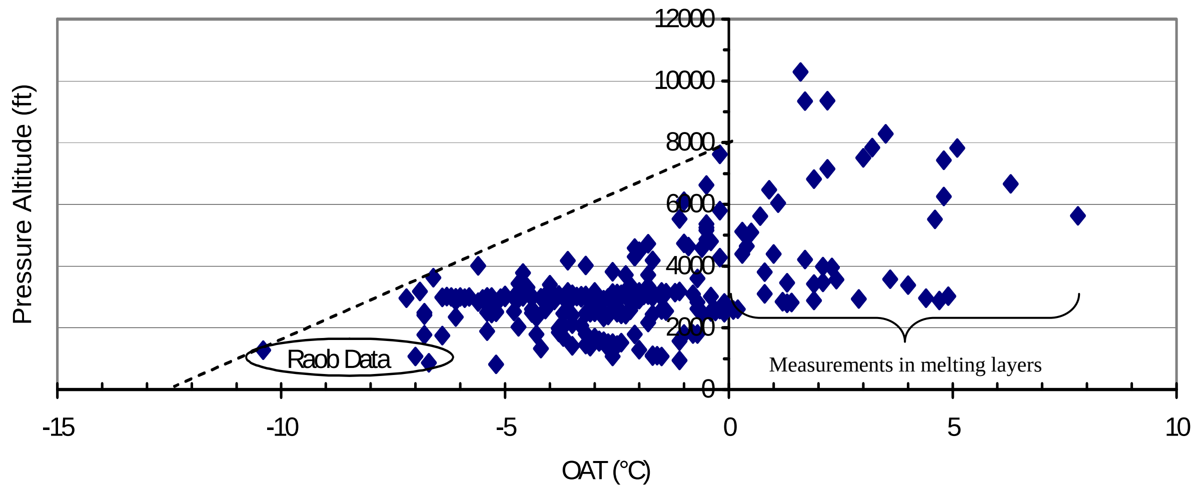

Figure 9. Measured Temperatures vs Pressure Altitude for FZRA Events in the Master SLD Database

The outer envelope (solid lines) in figure 8 is for continuous maximum icing conditions (from figure 2 of *Appendix C*). The bent dashed line is the apparent, practical cutoff (lower temperature limit) for FRDZ conditions, based on the available airborne measurements in the Master SLD Database and on 96,900 surface weather reports of FZDZ worldwide (see figure

D-1 in appendix D). Figure 8 represents 817 FZDZ events, totaling 2840 nmi of airborne measurements in FZDZ or other drizzle conditions.

The numerals in parentheses ( ) among the data points in figure 8 refer to the following, apparently SLD-related, accidents or incidents. The flights are identified as:

(1) TransAsia Airways flight GE-791, fatal accident on December 21, 2002, in the Taiwan Strait (latitude 25°N).

(2) Comair flight 5054, incident on March 19, 2001, between Bahamas and Florida (latitude 26°N).

(3) American Eagle flight 4184, fatal accident on October 31, 1994, over Roselawn, Indiana (latitude 41°N).

The positions of the numerals mark the approximate temperatures and altitudes at which the icing occurred.

The dashed line in figure 9 is the apparent, practical cutoff (lower temperature limit) for FZRA conditions, based on the available measurements in the Master SLD Database and from 71,800 surface weather reports of FZRA worldwide (see figure D-2 in appendix D). Figure 9 represents 264 FZRA events, totaling 1160 nmi of airborne measurements in FZRA conditions.

The temperature and altitude distributions shown in figures 8 and 9 are for FZDZ and FZRA in general.

3. NEW MODELS OF LWC VERSUS DROP SIZE DISTRIBUTIONS FOR FREEZING DRIZZLE AND FREEZING RAIN.

There are various ways to represent LWC distributions. Three simple and convenient models for aviation engineering purposes are presented here. All three models distinguish between FZDZ and FZRA, due mainly to the different drop size ranges that are involved. All attempt, in some way, to account for the presence or absence of ordinary cloud.

There are also a number of ways to depict droplet size distributions. Drop size distributions are not included as part of *Appendix C*, but they are thought to be necessary or helpful as part of an engineering description of SLD conditions, due to the wider range of droplet sizes involved. Each model of SLD conditions presented here includes a set of representative distributions of LWC versus drop size.

Because of the diversity of SLD conditions and the wide range of drop sizes, it does not seem feasible to include SLD conditions as a simple extension of the familiar LWC versus mean-effective diameter (MED) envelopes in *Appendix C*. One reason is that the temperature and altitude dependences of SLD are different from ordinary clouds represented by *Appendix C*. Another practical reason is the opinion that the existing engineering specifications in *Appendix C* should be left alone and kept separate from any specifications for SLD conditions so that any future changes to one will not necessarily affect the other. Therefore, no attempt was made to modify the *Appendix C* envelopes to accommodate SLD conditions.

3.1 VARIABLE COMPONENTS OF THE FREEZING DRIZZLE AND FREEZING RAIN MODELS.

3.1.1 Accounting for the Presence or Absence of Ordinary Clouds.

A distinction can be made between SLD that is coincident with, or separate from, ordinary clouds. FZDZ is usually encountered inside cloud layers but, in some cases, FZDZ may also be found for a distance below cloud base. FZRA falls into a cold layer that is usually partially filled with an ordinary stratiform cloud layer. The presence of clouds adds LWC in small droplet sizes that are not there in the absence of clouds. This extra LWC can increase the ice accretion rate and amount beyond that due to SLD alone.

A direct way of deciding whether clouds are present or not is to make use of the measured CWC in the ordinary cloud droplet sizes (1-50 µm diameter).

Model 1 (the cloud-option model) is based on this principle. Both the FZDZ and FZRA conditions are divided into two subcategories (cloud or no-cloud), depending on whether the CWC is respectively greater than or less than some arbitrary low threshold such as 0.05 g/m^3.

Model 2 (the two-point model) simply acknowledges two generally present main categories—ordinary cloud and SLD. A separate and continuously variable amount of CWC is selectable in combination with a separate and continuously variable amount of DWC or rainwater content (RWC). This scheme does not force the user to choose between the extremes of cloud or no-cloud. Rather, the cloud contribution can be proportioned as needed. The CWC can be set to zero if no ordinary cloud is to be considered.

Model 3 (the pure SLD model) describes only the FZDZ or FZRA drops alone without the inclusion of any droplets smaller than 50 µm in diameter. Ordinary cloud icing conditions are already represented in *Appendix C*. Therefore, only the additional icing conditions consisting of FZDZ and FZRA alone need to be represented. The proposed LWC distributions and maximum LWC values, as determined from the Master SLD Database, are discussed in detail in section 3.4. Model 3 can be applied separately or in combination with *Appendix C*, as necessary. If these *Appendix C* icing clouds are to be considered as part of the mix, suitable values of LWC and MVD for them can be obtained separately as usual from the familiar continuous maximum or intermittent maximum envelopes.

These three models are in addition to a fourth model that was devised independently by the IPHWG [12]. That model attempts to represent the presence or absence of clouds by using the overall MVD as a discriminator. The LWC and drop size measurements are grouped separately according to whether the MVD is less than or greater than 40 µm—the upper limit to MVDs in *Appendix C* conditions. Accordingly, the FZDZ or FZRA conditions are either inside or outside of *Appendix C*. Each of these four models will yield somewhat different values of maximum TLWC due to the different ways of grouping and averaging the data.

3.1.2 Representative LWC Distributions Versus Drop Size.

For most aircraft icing computations, some knowledge of the drop sizes associated with the LWC is required. Each of the drop size models introduced in this report includes a discretized LWC distribution scheme, which is useful in many icing computations and as input to computer codes. Up to ten drop size intervals are accepted by existing versions of the NASA/Lewis (LEWICE) computerized ice accretion code [13], for example.

- One-Point Representation. In the simplest case, a single drop size, the MVD, is often used to represent the entire LWC versus drop size distribution for computations of ice accretion amounts and ice shapes. While this simplistic reduction to a single drop size works well for ordinary clouds where the droplet diameters (and MVD) are confined to about 50 µm or less, it is less suitable as the drop size range widens, as for FZDZ and, especially, for FZRA. For SLD applications, the use of a single representative drop size has been rejected. None of the models use it. For SLD conditions, some higher resolution LWC distribution seems necessary.

- Two-Point Representation. As a simple extension of the single drop size (MVD) scheme commonly used for ordinary clouds, it is possible to adequately account for combinations of cloud and SLD by distributing the LWC over just two representative drop sizes—one for clouds and one for FZDZ or for FZRA. No further LWC distribution curves are needed.

  Model 2 makes use of this simple scheme, reflecting the natural bimodal character of LWC distributions in SLD conditions. This is illustrated in section 3.3.3. There, it is shown that important variables like total collection efficiencies, ice accretion rates, and even ice shapes, when computed with a two-point LWC distribution, are practically the same as those computed with the finer resolution LWC distributions described below.

- Medium Resolution, Fixed Interval Distributions. For a more faithful representation of the actual LWC versus drop size distributions, one can arbitrarily divide the drop size range into more size intervals.

  This is actually the basis of the Master SLD Database (see appendix C of this report) where 12 drop size intervals are used to span the SLD range. Each SLD event recorded in the Master SLD Database has a value for LWC in each of the 12 drop size intervals for which a nonzero value of LWC was detected.

  Models 1 and 3 are based on this scheme. They use 6 to 12 fixed-width drop size intervals to span the SLD drop size range. The first two intervals fit exactly within the conventional drop size range for clouds (1-100 µm), the next four intervals span the FZDZ range (100-500 µm), while the last six intervals cover the FZRA range (500-3000 µm). This arrangement has the advantages of matching the way size distributions are stored in the Master SLD Database and of preserving the bimodal character of the FZDZ and FZRA LWC distributions without adding too much complexity. Matching the database format makes it easier to extract data from the FAA Master SLD Database for analyzing special cases or subsets of the database.

The average values of LWC in each drop size interval were used to define a representative LWC distribution for each model and SLD subcategory. The resulting average values for model 1 are discussed in section 3.2.

Model 3 is the same as for model 1, except the first size bin, 1-50 µm for ordinary cloud droplets, is not used.

These different models and distributions are further described below, and the details are presented in the tables and figures in this section.

3.1.3 Maximum LWCs for SLD Conditions.

Analogous to the design of *Appendix C*, it is useful to establish a practical upper limit to the LWC to be expected in SLD conditions associated with stratiform clouds. The LWC curves in figures 1 and 4 of *Appendix C* are approximately 99th percentile values of LWC for ordinary supercooled stratiform clouds. The 99th percentile value is called the probable maximum value by the National Advisory Committee for Aeronautics and U.S. Weather Bureau researchers [14] who developed the original continuous maximum and intermittent maximum design criteria.

The data in the Master SLD Database can also be used to determine the 99th percentile values (see section 3.2 and appendix F), but only for short (1-5 nmi) events where enough samples have been obtained to generate reliable statistics. The results also depend on the manner of selecting any subcategories.

3.2 DETAILS OF MODEL 1 (THE CLOUD-OPTION MODEL).

3.2.1 Tabular Presentation.

The spreadsheet in table 1 lists the variables proposed for each SLD subcategory of model 1 when the presence or absence of cloud is used as a discriminator and a medium-resolution size distribution is used. The table is explained as follows:

- Row 7 lists the fixed MVDs assigned to each of the subcategories. The MVDs are average values obtained from all of the available high-resolution SLD flight data in the Master SLD Database assembled at the FAA William J. Hughes Technical Center.

- Row 8 gives an estimate of the 99th percentile value of TLWC applicable to each subcategory for the user-selected air temperature (row 10) and the user-selected HE (row 14). That is, row 8 contains in-cell formulae to compute the 99th percentile TLWC, depending on the values entered by the user in rows 10 and 14.

- Row 9 gives the OAT ranges over which the particular SLD conditions are believed to occur, based on flight data and other information.

- Row 10 allows the user to enter a specific temperature of interest (for FZDZ only). A formula embedded in row 8 will adjust the TLWC displayed in row 8 to account for the observed temperature dependence of the TLWC.

- Row 11 lists the altitude ranges over which the particular SLD conditions are believed to occur, based on flight data and other information.

- Row 12 lists the average single-heading pass lengths recorded by the research flights in these SLD conditions.

- Row 13 lists the maximum HEs of any of the SLD conditions intercepted by the research flights.

- Row 14 allows the user to enter a specific exposure distance of interest. A formula embedded in row 8 will adjust the TLWC displayed in row 8 in conformity with the LWC adjustment factor (F-factor) for continuous maximum conditions in figure 3 of *Appendix C*.

- Row 15 displays the F-factor corresponding to the exposure distance selected in row 14.

- Rows 18 through 29 give the proposed, medium-resolution, representative LWC distributions. The percent of TLWC in the middle column of each subcategory is the average value obtained from all the available data in the Master SLD Database. The individual LWCs in the left-hand column of each subcategory correspond to the percentages in the middle column, but the numerical values in the left-hand column will change with the value displayed in row 8.

Row 18 corresponds to ordinary clouds. Row 19 is an interval which may belong to FZDZ or to ordinary clouds, depending on the drop size threshold selected for separating the two. It may be argued that together, rows 18 and 19 represent the *Appendix C* portion of each subcategory. Rows 20 through 23 cover the FZDZ range. Rows 24 through 29 cover the FZRA range.

Table 1. Tabular Form of Model 1 for FZDZ and FZRA Variables

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1						Automatic LWC Calculator and								
2					LWC distributions and other pertinent variables for									
3			Model #1 of SLD Conditions: Based on the concept of four SLD categories determined by whether the SLD is in or out of cloud.											
4			Using medium-resolution dropsize intervals for actual average LWC distributions vs dropsize											
5														
6			FZDZ IN CLOUD *			FZDZ OUTSIDE OF CLOUD *			FZRA IN CLOUD *			FZRA OUTSIDE OF CLOUD *		
7	Total MVD (µm) *	=		45			105			300			700	
8	Max TLWC (g/m3)**	=		0.53			0.38			0.70			0.40	
9	OAT Range (°C)	=		0 to -30°C			0 to -30°C			0 to -12°C			0 to -12°C	
10	User-selected OAT	=		0	degC		0	degC						
11	Altitude Range	=		0 to 22,000 Ft ASL			0 to 22,000 Ft ASL			0 to 8000 Ft ASL			0 to 8000 Ft ASL	
12	Pass Avg. HE (nmi)	=		11			11			13			13	
13	HE Range (nmi)	=		1 - 90			1 - 90			1 - 80			1 - 80	
14	User-selected HE	=		1.6	nmi		1.6	nmi		1.6	nmi		1.6	nmi
15	(F-factor) ***	=		1.725			1.725			1.725			1.725	
16														
17	Dropsize Interval	Bin Ctr. Dia.(µm)	LWC(g/m3)	% of TLWC	Cum. TLWC (%)	LWC(g/m3)	% of TLWC	Cum.TLWC (%)	LWC(g/m3)	% of TLWC	Cum. TLWC (%)	LWC(g/m3)	% of TLWC	Cum. TLWC (%)
18	3 - 50 µm	15	0.34	64.4	64.4	0.08	21.1	21.1	0.32	45.3	45.3	0.04	11.2	11.2
19	50 - 100 µm	75	0.07	12.7	77.1	0.13	34.4	55.5	0.005	0.7	46	0.009	2.3	13.5
20	100 - 200 µm	150	0.07	13.2	90.3	0.10	26.7	82.2	0.011	1.5	47.5	0.006	1.5	15
21	200 - 300 µm	250	0.033	6.3	96.6	0.038	10	92.2	0.015	2.2	49.7	0.015	3.8	18.8
22	300 - 400 µm	350	0.013	2.4	99	0.021	5.6	97.8	0.024	3.4	53.1	0.021	5.3	24.1
23	400 - 500 µm	450	0.005	1	100	0.008	2.2	100	0.024	3.4	56.5	0.027	6.8	30.9
24	0.5 - 1.0 mm	750							0.165	23.6	80.1	0.159	40	70.7
25	1.0 - 1.5 mm	1250							0.076	10.9	91	0.084	21	91.7
26	1.5 - 2.0 mm	1750							0.032	4.5	95.5	0.021	5.3	97
27	2.0 - 3.0 mm	2500							0.013	1.9	97.4	0.006	1.5	98.5
28	3.0 - 4.0 mm	3500							0.011	1.5	98.9	0.003	0.8	99.3
29	4.0 - 5.0 mm	4500							0.008	1.1	100	0.003	0.7	100
30			0.53			0.38			0.70			0.40		
31														
32	Notes:													
33	* Outside of cloud is defined as FSSPLWC < 0.05 g/m3; inside of cloud is FSSPLWC >= 0.05 g/m3.													
34	* Total MVD's are average values computed from the FAA SLD Database at the FAA Technical Center													
35														
36	** TLWC is the total liquid water content---the sum of the cloud water content (CWC), drizzle water content (DWC) and rain water content (RWC).													
37	Max TLWC's are the estimated 99th percentile values---automatically adjusted for the user-selected OAT in row 12 (FZDZ only) and the user-selected horizontal extent (HE) in row 16,													
38		and based on actual statistical 99th percentile values of TLWC as listed below for OAT = 0 °C and HE = 1.6 nmi.												
39	The LWC distributions in the table represent average curves for each SLD category, but with values summed to the estimated maximum TLWC for each case.													
40														
41	*** The F-factor is automatically computed here from the user-selected HE's in row 16,					based on a linear approximation to the Continuous Maximum F-factor curve in Fig. 3 of 14 CFR-25, Appendix C.								
42	At HE = 1.6 nmi it gives the basic 99th percentile values of TLWC (listed below) from which are derived all the distance- and temperature-adjusted TLWC's computed and tabulated above.													
43	These basic 99th percentile values are based on a Weibull analysis of TLWC frequencies in the FAA SLD database at the FAA Technical Center for each of the four SLD categories above.													
44														
45	99th percentile values of TLWC for HE= 1.6 nmi and OAT = 0 °C (+32 °F) are:													
46				0.53 g/m3			0.38 g/m3			0.70 g/m3			0.40 g/m3	
47														

3.2.2 Pseudo-Continuous LWC Distributions.

Some icing practitioners prefer continuous curves of cumulative LWC across the applicable drop size range. From the cumulative LWC curves, the user can find what is usually needed—the MVD, the 10th…99th percentile LWCs, or the amount (or percent) of LWC above or below any particular droplet diameter, for example. For other applications, however, such fine resolution is not needed and the user may prefer distributions divided into intervals defined by increments in LWC or drop diameter, as in table 1.

Model 1 obtains LWC distribution curves by graphing the average values of LWC from table 1 and connecting the points with a smooth curve. Data from all flights in the entire Master SLD Database are used together to obtain the average values. Figure 10 shows the resulting pseudo-continuous, average LWC distributions, and figure 11 shows the average cumulative LWC curves for the four SLD subcategories.

These average curves are taken to be representative of the four subcategories as indicated. Different TLWC values can be assigned to the curves, depending on the temperature and HE of interest, as was explained in connection with table 1.

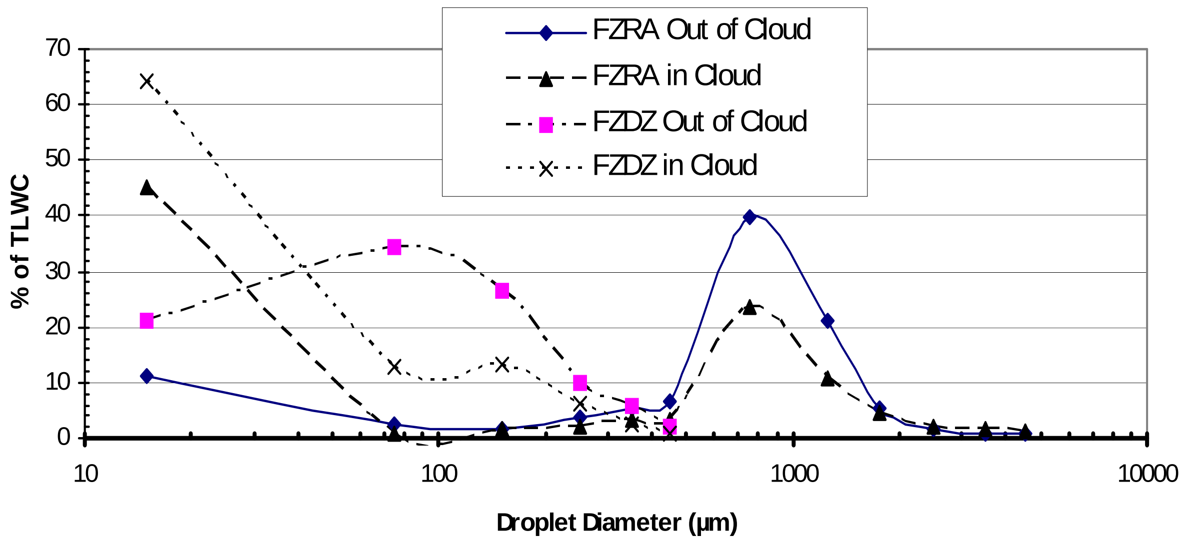

Figure 10. Average LWC vs Droplet Diameter for the Four Subcategories in Model 1 of SLD Conditions

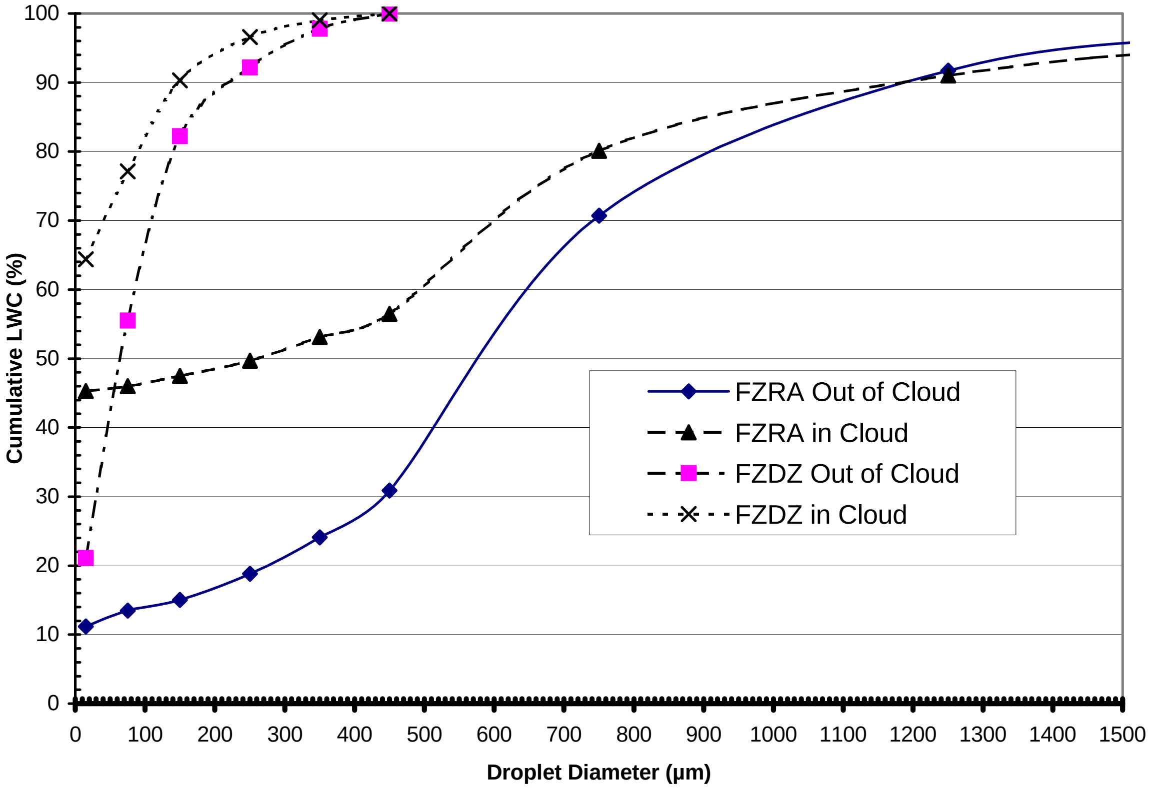

Figure 11. Cumulative Average LWC vs Droplet Diameter for the Four Subcategories in Model 1 of SLD Conditions

3.2.3 Maximum LWC.

The 99th percentile values of TLWC (TLWC = CWC + DWC + RWC) applicable over short distances (1-5 nmi) in each of the four SLD subcategories (FZDZ in cloud, FZDZ out of cloud, FZRA in cloud, and FZRA out of cloud) are listed in the first row of table 2. The values are 0.53 g/m^3, 0.38 g/m^3, 0.70 g/m^3, and 0.40 g/m^3, respectively (see table 1 and appendix E). These apply only to temperatures in the range of 0°C to -15°C. For FZDZ, there is a further reduction in LWC with decreasing temperature below -15°C.

Table 2. Statistical and Estimated 99th Percentile TLWC in SLD Conditions

	FZDZ (In cloud)	FZDZ (Out of cloud)	FZRA (In cloud)	FZRA (Out of cloud)
99th percentile TLWC at 1.6 nmi	0.53 g/m^3	0.38 g/m^3	0.70 g/m^3	0.40 g/m^3
Estimated maximum TLWC at 12 nmi	0.34 g/m^3	0.25 g/m^3	0.45 g/m^3	0.26 g/m^3
Estimated maximum TLWC at 17.4 nmi	0.31 g/m^3	0.22 g/m^3	0.41 g/m^3	0.23 g/m^3

The decreasing number of SLD samples lasting longer than about 5 nmi (see figure 6) prevents a reliable computation of 99th percentile values of TLWC for longer exposures, but these can be estimated using the SLD F-factor in equation 1. The estimated values of maximum TLWC for 12- and 17.4-nmi SLD exposures are given in table 2.

For exposure distances other than 12 or 17.4 nmi, the 1.6-nmi reference values should be similarly adjusted by the SLD F-factor in equation 1.

Note that the TLWCs are larger in cloud than out of cloud.

3.2.4 Advantages and Benefits of the Cloud Option Model.

Some of the advantages and benefits of the cloud option model are:

- Users can pick from four representative SLD situations with preassigned LWC versus drop size distributions.

- Active spreadsheet (table 1) automatically adjusts LWCs for user-selected outside air temperature and HE.

- Standardized, medium-resolution drop size intervals are compatible with LEWICE or other ice accretion codes.

3.3 DETAILS OF MODEL 2 (THE TWO-POINT MODEL).

3.3.1 Representative LWC Distribution Versus Drop Size.

Figures 12 and 13 present a simple schematic form of a two-point SLD characterization—one for FZDZ and one for FZRA.

In general, both FZDZ and FZRA may consist of large drops alone or in combination with ordinary supercooled stratiform cloud droplets (the latter being represented by *Appendix C*, continuous maximum conditions). The left-hand columns in figures 12 and 13 represent the *Appendix C* component centered at a representative drop diameter of 15 µm. (Data from reference 5 show that about 75% of all MVDs lie within ±5 µm of 15 µm in stratiform clouds.) The right-hand columns represent the large drop component of SLD conditions. These are centered at representative drop diameters of 150 µm for FZDZ and 1 mm for FZRA. The height of the two columns (denoting the amount of LWC in each) can be varied within limits by the user to represent various combinations of cloud and large droplets (SLD).

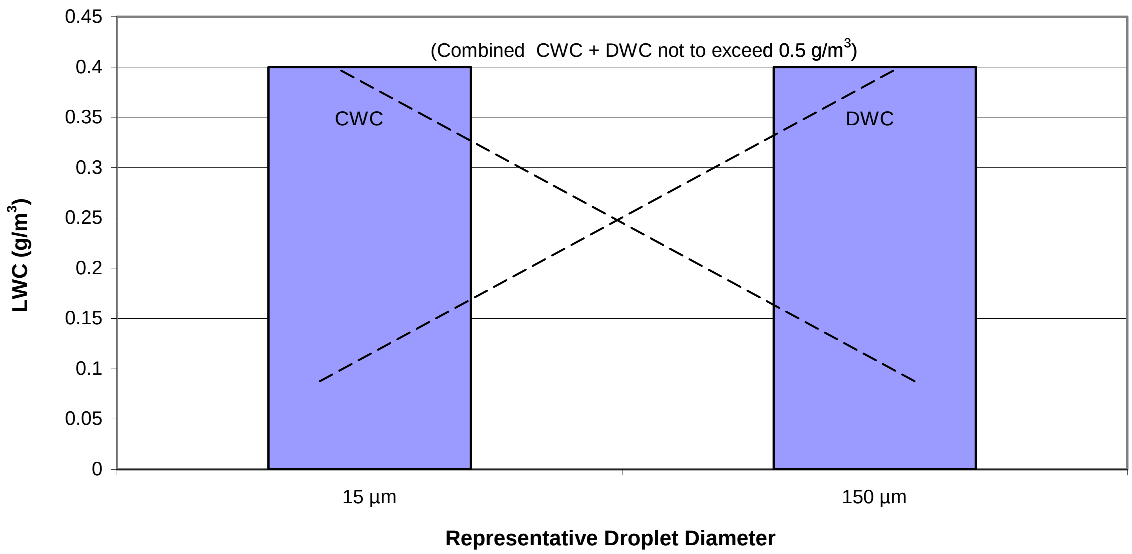

Figure 12. The Two-Point FZDZ Model
(Dashed lines indicate maximum value of CWC or DWC in combination with the other. Shaded bars indicate practical maximum LWCs for individual components (CWC and DWC).)

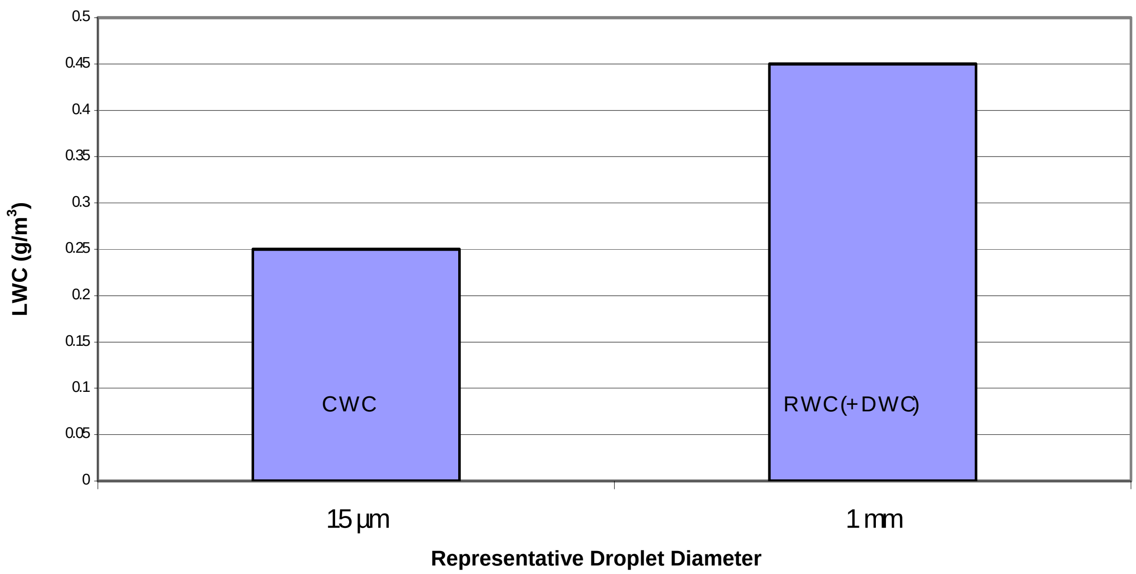

Figure 13. The Two-Point FZRA Model
(Any CWC or RWC within each range can be independently assigned. Bars indicate practical maximum LWCs for individual components (CWC and RWC).)

In particular, figure 12 reflects the following facts for freezing drizzle conditions:

- The cloud and large drop components are coupled—DWC grows at the expense of ordinary CWC.

- The practical maximum (99%) values for CWC and DWC individually are 0.4 g/m^3 for each, but in combination, the total LWC (TLWC = CWC + DWC) does not appear to exceed about 0.5 g/m^3 (see appendix E). That is, for a maximum practical DWC of 0.4 g/m^3, the CWC is not expected to exceed 0.1 g/m^3, and vice versa.

The crossed dashed lines are a user's aid for implementing this rule. One line represents the allowable CWC, while the other represents the simultaneously allowable DWC. The user can draw a vertical line on the graph, and the maximum practical CWC and DWC is indicated by where the vertical line intersects each dashed line. For example, a vertical line drawn at the 15-µm location indicates that a maximum DWC of only 0.1 g/m^3 (the lower dashed line) can be expected in combination with 0.4 g/m^3 of CWC (the upper dashed line). In the middle where the dashed lines cross, the maximum expected CWC and DWC are both 0.25 g/m^3. Finally, a vertical line drawn at the 150-µm location indicates that a maximum CWC of only 0.1 g/m^3 can be expected when the DWC is as high as 0.4 g/m^3.

Figure 13 reflects the following facts for FZRA conditions:

- The cloud and large drop components are not coupled—CWC, if present, is not related to the RWC. (Any cloud component will be a low-lying, supercooled stratiform layer producing the typical low-ceiling conditions usually associated with FZRA. The cloud layer depth may be a few hundred feet up to perhaps 3000 feet, thus limiting the available CWC to about 0.25 g/m^3 or less.)

- The practical maximum (99%) values for CWC and RWC are 0.25 g/m^3 and 0.45 g/m^3, respectively (see appendix E). These two components may exist in any proportion with a combined maximum TLWC (TLWC = CWC + RWC) of up to 0.7 g/m^3.

<u>3.3.2 Maximum LWC</u>.

There are individual maximum values for each of CWC, DWC, RWC, and TLWC. According to the available data in the Master SLD Database (see appendix E), the 99th percentile values for short distances are approximately:

- for FZDZ: CWC = 0.4 g/m^3, DWC = 0.4 g/m^3, and TLWC = 0.5 g/m^3
- for FZRA: CWC = 0.25 g/m^3, RWC = 0.45 g/m^3, and TLWC = 0.7 g/m^3

The estimated values of maximum TLWC for 12- and 17.4-nmi SLD exposures are given in table 3.

Table 3. Estimated Maximum LWC for the Two-Point Model

Exposure Distance	12 nmi	12 nmi	17.4 nmi	17.4 nmi
	FZDZ (g/m^3)	FZRA (g/m^3)	FZDZ (g/m^3)	FZRA (g/m^3)
Estimated maximum CWC	0.26	0.16	0.23	0.14
Estimated maximum DWC	0.26	-	0.23	-
Estimated maximum RWC	-	0.29	-	0.26
Estimated maximum TLWC	0.32	0.45	0.29	0.40

Note that the individual maximum values have been computed independently from each other, so the maximum value of TLWC is not necessarily the sum of the maximum values of CWC, DWC, and RWC in this table.

3.3.3 Advantages and Benefits of the Two-Point Model.

Some of the advantages and benefits of the two-point model are:

- Simple, and easy to use and understand.

- Eliminates the need to specify any MVDs or drop size distributions.

- Provides a smooth and natural transition from *Appendix C* conditions (left-hand column of figures 12 and 13) into SLD conditions (right-hand column).

- LEWICE computations indicate that for purposes of calculating impingement limits, local collection efficiency (ß), total collection efficiency (E), water catch, icing rates (mm/min), icing intensity (trace, light, moderate, or heavy), areal coverage of ice (% of chord, or wrap), ice mass deposition (pounds per foot of span), and even ice shapes on airfoils, this two-point LWC distribution works just as well as higher-resolution, multipoint distributions. (See table 4 for comparisons.)

Table 4. Comparison of Droplet Impingement and Ice Accretion Details for Different FZRA Models

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
4	Sample Application For NACA-23012 outer wing with chord=0.91 m (e.g., Beech B1900-D airplane)																					
5	Using LEWICE 1.6 with the following variables: OAT=-10C, ALT=2,000 Ft,																					
6		and	Exposure =	10	sec,	TAS=	90	m/sec =	175	kt												
7		simulating a 10-sec interval during descent and approach in freezing rain with a total liquid water content (TLWC=CWC+DWC+RWC) of 0.47 g/m3																				
8																						
9	**Condition :** Freezing Rain with large MVD; 25% of LWC in App. C, 75% in SLD to 2500 µm															10	sec exposure at 90 m/s					
10	LWC	MVD	Dropsize	Max	-----------Impingement Limits-----------					Total	-------------------------Ice Coverage---------------------						Ice	Water	Minutes	Icing	Icing	Max/Min
11			Distribution	Beta	Upper		Lower		Extent	Eff.	Max.	Upper Extent		Lower Extent		Extent	Mass	Catch	for 1 lb ice	Rate	Intensity	Assigned
12	(g/m3)	(um)			(+cm)	% Chord	(-cm)	% Chord	of wrap	(from	Depth	(cm)	% Chord	(cm)	% Chord	of wrap	(gm/foot in 10 sec)		(per ft of span)	(minutes	(new	Dropsizes
13					(from beta graph)				(cm)	LEWICE)	(mm)					(cm)	(rho=.9)	(rho=1)	(rho=.9)	per 1/4-in.)	scale)*	(microns)
14	0.47	620	Med. Resolution	0.86	22	24%	-30	-33%	52	0.78	0.32	20.5	23%	-28	-31%	48.5	10	49	7.6	3.4	Heavy	2500/15
15	0.47	350	Mod. Langmuir	0.85	21	23%	-30	-33%	51	0.73	0.32	20	22%	-28	-31%	48	9	45	8.4	3.4	Heavy	1444/7
16	0.47	-	15 & 1000 µm	0.86	22	24%	-31	-34%	52.8	0.78	0.32	20	22%	-29	-32%	49	10	49	7.6	3.4	Heavy	1000/15
17	0.47	1000	1000 µm	0.98	21.5	24%	-31	-34%	52.5	0.98	0.38	22	24%	-30	-33%	52	12	66	6.3	2.9	Heavy	1000/1000
18	0.47	15	15 µm	0.48	3	3%	-2	-2%	5	0.15	0.20	3.5	4%	-1.7	-2%	5.2	1.5	1	50	5.4	Mod-Hvy	15/15
19																						
20	Notes:	Candidate LWC distributions are presented in order of decreasing resolution																				
21			Medium resolution distribution (candidate version #2 or #4) with 9 dropsize intervals (follows the actual bi-modal freezing rain LWC distribution the most realistically).																			
22			Modified Langmuir distribution (candidate version #1) with 7, LWC-symmetrical dropsize intervals.																			
23			15 & 1000 µm 2-point distribution (candidate version #3), places 25% of LWC in cloud drop sizes at 15 µm and 75% at the rain drop LWC peak at 1000 µm.																			
24			1000 µm is a simple, 1-point distribution which places ALL the LWC in the rain drop size at 1000 µm																			
25			15 µm is an Appendix C comparison where all the LWC is placed at 15 µm.																			
26																						
27	**Conclusions:**																					
28	1. The impingement and ice accretion effects considered here are not very sensitive to differences in the first three LWC distributions.																					
29	2. The simple, 2-point LWC distribution works as well as the most realistic (coarse-bin) distribution, and slightly better than the modified-Langmuir distribution.																					
30	**3. The simple, 2-point LWC distribution appears to be the simplest way to represent FZDZ or FZRA in Appendix X.**																					
31																						
32																						
33	**Comparison Case (MKC-01Feb90):** Actual Freezing Rain Case at Kansas City, Feb. 01, 1990 for 12.5 minute exposure at:																					
34		TAS=140kt, OAT=-4C, ALT=2200 Ft to 600 Ft (ASL) during approach & landing																				
35	LWC	MVD	Dropsize	Max	-----------Impingement Limits-----------					Total	-------------------------Ice Coverage---------------------						Ice	Water	Minutes	Icing	Icing	Max/Min
36			Distribution	Beta	Upper		Lower		Extent	Eff.	Max.	Upper Extent		Lower Extent		Extent	Mass	Catch	for 1 lb ice	Rate	Intensity	Assigned
37	(g/m3)	(um)			(+cm)	% Chord	(-cm)	% Chord	of wrap	(from	Depth	(cm)	% Chord	(cm)	% Chord	of wrap	(gm/foot in 10 sec)		(per ft of span)	(minutes	(new	Dropsizes
38					(from beta graph)				(cm)	LEWICE)	(mm)					(cm)	(rho=.9)	(rho=1)	(rho=.9)	per 1/4-in.)	scale)*	(microns)
39	0.29	800	Med. Resolution	0.92	21	23%	-29	-32%	50	0.89	6.2	21.5	24%	-21.5	-24%	43	6.5	25	12	13	Moderate	4500/13
40																						
41																						
42	* Icing intensity scale:																					
43		Trace: icing rate = 1/4-inch in 1 hour or longer,					(less than 1/4-inch per hour)															
44		Light: icing rate = 1/4-inch in 15 - 60 minutes,					(1/4 to 1 inch per hour)															
45		Moderate: icing rate = 1/4-inch in 5 - 15 minutes,					(1 to 3 inches per hour)															
46		Heavy: icing rate = 1/4-inch in less than 5 minutes.					(more than 3 inches per hour)															

3.4 DETAILS OF MODEL 3 (THE PURE SLD MODEL).

3.4.1 Tabular Presentations.

Table 5 lists the average observed water concentrations in the drizzle drop size range from all 874 FZDZ events in the Master SLD Database.

Table 5. The DWC Distribution With Drop Size

Average Distribution				
Drop Diameter (μm)	DWC (g/m^3)	DWC (%)	DWC (Cumulative %)	Maximum DWC (g/m^3)
75	0.028	39	39	0.117
150	0.026	36	75	0.108
250	0.011	15	90	0.046
350	0.005	7	97	0.021
450	0.002	3	100	0.008
Totals	0.072	100		0.30*

*Maximum Total DWC and SLDLWC are estimated values for 17.4-nmi HEs.

Similarly, table 6 lists the average observed water concentrations in the rain drop size range from all 261 FZRA events in the Master SLD Database.

Table 6. The SLDLWC (= DWC + RWC) Distribution With Drop Size Average Distribution

Drop Diameter (μm)	SLDLWC (g/m^3)	SLDLWC (%)	SLDLWC Cumulative (%)	Maximum SLDLWC (g/m^3)
75	0.003	2.4	2.4	0.007
150	0.003	2.4	4.8	0.007
250	0.005	4.0	8.8	0.012
350	0.008	6.3	15.1	0.019
450	0.008	6.3	21.4	0.019
750	0.058	46.0	67.4	0.138
1250	0.028	22.2	89.6	0.067
1750	0.009	7.1	96.7	0.021
2500	0.003	2.4	99.1	0.007
3500	0.001	0.8	100	0.002
4500	0	0		0
Totals	0.126	100		0.30*

*Maximum Total DWC and SLDLWC are estimated values for 17.4-nmi HEs.

3.4.2 Pseudo-Continuous LWC Distributions.

Model 3 obtains LWC curves by graphing the average values of LWC in tables 4 and 5 and connecting the points with a smooth curve. Data from all flights in the entire Master SLD Database (see appendix C of this report) are used together to obtain the average values. Figure 14 shows the resulting pseudo-continuous, average LWC distributions, and figure 15 shows the cumulative average LWC curves.

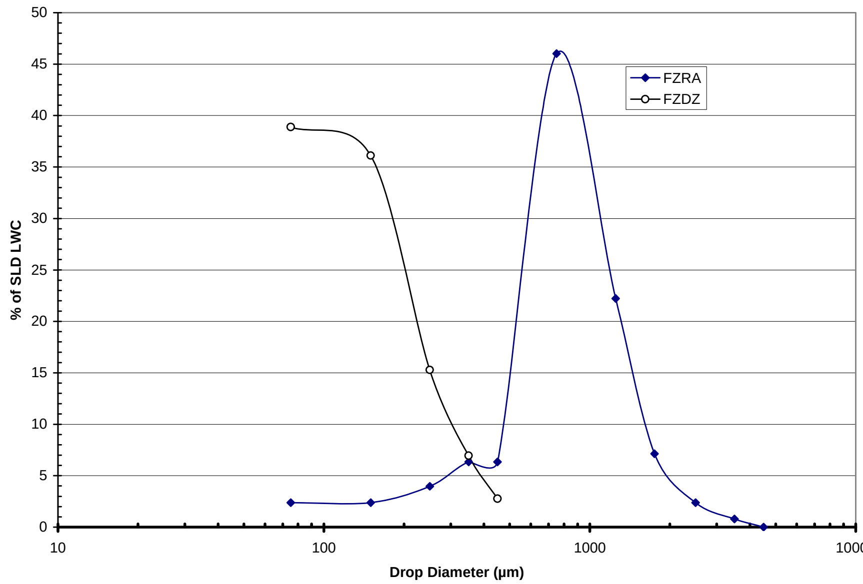

Figure 14. Average LWC vs Drop Diameter for Model 3, Pure FZRA and FZDZ

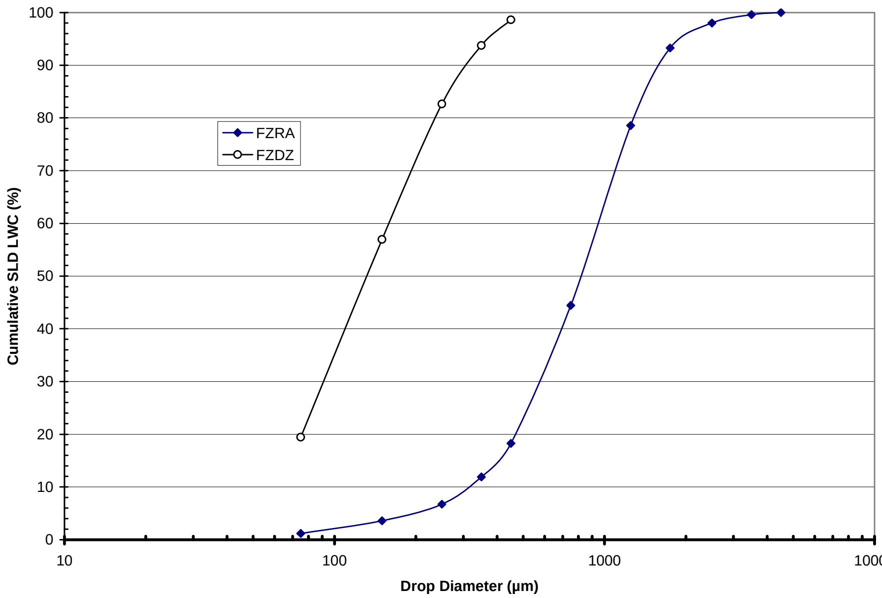

Figure 15. Cumulative Average LWC vs Drop Diameter for Model 3, Pure FZRA and FZDZ

The estimated values of maximum LWC for 1.6- and 17.4-nmi SLD exposures are given in table 7.

Table 7. Estimated Maximum LWC for Model 3

Exposure Distance	1.6 nmi	1.6 nmi	17.4 nmi	17.4 nmi
	FZDZ (g/m^3)	FZRA (g/m^3)	FZDZ (g/m^3)	FZRA (g/m^3)
Estimated maximum DWC	0.5	-	0.3	-
Estimated maximum RWC	-	0.5	-	0.3

3.4.3 Advantages and Benefits of the Pure SLD Model.

Some of the advantages and benefits of the pure SLD model are:

- A simple model with all the essential features for representing FZDZ or FZRA separately.
- A fixed, average LWC versus drop size distribution with LWC adjustable only for HE.
- Standardized, medium-resolution drop size intervals that are compatible with LEWICE or other ice accretion codes.

4. SUMMARY.

- Model 1 (Cloud-Option).

  This model is based on a direct test for the presence or absence of clouds, using ordinary CWC as an indicator. The CWC is the LWC contributed by drops in the size range below 50 µm in diameter. If the CWC is greater than some arbitrary threshold value, e.g., 0.05 g/m^3, then a cloud is declared to be present. Otherwise, the CWC is so small that it is considered to be negligible. In instrumented flight tests, the CWC can be computed from the commonly used droplet size forward scattering spectrometer probe, (FSSP), which counts and sizes droplets in the 1- to 50-µm-diameter range. The two SLD categories (FZDZ and FZRA) are sorted into two subcategories (cloud or no cloud) by using a CWC of 0.05 g/m^3, for example, as a discriminator.

- Model 2 (Two-Point).

  For this model, there are only two broad categories—ordinary cloud and either FZDZ or FZRA. The fractional amount of CWC is not fixed relative to the SLD component but is continuously variable. The CWC can range from zero to a maximum of 0.4 g/m^3 for FZDZ conditions and a maximum of 0.25 g/m^3 for FZRA conditions. Further explanations of the LWC assignments in model 2 can be found in section 3.3.

Model 2 makes no discriminations and assumes that ordinary clouds are generally present to some extent. It allows the user to assign a separate and variable amount of CWC in combination with a separate and variable amount of DWC or RWC.

- Model 3 (Pure SLD).

  This is a simpler representation of FZDZ and FZRA that does not overlap into the *Appendix C* range of drop sizes, but stays exclusively in the SLD range. *Appendix C* still exclusively represents ordinary icing conditions and model 3 exclusively represents SLD conditions. Model 3 can be used separately or together with *Appendix C*, as needed, except the observed limited depth of supercooled clouds associated with FZRA constrains the maximum probable CWCs to values smaller than otherwise would be allowed by *Appendix C*.

5. REFERENCES.

1. Johl, G., et al., “Investigation Into the Possibility of Retro-Fitting Improved Tailplane Ice Protection on Turboprop Aircraft,” SAE paper no. 2000-01-2113, *Advances in Aviation Safety Conference and Exposition*, April 2000.

2. NTSB, “Aircraft Accident Report, ATR Model 72-212, Roselawn, Indiana, October 31, 1994,” NTSB/AAR-96/01, National Transportation Safety Board, 1996.

3. Riley, J.T. (editor), “Proceedings of the FAA International Conference on Aircraft Inflight Icing, Volume 1,” FAA report DOT/FAA/AR-96/81,I, August 1996.

4. FAA, “FAA Inflight Aircraft Icing Plan,” Federal Aviation Administration, Washington, DC 20591, April 1997, pp. 35.

5. Jeck, R.K., “Distance-Scaled Water Concentrations Versus Mass-Median Drop Size, Temperature, and Altitude in Supercooled Clouds,” *Journal of the Atmospheric Sciences*, Vol. 65, 2008, pp. 2087-2106.

6. Jeck, R.K., “Snow and Ice Particle Sizes and Mass Concentrations at Altitudes up to 9 km (30,000 ft),” FAA report DOT/FAA/AR-97/66, August 1998.

7. Jeck, R.K., “A New Database of Supercooled Cloud Variables for Altitudes up to 10,000 Feet AGL and the Implications for Low-Altitude Aircraft Icing,” FAA report DOT/FAA/CT-83/21, August 1983.

8. Jeck, R.K., “Representative Values of Icing-Related Variables Aloft in Freezing Rain and Freezing Drizzle,” FAA report DOT/FAA/AR-TN95/119, March 1996.

9. Byers, H.R., *General Meteorology*, McGraw-Hill Book Co., New York, 1944.

10. Mason, B.J. and Howorth, B.P., "Some Characteristics of Stratiform Clouds Over North Ireland in Relation to Their Precipitation," *Quarterly Journal of the Royal Meterological Society*, Vol. 78, 1952, pp. 226-230.

11. Politovich, M.K., "Aircraft Icing Caused by Large Supercooled Droplets," *Journal of Applied Meteorology*, Vol. 28, 1989, pp. 856-868.

12. Cober, S., et al., "Data and Analysis for the Development of an Engineering Standard for Supercooled Large Drop Conditions," FAA report DOT/FAA/AR-09/10, March 2009.

13. Wright, W.B., "User Manual for the NASA Glenn Ice Accretion Code LEWICE Version 2.0," Technical Report NASA/CR-1999-209409, September 1999, 182 pages.

14. Jones, A.R. and Lewis, W., "Recommended Values of Meteorological Factors to be Considered in the Design of Aircraft Ice-Prevention Equipment," NACA TN-1855, March 1949.

APPENDIX A—AVAILABLE DATA

A.1 SOURCES OF DATA.

All of the data compiled here came from digital records provided by several agencies (mainly universities or government research organizations) whose instrumented aircraft have collected useful measurements in various supercooled large drops (SLD) environments. Airborne measurements of SLD variables (mainly liquid water content (LWC), drop sizes, icing rates, outside air temperature, altitude, and horizontal extent (HE)) were obtained mostly from recent flight research projects dedicated explicitly to finding and measuring SLD.

Table A-1 lists the individual projects and the amount of data (in terms of flight miles) contributed by each of them to the Master SLD Database at the Federal Aviation Administration (FAA) William J. Hughes Technical Center[1] (see appendix B of this report). Following the table, the field research projects from which data were obtained are described briefly to familiarize the reader with them and to indicate the scope of the atmospheric conditions that are represented. General references for each of the projects are provided.

Table A-1. Projects and Flights Included in the FAA Master SLD Database

Project*	Location	Agency**	Flights	Data Miles (nmi)	SLD Type
SCPP (1982-1986)	California	U. Wyoming	5	205	FZDZ
UND/FAA Icing (1990)	Kansas City	U. North Dakota	3	350	FZRA
WISP (1994)	Colorado	NCAR/U. Wyoming	3	419	FZDZ
NASA/FAA/NCAR SLD (1997-98)	Gt. Lakes	NASA/GRC	13	732	FZDZ and FZRA
CFDE-1 (1995)	Newfoundland	MSC	4	725	FZDZ
CFDE-3 (1997)	So. Ontario	MSC	5	1180	FZDZ and FZRA
Lockheed (C-130 Icg Flights)	So. Argentina	Lockheed/JTD	4	381	FZDZ
EURICE (1997)	Netherlands	NLR	1	36	FZDZ
	Spain	INTA	1	14	FZDZ
Juneau SLD (2000)	Alaska	U. Wyoming	3	416	FZDZ
AIRS-1 (1999-2000)	So. Ontario	MSC	4	245	FZDZ
Total			46	4703	

* Acronyms are explained in section A.3 of this appendix.

** Agency acronyms are NCAR, National Center for Atmospheric Research; MSC, Meteorological Service of Canada; JTD, JTD Environmental Services, Inc.; NLR, National Lucht-en Ruimtevaartlaboratorium (Holland); INTA, Instituto Nacional de Technica Aerospacial (Spain); NASA, National Aeronautics and Space Administration; GRC, Glenn Research Center.

[1] Contact persons Tim Smith (timothy.g.smith@faa.gov, 609-485-4185) and Jim Riley (james.t.riley@faa.gov, 609-485-4144), Flight Safety Team, FAA William J. Hughes Technical Center, Atlantic City International Airport, New Jersey 08405.

A.2 TYPE OF CLOUDS REPRESENTED.

Nearly all the data collected here are related to wintertime, stratiform cloud conditions because these are seen as the primary source of reported, SLD-related accidents and incidents. It is known, however, that SLD are generally plentiful in warm-season, vigorously growing convective clouds (Cg, TCu, Cb)[2] above the freezing level. Changnon, et al. [A-1] report that for large, growing convective clouds in Illinois, "Typical in-cloud results at -10°C reveal multiple updrafts that tend to be filled with large amounts of supercooled drizzle and raindrops." This means that aircraft penetrating the cores of these clouds in the 0° to -20°C range can expect to encounter intense bursts of SLD. The presence of substantial SLD in these updraft cores may cause the windshield to ice over more than usual and may prompt the flight crew to report severe icing conditions. Individual updraft cores are generally less than 1 or 2 km wide, however, and the characterization of these cloud penetrations would be analogous to the Intermittent Maximum conditions in Title 14 Code of Federal Regulations, Part 25, Appendix C.

Nevertheless, practically no SLD data from summer convective clouds has been obtained for this database. The main reasons were the emphasis on wintertime SLD concerns, time constraints on completing the data collection and analyses tasks, and the considerable effort that would be involved in finding, collecting, processing, and analyzing any available summer SLD data. Some practical factors that may mitigate the need for a characterization of summer SLD conditions are the relative ease of recognizing and avoiding strong convective activity, the confinement of summer SLD to relatively high altitudes (generally above 10,000 feet in the low- and mid-latitudes), and the relative brevity of inadvertent exposures (at least in Cg and TCu)[2].

A.3 DESCRIPTION OF THE FLIGHT PROJECTS.

The Sierra Cooperative Pilot Project (SCPP) in central California was a multiyear, wintertime weather modification exercise over the windward (western) slopes of the Sierra Nevada mountains [A-2]. The University of Wyoming's Beechcraft King Air, the primary cloud physics research aircraft for the project, flew a number of missions each winter from 1978 through 1984. Digital magnetic tapes of the data from onboard cloud and precipitation particle size spectrometers and other probes were obtained from the data archives maintained by the U.S. Bureau of Reclamation, the principal sponsor of the project. Data from selected portions of flights known to have encountered SLD have been processed into the database. Descriptions of some of these SLD encounters can be found in references A-3 and A-4. Some of these papers were the first to report on encounters with SLD and its adverse effects on the airplane. Flight altitudes ranged from 1.2 to 6.7 km (4,000 to 22,000 ft).

The University of North Dakota (UND)/FAA Icing Project included several research flights by the UND Citation-II instrumented airplane during 1990 as part of an FAA-funded effort to evaluate NEXRAD radar for use in detecting icing conditions. Fortunately, for SLD research, the airplane was able to sample freezing rain conditions near Kansas City on three different occasions (January 19, 1990 and February 1 and 14, 1990). The February 14 case was part of a major, widespread ice storm known as the "Valentine's Day" storm [A-5 and A-6]. Digital data from

[2]Cg—cumulus congestous, TCu—towering cumulus, Cb—cumulonimbus

onboard cloud and precipitation particle size spectrometers and other probes were obtained from the UND Aerospace Sciences Department for these three freezing rain flights.

The Winter Icing and Storms Project (WISP) commenced in 1988 [A-7] in response to the National Aircraft Icing Technology Plan [A-8] and the National Plan to Improve Aircraft Icing Forecasts [A-9] issued by the Federal Coordinator for Meteorological Services and Supporting Research. The Plans, especially the latter, focused on needed improvements in the detection, monitoring, and forecasting of aircraft icing conditions. Funded primarily by the FAA, scientists at the National Center for Atmospheric Research (NCAR) organized and conducted several multiagency measurement projects between 1990 and 1997 in which an instrumented airplane was available to measure cloud physics variables in icing conditions. A few flights in 1994 encountered SLD in northeastern Colorado and some of that data has been obtained for use in the Master SLD Database. Digital data from onboard cloud and precipitation particle size spectrometers and other probes were obtained from the University of Wyoming BE-200T King Air research airplane.

The NASA/NCAR/FAA SLD Project was a 2-year flight program organized by the National Aeronautics and Space Administration (NASA) Glenn Research Center (GRC) to study SLD in the Great Lakes region [A-10]. Thirteen of the seventy research flights over two winter seasons (1997-1998) yielded useful SLD data. Digital data from onboard cloud and precipitation particle size spectrometers and other probes were obtained from the NASA GRC DH-6 Twin Otter research airplane.

The First Canadian Freezing Drizzle Experiment (CFDE-1) was conducted out of St. Johns, Newfoundland by scientists at the Meteorological Service of Canada (MSC) in March 1995. The primary objectives were to characterize icing environments associated with freezing precipitation and to improve icing forecast techniques [A-11]. Twelve icing flights were flown using an instrumented Convair-580 airplane belonging to the Canadian National Research Council (NRC). Four of the flights yielded useful freezing drizzle data from onboard cloud and precipitation particle size spectrometers and other probes.

The Third Canadian Freezing Drizzle Experiment (CFDE-3) was conducted out of Ottawa, Ontario by the same MSC scientists from December 1997 through February 1998. Five of twenty-six flights on the NRC Convair-580 produced useful freezing drizzle and freezing rain data in the Ottawa-Lake Ontario-Montreal area.

The Lockheed C-130 icing flight tests were carried out in July of 1998 at the southern tip of South America. They encountered unexpected and extended SLD conditions during six of twelve flights. A description is given in reference A-12. The aircraft was instrumented with a forward scattering spectrometer probe (FSSP), optical array probe, and a Johnson-Williams hot-wire LWC meter. Lockheed-Martin provided the data from the SLD encounters to the FAA on a proprietary basis for inclusion in the Master SLD Database. The Lockheed-Martin data may not be released without written permission from Lockheed-Martin.

The **EU**ropean **R**esearch on Aircraft **I**ce **CE**rtification (EURICE) was a 2-year, scientifically based European project in aircraft icing research [A-13 and A-14]. Funded by the Directorate General VII for Transport of the European Commission, the project consisted of 12 collaborating universities, research organizations, industries, and aviation authorities from six countries. A major objective was to collect new data on supercooled clouds with emphasis on SLD. In March and April of 1997, three instrumented airplanes conducted flights in three different European regions where a small amount of useful SLD data was obtained. Digital data from onboard cloud and precipitation particle size spectrometers, and other probes were obtained.

The Juneau SLD Flights were funded by the FAA to obtain SLD measurements in the vicinity of Juneau, Alaska while the University of Wyoming BE-200T King Air research airplane was there for other purposes. Three flights in January 2000 resulted in useful freezing drizzle encounters. Digital data from onboard cloud and precipitation particle size spectrometers, and other probes were obtained.

The Alliance Icing Research Study (AIRS-1) Project was a multiagency, icing research project based in Ottawa, Ontario between 29 November 1999 and 19 February 2000. The primary objectives of the project were (1) to experiment with remote sensing of aircraft icing regions using satellite, aircraft, or ground-based systems and (2) to obtain additional data on the icing environment, especially in SLD. The majority of the research flights were conducted in the vicinity of Mirabel, Quebec. Of the 25 flights on the Convair-580 airplane provided by the Canadian National Research Council, 4 flights yielded useful SLD data. The project is described in reference A-15.

A.4 REFERENCES.

A-1. Changnon, S.A., et al., "Illinois Precipitation Research: A Focus on Cloud and Precipitation Modification," *Bulletin of the American Meteorological Society*, Vol. 72, 1991, pp. 587+.

A-2. Reynolds, D.W. and Dennis, A.S., "A Review of the Sierra Cooperative Pilot Project," *Bulletin of the American Meteorological Society*, Vol. 67, 1986, pp. 513 ff.

A-3. Sand, W.R, et al., "Icing Conditions Encountered by a Research Aircraft," *Journal of Climate and Applied Meteorology*, Vol. 23, 1984, pp. 1427-1440.

A-4. Cooper, W.A., et al., "Effects of Icing on Performance of a Research Airplane," *Journal of Aircraft*, Vol. 21, 1984, pp. 708-715.

A-5. Martner, B.E., et al., "Impacts of a Destructive and Well-Observed Cross-Country Winter Storm," *Bulletin of the American Meteorological Society*, Vol. 73, 1991, pp. 169-172.

A-6. Prater, E.T. and Borho, A.A., "Doppler Radar Wind and Reflectivity Signatures With Overrunning and Freezing Rain Episodes: Preliminary Results," *Journal of Applied Meterology*, Vol. 31, 1992, pp. 1350-1358.

A-7. Rasmussen, R., et al., "Winter Icing and Storms Project (WISP)," *Bulletin of the American Meteorological Society*, Vol. 73, 1992, pp. 951-974.

A-8. OFCM, "National Aircraft Icing Technology Plan," Report No. FCM-P20-1986, Office of the Federal Coordinator for Meteorology, Rockville, Maryland 20852.

A-9. OFCM, "National Plan to Improve Aircraft Icing Forecasts," Report No. FCM-P21-1986, Office of the Federal Coordinator for Meteorology, Rockville, Maryland 20852.

A-10. Miller, D., et al., "NASA/FAA/NCAR Supercooled Large Droplet Icing Flight Research: Summary of Winter 96-97 Flight Operations," Paper No. AIAA 98-0577, *36th AIAA Aerospace Sciences Meeting*, Reno, Nevada, American Institute of Aeronautics and Astronautics, Reston, Virginia 20191, 1998.

A-11. Isaac, G.A., et al., "Canadian Freezing Drizzle Experiment," Paper No. AIAA 99-0492, *37th AIAA Aerospace Sciences Meeting*, Reno, Nevada, American Institute of Aeronautics and Astronautics, Reston, Virginia 20191, 1999.

A-12. Burick, R.A. and Ryan, R.J., "FAA Certification of the Lockheed Martin C-130J Transport Ice Protection System," Paper No. AIAA 99-4016, AIAA Atmospheric Flight Mechanics Conference, American Institute of Aeronautics and Astronautics, Reston, Virginia 20191, 1999.

A-13. Amendola, A., et al., "EURICE: an European Effort for the Improvement of In-Flight Aircraft Icing Safety," Paper No. AIAA 98-0092, *36th AIAA Aerospace Sciences Meeting*, Reno, Nevada, American Institute of Aeronautics and Astronautics, Reston, Virginia 20191, 1998.

A-14. Hauf, T., "EURICE: WP2 Final Report," Centro Italiano Ricerche Aerospaziali (CIRA), 81043, Capua, Italy, 1998.

A-15. Isaac, G.A., et al., "Preliminary Results From the Alliance Icing Research Study (AIRS)," Paper No. AIAA 2001-0393, *39th AIAA Aerospace Sciences Meeting*, Reno, Nevada, American Institute of Aeronautics and Astronautics, Reston, Virginia 20191, 2001.

APPENDIX B—THE FEDERAL AVIATION ADMINISTRATION MASTER SUPERCOOLED LARGE DROPS DATABASE

The available data on supercooled large drops (SLD) conditions aloft comes from a variety of sources, as indicated in appendix A. Each source has its own data processing procedures, but most variables are common to all of the data sets. To get the best use from these diverse data sets, they had to be combined into a single, computerized, master database. This task was undertaken by the author at the Federal Aviation Administration (FAA) William J. Hughes Technical Center.

Patterned after an earlier database of supercooled cloud variables [B-1], the master database was designed to contain 75 common variables, as listed in table B-1. (Table B-2 lists the symbols and abbreviations that are used for three of the variables (PRECIP, AGENCY, and CLOUDTYP) in table B-1).

In addition to screening the data for acceptable quality, the principal selection rule for admitting data into the master database was the requirement to have at least 0.01 g/m^3 of liquid water in drops larger than 50 µm in diameter for at least 1 nmi in uninterrupted extent. This product of liquid water content (LWC) and exposure distance was arbitrarily established as the threshold of concern for SLD exposures and for building a database of significant SLD measurements.

In most of the source data, the value of each of the measured variables is recorded as a 1-second average. Data from the Meteorological Service of Canada (MSC) and National Aeronautics and Space Administration (NASA) Glenn Research Center (GRC) are further averaged over sequential 30- or 45-second intervals, and these longer averages are the ones available from those two sources for use in the master database. Most other sources have provided data as 1- or 5-second averages. Rather than bloat the master database with large numbers of 1- to 45-second averages, the data management philosophy has been to combine sequential intervals over which the variables remain constant within certain limits. These are termed uniform SLD intervals or SLD events. They vary in length but have the advantages of database economy as well as a built-in indication of uniformity of SLD conditions (at least as sampled by the various research airplanes).

B.1 DATA MANAGEMENT PHILOSOPHY.

The data originally obtained from various sources have been computerized in a condensed, standardized format according to the following scheme.

B.1.1 AVERAGING INTERVALS.

Modern, electronic, and electro-optical cloud physics probes and sensors provide digitized measurements, typically once per second or more, during flight in clouds. Therefore, an hour of flight may contain 3600 or more individual readouts from each sensor. Naturally, these large numbers of samples have to be reduced in some way to obtain a manageable set of data. Some sources supplied data already condensed to averages over some arbitrary time or distance intervals. For the 1-second data, and as much as possible for the pre-averaged data, the following averaging scheme has been devised.

Each variable (LWC, air temperature, droplet concentration, etc.) is averaged over continuous, uniform portions of SLD conditions, as indicated in table B-3. These averaging intervals are termed events. If the aircraft is still in usable SLD at the end of one event, then a new averaging interval (event) is immediately begun and continued until the next significant change in SLD properties occurs. Otherwise, the next event is not begun until the aircraft enters another usable interval of SLD.

This averaging scheme has a number of advantages:

- Inflexible, fixed intervals, such as 45-second averages, are avoided as much as possible. (These are undesirable because they may washout useful detail otherwise available with modern, high-resolution measurements.)

- The events can be short enough to resolve any significant changes in SLD characteristics along the flight path—i.e., the natural variability in SLD can be preserved and documented.

- Intervals of uniform, constant conditions within SLD conditions can be preserved whole so their durations and characteristics can be documented without the ambiguity that would occur if the average included voids or adjacent parcels having significantly different or variable properties.

- The averages can resolve extremes of droplet mass concentrations or other variables without dilution.

- The averages can preserve altitude-dependent changes in cloud properties observed during ascents or descents through SLD conditions.

- The scheme can accommodate broken or scattered SLD conditions as well as widespread continuous SLD conditions.

- Not only are data available on the extents of individual, uniform SLD intervals, but the overall horizontal extent (HE) of continuous or semi-continuous SLD conditions is available simply by summing the extents of consecutive events.

B.1.2 PASS-AVERAGE STATISTICS.

As an example of further averaging the data over other intervals for analysis, tables B-4 and B-5 list the maximum and mean values of several important variables for freezing rain (FZRA) and freezing drizzle (FZDZ) conditions, respectively. Sequential events in the database were combined into unidirectional passes through SLD conditions, and the variables were then averaged over these passes. This gives a more realistic idea of what actual flights would encounter.

B.1.3 DATA MILES AS A MEASURE OF FREQUENCY OF OCCURRENCE.

Using the number of cases or number of events, as is conventionally done to represent the frequency of occurrence of any of the variables, is not always satisfactory. The deficiency is twofold. First, momentary SLD events incorrectly carry just as much statistical weight as long-lasting events. Thus, there is no way to emphasize the statistical importance of an extended encounter with an extreme value of SLDLWC, for example, compared to a relatively insignificant, brief encounter. Second, the reader would have no information as to whether a given number of events represented 5 miles or 500 miles of in-flight measurements.

Data miles were therefore chosen as the most informative measure of frequency of occurrence. The term is defined as the distance flown (in nautical miles) during an individual SLD event. This convention automatically weights each SLD event (or measurement of SLDLWC, for example) by its duration or extent. The other principal advantage is that the reader can easily judge the statistical significance of a data set by the number of data miles it represents.

B.1.4 DATA FORMAT.

Table B-1 lists all of the variables that have been selected to describe the events.

A sample printout of all the variables associated with a few representative events is given in table B-6.

B.2 BIASES AND DEFICIENCIES IN THE DATA.

B.2.1 GEOGRAPHIC LIMITATIONS.

The SLD data in the master database were collected at a few locations in North America, such as the Great Lakes area, Colorado, Kansas, California, the Canadian east coast, and the Canadian Arctic, and a limited amount of data from Europe and the southern tip of South America.

There are known differences between geographical areas, however. For example, maritime areas have larger drops and lower drop concentrations. The frequency of occurrence of SLD conditions also varies by location, according to recent climatological studies. This has been confirmed by aircraft measurement campaigns. There is evidence that SLD has a high frequency of occurrence near the southern tip of South America and perhaps in Europe. However, there are very few in situ measurements from these areas. Nevertheless, if more data from these and other geographical locations are obtained, neither the representative LWC distributions nor the extreme values for LWC and other variables are expected to change significantly from those given in this report.

B.2.2 LACK OF CONVECTIVE CLOUD DATA.

Nearly all the data collected for this database belong to wintertime, stratiform cloud conditions because these are believed to be the primary source of reported, SLD-related accidents and incidents. It is known, however, that SLD are generally plentiful in warm-season, vigorously growing convective clouds (Cg, TCu, Cb)* above the freezing level. Changnon, et al. [B-2], report that for large, growing convective clouds in Illinois, “Typical in-cloud results at -10°C reveal multiple updrafts that tend to be filled with large amounts of supercooled drizzle and raindrops.” This means that aircraft penetrating the cores of these clouds in the 0° to -20°C range can expect to encounter intense bursts of SLD. The presence of substantial SLD in these updraft cores may cause the windshield to ice over more than usual and may prompt the flight crew to report severe icing conditions. Individual updraft cores are generally less than 1 or 2 km wide, however, and the characterization of these cloud penetrations would be analogous to the intermittent maximum conditions in Title 14 Code of Federal Regulations Part 25, Appendix C (hereinafter referred to as *Appendix C*).

Nevertheless, practically no SLD data from summer convective clouds has been obtained for this database. The main reasons were the emphasis on wintertime SLD concerns and the formidable effort that would be involved in finding, collecting, processing, and analyzing any available summer SLD data. Some practical factors that may mitigate the need for a characterization of summer SLD conditions are the relative ease of recognizing and avoiding strong convective activity, the confinement of summer SLD to relatively high altitudes (generally above 10,000 feet in the low- and mid-latitudes), and the relative brevity of inadvertent exposures (at least in Cg and TCu).

Some additional considerations are the following:

- The current intermittent maximum envelopes in *Appendix C* apply only to wintertime convective (cumuliform) clouds. They do not apply to thunderstorm interiors or to summertime, strongly convective clouds [B-3].

- Although an instantaneous maximum set of design conditions with LWCs up to 5 g/m^3 over 1/2-mile HEs, intended for representing summertime or tropical, tall convective clouds, was proposed by the National Advisory Committee for Aeronautics National Weather Service (in table 1 of reference B-4), they were never selected by the FAA for use in *Appendix C*. Thus, there is no precedent in *Appendix C* for including summertime icing conditions in ice protection design criteria.

- Thunderstorm interiors and strongly convective summertime clouds can contain shafts of SLD (see references B-2 and B-5, for example). Therefore, although these shafts can contain intense bursts of SLDLWC, the exposures are brief and are generally limited to conditions where the flight and freezing level is 10,000 ft or more above ground level (AGL).

- Some data exist (see references B-2 and B-5) for these summertime SLD conditions, but at this writing, none have been obtained from the original sources for inclusion in the database.

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* Cg—cumulus congestous, TCu—towering cumulus, Cb—cumulonimbus

Nevertheless, a recent fatal accident (TransAsia Airways Flight GE791, December 21, 2002) and a recent incident (Comair Flight 5054, March 19, 2001) demonstrate that high altitude (18,000 ft in both cases), 5- to 20-minute exposures to icing, and possible FZDZ aloft can cause loss of control that cannot always be recovered, even in 10,000 ft or more of warm air below a high freezing level. Because of this, there is a need to eventually add such conditions to the wintertime SLD data, which were the first concern. In the meantime, the existing intermittent maximum conditions in *Appendix C*, with LWCs up to 2.5 g/m^3, remain the closest substitute for summertime, high-altitude SLD conditions.

B.3 REFERENCES.

B-1. Jeck, R.K., “A New Data Base of Supercooled Cloud Variables for Altitudes up to 10,000 Feet AGL and the Implications for Low-Altitude Aircraft Icing,” FAA report DOT/FAA/CT-83/21, August 1983.

B-2. Changnon, S.A., et al., “Illinois Precipitation Research: A Focus on Cloud and Precipitation Modification,” *Bulletin of the American Meteorological Society*, 1991, pp. 587.

B-3. Lewis, W., “Review of Icing Criteria,” *Aircraft Ice Protection*, the report of a symposium sponsored by the FAA on April 28-30, 1969, Federal Aviation Administration, Washington, DC 20591.

B-4. Jones, A.R. and Lewis, W., “Recommended Values of Meteorological Factors to be Considered in the Design of Aircraft Ice-Prevention Equipment,” NACA TN-1855, March 1949.

B-5. Isaac, G.A. and Schemenauer, R.S., “Large Particles in Supercooled Regions of Northern Canadian Cumulus Clouds,” *Journal of Applied Meteorology*, Vol. 18, 1979, pp. 1056-1065.

B-6. Marshall, J.S. and Palmer, W., “The Distribution of Raindrops With Size,” *Journal of Meteorology*, Vol. 5, 1948, pp. 165-166.

B-7. Fiebrich, C.A., “Interesting Ice Accumulation on a Cup Anemometer During an Oklahoma Ice Storm,” *Bulletin of the American Meteorological Society*, May 2003, pp. 551-552.

Table B-1. Description of the Principal Variables

FLIGHT INFORMATION		
Variable	Type	Explanation or Example
PROJECT	Char	CFDE-1, SCPP, EURICE, etc., (see appendix A).
DATE	Num	MMDDYY that the flight took place
AGENCY	Char	MSC (CV-580), NASA (DH-6), etc., where the type of aircraft is given in parentheses.
LOCATION	Char	Name of the nearest city, airport, or Lat, Long for the sample
LOC_ID	Char	3-letter location code, such as DEN, SFO, STL, etc.
SURFELEV	Num	The elevation of the local surface in feet above sea level. Special missing data indicators are M, U, E, V, for mountainous, unknown, estimated, and variable values (consult ELEVNOTE for additional information).
ELEVNOTE	Char	For example, an entry of "5000-8500" indicates that the surface elevation ranges between 5000 and 8500 ft in the nearby downwind vicinity of the measurements.
ALT_CONV	Char	ASL, PA, or AGL indicate that all the height or altitude data are in terms of height above sea level, pressure altitude, or height above ground level, respectively.
TIMECONV	Char	Time zone code applicable to ST_TIME. For example, GMT = Greenwich Mean Time, MDT = Mountain Daylight Time (USA), PST = Pacific Standard Time (USA).
PROBE_ID	Char	Identifies which Particle Measuring Systems, Inc. (PMS) probes (FSSP, 1D-C, 2D-C 1D-P or 2D-P) were in use during the flight.
DIACUTOF	Char	The largest droplet size (mm) measurable by the available PMS probes.
CLOUD INFORMATION		
Variable	Type	Explanation or Example
CLOUDGRP	Char	A letter, A, B, C, etc., denoting a group of similar type clouds being sampled.
CLOUDNUM	Num	A number, 1, 2, 3, etc., denoting which cloud in CLOUDGRP contributed to the data for the present observation.
CLD_PASS	Char	A number, 1, 2, 3, etc., indicating which pass the current observation represents through the cloud identified by CLOUDGRP and CLOUDNUM.
CLOUDTYP	Char	Conventional cloud type abbreviations such as Cu, Sc, St, etc.
CLD_DIST	Char	Descriptive words, such as broken, scattered, etc., to indicate the prevailing cloud distribution.

Table B-1. Description of the Principal Variables (Continued)

CLOUD INFORMATION (continued)		
Variable	Type	Explanation or Example
CLDSTATE	Char	Coded notation indicating the state of the cloud particles sampled by the aircraft. For example: W = all water droplets, I = all ice particles, etc., (see table B-2).
PRECIP	Char	Conventional notation indicating the type and intensity of precipitation, if any, observed at flight level from the aircraft (a/c) or on the ground (gnd) below the cloud under study. For example: S- = light snow, G+ = heavy graupel, etc., (see table B-2).
CLDBASHT	Num	Numerical values, such as 3,650, 12,000, etc., giving cloud base height in feet according to the convention defined by ALT_CONV for the flight in question. Special missing data indicators are U, V, and E for unknown, variable, or estimated values (consult CLDBHNOT for additional information).
CLDBHNOT	Char	Additional information on the cloud base height. For example, the entry CLDBHNOT=11000 (along with CLDBASHT=E) indicates that the cloud base is estimated to be at 11,000 feet.
CLDTOPHT	Num	Numerical values giving cloud top height in feet at the time of the observation. (Other usage is the same as for CLDBASHT above.)
CLDTHNOT	Char	(Same usage as for CLDBHNOT above.)
CLDBAS_T	Num	Numerical values giving cloud base temperature in degrees Celsius. Special symbols for missing data are U, V, and E as above.
CLDBTNOT	Char	Additional information on cloud base temperature when CLDBAS_T = E or V.
CLDTOP_T	Num	Numerical values giving cloud top temperature in degrees Celsius. Special symbols for missing data are U, V, and E as above.
CLDTTNOT	Char	Additional information on cloud top temperature when CLDTOP_T = E or V.
WEATHER FACTORS		
Variable	Type	Explanation or Example
AIRMASS	Char	Conventional air mass abbreviations such as: mT = maritime tropical, McP = modified continental polar, etc.

Table B-1. Description of the Principal Variables (Continued)

WEATHER FACTORS (Continued)		
Variable	Type	Explanation or Example
WEATHER	Char	A coded description of the weather conditions associated with the clouds under study. A list of the code symbols are given in table B-2. For example, "Lc 200nm W & Ws Pr(S-)" means "a low pressure center 200 nautical miles to the west and widespread precipitation (light snow)."
SURFTEMP	Num	The surface air temperature (°C) in the vicinity of the airplane position.
FRZGLVL1	Num	The height (ft) of the lowest freezing level.
FRZGLVL2	Num	The height (ft) of the 2^{nd} lowest freezing level, if any.
FRZGLVL3	Num	The height (ft) of the 3^{rd} lowest freezing level, if any.
EVENT-RELATED VARIABLES		
Variable	Type	Explanation or Example
EVENT	Num	Sequential number of the event during the flight.
HEADING	Num	The average aircraft heading during this event.
ST_TIME	Char	The time, HH:MM:SS, at the beginning of the sample.
END_TIME	Char	The time, HH:MM:SS, at the end of the sample.
DURATION	Num	A number indicating the time duration (in seconds) of the SLD sample.
DISTANCE	Num	A number indicating the distance (in nautical miles) traveled by the aircraft during the sample.
EVENTDEF	Char	A letter code, A, B, C, etc., to indicate why the sample was terminated. The code is given in table B-3.
MANEUVER	Char	A description (level, slant, spiral) of the aircraft flight path during the sample.
EVENT-AVERAGED VARIABLES		
Variable	Type	Explanation or Example
TAS	Num	Average true airspeed (knots) during the sample.
ALT	Num	Average altitude (feet) during the sample, according to the convention defined by ALT_CONV.
TEMP	Num	Average outside (true) air temperature (°C) during the sample.
ICNGRATE	Num	Average icing rate (mm/min) indicated by an icing rate meter (usually a Rosemount model 871FA).
JWLWC	Num	Average value of the liquid water content (g/m^3) indicated by a Johnson-Williams hot-wire LWC meter.
KINGLWC	Num	Average value of the liquid water content (g/m^3) indicated by a CSIRO-King hot-wire LWC meter.

Table B-1. Description of the Principal Variables (Continued)

EVENT-AVERAGED VARIABLES (Continued)		
Variable	Type	Explanation or Example
FLWC	Num	Average value of the LWC (g/m^3) computed from the droplet size distribution indicated by the FSSP probe.
FSSPMVD	Num	Average value of the MVD computed from the FSSP alone.
FSSPCONC	Num	Average value of the droplet concentration (no./cm^3) indicated by the FSSP.
DRIZLWC	Num	Average value of the LWC (g/m^3) computed from the droplet size distribution between 50 and 500 µm diameter.
RAINLWC	Num	Average value of the LWC (g/m^3) computed from the droplet size distribution above 500 µm diameter.
LWC>50	Num	Average value of the LWC (g/m^3) computed from the droplet size distribution above 50 µm diameter.
TOTL_MVD	Num	Average value of the MVD computed for the entire droplet population of all sizes present.
C50_100	Num	Average value of the droplet concentration (no./liter) in the 50- to 100-µm range of the PMS probe(s).
C100_200	Num	Average value of the droplet concentration (no./liter) in the 100- to 200-µm range of the PMS probe(s).
C200_300	Num	Average value of the droplet concentration (no./liter) in the 200- to 300-µm range of the PMS probe(s).
C300_400	Num	Average value of the droplet concentration (no./liter) in the 300- to 400-µm range of the PMS probe(s).
C400_500	Num	Average value of the droplet concentration (no./liter) in the 400- to 500-µm range of the PMS probe(s).
C0.5_1	Num	Average value of the droplet concentration (no./liter) in the 0.5- to 1-mm range of the PMS probe(s).
C1_1.5	Num	Average value of the droplet concentration (no./liter) in the 1- to 1.5-mm range of the PMS probe(s).
C1.5_2	Num	Average value of the droplet concentration (no./liter) in the 1.5- to 2-mm range of the PMS probe(s).
C2_3	Num	Average value of the droplet concentration (no./liter) in the 2- to 3-mm range of the PMS probe(s).
C3_4	Num	Average value of the droplet concentration (no./liter) in the 3- to 4-mm range of the PMS probe(s).
C4_5	Num	Average value of the droplet concentration (no./liter) in the 4- to 5-mm range of the PMS probe(s).

Table B-1. Description of the Principal Variables (Continued)

EVENT-AVERAGED VARIABLES (continued)		
Variable	Type	Explanation or Example
M50_100	Num	Computed mass (g/m^3) of droplets in the 50- to 100-µm range of the PMS probe(s).
M100_200	Num	Computed mass (g/m^3) of droplets in the 100- to 200-µm range of the PMS probe(s).
M200_300	Num	Computed mass (g/m^3) of droplets in the 200- to 300-µm range of the PMS probe(s).
M300_400	Num	Computed mass (g/m^3) of droplets in the 300- to 400-µm range of the PMS probe(s).
M400_500	Num	Computed mass (g/m^3) of droplets in the 400- to 500-µm range of the PMS probe(s).
M0.5_1	Num	Computed mass (g/m^3) of droplets in the 500- to 1000-µm range of the PMS probe(s).
M1_1.5	Num	Computed mass (g/m^3) of droplets in the 1- to 1.5-mm range of the PMS probe(s).
M1.5_2	Num	Computed mass (g/m^3) of droplets in the 1.5- to 2-mm range of the PMS probe(s).
M2_3	Num	Computed mass (g/m^3) of droplets in the 2- to 3-mm range of the PMS probe(s).
M3_4	Num	Computed mass (g/m^3) of droplets in the 3- to 4-mm range of the PMS probe(s).
M4_5	Num	Computed mass (g/m^3) of droplets in the 4- to 5-mm range of the PMS probe(s).

Table B-2. Symbols and Abbreviations

PRECIPITATION CODE SYMBOLS	AGENCY CODES (for use as plotting symbols)	
	Agency	One-Letter Code
A = Hail	MSC (CV-580)	E
E = Sleet	NASA GRC (DH-6)	L
L = Drizzle	UND (Citation-II)	N
R = Rain	Lockheed (C-130J)	J
S = Snow	INTA (C-212)	I
SP = Snow pellets	U. Wyoming (King Air)	Y
ZL = Freezing drizzle	NLR (Fairchild Metro-II)	K
ZR = Freezing rain	NWS radiosonde data	U
+ = heavy	Surface weather observations	S
- = light		
w = showers		

CLOUD NAMES	
Layer Clouds	Convective Clouds
Ac = Altocumulus	Cb = Cumulonimbus
As = Altostratus	Cg = Cumulus congestus
Ln = Lenticular	Cu = Cumulus
Ns = Nimbostratus	TCu = Towering cumulus
Sc = Stratocumulus	
St = Stratus	

One, two, or three of the code letters listed below are assigned to the variable EVENTDEF to indicate why the sample averaging interval (event) was terminated. That is, all the measured variables are averaged over the flight path in the SLD until one of the following is met.

Table B-3. Rules for Defining Uniform SLD Intervals

A	Aircraft exits main cloud or SLD area
B	Outside air temperature (TEMP) changes by ±1.5°C
C	Outside air temperature (TEMP) rises above 0°C
E	Aircraft changes altitude (ALT) by ±500 feet (±150 meters)
H	Averaging interval arbitrarily terminated by the analyst
I	Icing rate crosses the 1-mm/min threshold (either way) for at least 1 nmi
K	Subsequent data from the FSSP is invalidated by snow or ice particles
L	Errors or malfunction of the 1- or 2-dimensional probe data
M	DWC and RWC decreases to below 0.01 g/m^3
N	DWC or RWC crosses the 0.1, 0.2, or 0.3 g/m^3 threshold (either way) for at least 1 nmi
Q	Airplane enters or exits an FSSP-recognizable cloud (generally defined by FSSPLWC >0.05 g/m^3 or FSSPCONC >50 cm^{-3})
R	Total (overall) MVD crosses the 50- or 500-µm threshold (either way) for at least 1 nmi
T	Airplane turns to reverse direction with respect to original (or last) heading

Note: A new event may or may not begin immediately after the termination of the present event, depending on the cloud and SLD conditions that follow.

Table B-4. Pass-Average Statistics for Freezing Rain From the Master SLD Database (October 2003 version)

Variable	Maximum Range	Mean Value
RWC (g/m^3)	0 to 0.3*	0.10
TWC (g/m^3)	0 to 0.5	0.2
Outside air temperature (°C)	0 to -7	-2
Altitude (ft AGL)	0 to 6900	3000
Icing rate (mm/min)	0 to 2	0.5
Pass length (nmi)	1 to 80	12
No. of passes	101	
Total FZDZ miles	1260 nmi	

* RWC = 0.3 g/m^3 corresponds to a rain rate of R = 4 mm/hr, from formula RWC=0.09(R**0.84), from Marshall & Palmer [B-6], or from R=3.6(RWC)($V_{fallspeed}$). (Note: A FZRA storm on 28-30 January 2002 in Oklahoma produced a rain rate of about 5 mm/hr for 2 hours on one of those days [B-7].)

Table B-5. Pass-Average Statistics for Freezing Drizzle From the Master SLD Database (October 2003 version)

Variable	Maximum Range	Mean Value
DWC (g/m^3)	0 to 0.4	0.07
TWC (g/m^3)	0 to 0.7	0.18
Outside air temperature (°C)	0 to -24	-6
Altitude (ft AGL)	0 to 18,000	6600
Icing rate (mm/min)	0 to 2.7	0.6
Pass length (nmi)	1 to 90	12
No. of passes	261	
Total FZDZ miles	3,057 nmi	

Table B-6. Sample Contents of the Master SLD Database at the FAA William J. Hughes Technical Center

Note: Missing values may be indicated by the characters A, U, X, and ".", where A=Absent, U=Unknown, X=malfunctioning, and "." = missing (i.e, value not entered yet).

Rec No.	PROJECT	AGENCY	ALT_CONV	AIRMASS	WEATHER	LOCATION	LOC_ID	ELEVNOTE
1	SCPP-85	U. Wyo.(King Air)	PA	mP	.	Central California Mountains	.	mountainous
2	SCPP-85	U. Wyo.(King Air)	PA	mP	.	Central California Mountains	.	mountainous
3	SCPP-85	U. Wyo.(King Air)	PA	mP	.	Central California Mountains	.	mountainous
4	SCPP-85	U. Wyo.(King Air)	PA	mP	.	Central California Mountains	.	mountainous
5	UND/FAA Icing Studies	U. No. Dakota (Citation II)	PA	cP	TCf & ZR	Kansas City, Missouri area	MKC	low hills
6	UND/FAA Icing Studies	U. No. Dakota (Citation II)	PA	cP	TCf & ZR	Kansas City, Missouri area	MKC	low hills
7	UND/FAA Icing Studies	U. No. Dakota (Citation II)	PA	cP	TCf & ZR	Kansas City, Missouri area	MKC	low hills
8	UND/FAA Icing Studies	U. No. Dakota (Citation II)	PA	cP	TCf & ZR	Kansas City, Missouri area	MKC	low hills
9	UND/FAA Icing Studies	U. No. Dakota (Citation II)	PA	cP	TCf & ZR	Kansas City, Missouri area	MKC	low hills
10	UND/FAA Icing Studies	U. No. Dakota (Citation II)	PA	cP	TCf & ZR	Kansas City, Missouri area	MKC	low hills
11	UND/FAA Icing Studies	U. No. Dakota (Citation II)	PA	cP	TCf & ZR	Kansas City, Missouri area	MKC	low hills
12	UND/FAA Icing Studies	U. No. Dakota (Citation II)	PA	cP	TCf & ZR	Kansas City, Missouri area	MKC	low hills
13	UND/FAA Icing Studies	U. No. Dakota (Citation II)	PA	cP	TCf & ZR	Kansas City, Missouri area	MKC	low hills
14	UND/FAA Icing Studies	U. No. Dakota (Citation II)	PA	cP	TCf & ZR	Kansas City, Missouri area	MKC	low hills
15	WISP-94	U. Wyo.(King Air)	PA	.	.	Denver, Colorado area	GXY	uneven, hilly
16	WISP-94	U. Wyo.(King Air)	PA	.	.	Denver, Colorado area	GXY	uneven, hilly
17	WISP-94	U. Wyo.(King Air)	PA	.	.	Denver, Colorado area	AKO	uneven, hilly
18	WISP-94	U. Wyo.(King Air)	PA	.	.	Denver, Colorado area	.	uneven, hilly
19	WISP-94	U. Wyo.(King Air)	PA	.	.	Denver, Colorado area	.	uneven, hilly
20	WISP-94	U. Wyo.(King Air)	PA	.	.	Denver, Colorado area	.	uneven, hilly
21	WISP-94	U. Wyo.(King Air)	PA	.	.	Denver, Colorado area	.	uneven, hilly
22	WISP-94	U. Wyo.(King Air)	PA	.	.	Denver, Colorado area	.	uneven, hilly
23	WISP-94	U. Wyo.(King Air)	PA	.	.	Denver, Colorado area	.	uneven, hilly
24	WISP-94	U. Wyo.(King Air)	PA	.	.	Denver, Colorado area	.	uneven, hilly
25	NASA/FAA SLD Flights	NASA/LeRC (Twin Otter)	PA	cP	.	Cleveland, Ohio area	.	.
26	NASA/FAA SLD Flights	NASA/LeRC (Twin Otter)	PA	cP	.	Cleveland, Ohio area	.	.

Rec No.	CLOUDTYP	CLD_DIST	CLDBTNOT	CLDTHNOT	CLDTTNOT	CLOUDGRP	TIMECONV	EVENTDEF	MANEUVER	PRECIP	CLDSTATE
1	.	.	.	.	.	A	GMT	J	Level	U	.
2	.	.	.	.	.	A	GMT	J	Level	U	.
3	.	.	.	.	.	A	GMT	H	Level	U	.
4	.	.	.	.	.	A	GMT	A	Level	U	.
5	St	scatt	.	>2900 ft	.	A	CST	E	Level	ZR	W
6	St	scatt	.	>2900 ft	.	A	CST	E	Descent	ZR	
7	St	scatt	.	>2900 ft	.	A	CST	E	Descent	ZR	
8	St	scatt	.	>2900 ft	.	A	CST	E	Descent	ZR	
9	St	scatt	.	>2900 ft	.	A	CST	E	Descent	ZR	
10	St	scatt	.	>2900 ft	.	A	CST	E	Ascent	ZR	
11	St	scatt	.	>2900 ft	.	A	CST	E	Ascent	ZR	
12	St	scatt	.	>2900 ft	.	A	CST	E,C	Ascent	ZR	W
13	St	scatt	.	>2900 ft	.	A	CST	E	Ascent	ZR	
14	St	scatt	.	>2900 ft	.	A	CST	H	Ascent	ZR	
15	.	.	.	.	inversion at top	1	MST	H	descent	U	mW
16	.	.	.	.	inversion at top	1	MST	A,E	Level	U	mW
17	.	.	.	.	inversion at top	1	MST	B,Q	Level	U	mW
18	.	.	.	.	inversion at top	1	MST	B,Q	Level	U	mW
19	.	.	.	.	inversion at top	1	MST	B,Q	Level	U	mW
20	.	.	.	.	inversion at top	1	MST	H	Level	U	mW
21	.	.	.	.	inversion at top	1	MST	E	Level	U	mW
22	.	.	.	.	inversion at top	1	MST	E,A	Level	U	mW
23	.	Wave tops	.	.	inversion at top	1	MST	Q,B	Level	U	mW
24	.	Wave tops	.	.	inversion at top	1	MST	Q,B	Level	U	mW
25	St	continuous	.	.	inversion at top	A	GMT	H	Level	U	W
26	St	continuous	.	.	inversion at top	A	GMT	H	Level	U	W

Rec No.	PROBE_ID	DIACUTOF	DATE	ST_TIME	END_TIME	AGCYID	SURFTEMP	FRZLVL_1	FRZLVL_2	FRZLVL_3	SURFELEV	CLOUDNUM
1	PMS 1DC+2DC+2DP	6.4mm	Feb 7, 1985	21:31:04	21:36:53	Y	8	5250	A	A	.	1
2	PMS 1DC+2DC+2DP	6.4mm	Feb 7, 1985	21:43:01	21:43:47	Y	8	5250	A	A	.	1
3	PMS 1DC+2DC+2DP	6.4mm	Feb 7, 1985	21:44:33	21:53:30	Y	8	5250	A	A	.	1
4	PMS 1DC+2DC+2DP	6.4mm	Feb 7, 1985	21:53:50	22:02:00	Y	8	5250	A	A	.	1
5	PMS 1DC+1DP	4.5mm	Jan 19, 1990	12:01:30	12:04:00	N	-1	760	2780	9500	760	1
6	PMS 1DC+1DP	4.5mm	Jan 19, 1990	12:04:01	12:04:38	N	-1	760	2780	9500	760	.
7	PMS 1DC+1DP	4.5mm	Jan 19, 1990	12:04:39	12:05:08	N	-1	760	2780	9500	760	.
8	PMS 1DC+1DP	4.5mm	Jan 19, 1990	12:05:09	12:05:44	N	-1	760	2780	9500	760	.
9	PMS 1DC+1DP	4.5mm	Jan 19, 1990	12:05:45	12:06:10	N	-1	760	2780	9500	760	.
10	PMS 1DC+1DP	4.5mm	Jan 19, 1990	12:06:11	12:06:25	N	-1	760	2780	9500	760	.
11	PMS 1DC+1DP	4.5mm	Jan 19, 1990	12:06:26	12:06:40	N	-1	760	2780	9500	760	.
12	PMS 1DC+1DP	4.5mm	Jan 19, 1990	12:06:41	12:07:07	N	-1	760	2780	9500	760	2
13	PMS 1DC+1DP	4.5mm	Jan 19, 1990	12:07:08	12:07:44	N	-1	760	2780	9500	760	.
14	PMS 1DC+1DP	4.5mm	Jan 19, 1990	12:07:45	12:08:01	N	-1	760	2780	9500	760	.
15	PMS 1DC+2DC+2DP	6.4mm	Feb 21, 1994	12:28:17	12:28:52	Y	.	7300	A	A	5000	1
16	PMS 1DC+2DC+2DP	6.4mm	Feb 21, 1994	12:29:47	12:34:19	Y	.	7300	A	A	4950	1
17	PMS 1DC+2DC+2DP	6.4mm	Feb 21, 1994	12:45:50	12:48:12	Y	.	7300	A	A	4500	1
18	PMS 1DC+2DC+2DP	6.4mm	Feb 21, 1994	12:50:13	12:51:09	Y	.	7300	A	A	.	1
19	PMS 1DC+2DC+2DP	6.4mm	Feb 21, 1994	12:54:09	12:56:36	Y	.	7300	A	A	.	1
20	PMS 1DC+2DC+2DP	6.4mm	Feb 21, 1994	12:59:08	13:01:07	Y	.	7300	A	A	.	1
21	PMS 1DC+2DC+2DP	6.4mm	Feb 21, 1994	13:03:12	13:04:46	Y	.	7300	A	A	.	1
22	PMS 1DC+2DC+2DP	6.4mm	Feb 21, 1994	13:06:00	13:06:46	Y	.	7300	A	A	.	1
23	PMS 1DC+2DC+2DP	6.4mm	Feb 21, 1994	13:24:03	13:32:35	Y	.	7300	A	A	.	1
24	PMS 1DC+2DC+2DP	6.4mm	Feb 21, 1994	13:34:47	13:42:04	Y	.	7300	A	A	.	1
25	PMS 1DC+2DC	.97mm	Jan 27, 1997	13:49:00	13:57:15	L	0	800	A	A	800	1
26	PMS 1DC+2DC	.97mm	Jan 27, 1997	14:29:45	14:37:15	L	0	800	A	A	800	1

Rec No.	CLD_PASS	CLDBASHT	CLDTOPHT	CLDBAS_T	CLDTOP_T	DURATION	DISTANCE	TAS	ALT	TEMP	ICNGRATE	JWLWC	KINGLWC	FSSPLWC	FSSPMVD
1	1	.	.	.	.	349	16.0	165	10000	-7.9	.	.	.	0.08	23
2	1	.	.	.	.	46	2.1	167	10000	-7.5	.	.	.	0.00	.
3	2	.	.	.	.	537	25.0	170	10000	-7.5	.	.	.	0.00	.
4	3	.	.	.	.	490	22.0	165	9250	-7.0	.	.	.	0.04	21
5	1	1550	.	-2.7	.	151	6.6	157	2334	-2.8	.	X	A	0.03	14
6	1	1550	.	-2.7	.	38	1.7	160	2120	-3.5	.	X	A	0.02	18
7	1	1550	.	-2.7	.	30	1.4	165	1602	-2.9	.	X	A	0.01	.
8	1	1550	.	-2.7	.	36	1.6	157	1103	-1.6	.	X	A	0.00	.
9	1	1550	.	-2.7	.	26	1.1	153	950	-1.1	.	X	A	0.00	.
10	1	1550	.	-2.7	.	15	0.7	162	1505	-2.7	.	X	A	0.00	.
11	1	1550	.	-2.7	.	15	0.7	168	2037	-3.7	.	X	A	0.00	.
12	1	1550	.	-2.7	.	27	1.3	169	2575	-1.5	.	X	A	0.05	12
13	1	1550	.	-2.7	.	37	1.8	179	2932	2.9	.	X	A	0.01	.
14	1	1550	.	-2.7	.	17	0.8	173	3385	4.0	.	X	A	0.01	.
15	1	U	7830	U	-9.1	36	1.7	170	7630	-9.1	.	0.13	0.30	0.55	.
16	1	U	7830	U	-9.1	273	12.0	155	6920	-6.9	.	.	.	.	.
17	2	U	7830	U	-9.1	143	7.4	186	7620	-9.4	.	.	.	.	.
18	2	U	7830	U	-9.1	57	2.9	183	7620	-9.6	.	.	.	.	.
19	2	U	7830	U	-9.1	148	7.2	175	7450	-9.5	.	.	.	.	.
20	2	U	7830	U	-9.1	120	6.1	183	7665	-10.2	.	.	.	.	.
21	2	U	7830	U	-9.1	95	4.6	174	5040	-7.5	.	.	.	.	.
22	2	U	7830	U	-9.1	47	2.2	168	7600	-9.6	.	.	.	.	.
23	3	U	7830	U	-9.1	513	25.0	176	7670	-9.9	.	.	.	.	.
24	4	U	7830	U	-9.1	438	21.0	174	7700	-9.9	.	.	.	.	.
25	1	6000	8200	-3.0	-6.0	495	19.0	135	6550	-3.6	.	A	0.34	0.31	18
26	2	6000	8200	-3.0	-6.0	450	17.0	135	6550	-3.8	.	A	0.31	0.29	20

Rec No.	FSSPCONC	DRIZLWC	RAINLWC	LWCGT50	M50_100	M100_200	M200_300	M300_400	M400_500	M05_1MM	M1_15MM	M15_2MM	M2_3MM	M3_4MM
1	77	0.220	0.000	0.220	.020	.030	.070	.070	.030	.000	.000	.000	.000	.000
2	0	0.030	0.000	0.030	.000	.002	.015	.006	.003	.000	.000	.000	.000	.000
3	8	0.120	0.000	0.120	.015	.030	.040	.025	.008	.006	.000	.000	.000	.000
4	17	0.220	0.000	0.220	.020	.040	.070	.060	.030	.	.000	.000	.000	.000
5	80	0.011	0.142	0.153	.000	.001	.003	.003	.004	.070	.041	.025	.004	.001
6	25	0.009	0.180	0.189	.000	.002	.003	.003	.001	.066	.065	.043	.005	.000
7	1	0.008	0.163	0.171	.000	.001	.003	.002	.003	.071	.049	.034	.008	.000
8	1	0.005	0.128	0.133	.000	.001	.001	.001	.001	.048	.030	.021	.027	.002
9	0	0.011	0.082	0.093	.000	.001	.001	.000	.009	.029	.022	.023	.007	.000
10	0	0.002	0.154	0.156	.000	.001	.001	.000	.000	.028	.022	.016	.011	.013
11	1	0.005	0.145	0.151	.000	.000	.002	.003	.000	.030	.022	.034	.041	.017
12	87	0.017	0.169	0.186	.000	.002	.003	.004	.008	.055	.038	.031	.040	.005
13	1	0.007	0.149	0.156	.000	.001	.002	.003	.002	.057	.039	.038	.014	.000
14	1	0.002	0.134	0.137	.000	.001	.001	.000	.000	.054	.042	.031	.007	.000
15	263	0.004	0.000	0.004	.002	.002	.000	.000	.000	.000	.000	.000	.000	.000
16	331	0.006	0.000	0.006	.002	.002	.000	.001	.001	.000	.000	.000	.000	.000
17	185	0.004	0.000	0.004	.001	.001	.002	.000	.000	.000	.000	.000	.000	.000
18	170	0.001	0.000	0.001	.001	.000	.000	.000	.000	.000	.000	.000	.000	.000
19	177	0.004	0.000	0.004	.003	.001	.000	.000	.000	.000	.000	.000	.000	.000
20	210	0.003	0.000	0.003	.003	.001	.000	.000	.000	.000	.000	.000	.000	.000
21	470	0.015	0.000	0.015	.002	.005	.003	.002	.003	.000	.000	.000	.000	.000
22	205	0.006	0.000	0.006	.004	.002	.000	.000	.000	.000	.000	.000	.000	.000
23	190	0.004	0.000	0.004	.003	.001	.000	.000	.000	.000	.000	.000	.000	.000
24	245	0.005	0.000	0.005	.004	.001	.000	.000	.000	.000	.000	.000	.000	.000
25	162	0.036	0.000	0.036	.035	.001	.000	.000	.000	.000	.000	.000	.000	.000
26	114	0.037	0.000	0.037	.032	.005	.000	.000	.000	.000	.000	.000	.000	.000

Rec No.	C50_100	C100_200	C200_300	C300_400	C400_500	C05_1MM	C1_15MM	C15_2MM	C2_3MM	C3_4MM	C4_5MM	TOTL_MVD
1	124	13.0	8.00	3.00	0.50	0.0	0.00	.000	.0000	.0000	.0000	170
2	0.5	0.7	1.70	0.20	0.05	0.0	0.00	.000	.0000	.0000	.0000	110
3	104	15.0	5.00	1.00	0.10	0.0	0.00	.000	.0000	.0000	.0000	170
4	185	16.0	8.00	3.00	0.70	.	0.00	.000	.0000	.0000	.0000	160
5	1.4	0.7	0.34	0.13	0.09	0.4	0.04	.011	.0006	.0001	.0000	650
6	1.5	1.0	0.31	0.16	0.04	0.3	0.06	.019	.0011	.0000	.0000	900
7	1.1	0.5	0.32	0.09	0.07	0.4	0.05	.015	.0010	.0000	.0000	950
8	1.3	0.6	0.20	0.04	0.03	0.3	0.03	.009	.0040	.0001	.0000	800
9	1.4	0.5	0.16	0.00	0.19	0.1	0.02	.009	.0015	.0000	.0000	850
10	0.4	0.3	0.18	0.00	0.00	0.2	0.02	.007	.0020	.0007	.0013	1300
11	1.2	0.2	0.31	0.10	0.00	0.1	0.02	.013	.0050	.0010	.0000	750
12	1.9	1.3	0.32	0.16	0.17	0.3	0.04	.013	.0059	.0004	.0000	500
13	1.3	0.7	0.26	0.13	0.05	0.3	0.04	.016	.0030	.0000	.0000	850
14	0.4	0.4	0.08	0.04	0.00	0.3	0.04	.014	.0012	.0000	.0000	900
15	21.0	1.0	0.00	0.00	0.00	0.0	0.00	.000	.0000	.0000	.0000	.
16	15.0	1.5	0.05	0.02	0.02	0.0	0.00	.000	.0000	.0000	.0000	.
17	10.0	0.2	0.03	0.00	0.00	0.0	0.00	.000	.0000	.0000	.0000	.
18	9.0	0.4	0.01	0.00	0.00	0.0	0.00	.000	.0000	.0000	.0000	.
19	26.0	1.2	0.01	0.01	0.00	0.0	0.00	.000	.0000	.0000	.0000	.
20	25.0	0.6	0.00	0.00	0.00	0.0	0.00	.000	.0000	.0000	.0000	.
21	19.0	4.0	0.35	0.08	0.06	0.0	0.00	.000	.0000	.0000	.0000	.
22	35.0	2.0	0.02	0.00	0.00	0.0	0.00	.000	.0000	.0000	.0000	.
23	27.0	0.7	0.00	0.00	0.00	0.0	0.00	.000	.0000	.0000	.0000	.
24	45.0	1.0	0.00	0.01	0.00	0.0	0.00	.000	.0000	.0000	.0000	.
25	345	2.0	0.00	0.00	0.00	0.0	0.00	.000	.0000	.0000	.0000	18
26	274	6.0	0.00	0.00	0.00	0.0	0.00	.000	.0000	.0000	.0000	20

APPENDIX C—DEPTH OF FREEZING DRIZZLE AND FREEZING RAIN CONDITIONS

The Federal Aviation Administration (FAA) Master Supercooled Large Drops (SLD) Database contains some cases in which the vertical extent of the SLD conditions is known, due to the vertical profiling accomplished by the research airplanes. These cases have been copied from the database and selected information is displayed in spreadsheet format in tables C-1 and C-2.

In the tables, column H lists, in ascending order, the observed depths of these freezing rain (FZRA) and freezing drizzle (FZDZ) cases, respectively.

From the available data, FZDZ may be as deep as about 12,000 feet, with an average depth of 3500 feet. FZRA is considerably shallower with a maximum observed depth of about 4900 feet, and an average depth of 2900 feet.

There are even fewer cases where the depth of any accompanying clouds is known, but the available data indicate that clouds associated with FZDZ can be up to 7900 feet deep, with an average depth of about 4000 feet. Clouds that are present along with FZRA are shallower, with a maximum observed depth of 3000 feet and an average depth of 1700 feet.

Table C-1. Record of FZRA Depths in the Master SLD Database

	A	B	C	D	E	F	G	H	I	J	K
55				Type of	Time	Lowest	Highest	Depth (ft)	Low Cloud	Low Cloud	Low Cloud
56	Project	Date	Location	SLD	Interval	Altitude(ft)	Altitude(ft)	of FZRA	Base (ft)	Top (ft)	Depth (ft)
57	CFDE-3	7-Jan-98	Pembroke, Ont.	FZRA	1816-1818	1300	1700	400			
58	NASA SLD	4-Feb-98	Parkersburg, WV	FZRA	1832-1932	3025	3710	685			
59	FAA Icing	19-Jan-90	Kansas City	FZRA	1244-1301	1280	2800	1520	1550	2820	1270
60	CFDE-3	8-Jan-98	Trenton, Ont.	FZRA	2251-2257	1090	2830	1740	2000	5000	3000
61	CFDE-3	23-Jan-98	Lake Ontario	FZRA	1926-1933	2495	4640	2145			
62	CFDE-3	8-Jan-98	Montreal	FZRA	2035-2045	1770	4280	2510	1500	3000	1500
63	CFDE-3	8-Jan-98	Ottawa	FZRA	2354-2403	1790	4300	2510	1500	3300	1800
64	NASA SLD	4-Feb-98	Parkersburg, WV	FZRA	1600-1640	1200	3900	2700	1300	3900	2600
65	FAA Icing	19-Jan-90	Kansas City	FZRA	1201-1208	0	2780	2780	1550	2780	1230
66	NASA SLD	24-Jan-97	Cleveland	FZRA	2010-2020	2950	5840	2890			
67	CFDE-3	8-Jan-98	Montreal	FZRA	2110-2112	2410	5800	3390			
68	FAA Icing	1-Feb-90	Kansas City	FZRA	1657-1709	0	3500	3500	2180	3500	1320
69	FAA Icing	1-Feb-90	Kansas City	FZRA	1915-1935	0	3500	3500	1730	2510	780
70	CFDE-3	23-Jan-98	Lake Ontario	FZRA	1912-1918	1805	5360	3555			
71	CFDE-1	10-Mar-95	Newfoundland	FZRA	1654-1659	0	3600	3600	1000	3500	2500
72	CFDE-3	8-Jan-98	Ottawa	FZRA	1931-1935	2540	6620	4080	2600	3300	700
73	CFDE-3	8-Jan-98	Montreal	FZRA	2054-2109	820	5155	4335	1100	3500	2400
74	FAA Icing	14-Feb-90	Kansas City	FZRA	1536-1552	0	4450	4450	2200	3550	1350
75	FAA Icing	14-Feb-90	Kansas City	FZRA	1400-1414	0	4875	4875	1930	3930	2000
76											
77				Column Averages =		1288	4192	2903	1703	3430	1727

Table C-2. Record of FZDZ Depths in the Master SLD Database

	A	B	C	D	E	F	G	H	I	J	K
3				Type of	Time	Lowest	Highest	Depth (ft)	FZDZ Cloud	FZDZ Cloud	FZDZ Cloud
4	Project	Date	Location	SLD	Interval	Altitude(ft)	Altitude(ft)	of FZDZ	Base (ft)	Top (ft)	Depth (ft)
5	NASA SLD	24-Jan-97	Mansfield, OH	FZDZ	2121-2125	9100	9500	400			
6	C-130 Icing	8-Jul-98	Cape Horn	FZDZ	1304-1407	12900	13500	600			
7	CFDE-3	8-Jan-98	Montreal	FZDZ	2117-2119	11420	12290	870			
8	NASA SLD	27-Feb-98	Saginaw, MI	FZDZ	1714-1731	12095	13200	1105			
9	CFDE-3	23-Jan-98	Smiths Falls, Ont.	FZDZ	1704-1707	12410	13580	1170			
10	C-130 Icing	28-Jun-98	Cape Horn	FZDZ	1225-1235	16800	18000	1200			
11	C-130 Icing	5-Jul-98	Cape Horn	FZDZ	1216-1234	11400	12800	1400			
12	CFDE-1	22-Mar-95	Newfoundland	FZDZ	1448-1513	7240	8700	1460			
13	C-130 Icing	25-Jun-98	Cape Horn	FZDZ	1610-1714	9700	11400	1700	9700	11400	1700
14	NASA SLD	12-Jan-98	Kalamazoo, MI	FZDZ	2136-2141	1000	2770	1770	1600	7500	5900
15	NASA SLD	19-Feb-98	Cleveland	FZDZ	1317-1320	2400	4350	1950	1800	5600	3800
16	NASA SLD	20-Mar-97	Sandusky, OH	FZDZ	1322-1342	3960	5940	1980	3700	7000	3300
17	NASA SLD	20-Mar-97	Cleveland	FZDZ	1254-1258	5390	7380	1990	4800	8200	3400
18	NASA SLD	26-Jan-98	Green Bay, WI	FZDZ	1819-1837	2670	4745	2075	1000	6700	5700
19	NASA SLD	26-Jan-98	Green Bay, WI	FZDZ	2020-2042	2290	4615	2325	1100	6200	5100
20	CFDE-3	23-Jan-98	Ottawa	FZDZ	1557-1559	7330	9775	2445			
21	CFDE-1	7-Mar-95	Newfoundland	FZDZ	0612-0616	7050	9545	2495			
22	CFDE-3	8-Jan-98	Trenton, Ont.	FZDZ	2326-2330	11705	14350	2645			
23	CFDE-1	7-Mar-95	Newfoundland	FZDZ	0505-0518	1375	4090	2715			
24	Alaska SLD	20-Jan-00	Juneau, AK	FZDZ	1929-1931	1375	4100	2725			
25	NASA SLD	22-Jan-98	Cleveland	FZDZ	1447-1456	850	3645	2795	2000	5100	3100
26	CFDE-3	23-Jan-98	Lake Ontario	FZDZ	1919-1923	6090	8900	2810			
27	CFDE-3	7-Jan-98	Ottawa	FZDZ	1759-1802	6700	9600	2900			
28	Alaska SLD	20-Jan-00	Juneau, AK	FZDZ	1946-1950	800	3740	2940			
29	NASA SLD	27-Feb-98	Sandusky, OH	FZDZ	1348-1417	11155	14300	3145	7000	14900	7900
30	CFDE-1	9-Mar-95	Newfoundland	FZDZ	1655-1722	885	4090	3205			
31	CFDE-3	17-Feb-98	Lake Ontario	FZDZ	1753-1803	15800	19200	3400			
32	CFDE-3	6-Jan-98	Sudbury, Ont.	FZDZ	2148-2154	1470	5000	3530			
33	Alaska SLD	19-Jan-00	Sitka, AK	FZDZ	2338-2349	1035	4710	3675			
34	NASA SLD	20-Mar-97	Cleveland	FZDZ	1402-1430	2750	6450	3700	3700	6600	2900
35	Alaska SLD	23-Jan-00	Juneau, AK	FZDZ	1937-1944	2755	6460	3705			
36	CFDE-1	7-Mar-95	Newfoundland	FZDZ	0528-0539	1505	5450	3945			
37	NASA SLD	11-Dec-97	Youngstown, OH	FZDZ	1430-1459	1425	5470	4045	1430	7200	5770
38	Alaska SLD	19-Jan-00	Sitka, AK	FZDZ	2440-2453	745	4890	4145			
39	NASA SLD	24-Feb-98	Findlay, OH	FZDZ	1407-1440	3740	7975	4235	3500	6070	2570
40	CFDE-3	23-Jan-98	Lake Ontario	FZDZ	1837-1858	2590	7215	4625			
41	CFDE-3	23-Jan-98	Lake Ontario	FZDZ	1938-1943	6560	11340	4780			
42	Alaska SLD	23-Jan-00	Juneau, AK	FZDZ	2220-2230	680	6400	5720			
43	CFDE-1	9-Mar-95	Newfoundland	FZDZ	1821-1834	660	6925	6265			
44	Alaska SLD	19-Jan-00	Juneau, AK	FZDZ	2255-2300	0	6630	6630			
45	CFDE-1	7-Mar-95	Newfoundland	FZDZ	0623-0634	1450	8375	6925			
46	CFDE-3	7-Jan-98	Trenton, Ont.	FZDZ	2104-2114	6300	16240	9940			
47	NASA SLD	5-Feb-98	Zanesville, OH	FZDZ	1412-1505	1445	11900	10455	2000	3200	1200
48	CFDE-3	7-Jan-98	Ottawa	FZDZ	2153-2209	840	12600	11760			
49											
50				Column Averages =		5178	8685	3507	3333	7359	4026

APPENDIX D—WORLD-WIDE DISTRIBUTION AND FREQUENCY OF FREEZING DRIZZLE AND FREEZING RAIN

D.1 Results From Archived Surface Weather Observations.

A large number of worldwide surface weather observations is available on a set of compact discs available from the U.S. National Climatic Data Center [D-1]. The data are hourly and 3-hourly observations from about 1500 locations and spanning the years 1982 through 1997. A computerized search* of these data found cases where freezing drizzle (FZDZ) or freezing rain (FZRA) were reported. These records were then studied further, primarily to determine frequency of occurrence in major geographical regions and to learn the range and frequency of surface air temperatures in which FZDZ and FZRA occur.

Table D-1 lists the gross geographic variability.

Table D-1. Geographical Occurrences of FZDZ and FZRA

Number of Reports in 15 Years		
Region	FZDZ	FZRA
Worldwide	96,900	71,800
United States	67,800	57,600
Europe	22,300	10,800
Asia and SE Europe	6,500	3,300
Tropical and Other*	300	100

*Includes Middle-East, Africa, South America, the Caribbean, and Australia

Note, although the relative number of reports in each geographic region seems reasonable as an indication of the comparative probabilities of occurrence, a major bias exists that prevents exact comparisons. This is because the National Climatic Data Center archive data set contains hourly records for most U.S. reporting stations but only 3-hourly, or sometimes 6-hourly, records from the other geographic regions. This means that FZRA and FZDZ events may be underreported for locations outside the U.S. For example, a FZDZ event lasting 6 hours would be reported six or seven times with hourly records, but only two or three times with 3-hourly records, and only once or twice with 6-hourly records. Some events lasting less than 3 hours could be missed altogether in 3-hourly records, and some events lasting less than 6 hours could be missed in 6-hourly records.

Figures D-1 and D-2 display the combined worldwide frequency of occurrence of different air temperatures observed along with FZDZ and FZRA, respectively. For both types, 99 percent of the events occurred at surface air temperatures greater than -10°C.

* Thanks to Manny Rios (Flight Safety Team, Federal Aviation Administration William J. Hughes Technical Center) for this major effort.

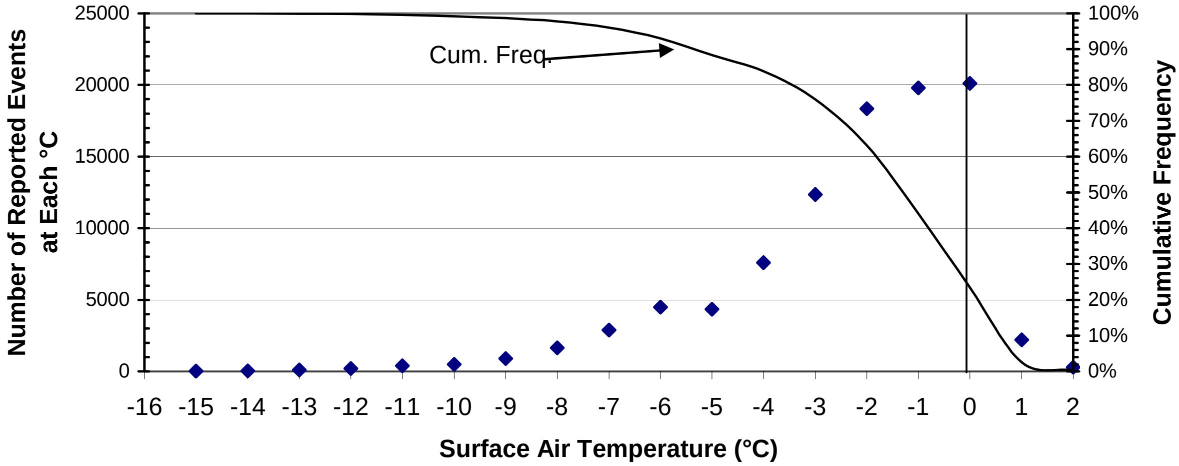

Figure D-1. Worldwide Frequency of FZDZ Over 16-Year Period

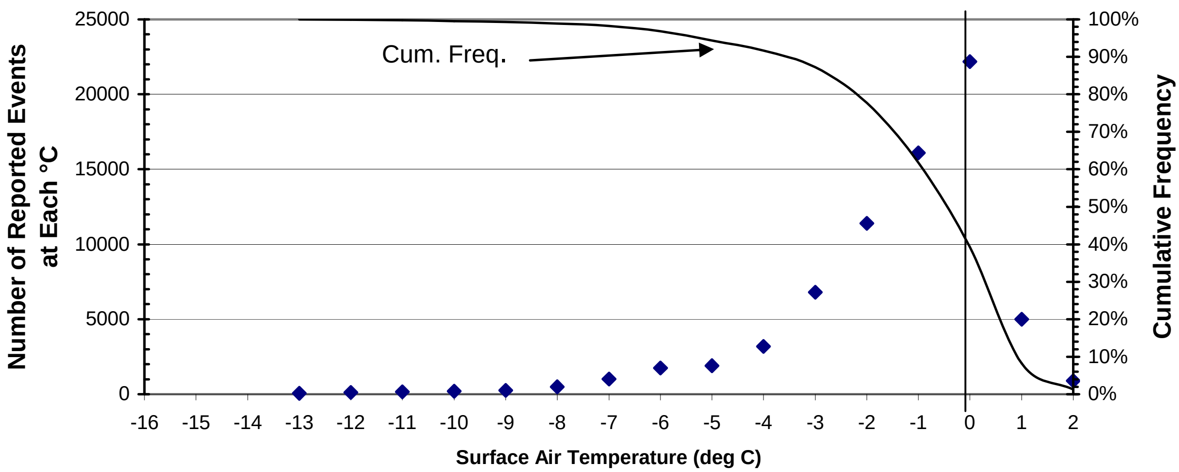

Figure D-2. Worldwide Frequency of FZRA Over 16-Year Period

D.2 REFERENCE.

D-1. National Climatic Data Center, "International Surface Weather Observations (1982-1997)," a five-volume data set released on compact discs by the National Climatic Data Center, 1998, Asheville, North Carolina (see http://www.ncdc.noaa.gov/oa/about/ncdcordering.html).

APPENDIX E—ESTIMATING EXTREME VALUES OF TOTAL LIQUID WATER CONTENT

For present purposes, the total liquid water content (TLWC) at a point or interval along a flight path is the sum of the ordinary cloud water content, the drizzle water content, and/or any rain water content that happens to be present at that location. The TLWC can range from zero up to some practical limit, which may be taken to be the 99th or larger percentile value of TLWC.

E.1 THE PROCEDURE.

The first step in an extreme values prediction of a variable is to plot a cumulative frequency of occurrence graph for the variable. A representative distribution function (gamma, log-normal, Gumbel, Weibull, or polynomial) (see reference E-1) is then fit to the cumulative frequency plot. The fitted curve serves to smooth out any irregularities in the observed frequency distribution that result from a finite number of samples. It also serves as an approximation to the true curve that would result if an ideally large data set of random samples were available. The curve is then used to interpolate or extrapolate to the apparent values of the variable that correspond to the desired 95th, 99th, or 99.9th percentile frequencies of occurrence. (The experimental data set is usually not adequate for extracting these extreme values directly from an unfitted cumulative frequency distribution. This is because the extreme values, being infrequent and therefore hard to find in nature, are likely to be under-represented or not found in a limited number of samples.)

The percentile associated with a given value of TLWC indicates the percentage of observations in which the TLWC value may be expected to be unexceeded. For example, a 99th percentile TLWC of 0.5 g/m^3 means that in 99% of the observations, the TLWC will be no larger than 0.5 g/m^3. The exceedence probability is simply the percentile subtracted from 100%. For the present example, the probability of exceeding 0.5 g/m^3 is 0.01 (or 1%).

The choice of curve to be fitted to the data depends on the type of data and on whether the data are naturally predisposed to follow some kind of mathematical function such as an exponential. Masters [E-2] found that the Weibull distribution function gives a better fit than the Gumbel function to the cumulative frequency of occurrence plots for ordinary cloud liquid water content (LWC). It is known that the Weibull function works well for certain natural phenomena and for lifetime analyses of mechanical systems. The Weibull function also has the advantage that it is a straight line when plotted on log-log graph paper. This makes it easy to use, computationally, and easy to draw and interpolate.

The accuracy (reliability) of the predicted extreme values depends on (1) the goodness of fit between the chosen distribution function and the available data and (2) how well the available data represent actual conditions. The representativeness usually improves with the number and randomness of the available samples. In any case, the larger the percentile in question, the greater is its sensitivity to an inadequate number of samples, and therefore, the larger is the uncertainty in its predicted value.

Even so, any curve fitting technique for estimating extreme values of TLWC has only limited usefulness when there is an inadequate number of samples. This may be the case especially for certain conditions, such as low temperatures, or high altitudes, or long horizontal extents (HE). This means that separate frequency of occurrence plots may not be reliable for these subcategories, and therefore, any fitted curves are also unreliable for predicting extreme values for them.

E.2 APPLICATION TO SUPERCOOLED LARGE DROPS CONDITIONS.

Briefly, the Weibull function is a straight line when plotted in the form of log(TLWC) versus log(log(100/(100-P))), where P is the cumulative frequency of occurrence, in percent, corresponding to each value of TLWC for the sample at hand. Interpolation or extrapolation may be done graphically or from the straight line formula

$$\log(TLWC) = (\text{slope}) \times \log(\log((100/(100-P))) + \text{intercept}$$

where $W(P) = \log(\log((100/(100-P)))$ is the Weibull function. The slope and intercept are obtained from a least squares fit of a straight line to the cumulative probability plot of observed TLWCs.

This can be used to compute (predict) the value of TLWC that corresponds to any desired value of P (e.g., 95%, 99%, or 99.9%).

The cumulative percentile values (P) for TLWC increments in the Master Supercooled Large Drops (SLD) Database are listed in table E-1. The cumulative values of TLWC straddle a straight line when values of log(TLWC) are plotted versus their corresponding value of W(P). This is illustrated in figures E-1 and E-2.

Table E-1. Cumulative Frequencies of Occurrence and Weibull Function Values for TLWCs in the Master SLD Database

	A	B	C	D	E	F	G	H	I	J	K
32	**For SLD Model #1**										
33		FZRA in cloud				FZDZ in cloud			Note: "In cloud" means CWC >= 0.05 g/m3)		
34	TLWC	Cum.% (P)	W(P)		TLWC	Cum.% (P)	W(P)		"Out of cloud" means CWC < 0.05 g/m3.		
35	0.15	24.8	-1.26		0.15	38.35	-0.73				
36	0.2	38.05	-0.74		0.2	58.2	-0.14				
37	0.25	54.9	-0.23		0.25	70.9	0.21				
38	0.3	70.8	0.21		0.3	80.8	0.50				
39	0.36	79.65	0.47		0.35	88.15	0.76				
40	0.41	84.1	0.61		0.4	91.8	0.92				
41	0.5	90.3	0.85		0.45	95.9	1.16				
42	0.56	96.45	1.21		0.5	97.6	1.32				
43	0.66	98.25	1.40		0.55	99.57	1.70				
44									**For SLD Model #1**		
45									Weibull Estimated TLWC's (g/m3)		
46		FZRA out of cloud				FZDZ out of cloud			from graphs		
47	TLWC	Cum.% (P)	W(P)		TLWC	Cum.% (P)	W(P)			99%	99.9%
48	0.1	37.15	-0.77		0.1	63.75	0.01		FZDZ + cloud	0.53	0.7
49	0.15	63.5	0.01		0.15	79.4	0.46				
50	0.2	87.15	0.72		0.2	89.3	0.80		FZDZ - cloud	0.38	0.53
51	0.25	92.6	0.96		0.25	93.5	1.01				
52	0.3	94.6	1.07		0.32	98.47	1.43		FZRA + cloud	0.7	0.84
53	0.35	97.3	1.28		0.46	99.62	1.72				
54	0.47	99.3	1.60						FZRA - cloud	0.4	0.5
55											

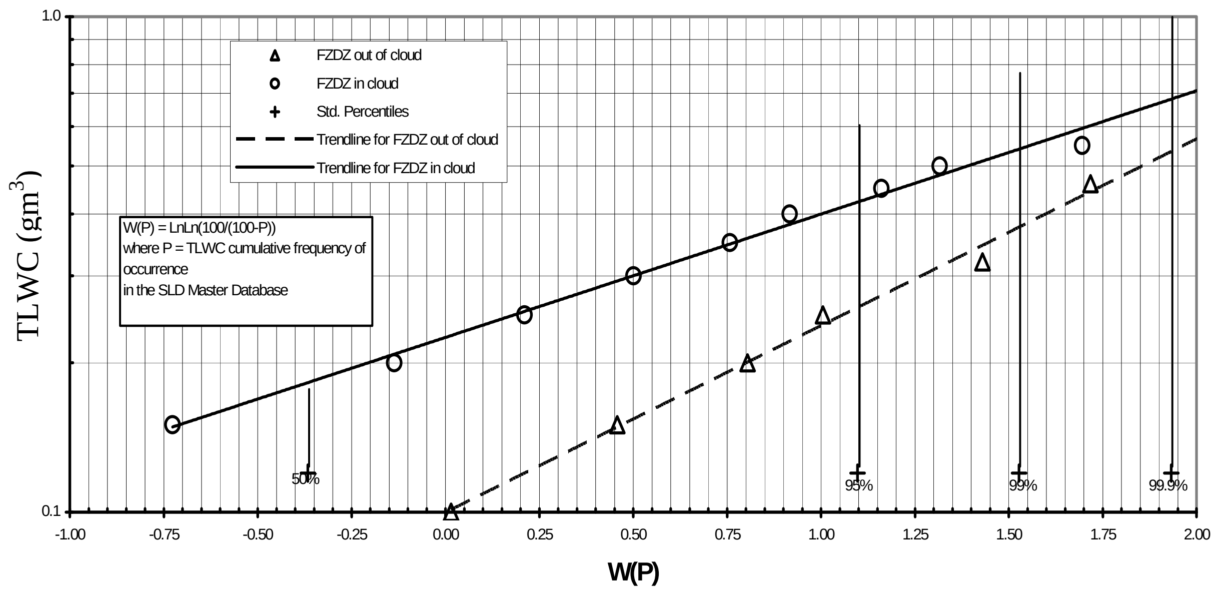

Figure E-1. Weibull-Estimated TLWC Percentiles for FZDZ Subcategories in SLD Model 1

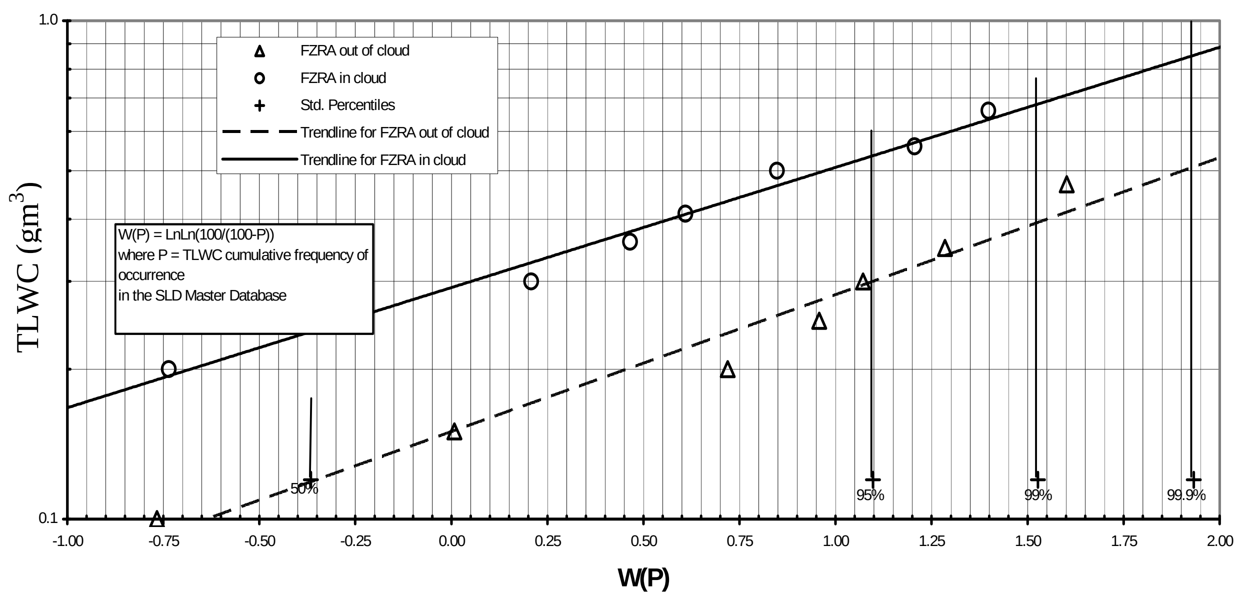

Figure E-2. Weibull-Estimated TLWC Percentiles for FZRA Subcategories in SLD Model 1

The crucial step is in drawing a best-fit straight line through the data points. When this is done manually with a ruler on graph paper, some judgment is required, meaning that different individuals may draw somewhat different lines when the data points have some scatter. This means that the estimates for the 99.9%, etc., values will differ, depending on the analyst.

Computerized spreadsheets help standardize this process and make it repeatable by anyone interested. The spreadsheet charting capabilities are used to graph the tabular data as in figures E-1 and E-2, and automatically draw a straight trendline through the plotted points. By using the built-in trendline feature of the spreadsheet software, everyone should get the same straight line and the same results.

The 50%, 95%, 99%, and 99.9% estimated values of TLWC can be read from the graphs where the trendlines cross the 50%, etc., positions on the W(P) axis.

E.2.1 Adjusting for HE.

Because the maximum average TLWCs decrease with increasing averaging distance, the TLWC exceedence probabilities should be computed separately for different HEs. Ideally, the analysis would use separate cumulative frequency distribution curves for the TLWCs averaged over each 5-mile increment in HE. Due to the limited number of encounters lasting longer than about 5 nmi, however, that is impractical and a compromise is necessary. The procedure adopted here is to use the Weibull method to compute the 99th percentile or other extreme values of TLWC for exposures over short distances (1-5 nmi) where plentiful samples have been obtained (figure 6 in section 2). The LWC adjustment curve (F-factor in figure 3 of Title 14 Code of Federal Regulations Part 25, Appendix C (hereinafter referred to as *Appendix C.*)) is then used to estimate extreme TLWCs for longer exposures. This assumes that the F-factor represents SLD conditions as well as ordinary cloud conditions, or at least that it is better than trying to independently estimate extreme values for longer, but sparsely sampled, SLD exposures.

In summary, the graphs in figures E-1 and E-2, and the percentile values of TLWC derived from them, are for short (1 to 5 nmi) SLD exposures. The extreme (99th percentile) values of TLWC for longer exposures (e.g., 17.4 nmi) are estimated using the Continuous Maximum F-factor (figure 3 of *Appendix C*).

E.3 A SIMPLE WAY TO DISTINGUISH BETWEEN WEIBULL AND GUMBEL DISTRIBUTIONS.

By graphing the cumulative frequency of occurrence of values of a variable (e.g., TLWC, in this case), against TLWC and log(TLWC), one can easily tell whether the cumulative distribution is a Gumbel or a Weibull distribution. A Gumbel distribution will plot as a straight line against TLWC, whereas a Weibull distribution will plot as a straight line against log(TLWC). The difference is visually apparent in the graphs, as in the examples shown in sections E.3.1 and E.3.2.

E.3.1 The Weibull Function.

This function may be written in the form

$$f(x) = 1 - exp(-a(x)^{B})$$

where $f(x)$ = P(%)/100, and x = TLWC in this case. P(%) are the cumulative percentiles corresponding to individual increments in TLWC, and a and B are other parameters.

The equation above can be made easier for graphing if some simple algebraic manipulation is applied.

First, it is rearranged

$$1 - f(x) = exp(-a(x)^B)$$

Then, the natural logarithm of each side is taken

$$Ln[1 - f(x)] = -a(x)^B$$

or

$$Ln\{1 / [1 - f(x)]\} = a(x)^B$$

The logarithm taken again gives

$$LnLn\{1 / [1 - f(x)]\} = Ln(a) + B \bullet Ln(x)$$

and since $f(x) = P(\%)/100$, it can be written

$$LnLn\{100/[100 - P]\} = Ln(a) + B \bullet Ln(x)$$

or

$$F(P) = Ln(a) + B \bullet Ln(x)$$

This has the form of a simple linear equation if the left side of the equation is plotted against $Ln(x)$. More rearranging gives the general form

$$Ln(\text{TLWC}) = (\text{slope}) \bullet F(P) + \text{intercept}$$

E.3.2 The Gumbel Function.

This is a double exponential that may be written in the form

$$f(x) = 1 - exp[-exp^{(-ax)}]$$

where x = TLWC and $f(x) = P(\%)/100$, as before. Rearranging and taking the natural logarithm of each side as before gives

$$Ln[1 - f(x)] = -exp^{-ax}$$

or

$$Ln\{1 / [1 - f(x)]\} = exp^{-ax}$$

and taking the logarithm once again

$$LnLn\{1 / [1 - f(x)]\} = -ax$$

or

$$LnLn\{100/[100 - P]\} = -ax$$

This has the form of a simple linear equation if the left side of the equation is plotted against x. A little more rearranging gives the general form

$$\text{TLWC} = (\text{slope})\bullet F(P)$$

where F(P) = *LnLn*{100/[100 – P]}.

E.3.3 Testing Some Real Data.

Table E-2 lists some cumulative TLWCs from the Master SLD Database.

Table E-2. Cumulative Frequencies of TLWC for FZDZ With MVD >40 µm

TLWC (g/m^3)	P (Cumulative %)	F(P)*
0.1	39.8	-0.68
0.15	59.5	-0.10
0.2	74.7	0.32
0.25	82.25	0.55
0.3	89.5	0.81
0.35	93.4	1.00
0.42	96.4	1.20
0.48	98.36	1.41

*where F(P) = *LnLn*{100/[100 – P]}

The values of F(P) are plotted against TLWC in figure E-3 and against Ln(TLWC) in figure E-4. If the data follow a Gumbel distribution, the graph in figure E-3 will be linear. If the data follow a Weibull distribution, then the graph in figure E-4 will be linear. A quick visual examination clearly shows that figure E-4 has the linear graph, and therefore, the data follow the Weibull distribution.

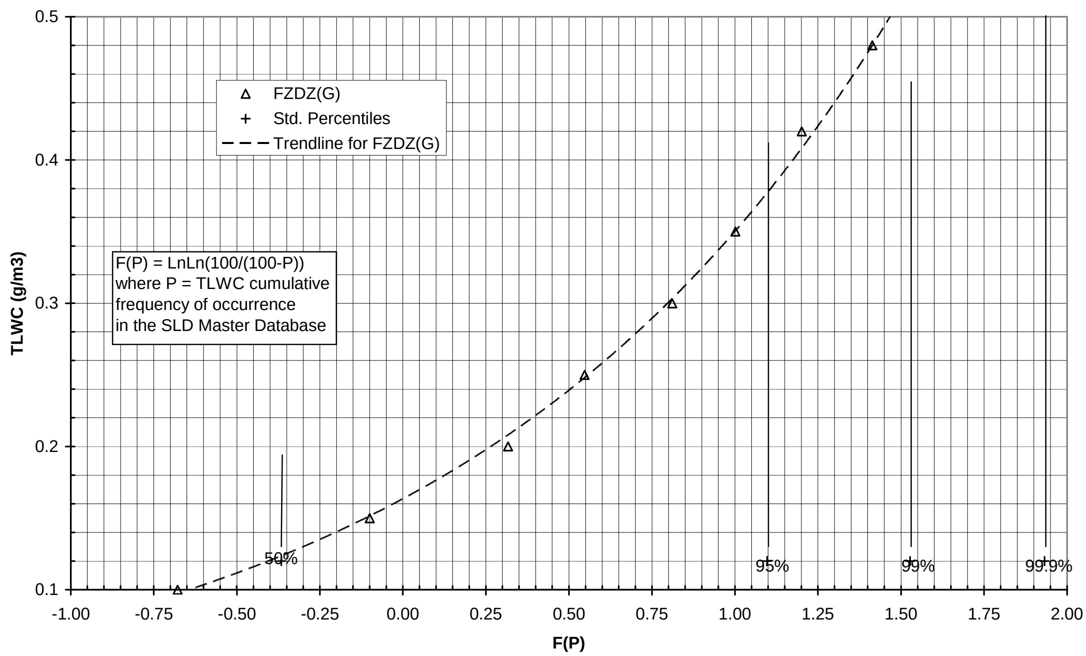

Figure E-3. Cumulative TLWC Percentiles for FZDZ Plotted as a
Log-Log Function F(P) vs TLWC
(A Gumbel distribution of TLWC percentiles would plot as a straight line against TLWC)

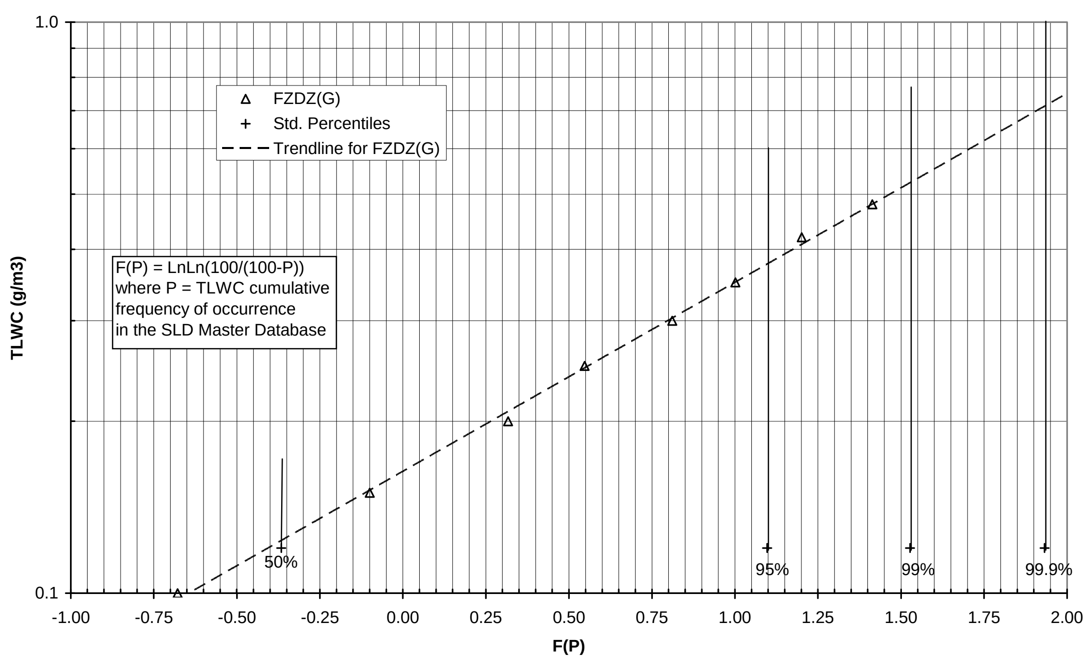

Figure E-4. Cumulative TLWC Percentiles for FZDZ Plotted as a
Log-Log Function F(P) vs Log(TLWC)
(A Weibull distribution of TLWC percentiles plots as a straight line against log(TLWC))

E.4 REFERENCES.

E-1. Miller, I. and Freund, J.E., *Probability and Statistics for Engineers*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1965.

E-2. Masters, C.O., "A New Characterization of Supercooled Clouds Below 10,000 Feet AGL," FAA report DOT/FAA/CT-83/22, June 1983.

APPENDIX F—DETECTING SUPERCOOLED LARGE DROP CONDITIONS IN FLIGHT

This appendix examines the feasibility of detecting supercooled large drops (SLD) in flight by using a hypothetical icing rate sensor that is sensitive only to drops larger than 50 µm in diameter[1]. For this exercise, the hypothetical detector is operated in real SLD conditions as recorded in the Master SLD Database. The purpose of this study is to (1) determine how many of the actual SLD encounters in the Master SLD Database would be detected, and how quickly, by the hypothetical sensor, and (2) estimate what sensitivity is needed to detect SLD conditions in a reasonable amount of time. The study attempts to answer questions like: How many passes had enough SLD to "trip" the detector (i.e., issue an SLD alert)? How long does it take before an alert is issued?

F.1 THE HYPOTHETICAL SLD DETECTOR.

Consider a small diameter probe, like a 1/4-inch-diameter rod, for example, which is somehow sensitive only to supercooled drops larger than 50 µm in diameter. The collection efficiency is taken to be unity for all these drops. During exposure to SLD conditions, the probe collects ice until a mass of ice, equivalent to a depth of about 0.5 mm on the forward half, has accumulated, at which time an icing alert signal is passed to the airplane instrument panel. The 0.5-mm threshold is called the trip point for the detector.

The following assumptions were made:

1. The SLD detector is sensitive only to drops larger than 50 µm in diameter.

2. The SLD detector signals an alert after 0.5 mm of ice buildup on the sensor.

3. There are no Ludlam-limit effects, i.e., all drops freeze and stick without runback or blowoff.

F.2 THE MASTER SLD DATABASE.

At this writing, the Master SLD Database contains about 4400 nmi of quality in-flight measurements of icing-related variables in freezing drizzle (FZDZ) and freezing rain (FZRA) conditions aloft. This comprises over 323 unidirectional passes of various lengths from 1 to 90 nmi with an average of about 12 nmi. One of the variables in the database is the liquid water concentration (LWC) in drop sizes larger than 50 µm diameter is called SLDLWC. The present study assumes that the hypothetical SLD detector is sensitive only to the SLDLWC.

F.2.1 QUESTIONS TO BE ANSWERED.

Given the nature of SLD conditions as recorded in the database, the following questions would be of interest to anyone contemplating the design or adequacy of an SLD detector.

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[1] For this exercise, it could also be a sensor that is sensitive to all drop sizes but is used here for FZDZ and FZRA that is below cloud where only drops larger than 50 µm are present.

1. How many passes in the Master SLD Database have enough SLDLWC and lasted long enough to cause the SLD detector to trip?

   a. How many passes would give at least one SLD alert?
   b. How many passes would cause more than one SLD alert during the pass?

2. How many passes would have given an alert within 30 seconds after entering the SLD conditions?

3. What is the distribution of trip times (i.e., the time to accumulate 0.5 mm of ice) among all of the SLD passes?

4. How are the trip times related to icing rate?

5. How are the trip times related to icing intensity?

6. How are the trip times related to SLDLWC?

F.2.2 THE PROCEDURE.

The icing rate on the SLD detector is given by reference F-1 as

$$\text{Rate (mm/min)} = dD/dT = (A)(\beta)(\text{SLDLWC})(\text{TAS}) \qquad \text{(F-1)}$$

Where A = 0.0305, $\beta \approx 1$ (for drops >50 μm diameter), and true airspeed (TAS) is in knots. If dT is the duration of the pass (in minutes), then (dT/60) x TAS is the pass length in nautical miles (nmi). If the threshold ice depth is dD = 0.5 mm, then equation F-1 can be rewritten as

$$(\text{SLDLWC})(\text{PassLength}) = 0.27\ (\text{g/m}^3)(\text{nmi}) \qquad \text{(F-2)}$$

That is, 0.5 mm will accrete and an SLD alert will be annunciated, whenever the product of SLDLWC and Pass Length reaches 0.27. Smaller values of SLDLWC will take longer, and larger values of SLDLWC will take shorter distances to accrete 0.5 mm. In any case, 0.5 mm will be reached for each multiple of 0.27. To a first approximation, this result is independent of airspeed.

F.2.2.1 The Minimum Recorded SLD Condition.

To be included in the Master SLD Database, an SLD condition must have an SLDLWC of at least 0.01 g/m^3 and a duration (pass length) of at least 1 nmi. According to equation F-2, this minimal condition will not trigger the SLD detector. An SLDLWC of 0.01 g/m^3 would have to last for 27 nmi before an SLD alert would be signaled. At an airspeed of 200 kt, this would take 8 minutes. If these minimum SLD conditions persisted indefinitely along the flight path, it would take 102 minutes (1.7 hours) to accrete 1/4 inch of ice on the probe, which is in the trace icing category, according to a recently proposed icing intensity scale [F-2 and F-3] (See answer to question 5.).

F.3 THE RESULTS.

The questions posed in section F.2.1 are answered in order as follows.

F.3.1 QUESTION 1a. HOW MANY PASSES IN THE ENTIRE MASTER SLD DATABASE WOULD CAUSE AT LEAST ONE SLD ALERT?

To answer this question, it is only necessary to query the database to find out how many passes satisfy equation F-2. The result is shown in table F-1. About 30% of the passes in the Master SLD Database would not trip the SLD detector. This is because they did not contain enough SLDLWC or last long enough to be detected, i.e., to build up 0.5 mm of ice on the detector.

F.3.2 QUESTION 1b. HOW MANY PASSES WOULD CAUSE MORE THAN ONE SLD ALERT DURING THE PASS?

Table F-1 shows that about 34% of the passes would generate two or more alerts. About 14% would generate five or more alerts.

F.3.3 QUESTION 2. HOW MANY PASSES WOULD GIVE AN SLD ALERT WITHIN 30 SECONDS OF ENTERING THE SLD CONDITIONS?

In this case, the pass length in equation F-2 is replaced by the distance traveled in 30 seconds. This is dependent on the airspeed. For greater airspeeds, a longer distance is covered in 30 seconds, and therefore, a smaller SLDLWC will satisfy equation F-2. Slower airspeeds will cover shorter distances in 30 seconds, and therefore, the SLDLWC must be greater to accumulate 0.5 mm of ice in that time.

To illustrate the airspeed effect, consider airspeeds of 100, 150, 200, and 250 kt. The distances covered in 30 seconds at each of these airspeeds are 0.8, 1.25, 1.7, and 2.1 nmi, respectively. From equation F-2, the minimum SLDLWC required for these distances are 0.38, 0.26, 0.19, and 0.15 g/m^3, respectively. The database now must be queried to find out how many passes had not only the minimum required SLDLWC but simultaneously had pass lengths that were at least as long as the corresponding distances listed above. The results are shown in table F-2. Only 15% of the passes in the database would trip the SLD detector in 30 seconds if the airspeed were 250 kt. At 100 kt, only two (less than 1%) of the passes would have given an SLD alert in 30 seconds. (Note that this does not mean that the detector underperforms at slower airspeeds. It only reflects that ice accretes more slowly on the probe (and on the airframe) at slower airspeeds. The detection threshold is the same, 0.5 mm, in all cases.)

F.3.4 QUESTION 3. HOW LONG DOES IT TAKE BEFORE AN ALERT IS SIGNALED IN SLD CONDITIONS?

To answer this question, equation F-1 is solved for dT. After setting dD = 0.5 mm, equation F-1 becomes

$$dT = 0.5/(0.0305*SLDLWC*TAS) \qquad \text{(F-3)}$$

The result is obviously dependent on the airspeed. For each pass, the pass-average value of SLDLWC is inserted in equation F-3 and the time (dt) required to accumulate 0.5 mm of ice at each of the four airspeeds (100, 150, 200, and 250 kt) is computed. The results are shown in figures F-1 to F-4 for FZDZ and FZRA separately, where the 100 and 250 kt results are given to illustrate the airspeed dependence.

The time required to signal an alert decreases with increasing airspeed (assuming no retardation of the icing due to heating affects at the increased airspeed). But in all cases, about 35% of the recorded SLD passes would not be detected at all. At 100 kt, some SLD conditions would require 5-6 minutes before an alert is sounded, while at 250 kt, the longest alert delay is about 2.5 minutes.

F.3.5 QUESTION 4. HOW IS THE DETECTION TIME RELATED TO THE ICING RATE?

Low icing rates will result in longer times, and higher icing rates will result in shorter times before the SLD alert is annunciated. Icing rate depends not only on the SLDLWC but also on the airspeed. Using equation F-1, the expected icing rate for actually recorded values of SLDLWC can be computed for different airspeeds as above. The results are shown in figures F-5 to F-8 for FZDZ and FZRA separately, where the 100 and 250 kt results are given to illustrate the airspeed dependence.

Icing rates greater than about 0.3 mm/min will signal an alert in less than 2 minutes at any speed above 100 kt, if the SLD lasts long enough to accumulate 0.5 mm of ice on the probe.

F.3.6 QUESTION 5. HOW IS THE ANNUNCIATION TIME RELATED TO ICING INTENSITY?

The icing rate, in units of millimeters per minute on the hypothetical SLD detector, is given by

$$\text{Icing Rate (mm/min)} = 0.5 \text{ x (ALERTS per minute)} \qquad \text{(F-4)}$$

Thus, if there was one alert every 30 seconds, the icing rate would be

$$(0.5 \text{ mm})(1)/(0.5 \text{ min}) = 1 \text{ mm/min}$$

According to a recently proposed icing intensity scale [F-2], the icing rates, shown in table F-3, are associated with the terms trace, light, moderate, and heavy.

The icing rates computed from equation F-4 for all the passes in the Master SLD Database can then be compared to this scale to see what icing intensities are represented in the database. The results are given in table F-4.

These intensities refer to SLD accretion rates on a small-diameter rod (the hypothetical SLD detector) where the droplet collection efficiency is unity. For other airplane components where the collection efficiency is less, the icing intensities may be lower too. The actual collection efficiencies, and hence, the actual icing rates on any component of interest can be computed using the National Aeronautics and Space Administration software (LEWICE) for computing ice accretions on aircraft or a similar computer code [F-2] for ice accretions. Note that if the aircraft is in ordinary icing conditions in addition to SLD, then an additional icing accumulation and rate will be present on unheated aircraft components due to the smaller cloud drops.

Again, the icing intensity (rate) and the annunciation time depend not only on the SLDLWC but also on the airspeed. The expected times-to-alert for actually recorded values of SLDLWC can be plotted against icing intensities for different airspeeds as above. The results are shown in figures F-9 to F-12 for FZDZ and FZRA separately, where the 100 and 250 kt results are given to illustrate the airspeed dependence.

As expected, the greater the intensity, the sooner the presence of SLD will be annunciated. Note that the recorded SLDLWCs may not result in heavy icing unless the airspeed is greater than 100 kt.

F.3.7 QUESTION 6. HOW IS THE ANNUNCIATION TIME RELATED TO SLDLWC ITSELF?

Once again, equation F-1 can be used to compute the answer, which also depends on the airspeed. The results are shown in figures F-13 to F-16 for FZDZ and FZRA separately, where the 100 and 250 kt results are given to illustrate the airspeed dependence.

The dependence on SLDLWC is similar to the dependence on icing rate. The annunciation time will be less than about a minute if the SLDLWC is greater than about 0.2 g/m^3 at 100 kt or greater than about 0.06 g/m^3 at 250 kt, and the SLD lasts long enough to accumulate 0.5 mm.

One other result is that equation F-2 indicates that an SLDLWC of at least 0.016 g/m^3 is required to be detected in an exposure lasting 17.4 nmi. Any SLD cases with less SLDLWC will not be detected in 17.4 nmi.

F.4 CONCLUSIONS.

The principal conclusions from this exercise are:

- The time required to signal the presence of supercooled large drop (SLD) conditions depends on the sensitivity of the SLD detector and, for an ice accretion-based detector, on the airspeed, with faster detection generally associated with greater airspeed. The distance required to signal an alert is the same, however. That is, the distance to alert is independent of the airspeed.

- An SLD detector with a detection threshold of 0.5 mm of ice accumulation does not detect about 30% of the SLD passes recorded in the Master SLD Database. This is due to the low liquid water content (LWC) in drops larger than 50 µm in diameter (SLDLWC), the short duration, or both, for that 30% of the passes. For the other 70% of the cases, the time required to signal an alert ranges from about 30 seconds up to 6 minutes, depending on the particular case and on the airspeed.

- Only about 15% of the SLD cases in the database would have generated an alert within 30 seconds at 250 kt, while fewer than 1% would generate an alert within 30 seconds at 100 kt.

F.5 REFERENCES.

F-1. Jeck, R., "Calibration and Use of Goodrich Model 0871FA Ice Detectors in Icing Wind Tunnels," *Journal of Aircraft*, Vol. 44, 2007, pp. 300-309.

F-2. Jeck, R., "A Workable, Aircraft-Specific Icing Severity Scheme," Paper No. AIAA-98-0094, *36th AIAA Aerospace Sciences Meeting*, Reno, Nevada, January 12-15, 1998.

F-3. FAA Advisory Circular 91-74A, "Pilot Guide: Flight in Icing Conditions," December 2007.

Table F-1. The Number of SLD Alerts the Hypothetical SLD Detector Would Annunciate During Passes Through all SLD Cases in the Master SLD Database
(Detector annunciates SLD after each 0.5-mm buildup of ice on the detector)

Alerts	No. of Passes	Percent of Total	Cumulative Passes	Cumulative Percent of Total
0	85	28.91	85	28.91
1	70	23.81	155	52.72
2	39	13.27	194	65.99
3	25	8.50	219	74.49
4	18	6.12	237	80.61
5	16	5.44	253	86.05
6	4	1.36	257	87.41
7	6	2.04	263	89.46
8	4	1.36	267	90.82
9	1	0.34	268	91.16
10	3	1.02	271	92.18
11	3	1.02	274	93.20
12	3	1.02	277	94.22
13	3	1.02	280	95.24
16	4	1.36	284	96.60
17	1	0.34	285	96.94
18	1	0.34	286	97.28
19	1	0.34	287	97.62
20	1	0.34	288	97.96
22	1	0.34	289	98.30
23	1	0.34	290	98.64
28	1	0.34	291	98.98
42	1	0.34	292	99.32
44	1	0.34	293	99.66
56	1	0.34	294	100.00

Row 1 shows that nearly 30% of all SLD encounters would go undetected.

Table F-2. Number of Passes in all SLD Conditions in the Master SLD Database That Would Trip the Hypothetical SLD Detector in 30 Seconds due to Drops >50 µm Diameter

	No. of Passes	Percent of Total	Cumulative Passes	Cumulative Percent of Total
At an Airspeed of 250 kt				
No SLD Alerts in 30 seconds	275	85.1	275	85.1
SLD Alerts in 30 seconds	48	14.9	323	100.0
At an Airspeed of 200 kt				
No SLD Alerts in 30 seconds	299	92.6	299	92.6
SLD Alerts in 30 seconds	24	7.4	323	100.0
At an Airspeed of 150 kt				
No SLD Alerts in 30 seconds	311	96.3	311	96.3
SLD Alerts in 30 seconds	12	3.7	323	100.0
At an Airspeed of 100 kt				
No SLD Alerts in 30 seconds	321	99.4	321	99.4
SLD Alerts in 30 seconds	2	0.6	323	100.0

Table F-3. Approximately Equivalent Versions of Measurable Icing Intensity

Trace	1/4-inch (6-mm) accumulation in 1 hour or longer 0.5 mm in 5 minutes or longer Less than 0.1 mm/min Less than 1/4 inch per hour
Light	1/4-inch accumulation in 15-60 minutes 0.5 mm in 1 to 5 minutes 0.1 to 0.4 mm/min ¼ inch to 1 inch (25 mm) per hour
Moderate	1/4-inch accumulation in 5-15 minutes 0.5 mm in 20 to 60 seconds 0.4 to 1.3 mm/min, 1 to 3 inches per hour
Heavy	1/4-inch accumulation in less than 5 minutes 0.5 mm in less than 20 seconds More than 1.3 mm/min More than 3 inches per hour

(These intensities depend only on the rate of accumulation and apply to any unheated component at any airspeed. Different components and different airspeeds will have different accumulation rates.)

Table F-4. Distribution of Pass-Average Icing Intensities in the Master SLD Database

Intensity	No. of Passes	Percent of all Passes	Cumulative Percent
Trace	97	33	33
Light	107	36	69
Moderate	82	28	97
Heavy	8	3	100

```
Percentage
 Of Passes
   |                                                                                                      ***
30 +                                                                                                      ***
   |                                                                                                      ***
   |                                                                                                      ***
   |                                                                                                      ***
   |                                                                                                      ***
20 +                                                                                                      ***
   |                                                                                                      ***
   |                                                                                                      ***
   |                                                                                                      ***
   |                                                                                                      ***
10 +            ***  ***                                                                                  ***
   |            ***  ***  ***  ***                                                                        ***
   |            ***  ***  ***  ***  ***       ***                                                         ***
   |            ***  ***  ***  ***  ***  ***  ***  ***                                                    ***
   |       ***  ***  ***  ***  ***  ***  ***  ***  ***  ***  ***  ***  ***                                     ***
   +------------------------------------------------------------------------------------------------------------
      0.0  0.5  1.0  1.5  2.0  2.5  3.0  3.5  4.0  4.5  5.0  5.5  6.0  6.5  7.0  7.5  8.0  8.5          Percent
                                                                                                            not
   ANNUNCIATION TIME (minutes) (rounded to the nearest half-minute)                                    Detected
```

Figure F-1. Distribution of Times Required for Hypothetical SLD Detector to Annunciate FZDZ Conditions (Due to Drops >50 μm Diameter) in Passes at 100 kt Through all FZDZ Cases in the Database

```
Percentage
 Of Passes
   |                                                                                                      ***
30 +                                                                                                      ***
   |                                                                                                      ***
   |                                                                                                      ***
   |                                                                                                      ***
   |       ***                                                                                            ***
20 +       ***                                                                                            ***
   |       ***  ***                                                                                       ***
   |       ***  ***                                                                                       ***
   |       ***  ***                                                                                       ***
   |       ***  ***  ***                                                                                  ***
10 +       ***  ***  ***                                                                                  ***
   |       ***  ***  ***  ***                                                                             ***
   |       ***  ***  ***  ***                                                                             ***
   |       ***  ***  ***  ***  ***                                                                        ***
   |  ***  ***  ***  ***  ***  ***                                                                        ***
   +------------------------------------------------------------------------------------------------------------
      0.0  0.5  1.0  1.5  2.0  2.5  3.0  3.5  4.0  4.5  5.0  5.5  6.0  6.5  7.0  7.5  8.0  8.5          Percent
                                                                                                            not
    ANNUNCIATION TIME (minutes) (rounded to the nearest half-minute)                                   Detected
```

Figure F-2. Distribution of Times Required for Hypothetical SLD Detector to Annunciate FZDZ Conditions (Due to Drops >50 µm Diameter) in Passes at 250 kt Through all FZDZ Cases in the Database

```
Percentage
 Of Passes
   |                 ***
   |                 ***
25 +                 ***
   |                 ***
   |                 ***
   |                 ***
   |                 ***
20 +                 ***
   |                 ***
   |                 ***                                                                                  ***
   |            ***  ***                                                                                  ***
   |            ***  ***                                                                                  ***
15 +            ***  ***                                                                                  ***
   |            ***  ***                                                                                  ***
   |            ***  ***                                                                                  ***
   |            ***  ***                                                                                  ***
   |            ***  ***                                                                                  ***
10 +            ***  ***  ***                                                                             ***
   |            ***  ***  ***  ***                                                                        ***
   |       ***  ***  ***  ***  ***                                                                        ***
   |       ***  ***  ***  ***  ***                                                                        ***
   |       ***  ***  ***  ***  ***  ***                                                                   ***
 5 +       ***  ***  ***  ***  ***  ***                                                                   ***
   |       ***  ***  ***  ***  ***  ***                                                                   ***
   |       ***  ***  ***  ***  ***  ***       ***                                                         ***
   |       ***  ***  ***  ***  ***  ***       ***                                                         ***
   |       ***  ***  ***  ***  ***  ***  ***  ***       ***            ***                                ***
   +------------------------------------------------------------------------------------------------------------
      0.0  0.5  1.0  1.5  2.0  2.5  3.0  3.5  4.0  4.5  5.0  5.5  6.0  6.5  7.0  7.5  8.0  8.5          Percent
                                                                                                            not
                     ANNUNCIATION TIME (minutes) (rounded to the nearest half-minute)                  Detected
```

Figure F-3. Distribution of Times Required for Hypothetical SLD Detector to Annunciate FZRA Conditions (Due to Drops >50 µm Diameter) in Passes at 100 kt Through all FZRA Cases in the Database

```
Percentage
 Of Passes
   |       ***
   |       ***
50 +       ***
   |       ***
   |       ***
   |       ***
   |       ***
40 +       ***
   |       ***
   |       ***
   |       ***
   |       ***
30 +       ***
   |       ***
   |       ***
   |       ***
   |       ***
20 +       ***  ***
   |       ***  ***                                                                                       ***
   |       ***  ***                                                                                       ***
   |       ***  ***                                                                                       ***
   |       ***  ***                                                                                       ***
10 +       ***  ***                                                                                       ***
   |       ***  ***                                                                                       ***
   |       ***  ***                                                                                       ***
   |       ***  ***  ***                                                                                  ***
   |  ***  ***  ***  ***                                                                                  ***
   +-----------------------------------------------------------------------------------------------------------
      0.0  0.5  1.0  1.5  2.0  2.5  3.0  3.5  4.0  4.5  5.0  5.5  6.0  6.5  7.0  7.5  8.0  8.5         Percent
                                                                                                            not
   ANNUNCIATION TIME (minutes) (rounded to the nearest half-minute)                                   Detected
```

Figure F-4. Distribution of Times Required for Hypothetical SLD Detector to Annunciate FZRA Conditions (Due to Drops >50 μm Diameter) in Passes at 250 kt Through all FZRA Cases in the Database

```
ANNUNCIATION TIME (minutes)
         |   E
     >10 +L  YELLEEL    J   E
         /
         |   E
         |
       9 +
         |
         |
       8 +
         |
         |
       7 +   L
         |     E
         |   ELYY
       6 +      E
         |     L E
         |    LLLA
       5 +      E
         |    E LLE
         |     LLLE
       4 +     LL LEL
         |     E I  L
         |      EELELLE
       3 +         EYLEE
         |         K KEEEL
         |         E EAALA E
       2 +           E  JJ EE J
         |               J  J  AE AJ
         |                  J      E J  EA
       1 +                  J        J     JJ JA J AY
         |                                           J  J    J           J J
         |                                                                            J
       0 +
        .+------------+------------+------------+------------+------------+------------+
         0.0          0.2          0.4          0.6          0.8          1.0         1.2

                                        FZDZ ICING RATE (mm/min)
```

Note: Plotting symbols indicate source of data. The points plotted at >10 on the ordinate are passes which would not signal an alert.

Figure F-5. Time Required for Hypothetical SLD Detector to Annunciate SLD Conditions, Depending on the Icing Rate on a 1/4-Inch (6.35-mm) Diameter Cylinder, in Passes at 100 kt Through all FZDZ Cases in the Database

```
ANNUNCIATION TIME (minutes)
         |
     >10 +L  YELLEEL    J   E
         /
         |
         |
       9 +
         |
         |
       8 +
         |
         |
       7 +
         |
         |  Y
       6 +
         |
         |
       5 +
         |
         |   E
       4 +   E
         |
         |
       3 +
         |   LLYY
         |     LLE
       2 +    LLLLE
         |     LLLLEL
         |     EEELELLEE
       1 +         EYEEELL E
         |              JJ AE JAE AE J  E
         |                  J        J  AA JJ JA J AYJ  J    J           J J          J
       0 +
         .+------------+------------+------------+------------+------------+------------+
          0.0          0.5          1.0          1.5          2.0          2.5          3.0

                                        FZDZ ICING RATE (mm/min)
```

Note: Plotting symbols indicate source of data. The points plotted at >10 on the ordinate are passes which would not signal an alert.

Figure F-6. Time Required for Hypothetical SLD Detector to Annunciate SLD Conditions, Depending on the Icing Rate, on a 1/4-inch (6.35 mm) Diameter Cylinder in Passes at 250 kt Through all FZDZ Cases in the Database

```
ANNUNCIATION TIME (minutes)
         |
     >10 +N
         /
         |
       9 +
         |
         |
       8 +
         |
         |
       7 +
         |
         |    E
       6 +
         |
         |
       5 +
         |      E
         |
       4 +       LEE
         |        E
         |
       3 +           N EN
         |             LEL
         |            E ENLE
       2 +              LE NE
         |              N   NNEEEE
         |                  N   ENENNNE
       1 +                           E   N N NN     E
         |                                         N        N   N            N    N
         |
       0 +
         ++------------+------------+------------+------------+------------+------------+
         0.0          0.2          0.4          0.6          0.8          1.0          1.2

                                        FZRA ICING RATE (mm/min)
```

Note: Plotting symbols indicate source of data. The points plotted at >10 on the ordinate are passes which would not signal an alert.

Figure F-7. Time Required for Hypothetical SLD Detector to Annunciate SLD Conditions, Depending on the Icing Rate on a 1/4-Inch (6.35-mm) Diameter Cylinder, in Passes at 100 kt Through all FZRA Cases in the Database

```
ANNUNCIATION TIME (minutes)
         |
     >10 +N
         /
         |
       9 +
         |
         |
       8 +
         |
         |
       7 +
         |
         |
       6 +
         |
         |
       5 +
         |
         |
       4 +
         |
         |
       3 +
         |    E
         |
       2 +      E
         |       LEE
         |        E  N
       1 +           LELNNLL
         |              NE NNNEEENENNNE
         |                      E    N   N N NN    NE       N   N            N    N
       0 +
         ++------------+------------+------------+------------+------------+------------+
         0.0          0.5          1.0          1.5          2.0          2.5          3.0

                                        FZRA ICING RATE (mm/min)
```

Note: Plotting symbols indicate source of data. The points plotted at >10 on the ordinate are passes which would not signal an alert.

Figure F-8. Time Required for Hypothetical SLD Detector to Annunciate SLD Conditions, Depending on the Icing Rate on a 1/4-Inch (6.35-mm) Diameter Cylinder, in Passes at 250 kt Through all FZRA Cases in the Database

```
                                   ANNUNCIATION TIME (minutes)
     |  E
 >10 +  Y                   L
     /
     |  E
     |
   9 +
     |
     |
   8 +
     |
     |
   7 +  L
     |  E
     |  Y
   6 +  E
     |  L                   E
     |  L                   A
   5 +  E
     |  L                   L
     |  L                   L
   4 +  L                   L
     |  E                   L
     |  E                   L
   3 +                      L
     |                      L
     |                      L
   2 +                      E
     |                      E
     |                      E                   E
   1 +                      J                   J
     |                                          J
     |                                          J
   0 +
     .--+-------------------+-------------------+--
      Trace               Light              Moderate

                      FZDZ ICING INTENSITY
```

Note: Plotting symbols indicate source of data. The points plotted at >10 on the ordinate are passes which would not signal an alert.

Figure F-9. Time Required for Hypothetical SLD Detector to Annunciate SLD Conditions, Depending on the Icing Intensity on a 1/4-Inch (6.35-mm) Diameter Cylinder, in Passes at 100 kt Through all FZDZ Cases in the Database

```
                ANNUNCIATION TIME (minutes)
                          |
                      >10 +  L                   Y                   E
                          /
                          |
                          |
                        9 +
                          |
                          |
                        8 +
                          |
                          |
                        7 +
                          |
                          |  Y
                        6 +
                          |
                          |
                        5 +
                          |
                          |                      E
                        4 +                      E
                          |
                          |
                        3 +
                          |                      Y
                          |                      L
                        2 +                      L
                          |                      L
                          |                      L                   L
                        1 +                      E                   L
                          |                                          E
                          |                                          J                   J
                        0 +
                          .--+-------------------+-------------------+-------------------+--
                           Trace               Light              Moderate             Heavy

                                                    FZDZ ICING INTENSITY
```

Note: Plotting symbols indicate source of data. The points plotted at >10 on the ordinate are passes which would not signal an alert.

Figure F-10. Time Required for Hypothetical SLD Detector to Annunciate SLD Conditions, Depending on the Icing Intensity on a 1/4-Inch (6.35-mm) Diameter Cylinder, in Passes at 250 kt Through all FZDZ Cases in the Database

```
                                     ANNUNCIATION TIME (minutes)
    |
>10 +  N
    /
    |
  9 +
    |
    |
  8 +
    |
    |
  7 +
    |
    |  E
  6 +
    |
    |
  5 +
    |  E
    |
  4 +                          L
    |                          E
    |
  3 +                          N
    |                          L
    |                          N
  2 +                          N
    |                          N
    |                          N                       N
  1 +                                                  N
    |                                                  N
    |
  0 +
    +--+-----------------------+-----------------------+--
     Trace                   Light                  Moderate

                           FZRA ICING INTENSITY
```

Note: Plotting symbols indicate source of data. The points plotted at >10 on the ordinate are passes which would not signal an alert.

Figure F-11. Time Required for Hypothetical SLD Detector to Annunciate SLD Conditions, Depending on the Icing Intensity on a 1/4-Inch (6.35-mm) Diameter Cylinder, in Passes at 100 kt Through all FZRA Cases in the Database

```
           ANNUNCIATION TIME (minutes)
                |
            >10 +  N
                /
                |
              9 +
                |
                |
              8 +
                |
                |
              7 +
                |
                |
              6 +
                |
                |
              5 +
                |
                |
              4 +
                |
                |
              3 +
                |                      E
                |
              2 +                      E
                |                      L
                |                      E                   N
              1 +                                          N
                |                                          N
                |                                          N                   N
              0 +
                +--+-------------------+-------------------+-------------------+--
                  Trace               Light              Moderate             Heavy

                                             FZRA ICING INTENSITY
```

Note: Plotting symbols indicate source of data. The points plotted at >10 on the ordinate are passes which would not signal an alert.

Figure F-12. Time Required for Hypothetical SLD Detector to Annunciate SLD Conditions, Depending on the Icing Intensity on a 1/4-Inch (6.35-mm) Diameter Cylinder, in Passes at 250 kt Through all FZRA Cases in the Database

```
ANNUNCIATION TIME (minutes)
         |    E
    >10 +   LYLLLEL LY E
         /
         |     E
         |
      9 +
         |
         |
      8 +
         |
         |
      7 +      L
         |      E
         |      Y
      6 +      E
         |      L
         |       L
      5 +       E
         |       L
         |        L
      4 +        LL
         |         L
         |         LL
      3 +          LE
         |           EL
         |            LE
      2 +              EE
         |                EAE
         |                    JEEK
      1 +                       IJJJJJA YA
         |                                JJ  J      J    J
         |                                                     J J
      0 +
         +--+------------+------------+------------+------------+------------+--
          0.00         0.10         0.20         0.30         0.40         0.50

                                      FZDZ LWC (g/m^3)
```

Note: Plotting symbols indicate source of data. The points plotted at >10 on the ordinate are passes which would not signal an alert.

Figure F-13. Time Required for Hypothetical SLD Detector to Annunciate SLD Conditions, Depending on the FZDZ LWC, in Passes at 100 kt Through all FZDZ Cases in the Database

```
ANNUNCIATION TIME (minutes)
         |
     >10 +   LYLLLEL LY E
         /
         |
         |
       9 +
         |
         |
       8 +
         |
         |
       7 +
         |
         |    Y
       6 +
         |
         |
       5 +
         |
         |    E
       4 +     E
         |
         |
       3 +
         |      Y
         |      LL
       2 +       L
         |        LL
         |         LLE
       1 +           ELEE
         |              JEEAE JEE
         |                      JKJJJJJA YJJ  J      J    J    J J
       0 +
         +--+------------+------------+------------+------------+------------+--
          0.00         0.10         0.20         0.30         0.40         0.50

                                      FZDZ LWC (g/m^3)
```

Note: Plotting symbols indicate source of data. The points plotted at >10 on the ordinate are passes which would not signal an alert.

Figure F-14. Time Required for Hypothetical SLD Detector to Annunciate SLD Conditions, Depending on the FZDZ LWC, in Passes at 250 kt Through all FZDZ Cases in the Database

```
ANNUNCIATION TIME (minutes)
          |
      >10 +     E   N NNE N  LNNNNN N  N      N
          /
          |
        9 +
          |
          |
        8 +
          |
          |
        7 +
          |
          |       E
        6 +
          |
          |
        5 +
          |         E
          |
        4 +          EL
          |            E
          |
        3 +             NN
          |              EEL
          |                LNE
        2 +                  LNEE
          |                     ENNN
          |                         NENNNNN
        1 +                                 LN N      E
          |                                              N  N NNE    N   N    N
          |
        0 +
          +--+--------+--------+--------+--------+--------+--------+--------+--------+--
           0.00     0.05     0.10     0.15     0.20     0.25     0.30     0.35     0.40
```

FZRA LWC (g/m^3)

Note: Plotting symbols indicate source of data. The points plotted at >10 on the ordinate are passes which would not signal an alert.

Figure F-15. Time Required for Hypothetical SLD Detector to Annunciate SLD Conditions, Depending on the FZRA LWC, in Passes at 100 kt Through all FZRA Cases in the Database

```
ANNUNCIATION TIME (minutes)
          |
      >10 +     E   N NNE N  LNNNNN N  N      N
          /
          |
        9 +
          |
          |
        8 +
          |
          |
        7 +
          |
          |
        6 +
          |
          |
        5 +
          |
          |
        4 +
          |
          |
        3 +
          |       E
          |
        2 +         E
          |          EL
          |            EN
        1 +              NELNL
          |                   NEENNNNENNNN
          |                               N LN N      E   N  N NNE    N   N    N
        0 +
          +--+--------+--------+--------+--------+--------+--------+--------+--------+--
           0.00     0.05     0.10     0.15     0.20     0.25     0.30     0.35     0.40

                                          FZRA LWC (g/m^3)
```

Note: Plotting symbols indicate source of data. The points plotted at >10 on the ordinate are passes which would not signal an alert.

Figure F-16. Time Required for Hypothetical SLD Detector to Annunciate SLD Conditions, Depending on the FZRA LWC, in Passes at 250 kt Through all FZRA Cases in the Database

APPENDIX G—ON THE PROBABILITY OF EXCEEDING TITLE 14 CODE OF FEDERAL REGULATIONS PART 25, APPENDIX C, CONDITIONS (I.E., ON THE PROBABILITY OF ENCOUNTERING SUPERCOOLED LARGE DROPS)

The Title 14 Code of Federal Regulations (CFR) Part 25, Appendix C (hereinafter referred to as *Appendix C*) envelopes in question are the liquid water content (LWC) versus mean-effective diameter (MED) (or medium volume diameter (MVD)) curves in figures 1 and 4 of *Appendix C* in 14 CFR Parts 25 and 29. Basically, icing conditions will be outside *Appendix C* if the LWC exceeds the indicated maximum probable value for a given temperature and MVD or if the MVD exceeds the maximum value (40 and 50 microns, respectively).

G.1 PROBABILITY OF EXCEEDING LWC.

The LWC curves in figures 1 and 4 of *Appendix C* represent approximately the 99th percentile values of LWC. That is, there is approximately a 1% chance of encountering larger LWC values as an average over any given exposure distance (horizontal extent).

Figure G-1 illustrates the case for stratiform clouds where only a few of the many recorded LWC averages lie above the Continuous Maximum LWC limit for 0°C and MVD = 15 μm. (The usual LWC versus MVD curve for 0°C has been converted here to LWC versus Horizontal Extent for ease in plotting the wide range of horizontal extents involved [G-1].

G.2 WHAT IS THE PROBABILITY OF EXCEEDING MVD (A SUPERCOOLED LARGE DROPS CONDITION)?

The limits of MVD can be exceeded only in a freezing rain (FZRA) or freezing drizzle (FZDZ) situation (although some of these FZRA and FZDZ encounters within clouds will still have MVDs within the *Appendix C* limits of 40 or 50 microns).

- Freezing rain is a condition not contemplated by *Appendix C*, so every freezing rain encounter is likely to have an MVD outside the *Appendix C* range. That is, whenever a flight passes through freezing rain, the probability of exceeding *Appendix C* conditions can be expected to be 100%. The exception is where the rain rate is very light and the aircraft is also passing through a regular cloud at the same time. Then, the cloud LWC and drop sizes may weight the overall MVD to a value within *Appendix C*.

  The question may then be reduced to: How often do aircraft encounter freezing rain? The answer obviously depends on the season of the year, the geographic location (freezing rain occurs in some regions more than others), the flight level (freezing rain is limited to altitudes below 7000 ft above ground level (AGL), and more often to altitudes below 3300 ft AGL), the duration and location of any freezing rain relative to the air traffic density, and the willingness of pilots to avoid flying in areas of forecasted or reported freezing rain conditions.

- Freezing drizzle is defined as drops with diameters from 500 μm down to perhaps 50 μm. Less is presently understood about the conditions that give rise to freezing drizzle in clouds, so its probablity of occurrence is harder to specify. Drizzle formation depends on having certain weather/cloud/geographical conditions (e.g., oceanic clouds at low altitudes) and possibly other, presently unknown conditions. If the necessary conditions are present, then the probability of drizzle formation is high (but not exactly known). If the required conditions are absent, then the probability for drizzle is zero.

One way to assess the probability of encountering freezing drizzle is to study the recorded MVDs in the large database of supercooled cloud variables at the Federal Aviation Administration (FAA) William J. Hughes Technical Center [G-2]. Figure G-2 shows that in stratiform clouds, the MVDs are highly clustered around 15 microns with 75% to 80% of all MVDs falling in the 10- to 20-micron range. This means that 15 ±5 μm is the normal or equilibrium range of MVDs for stratiform clouds, and few, if any, of these clouds have developed a significant number of drizzle-sized droplets. MVDs larger than perhaps 20 or 25 μm are an indication that drizzle drops are becoming sufficiently numerous to nudge the MVD to larger than normal values. The database indicates that MVDs larger than about 20 μm can be occasionally found at temperatures warmer than -20°C and at altitudes below 14,000 ft above sea level, and that 90% of all MVDs larger than 30 μm in the database were in maritime air. Therefore, the probability of encountering drizzle in flight depends on the in-cloud temperature, the altitude, the type of air mass, and probably other factors as well.

In the mix of stratiform clouds represented in the master database [G-2] of supercooled cloud variables, only about 10% of the distance flown was in MVDs larger than 20 μm, and 2%-7% of the distance was in MVDs larger than 25 μm. In both layer and convective clouds, however, 99% of all recorded MVDs in the database are smaller than 35 microns. This is not that drizzle was unseen in the 12,000 nmi of MVD measurements in the database, but that the resultant MVDs exceeded the *Appendix C* limits (40 and 50 μm) less than 1% of the time for the mix of flights included in the database.

G.3 WHAT IS THE PROBABILITY OF SLD OCCURRING WITHIN *APPENDIX C* LIMITS?

Looking at these questions from another way, one may ask: During the small percentage of time that SLD is encountered, how often are ordinary clouds present at the same time? And, what percent of the time is the overall MVD within the range of *Appendix C* (i.e., MVD <40 μm)?

These questions can be answered by querying the Master SLD Database. The results are shown in table G-1.

Thus, for nearly half of the time in FZDZ, the MVD will be within the *Appendix C* limit of 40 μm. If FZDZ is encountered within clouds, the MVD can be expected to be within *Appendix C* 70 percent of the time. The percentages for FZRA are less, but the trend is the same.

G.4 SPECIAL EXCEEDANCE CONDITION.

Another way to define an exceedance condition for *Appendix C* is to base it on the amount of LWC in the SLD size range (i.e., the drops larger than some agreed-upon threshold, such as 50 or 100 μm diameter) regardless of the MVD. If the SLDLWC exceeds some threshold value, such as 0.01 g/m^3, for some minimum amount of time, then this could be regarded as an exceedance condition. (All the measurements in the Master SLD Database meet this condition.) Currently, this SLDLWC measurement is practical only for research flights equipped with suitable cloud physics instrumentation. Future developments may provide a simple LWC sensor or special SLD icing rate meter for this purpose.

G.5 SUMMARY.

Statistically, the LWC limits of *Appendix C* may be exceeded about 1% of the time, but actual flight altitudes and weather and cloud conditions will affect this probability for any given flight.

The MVD limits of *Appendix C* can be expected to be exceeded nearly 100% of the time when flying in FZRA or FZDZ outside of cloud.

Otherwise, the MVD limits of *Appendix C* can be expected to be exceeded less than 1% of the time in a random mix of flights which may include occasional, localized FZDZ conditions.

In FZDZ alone, there is about a 50% probability of exceeding the 40-μm MVD limit. This is based on statistics from the new master database of SLD conditions at the FAA William J. Hughes Technical Center. Again, actual flight altitudes, air temperatures, weather and cloud conditions, and geographic location will affect the probability of encountering FZDZ on any particular flight.

G.6 REFERENCES.

G-1. Jeck, R.K., "Icing Design Envelopes (14 CFR Parts 25 and 29, Appendix C) Converted to a Distance-Based Format," FAA report DOT/FAA/AR-00/30, April 2002.

G-2. Jeck, R.K., "Advances in the Characterization of Supercooled Clouds for Aircraft Icing Applications," FAA report DOT/FAA/AR-07/4, November 2008.

Table G-1. Fraction of Recorded SLD Events Occurring in *Appendix C* or in Cloud

	Percent With MVD <40 μm	Percent in Cloud
All SLD	43	57
All FZDZ	48	67
FZDZ in cloud	70	
FZDZ out of cloud	3.5	
All FZRA	20	43
FZRA in cloud	44	
FZRA out of cloud	<1	

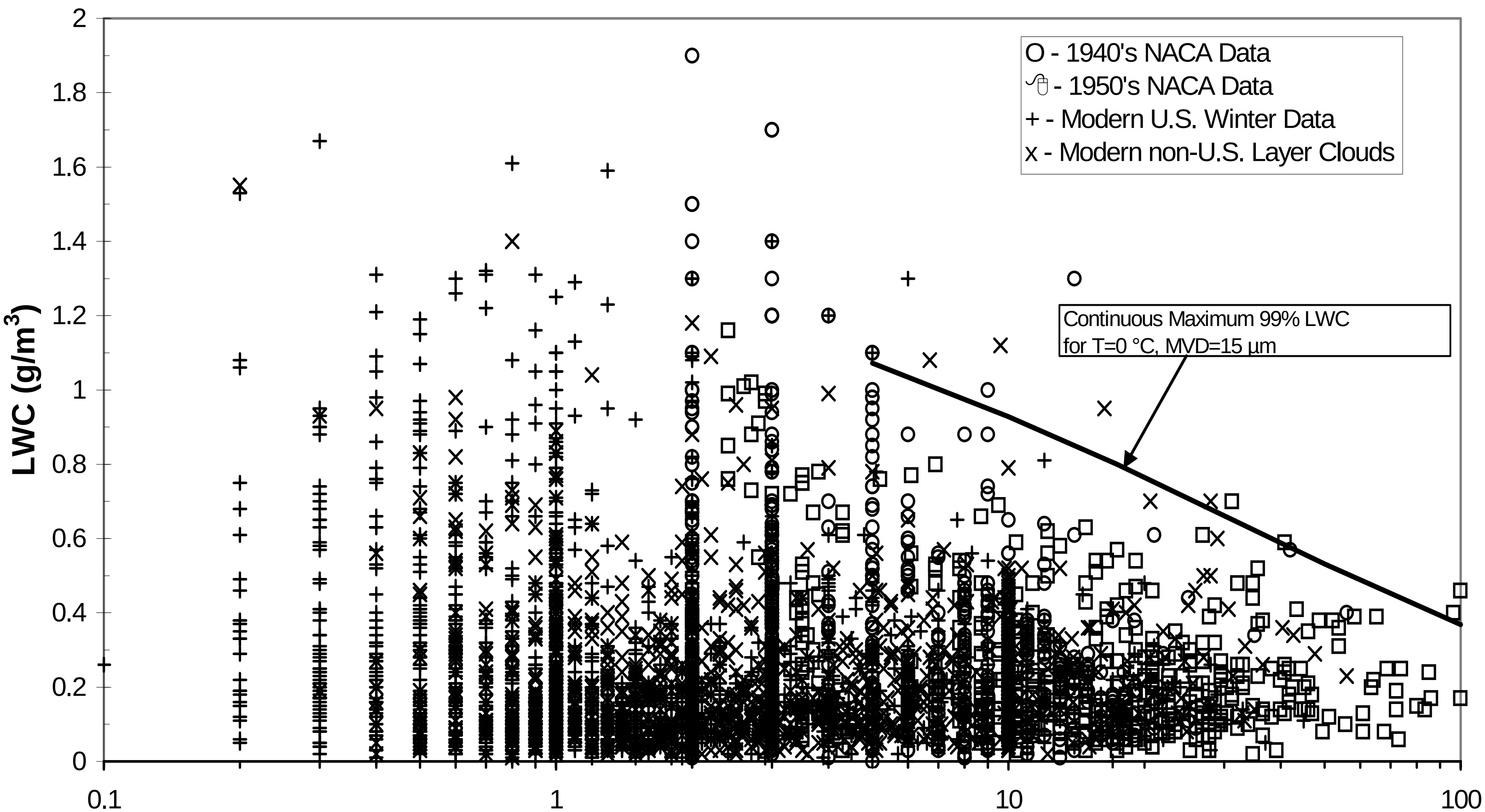

Figure G-1. Supercooled Layer Cloud Data
Compared to *Appendix C*, Continuous Maximum LWC Envelope

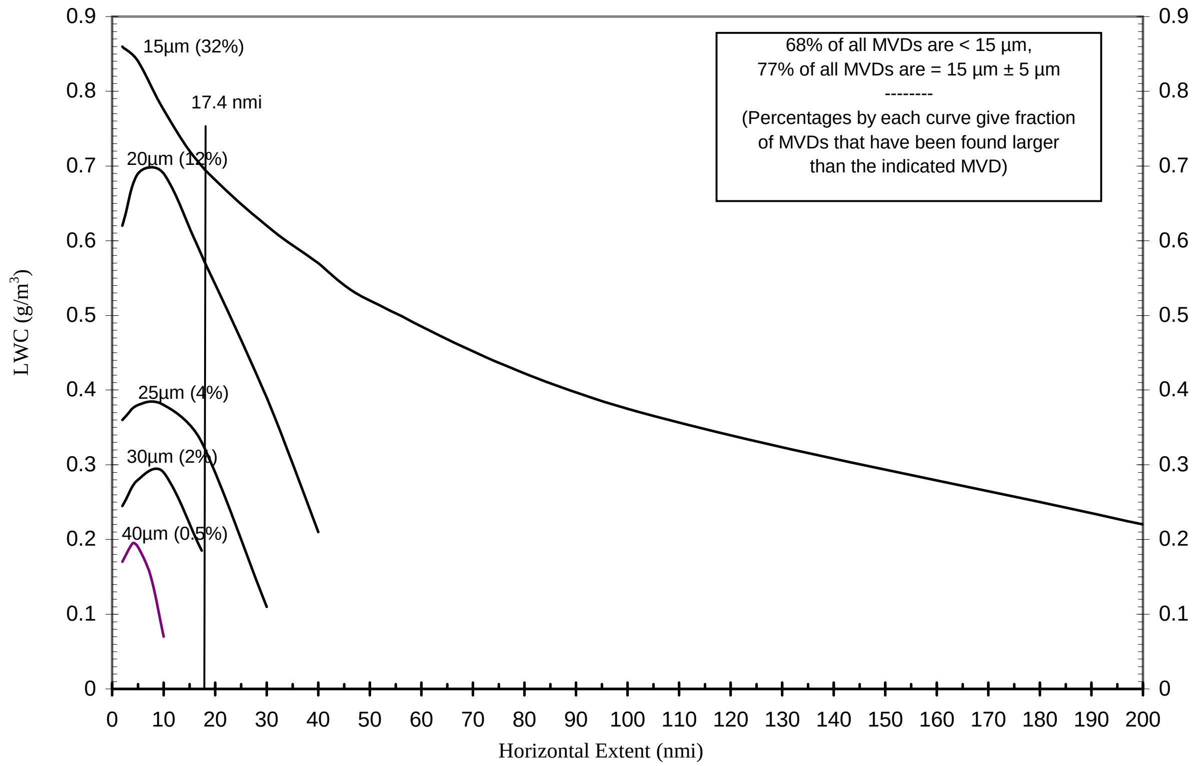

Figure G-2. Natural Duration Limits and 99% LWC Limits for Selected, Sustained MVDs in Stratiform Clouds at 0° to -10°C (Curves will be lower for temperatures below -10°C.)

APPENDIX H—FINDING SUPERCOOLED LARGE DROPS FOR NATURAL ICING FLIGHT TESTS

The two supercooled large drops (SLD) regimes, freezing rain (FZRA) and freezing drizzle (FZDZ), are significantly different and search strategies must be devised for each of them separately.

H.1 FREEZING RAIN.

The following guidance will help in planning and locating (or avoiding) freezing rain conditions.

- Vertical Characteristics. As explained in a recent study [H-1], wintertime FZRA is generally a relatively low-altitude phenomenon. It is characterized by light rain falling into a subfreezing layer of air (herein called the cold layer) extending from or near ground level up to a few thousand feet (see figure 1 in section 1 of this report). The average depth of these cold layers is about 3000 to 4000 ft, with a maximum probable depth of about 7000 ft in some northerly locations (e.g., Green Bay, Wisconsin).

- Horizontal Characteristics. Wintertime FZRA is associated with warm frontal conditions where warm air (from the south) is moving (northward) up and over a shallow (1000 to 4000 ft deep) cold layer already in place at the surface (see figure 2 of section 1 of this report). This situation usually results in an elongated band of FZRA conditions of the order of 100 miles (or less) wide by several hundreds of miles long (figure H-1a). These bands of FZRA usually migrate slowly northward, although in extreme cases, they may remain nearly stationary for up to several days.

- Geographic Locations. Not all wintertime locations are affected by FZRA. Climatological studies (see figure 1 of reference H-1) show that FZRA is more common in certain geographical areas. In North America, the most common areas are in the central and north central states and up into south central Canada. The geography is important—alternating invasions of subfreezing air from the north followed by warm, humid air from the south must be generally available, as shown in figure H-1a. These conditions are most readily met in the areas mentioned above. In contrast, most of northern Europe is less prone to FZRA because the Alps and Pyrenees mountain ranges block the influx of warm, moist air from the Mediterranean Sea.

- Forecasting FZRA Conditions. The location of FZRA is easy to anticipate. If it occurs, it will occur along the southerly boundary of a stalled, invading cold air mass in the eastern half of the United States. The likelihood of an occurrence is relatively easy to forecast a day or more in advance because the precursor conditions of warm air movement aloft are well known. The presence of FZRA is easy to track on an hourly basis from surface weather reports. (See figures H-1b and H-1c.)

- Operational Concerns and Critical Conditions. Based on the characteristics outlined above, the confinement to relatively low altitudes means that FZRA is mainly a concern for takeoffs, landings, and ground maneuvers. Since FZRA coats all upward and forward-facing surfaces, any and all aircraft will be affected to some extent, regardless of size or ice protection system.

During descent, the aircraft will not enter any FZRA until the top of the surface cold layer is reached, typically at 1000 to 4000 ft above ground level (AGL). At least part of the approach will be in FZRA conditions in the cold layer. During this time, the aircraft will accrete ice over all surfaces, and operational procedures or low engine power may prevent the usual ice protection systems from working. Low ceilings are also typical with FZRA, as indicated in figures H-1b and H-1c.

- Weather Forecasting Needs. As mentioned earlier, forecasting the location and onset of FZRA conditions is easier than for most other icing conditions. Adequate advance notice is available simply by watching The Weather Channel on cable television. Improved icing maps http://adds.aviationweather.gov/icing/, real-time satellite imagery (http://www.rap.ucar.edu/weather/satellite/), and surface weather observations (http://weather.noaa.gov/index.html) are readily available on the Internet. These provide supplementary documentation as well as guidance during a deployment to FZRA locations.

- Test Instrumentation. Demonstration flights for certification purposes in FZRA can make use of the normal complement of onboard met-data sensors. These include:

  - Time (hh:mm:ss)
  - Altitude (ft, AGL)
  - Icing rate (mm/min) with a Rosemount 871-FA or similar icing rate meter
  - Outside air temperature (OAT)
  - Total air temperature (TAT)
  - Airspeed

  Any other pertinent variables such as angle of attack (AOA) and flap settings. (The representative drop size for FZRA will automatically be of the order of 1 mm and may not need to be measured for demonstration flights.)

  In addition, the record should include continuous video coverage of the wings or other surfaces of interest or concern. One video camera aimed at the wing-tip area will be useful in documenting the presence and density of any normal icing clouds that may be present in addition to the FZRA in the surface cold layer.

  The icing rate meter (research type, with an analog voltage output) will clearly document the occurrence, duration, and intensity of the icing conditions during the FZRA exposure. References H-2 and H-3 show how to convert the recorded icing rate into an icing intensity level (trace, light, moderate, or heavy) so that the exposure can be ranked in familiar terms. See figure H-2 for an example. The recorded icing rate and duration can even be used to estimate the depth of ice that builds up on various aircraft components during the exposure.

The OAT versus time and altitude will document the depth of the surface cold layer and the range of temperatures to which the aircraft is exposed in FZRA conditions.

Hourly surface weather observations at the airport in use may contain other pertinent data, such as FZRA rates (mm/hour) and amounts (mm) during the demonstration flights.

All these variables can be used together to suitably characterize the FZRA exposure for demonstration flights. The more troublesome liquid water content (LWC) and drop size measurements may not be necessary for these purposes.[1]

This minimal, but adequate, instrumentation list makes it easier to get FZRA data on short notice without having to dedicate the aircraft to instrument installation.

H.2 FREEZING DRIZZLE.

FZDZ is not as confined, geographically and vertically, as FZRA. At the present time, it is not as easy to locate or forecast FZDZ. This makes it more difficult to plan a demonstration flight campaign for FZDZ. Nevertheless, FZDZ has the following characteristics, which provide some guidance.

- Vertical Characteristics. Recent research flights find that FZDZ conditions can occur at altitudes up to about 18,000 ft ASL. In some cases, the FZDZ is confined to shallow layers in or below clouds and thus can be easily exited if recognized. This is most likely the situation in continental clouds. In some coastal cases, FZDZ has been recorded vertically through thousands of feet and, therefore, cannot necessarily be averted, depending on the (probably unknown) horizontal extent.

- Horizontal Characteristics. Dedicated research flights have recorded passes through FZDZ conditions averaging about 12 nmi in length. Ninety-five percent of unidirectional passes through FZDZ are less than 30 nmi long.

- Geographical Preferences. Experience indicates that drizzle is easier to find in clouds belonging to maritime air masses. Indeed, FZDZ has been recorded in research flights along coastal areas of Newfoundland, Nova Scotia, Alaska, the western side of the Sierra Nevada mountains in central California, and even at the southern tip of South America.

- Operational Concerns and Critical Conditions. The effects of FZDZ seem to range from a possibly rapid increase in drag due to sandpaper-like ice forming on the underside of the wing [H-4] to a ridge of ice forming behind the boots or heated zone of the wing, as is suspected in the Roselawn accident case (see section 1.1 of this report). FZDZ has also been implicated in tailplane icing accidents and incidents.

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[1] Commonly used hot-wire LWC sensors notoriously underestimate LWC contributions from drops larger than about 40 µm in diameter. Drop size measurements in the raindrop size range require specialized electro-optical probes that are expensive and troublesome to install and operate. Instead, a suitable icing rate sensor may characterize these FZRA exposures sufficiently.

- The above-mentioned horizontal characteristics indicate that FZDZ is patchy and that straight-through passes are relatively short. Other data in the Master SLD Database at the Federal Aviation Administration William J. Hughes Technical Center shows that the water content of drizzle is less than 0.1 g/m^3, on average, and that momentary maxima are only about 0.4 g/m^3.

- The above considerations suggest that the climb, cruise, and descent phases are where FZDZ is more likely to be encountered, with a possible FZDZ exposure of about 12 nmi during any one of the phases.

- Weather Forecasting Needs. Summertime convective (Intermittent Maximum) clouds often contain FZDZ and could be an acceptable substitute for flight in wintertime FZDZ conditions. Vigorous summertime convective clouds are easier to forecast and to find than wintertime FZDZ conditions. The required summertime clouds need not be thunderstorms, which have additional dangers. Ordinary, isolated cumulus congestus (Cg) clouds, which sometime develop into thunderstorms, are suitable in their pre-thunderstorm stages. Also, these Cg clouds often develop as distinct feeder cells on the upwind side of an on-going thunderstorm, and cloud physics research flights have often taken advantage of them to get data on high LWC conditions (see figure H-3). The horizontal extents of Cg clouds are in the range of 1-5 nmi, so several passes could be made to accumulate enough icing to provide a rigorous test. In mid-latitude, summertime conditions, the freezing level is usually above about 10,000 ft, providing plenty of room to perform iced-up maneuvers and to deice when necessary.

H.3 REFERENCES.

H-1. Jeck, R.K., "Representative Values of Icing-Related Variables Aloft in Freezing Rain and Freezing Drizzle," FAA report DOT/FAA/AR-TN95/119, March 1996.

H-2. Jeck, R.K., "A Workable, Aircraft-Specific Icing Severity Scheme," Paper No. AIAA-98-0094, *36th Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, January 12-15, 1998.

H-3. Jeck, R.K., "Icing Design Envelopes (14 CFR Parts 25 and 29, Appendix C) Converted to a Distance-Based Format," FAA report DOT/FAA/AR-00/30, April 2002.

H-4. Cooper, W.A., et al., "Effects of Icing on Performance of a Research Airplane," *Journal of Aircraft*, Vol. 21, 1984, pp. 708-715.

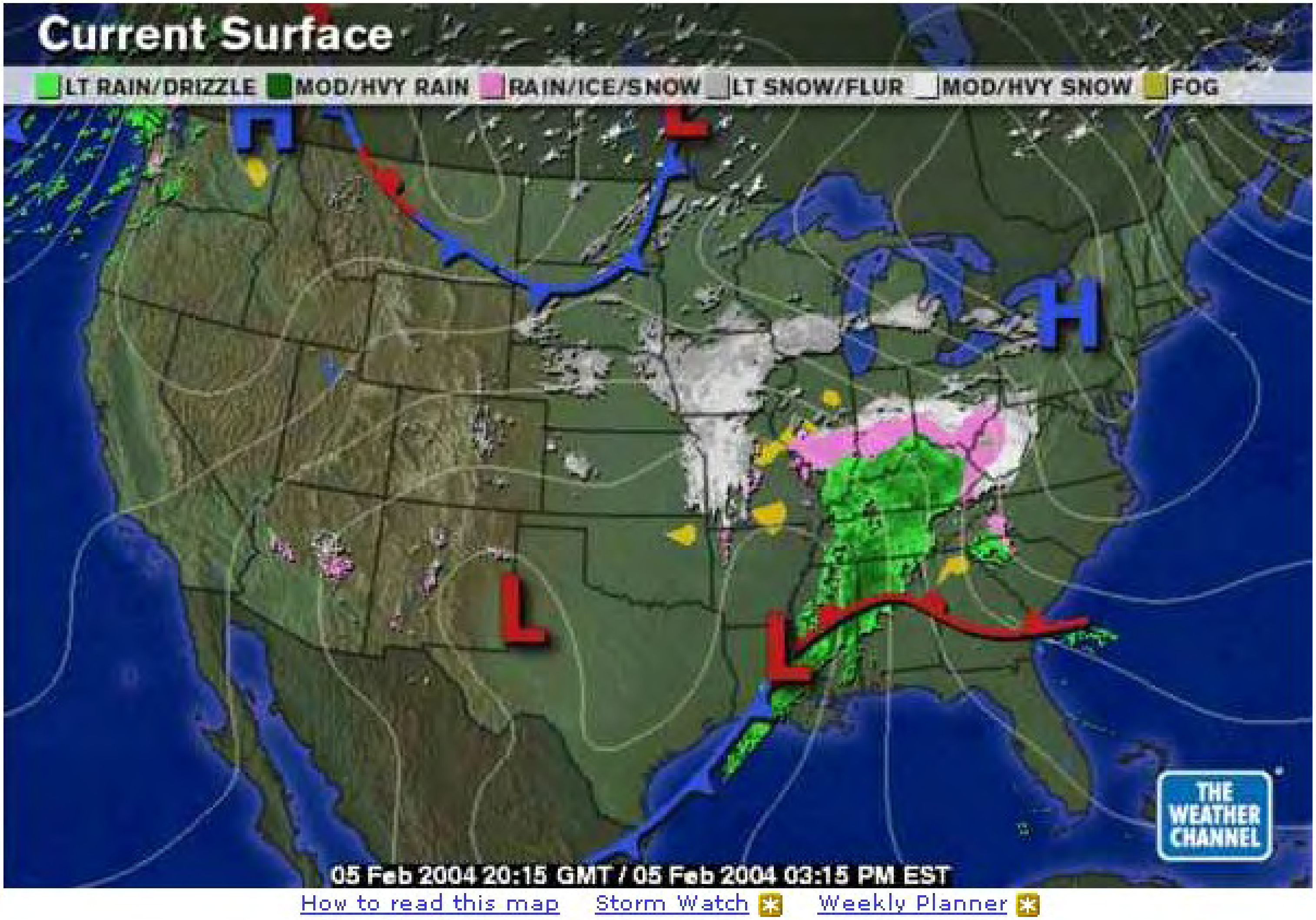

Figure H-1a. Typical Weather Chart Available from www.weather.com
(Pink color stretching across lower portions of Illinois, Indiana, Ohio, and West Virginia indicates an area of freezing rain.)

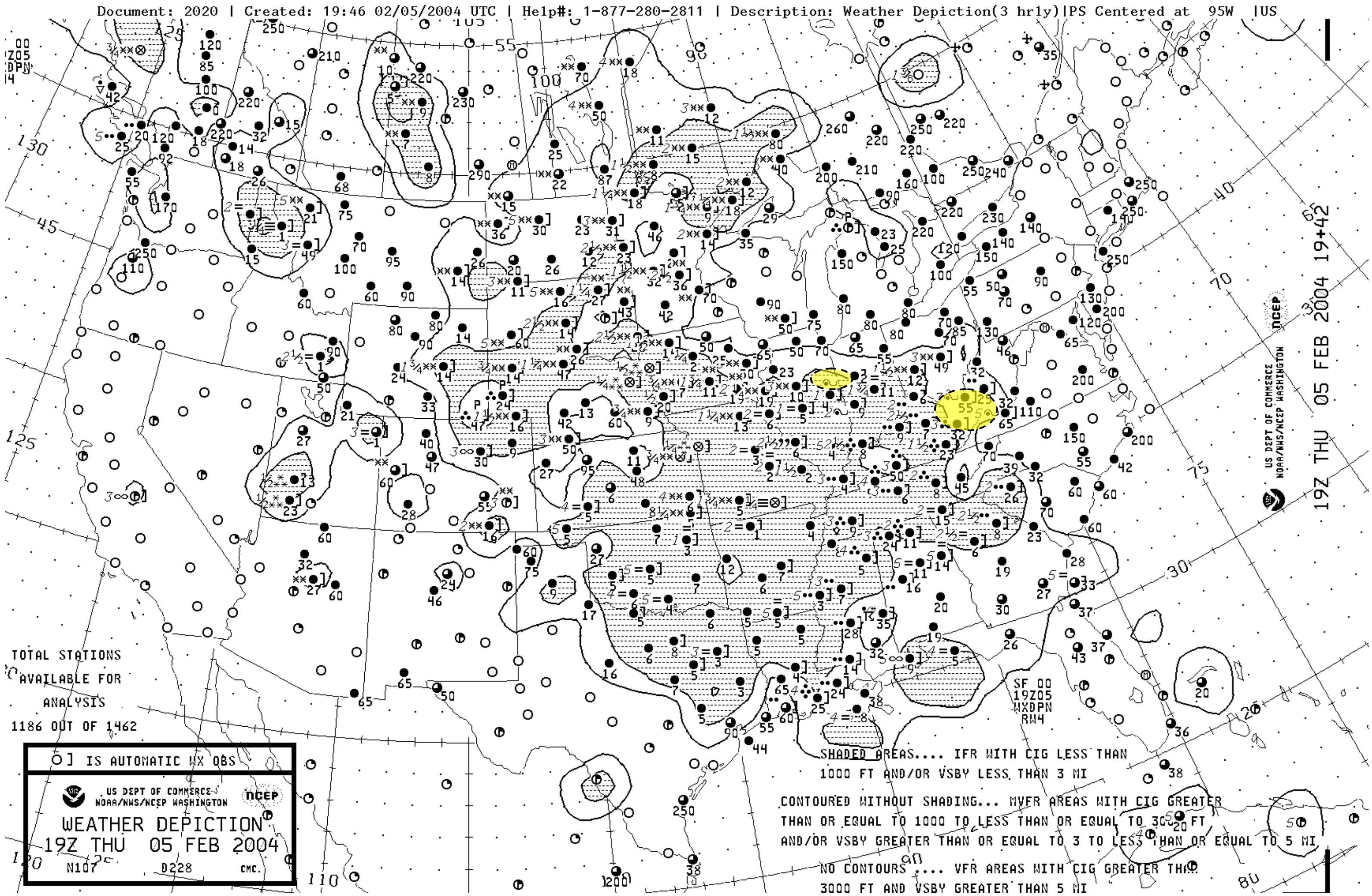

Figure H-1b. Routine Hourly Weather Depiction Chart
Showing Surface Weather, Ceiling Heights, and Instrument Flight Rules (IFR), Visual Flight Rules (VFR) Regions, February 2004
(FZRA, denoted by the symbol "~" overlying a dot, is occurring in the same band shown in Figure H-1a.)
(These charts may be found at http://aviationweather.gov/data/iffdp/2020.gif)

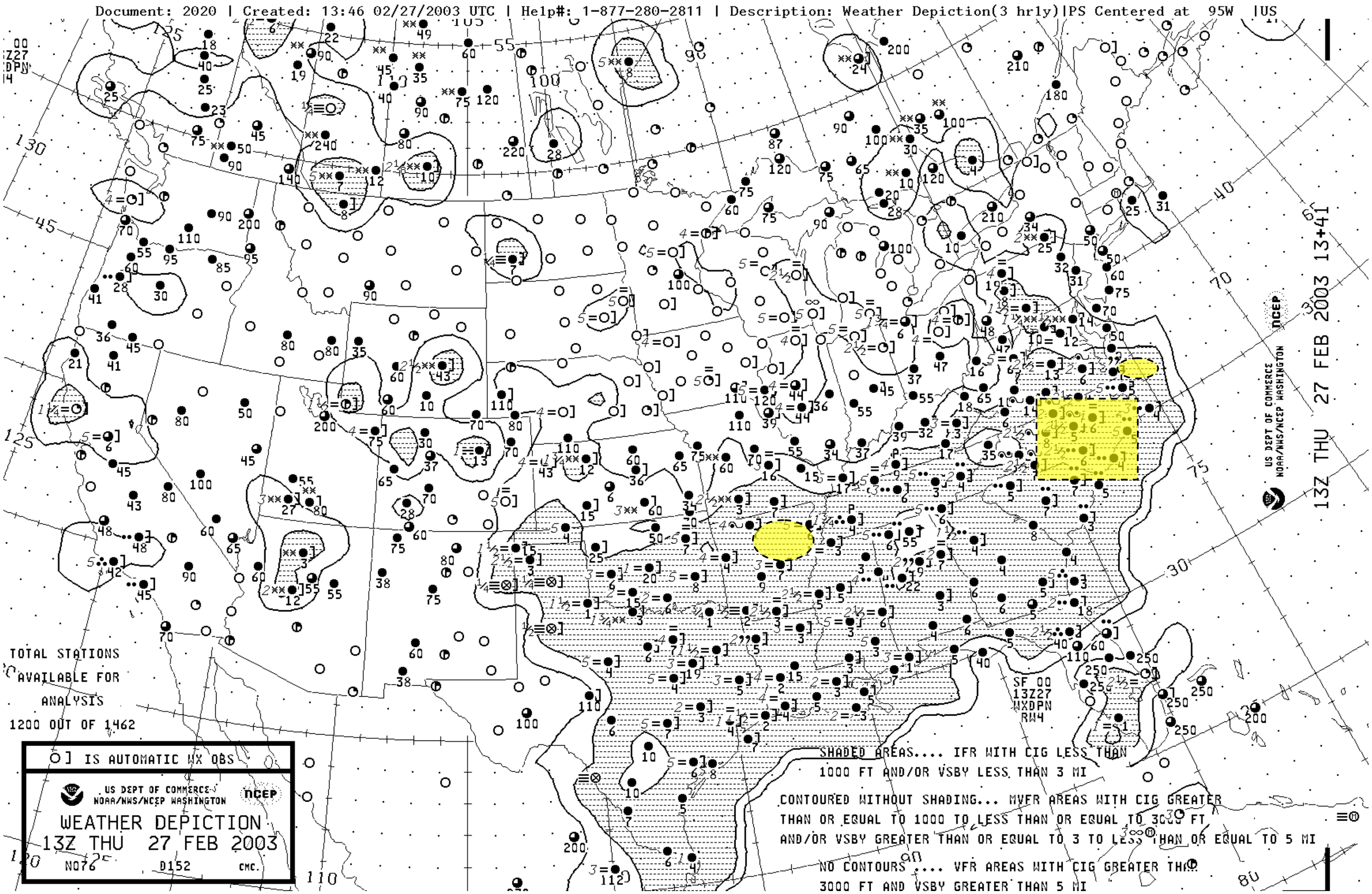

Figure H-1c. Routine Hourly Weather Depiction Chart
Showing Surface Weather, Ceiling Heights, and Instrument Flight Rules (IFR), Visual Flight Rules (VFR) Regions, February 2003
(FZRA, denoted by the symbol “~” overlying a dot, is occurring from eastern Tennessee up into southern Virginia)

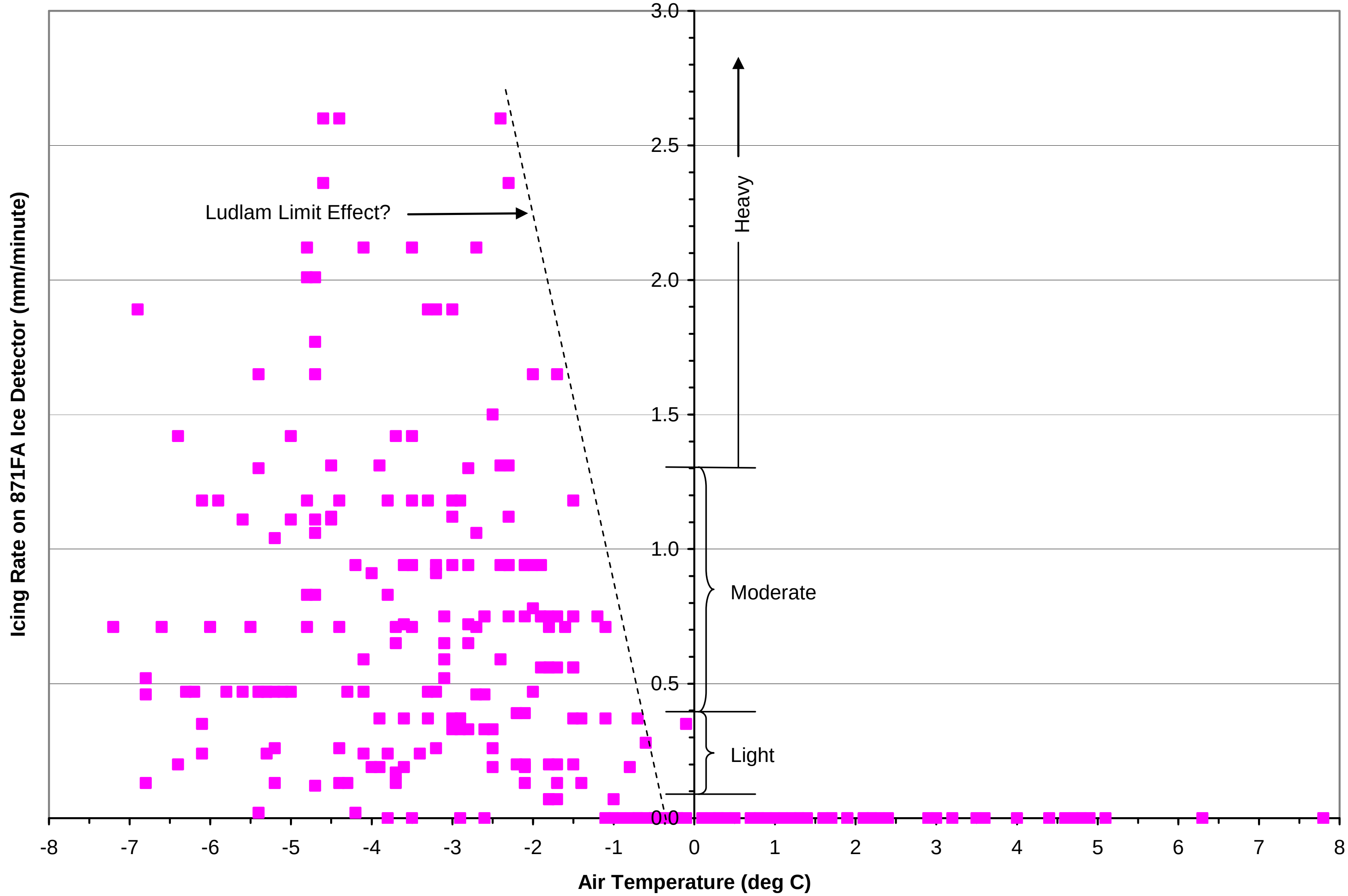

Figure H-2. Icing Rates in FZRA Events in the Master SLD Database

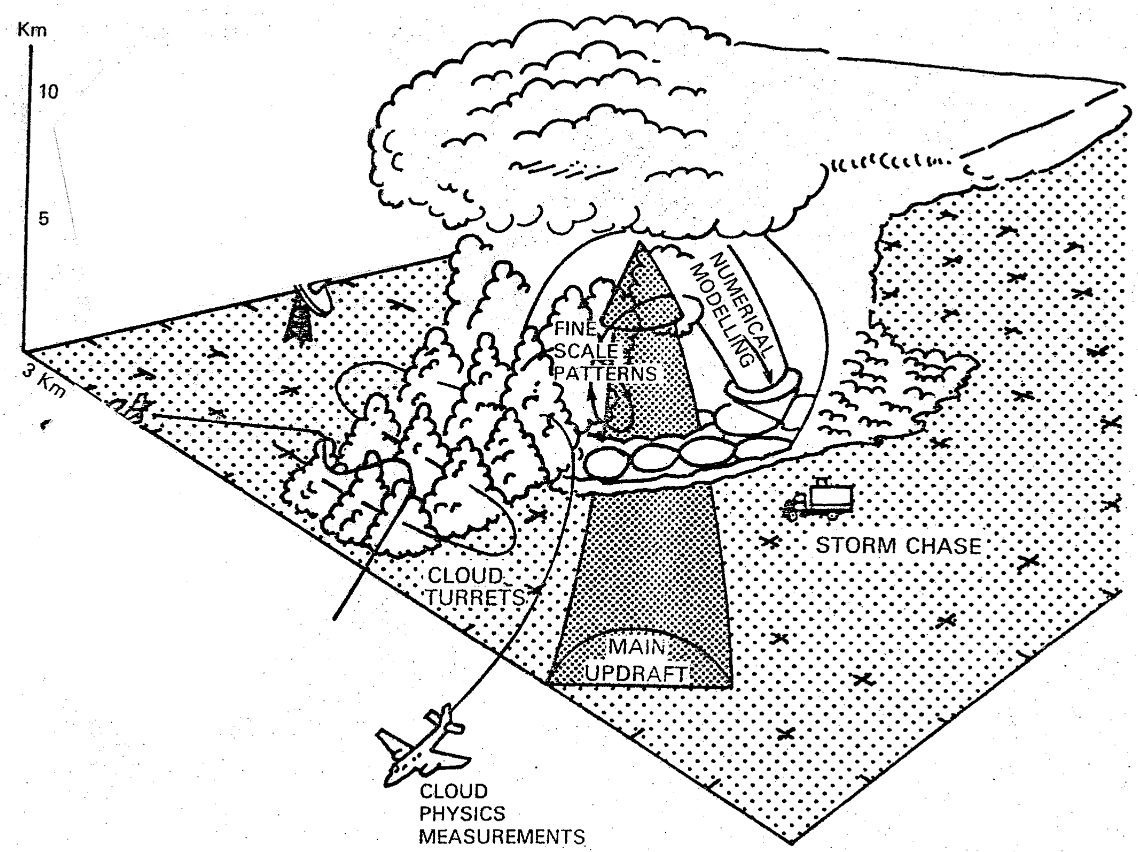

Figure H-3. Illustration of Tactic for Exploiting Flanking Feeder Cells for Intermittent Maximum and Possible FZDZ Conditions.

This figure is borrowed from a cloud seeding research project, showing a way to encounter larger-than-usual LWCs and supercooled drops of vigorous convective clouds while avoiding the dangerous confines of adjacent, isolated thunderstorms.