"A NEW CHARACTERIZATION OF THE ICING ENVIRONMENT BELOW 10,000 FEET AGL FROM 7,000 MILES OF MEASUREMENTS IN SUPERCOOLED CLOUDS"

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This is a report of accomplishment in response to a growing requirement over the past decade for a new assessment of aircraft icing conditions in wintertime clouds at altitudes up to about 10,000 feet. The requirement has been documented in past workshops [1-5], and comes primarily from the helicopter community which wants ice-protected rotorcraft to meet increasing demands for "all-weather" operations. Currently, only a few of the larger helicopters are equipped with certification of ice-protection devices. This is because the current FAA criteria for design and certification of ice-protection equipment results in power and payload penalties that smaller rotorcraft cannot tolerate. The FAA criteria (promulgated in the Federal Aviation Regulations, Part 25 (FAR-25), Appendix C) were actually designed for large, transport-category aircraft capable of flying to 20,000 feet or more. For this reason, there have been concerns that the current criteria may be too severe for low-performance aircraft, such as helicopters, which generally operate at altitudes below 10,000 feet.

The aircraft icing hazard comes from the fact that cloud droplets generally remain liquid even at temperatures several tens of degrees below freezing–a condition called supercooling. These droplets will freeze practically instantaneously on a passing aircraft, however, and form ice on exposed surfaces. The amount of ice depends primarily on the amount of water, or the liquid water content (LWC) of the droplets, the size of the droplets, the temperature of the aircraft surfaces, and, of course, on the horizontal extent of the supercooled clouds along the flight path. Information on the natural occurrence of these variables is obtained from research flights through subfreezing clouds.

The current FAA criteria in FAR-25 are based on research flights undertaken about 35 years ago. Recent advances in cloud physics instrumentation have, therefore, prompted calls for new measurements and for a re-evaluation of the old data for accuracy and reliability. The net requirement is for a reliable, range from ground level to 10,000 feet.

In response to this requirement, about 7,000 nautical miles (NM) of airborne measurements in supercooled clouds at altitudes up to 10,000 feet (3 km) have been computerized at the Naval Research Laboratory (NRL) to form a new data base for low-altitude, aircraft icing applications. Half of the data is from the National Advisory Committee for Aeronautics (NACA) aircraft icing studies of 1946-50 where ice accretion on rotating multicylinders was the primary measurement technique for LWC and droplet size. The other half is from recent research flights by the NRL and other organizations using optical, cloud droplet size spectrometers manufactured by Particle Measuring Systems. These measure droplet sizes, with LWC recorded droplet size distribution. A complete description of this new data base and a number of analyses of the data are contained in a report [6] to the FAA, the sponsor of the project.

The principal conclusions are:

1. The NACA and modern data generally agree in most aspects, indicating that the NACA data are accurate and reliable except possibly for indicated droplet diameters larger than 35μm.

2. The "Intermittent Maximum" and "Continuous Maximum" graphs (envelopes) in FAR-25, Appendix C, do not correctly describe the icing environment in the altitude range from 0 to 10,000 feet AGL. The differences are in the following items:

a) Maximum values of liquid water content.

The maximum observed LWC of 1.1 g/m^3 for layer clouds below 10,000 feet AGL is about 50% larger than the "Continuous Maximum" value of 0.8 g/m^3 (Figure 1). The maximum observed LWC of 1.7 g/m^3 for convective clouds below 10,000 feet AGL over CONUS is about half the "Intermittent Maximum" value of 2.9 g/m^3 (Figure 2).

b) Upper and lower limit to the median volume diameter (MVD) of cloud droplets.

The Continuous Maximum and Intermittent Maximum envelopes extend to MVDs of 40 and 50μm, respectively, as is indicated by a few of the NACA data points (Figure 3). However, the modern measurements show no credible MVDs larger than supercooled clouds below 10,000 feet AGL (Figures 1 and 4). The few MVDs that are reported to be larger than 35μm in the NACA data are questionable in view of the assessment by the NACA researchers themselves that large MVDs are likely to contain large positive errors due to limitations of the multicylinder technique [7]. Also, neither of the FAR-25 envelopes extend to MVDs below 15μm, although the NACA and modern measurements indicate a large fraction of MVDs between 3 and 15μm, especially for layer clouds.

In addition, the present analyses reveal temperature dependences of MVD that are not conveyed in the FAR-25 envelopes. The modern data demonstrate that the <u>upper limit</u> to MVDs in <u>layer</u> clouds decreases from about 35μm at 0^o to 15μm at temperatures below -20^{o}C (Figure 4). Both the NACA and modern CONUS data show that for convective clouds, the <u>average</u> MVD exhibits the opposite behavior and <u>increases</u> with decreasing temperature from about 15μm at 0^o to about 30μm at about -17^{o}C (Figure 5). The modern upper limit

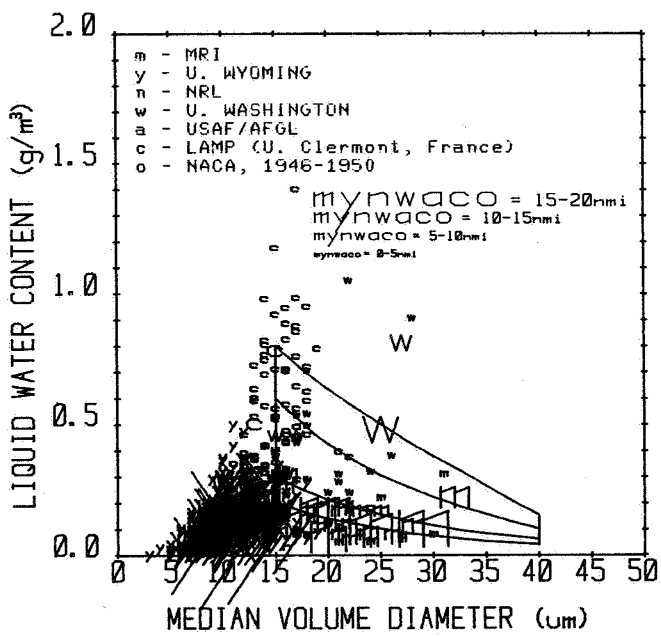

Figure 1. Scatterplot of observed LWC, MVD combinations in the modern data for supercooled layer clouds (St, Sc, Ns, As, Ac) up to 10,000 feet AGL. The various plotting symbols represent different data sources as indicated in the key. The size of each symbol is proportional to its statistical weight (i.e., the observed horizontal extent of the associated icing event) as shown by the scale above the graph. The Continuous Maximum envelope from Figure 1 of FAR 25, Appendix C, is superimposed for comparison.

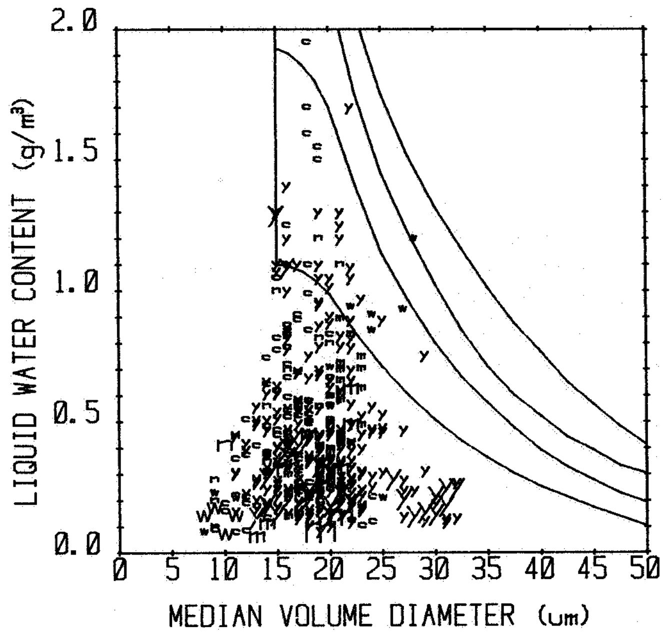

Figure 2. Scatterplot of observed LWC, MVD combinations in the modern data for supercooled convective clouds (Cu, Cb) up to 10,000 feet AGL. A total of 960 data miles is represented in this graph. The Intermittent Maximum envelope from Figure 4 of FAR 25, Appendix C is superimposed for comparison.

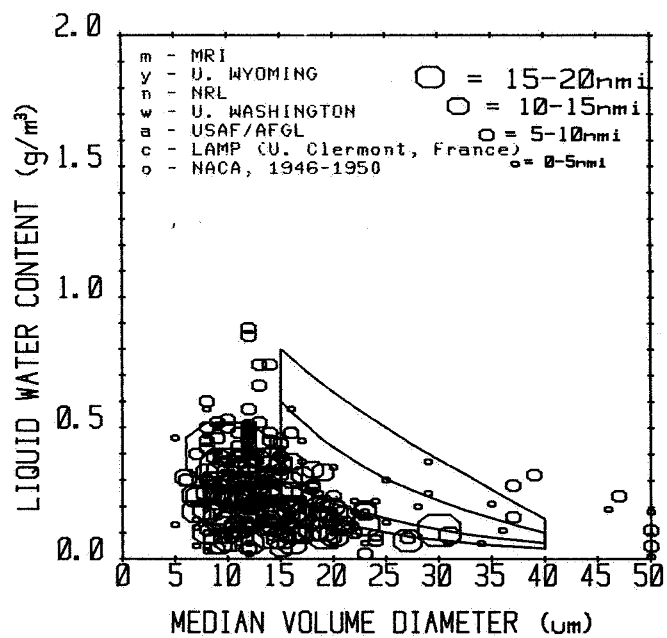

Figure 3. Scatterplot of observed LWC, MVD combinations in the NACA data for supercooled layer clouds up to 10,000 feet AGL. A total of 2565 data miles is represented in this graph.

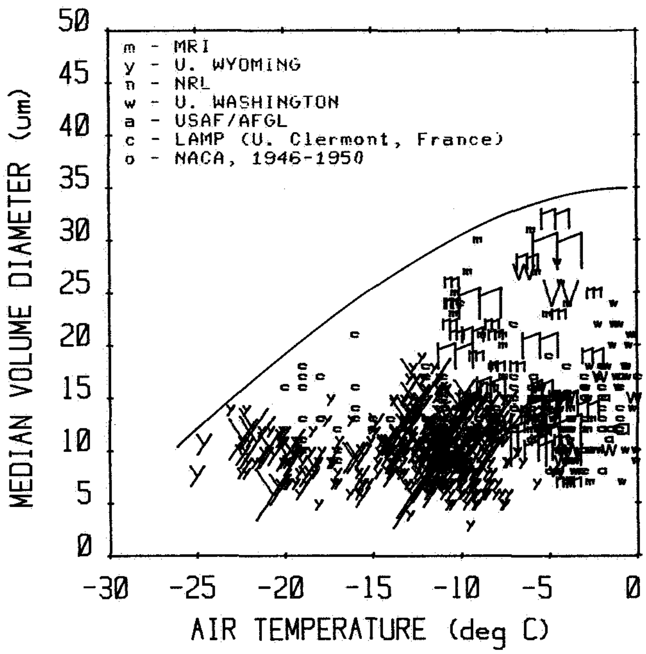

Figure 4. Scatterplot of MVD vs. OAT for modern data from supercooled layer clouds up to 10,000 feet AGL. The solid line bounding the data points represents the apparent upper limit to MVD over CONUS as a function of temperature. A total of 2565 data miles is represented in this graph.

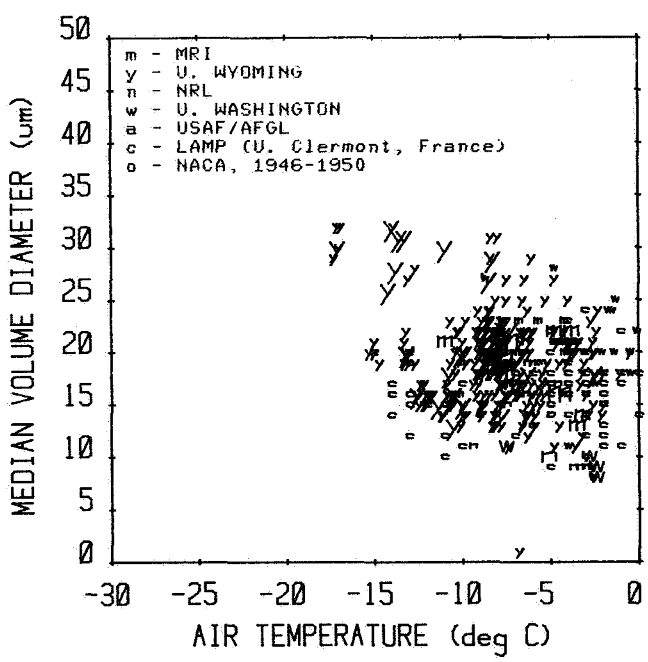

Figure 5. Scatterplot of MVD vs. OAT for modern data from supercooled convective clouds up to 10,000 feet AGL. A total of 960 data miles is represented in this graph.

to MVDs for convective clouds remains at about 35μm over the observed temperature range, however.

c) Low temperature limits.

Minimum temperatures observed in either the NACA or modern data below 10,000 feet AGL are -17°C for convective clouds (Figure 6), and -25°C for

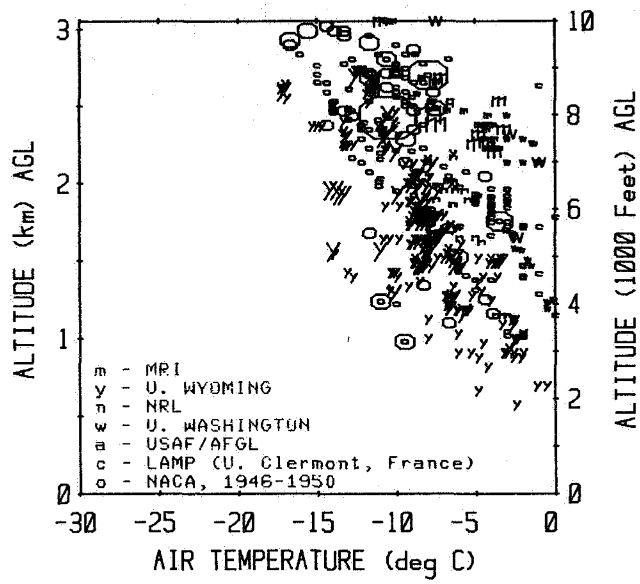

Figure 6. Scatterplot of icing event temperatures vs. altitude for NACA and modern data from supercooled convective clouds up to 10,000 feet AGL. A total of 1545 data miles is represented in this graph.

layer clouds (Figure 7). That is, convective clouds appear to be completely absent at temperatures less than about -17°C at altitudes below 10,000 feet AGL. Nearly all layer clouds with temperatures below -17°C were found in the vicinity of the Great Lakes in January. These coldest layer clouds were found at altitudes between 4,000 and 6,000 feet AGL, (i.e., all clouds sampled elsewhere at higher altitudes were all warmer).

d) Horizontal extent specifications.

A review of the literature reveals no standard definition of horizontal extent and, therefore, confusing and inconsistent usage of "horizontal extent" information occurs in practice. When horizontal extent is defined as the duration of uniform cloud intervals (icing events) as used in this study, the following results are found. Horizontal extents of up to 50 NM have been observed (in upslope cloud

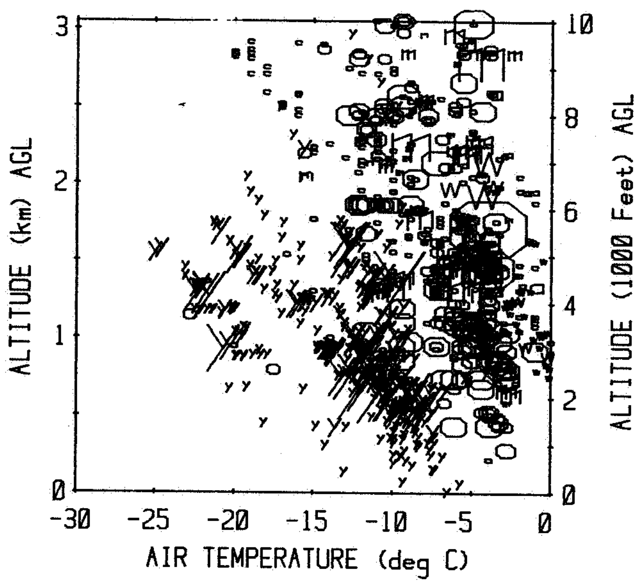

Figure 7. Scatterplot of icing event temperatures vs. altitude for NACA and modern data from supercooled layer clouds up to 10,000 feet AGL. A total of 5215 data miles is represented in this graph.

over eastern Colorado and western Kansas), but 90% of all cases are shorter than 15 NM and 50% are shorter than 5 NM. <u>Maximum</u> horizontal extents decrease with increasing LWC, but all values of horizontal extent up to the maximum are observed and the shorter events are most common (Figure 8).

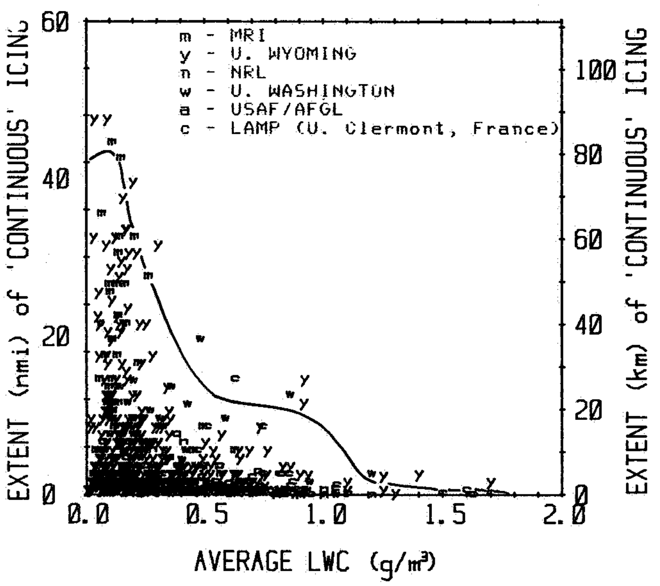

Figure 8. Scatterplot of modern observed horizontal extents of entire icing encounters vs. average LWC over the encounter. In this figure, an icing encounter is defined as a series of one or more icing events traversed consecutively until a cloud gap of 1 NM or more is reached. The horizontal extent of the encounter is the sum of the horizontal extents of the component icing events but does not include the extent of permissible cloud gaps. Data are for all supercooled cloud types at altitudes up to 10,000 feet AGL. A total of 3645 data miles is represented in this graph. The curved line is the 99th percentile of horizontal extent for these encounters as a function of average LWC.

3. A new characterization can be made to replace the FAR-25 envelopes for altitudes below 10,000 feet AGL (Figure 9).

The main features of the new characterization are:

a) Simplicity: a single set of envelopes will suffice.

Although it is instructive to distinguish between layer and convective clouds for scientific analyses, there appears to be no compelling, practical reason to do so for icing certification or design

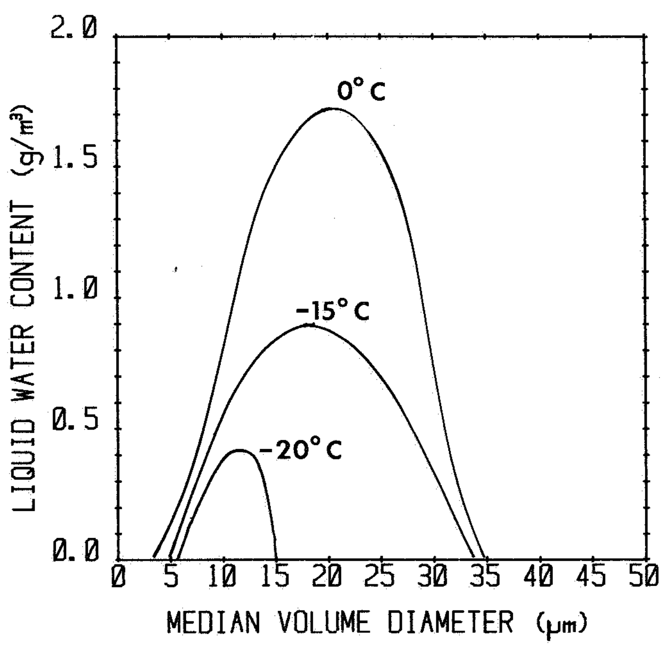

Figure 9. Approximate extreme values of LWC and MVD combinations observed in supercooled clouds at altitudes up to 10,000 feet AGL. The curved lines represent the approximate extreme values of LWC and MVD observed in any supercooled cloud icing event up to 10,000 feet AGL over CONUS and up to the temperatures indicated. The curves are based on about 7000 NM of measurements.

criteria a long as there are companion guidelines which specify horizontal extent requirements as a function of LWC. A new, single set of "icing envelopes" (i.e., temperature dependent contours of maximum LWC vs MVD) can be established as in Figure 9 for both layer and convective clouds together as a unified description of the overall icing environment for altitudes up to 10,000 feet AGL. This envelope would specify extreme LWC, MVD and temperature criteria for both design and flight test purposes, but information available elsewhere in Reference [6] would be needed to guide the selection of practical test points for in-flight certification checks. For this unified set of envelopes, the maximum LWC will range from about 1.7 g/m^3 at 0^o to about 0.4 g/m^3 at temperatures from -20°C to -30°C, the approximate lower limit of cloud temperatures below 10,000 feet AGL.

b) True representation of MVD extremes and their temperature dependence.

Minimum MVDs will be about 5μm at all temperatures. Maximum MVDs will be about 35μm from 0°C to -20°C. At -20°C, the approximate temperature below which no convective clouds will be found at altitudes below 10,000 feet AGL, the maximum MVD drops abruptly to 15μm.

c) Clarify the meaning and usage of "horizontal extent."

Distance criteria should be re-defined by relating them directly to measured horizontal extents of definable icing "encounters" (i.e., series of one or more icing events separated by distances less than some specified limit, such as 1 NM, for example).

References

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