JOURNAL OF AIRCRAFT
Vol. 29, No. 4, July–Aug. 1992

Assessment of One-Dimensional Icing Forecast Model Applied to Stratiform Clouds

Arnold Tunick* and Henry Rachele†
U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, New Mexico 88002

Aircraft icing can seriously impair aircraft performance. In this paper we assess a one-dimensional icing forecast model (presently residing at the U.S. Army Atmospheric Sciences Laboratory) by using recent airborne collected microphysics data. Our prime interest was the variation of potential aircraft icing in stratiform clouds. We discuss the icing model microphysics, including algorithms used to determine icing severity indices, temperature, liquid water content (LWC), and median volume diameter (MVD) of supercooled water droplets. Output from the one-dimensional model suggests that the icing potential in stratiform clouds does not exceed "light." The model more often forecasts "trace" icing for both fixed-wing aircraft and helicopters. The model does not compute a value for LWC great enough to allow for more serious icing events. We therefore conclude that a method must be established to obtain better estimates of drop-size characteristics and LWC (for stratus clouds) to forecast the full range of potential icing for Army aircraft. Otherwise when using the one-dimensional model as currently structured, one would not expect any more than "light" icing when stratus clouds are observed.

Nomenclature

C_p = specific heat at constant pressure for dry air, 0.239 cal/g
e_s = saturation vapor pressure for water in millibars
g = acceleration due to gravity, 9.8 m/s^2
L = latent heat of condensation, 595.0 − 0.5T (°C) cal/g
M_v = molecular weight of water vapor, 18.016 g/mole
P = atmospheric pressure in millibars
R = gas constant of dry air, 0.6855 cal/g K
R_s = mixing ratio in g/g
R^* = universal gas constant, 1.986 cal/K mole
T = absolute temperature in K unless specified otherwise
z = height above ground in meters
$(\ )_0$ = value at reference condition (height)
γ_w = moist adiabatic lapse rate in K/m
ρ_a = ambient air density in g/m^3

I. Introduction

THE purpose of this project is to compute and analyze the variation of potential aircraft icing in statiform clouds, by using a combination of a one-dimensional icing forecast model[1] and microphysics data collected by Jeck.[2] The origin of the aircraft icing model discussed in this paper is a modification to the updated Smith-Feddes model.[3]

II. One-Dimensional Icing Forecast Model

The general procedure presented by Luers for determining the potential level of icing (trace, light, moderate or severe) is as follows: for a given mean effective drop size of the drop-size distribution at the midpoint of a cloud and the expected amount of liquid water content (LWC) at that height, one determines if the level of LWC falls in the range of light (LWC_l), moderate (LWC_m), or severe (LWC_s) as given in Table 1. In discussions with Luers, he suggested that the mean effective drop-size used in his study is assumed to be equivalent to the median volume diameter (MVD) drop size used by Jeck. Luers specifies a mean effective drop-size value of 10–12 μm diameter for stratiform clouds (stratus and stratocumulus).

The expected amount of LWC initially is based on the adiabatic approximation and is computed as follows: starting at the cloudbase, one computes 1) the moist adiabatic lapse rate of temperature; 2) the moist adiabatic temperature at a level of 10 m above the cloudbase; 3) the mixing ratio R_s at this new temperature; and 4) the liquid water generated over the 10-m layer as the difference between the lower and the upper values of R_s. This difference is converted to grams per cubic meter by multiplying by the mean dry air density over the 10-m layer. Equations that can be used, as summarized above, are presented in Rogers and Hanley[5]; that is

$$T(z) = T_0 - \gamma_w z \tag{1}$$

$$P(z) = P_0 \left(\frac{T(z)}{T_0}\right)^{g/R\gamma_w} \tag{2}$$

$$e_s(z) = 6.11 \exp\left[\frac{M_v L}{R^*}\left(\frac{1}{273} - \frac{1}{T(z)}\right)\right] \tag{3}$$

$$R_s(z) = 0.622\left(\frac{e_s(z)}{P(z) - e_s(z)}\right) \tag{4}$$

$$\Delta R_s = R_s(z) - R_s(0) \tag{5}$$

$$\Delta\,(\mathrm{LWC}) = -\rho_a \Delta R_s \tag{6}$$

In contrast, Jeck,[6] suggested that the procedure to compute LWC may be more detailed than necessary since the expres-

Table 1 Icing severity levels as a function of LWC[4]

	Mean effective drop size, μm					
	10	15	20	30	40	50
LWC_s, g/m^3	2.5	1.3	0.85	0.65	0.55	0.50
LWC_m	= ← — — — 0.5 (LWC_s) — — — →					
LWC_l	= ← — — — 0.1 (LWC_s) — — — →					

Received Oct. 24, 1990; presented as Paper 91-0352 at the AIAA 29th Aerospace Sciences Meeting, Reno, NV, Jan. 7–10, 1991; revision received Aug. 16, 1991; accepted for publication Aug. 19, 1991.

*Meteorologist. Member AIAA.
†Mathematician.

sion LWC = 1/2.87 ($W0 - W1$) P/T from Ref. 7 (for cumulus clouds), is adequate for this application. To correct the LWC, presumably for entrainment, the value for stratus clouds is divided by 2. In the expression above $W0$ (g/kg) is the saturation mixing ratio at the cloudbase; $W1$ (g/kg) is the saturation mixing ratio at the flight altitude; P(mbar) is the flight altitude pressure; and T(K) is the flight altitude temperature.

The Luers procedure, is repeated until the LWC at the midpoint of the geometric cloud layer is computed. This value of adiabatic LWC is then adjusted for entrainment effects depending on the cloud type. In the case of stratiform clouds, Luers adjusts these values following Warner's (Ref. 8) study of LWC in cumulus cloud. The correction factor is

$$\mathrm{LWC} = \mathrm{LWC}_a(az + b), \qquad (7)$$

where a and b are given in Table 2.

Knowing the height and temperature of the cloudbase and the cloud top height, one approximates the temperature at the midpoint of the cloud needed for the above computations by using the moist adiabatic approximation given by Luers, that is

$$\frac{\mathrm{d}T}{\mathrm{d}z} = -g \left(\frac{1 + 0.621 \dfrac{e_s}{p} \dfrac{L}{RT}}{C_p + 0.621 \dfrac{L}{P} \dfrac{\mathrm{d}e_s}{\mathrm{d}T}} \right) \qquad (8)$$

The saturation vapor pressure is computed by using

$$e_s = 6.112 \exp \left(\frac{17.67T}{T + 243.5} \right) \qquad (9)$$

$$\frac{\mathrm{d}e_s}{\mathrm{d}T} = \frac{4.303 \times 10^3}{(T + 243.5)} e_s \qquad (10)$$

where T = temperature in degrees Celsius.

Table 2 Parameters for LWC/LWC$_a$ ratio [Eq. (7)] for stratus type clouds

Height above cloudbase, km	a	b
0–0.032	−11	1.0
0.032–0.177	−1.4	0.6915
0.177–0.726	−0.356	0.505
0.726–1.5	−0.0608	0.2912
1.5	0.0	0.2

Table 3 Fixed wing potential icing index

If		
$0 \le \mathrm{LWC} < \mathrm{LWC}_1$	and	$T < 0$°C, trace
$\mathrm{LWC}_l \le \mathrm{LWC} < \mathrm{LWC}_m$		$T < 0$°C, light
$\mathrm{LWC}_m \le \mathrm{LWC} < \mathrm{LWC}_s$		$T \le -5$°C, moderate -5°C $< T < 0$°C, light
$\mathrm{LWC}_s \le \mathrm{LWC}$		$T \le -5$°C, severe -5°C $< T \le -3$°C, moderate -3°C $< T < 0$°C, light
Otherwise		
either LWC = 0	or	$T \ge 0$°C, no icing

Table 4 Helicopter (rotor-blade) potential icing index

If		
$0 < \mathrm{LWC} < \mathrm{LWC}_l$	and	$T < 0$°C, trace
$\mathrm{LWC}_l \le \mathrm{LWC} < \mathrm{LWC}_m$		$T < -5$°C, light -5°C $< T < 0$°C, trace
$\mathrm{LWC}_m \le \mathrm{LWC} < \mathrm{LWC}_s$		$T \le -10$°C, moderate -5°C $< T < 0$°C, trace
$\mathrm{LWC}_s \le \mathrm{LWC}$		$T \le -10$°C, severe -10°C $< T \le -5$°C, light -5°C $< T < 0$°C, trace
Otherwise		
either LWC = 0	or	$T \ge 0$°C, no icing

Finally, Luers provides tables [see Table 3 for fixed-wing aircraft and Table 4 for helicopter (rotor-blade) aircraft] that allow one to determine the level of potential icing as a function of LWC and temperature. Note the dependence of icing severity on temperature. Dynamic heating of the winged or rotor surfaces play an important role in determining the ice accretion efficiency of the super-cooled liquid water droplets.

III. LWC and Median Volume Drop-Size Variations

A review of Jeck's data base[2] shows that the median volume drop size and LWC in stratus clouds can vary considerably as a function of temperature (see Figs. 1 and 2).

These figures illustrate scatterplots of LWC and MVD vs air temperature from supercooled layer clouds. The data are taken from the various sources shown in the figures. Notice in Fig. 1 that LWC falls off for temperatures below −15°C. This is due to the depletion of supercooled water caused by ice crystal formation. Also note that most observations in Fig. 1 have LWC < 0.3 g/m^3. Most LWC's in stratus are small; however, good data will show that the larger ones do exist. Correlations between LWC and MVD data and observed dependence on icing, is still an open question.[6] The different size symbols in Figs. 1 and 2 represent the various in-flight distances over which the data was averaged. The solid line according to Jeck represented the apparent hand-drawn upper limits to LWC and MVD. These extreme values may be important as they relate to aircraft icing, since according to Borovikov et al.,[9] ". . . the intensity and character of the icing depend first and foremost on the water content and the size of droplets in clouds of various forms. Stratocumulus and stratus clouds, for example, are in the overwhelming majority of cases liquid, super-cooled, less often mixed and extremely rarely crystal. Therefore, the icing probability in these clouds is very high, over 80–85%." In agreement is Hansman[10] who states, ". . . it is clear that the shape of the ambient size distribution is a very important factor in determining the icing severity of a particular cloud. A relatively low cloud LWC is a significant icing threat if it consists of large droplets. On the other hand, if the cloud consists of small droplets, even very high LWC would only cause trace icing." In addition, Politovich[11] remarks, "For (stratiform clouds) it is not the number of cloud droplets that is important in determining icing rate, but their size." These comments on droplet size

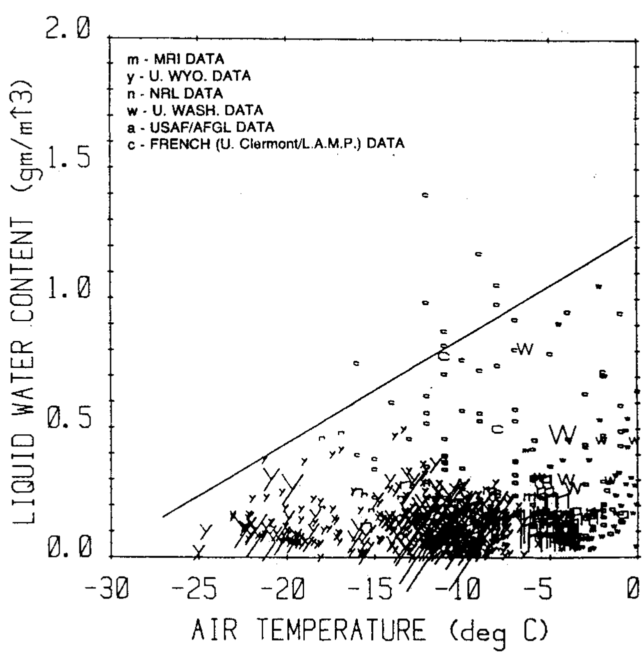

Fig. 1 Scatterplot of LWC vs air temperature from supercooled layer clouds up to 10,000 ft AGL. The different size symbols represent the various in flight distances over which the data were averaged.

Table 5 Potential icing severity for LWC and MVD values in the temperature range from 0.0°C to −15.0°C

Case	LWC, g/m³	MVD, μm	Potential icing severity: Fixed wing	Potential icing severity: Helicopter
Average	0.18	11.0	Trace	Trace
Intermediate	0.55	18.0	Moderate $T \leq -5.0$ Light $-5.0 < T < 0.0$	Moderate $T \leq -10.0$ Light $-10.0 < T \leq -5.0$ Trace $-5.0 < T < 0.0$
Extreme	0.9	27.0	Severe $T < -5.0$ Moderate $-5.0 < T \leq -3.0$ Light $-3.0 < T < 0.0$	Severe $T \leq -10.0$ Light $-10 < T \leq -5.0$ Trace $-5.0 < T < 0.0$

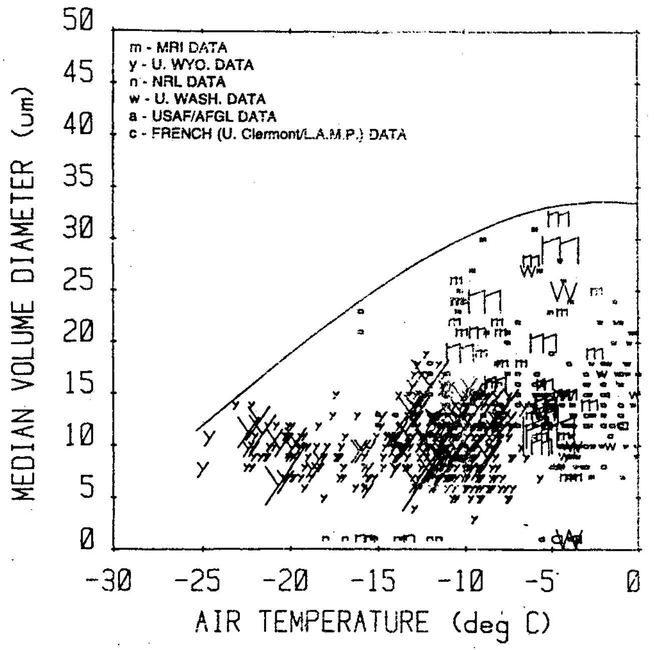

Fig. 2 Scatterplot of median volume diaster (MVD) vs air temperature from supercooled layer clouds up to 10,000 ft AGL. The different size symbols represent the various flight distances over which the data were averaged.

and number relate to the efficiency with which supercooled water droplets collide and then freeze on winged surfaces. Small droplets tend to remain within the airflow over and past the metallic surface. Larger droplets fall across the streamlines onto an aircraft mainframe and wing (or rotor blade). In view of the observed variations of MVD and LWC in stratus clouds, we decided to assess the potential for icing as a function of these two variables.

IV. Icing Forecast Analysis

Using the procedure outlined in the one-dimensional icing forecast model section and the data provided in Sec. III, we computed the potential icing for average, extreme and intermediate values of LWC and MVD for specified values of temperature. These results are presented in Table 5. We concluded that this dependence of icing severity on temperature is due to dynamic heating.

Average values (for low stratus clouds) of LWC and MVD from Jeck's data regardless of their frequency of occurrence, result in forecasts of not more than "light" and more often only "trace" icing using the one-dimensional model presented in this paper. Table 1 shows that for the average droplet MVD (that is, 10–12 μm) the computed LWC is not sufficient to produce more serious icing activity. Values greater than the mean (that is, 0.5–0.9 g/m³ LWC and 15–25 μm MVDs), allow the full range of potential icing to be recognized. Again, the current literature suggests that the largest droplet sizes, although possibly few in number, are most likely to cause the more severe icing episodes. However, our perception (based on available data) is that the probabilities of these extreme values of LWC and MVD occurring simultaneously is small. Quantitative data involving joint probabilities of LWC and MVD occurring simultaneously were not available from Jeck.[2] Also in Table 5 one should recognize the dependency of icing severity on temperature. As an example, dynamic heating of rotor blades will cause some ice to shed thereby requiring cooler temperatures for more hazardous events to occur.

The results discussed above are supported by those documented by McGinley et al.[12] from an initial validation of the Luers icing model during the 1990 Winter Icing and Storms Program (WISP) in the Denver-Boulder Front Range region. In their study they report, "even though LWC values from the one-dimensional model were above .5 g/m³, the algorithm only forecast light or trace amounts of aircraft icing." Additionally they concluded that the model characteristically underforecast potential icing severity. This could place Army aircraft at considerable risk.

V. Summary and Conclusions

The potential for icing on fixed-wing and rotary aircraft was examined for stratiform cloud conditions. The methodology developed by Luers and currently adopted by the U.S. Army Atmospheric Sciences Laboratory for estimating icing levels requires that one have estimates of temperature, LWC, and MVD drop-size at the geometric midpoint of the cloud, and hence one must also know the heights of the base and the top of the cloud. The temperature used in this procedure is computed by using the moist adiabatic lapse rate and an estimate of temperature at the cloudbase. The LWC is computed using Rogers and Hanley's procedure (assuming adiabatic conditions) and adjusted according to Warner's empirical results for cumulus clouds. The MVD drop size for stratus clouds is assumed to lie between 10 and 12 μm. Based on this methodology, we found that icing potential in layer clouds for fixed-wing aircraft and helicopters could not exceed the "light" level and more often did not exceed the "trace" level for all temperature below 0°C.

Since larger drops and LWC amounts are found near the top of the cloud in most stratiform layers,[13] use of cloud midpoint temperatures, LWC, and average MVD drop size may result in erroneous icing potential estimates. Using Jeck's database for stratiform clouds (which showed significant variations of LWC and MVD with temperature) and the potential icing level criteria of Luers we found that the icing potential for average to extreme values of LWC and MVD ranged from light to severe on fixed-wing aircraft and from a trace to severe for helicopters. Our conclusion is that a procedure must be established to obtain better estimates of LWC and MVD (for stratus clouds). Also, our understanding of the probabilities of high values of LWC and MVD occurring simultaneously must be enhanced.

VI. Suggestions for Future Research

In Sec. V we suggested that additional research or data analysis concerning LWC and MVD probabilities and statistics could enhance our understanding of icing potentials. Also, according to Newton[14] relaxation or improvement of the criteria outlined in Table 1 would certainly be a major benefit to the implementation of the Icing Forecast Model. For example if one wanted to consider effects of imbedded convection in a stratus type cloud, which was outside the scope of this study, it would be best to allow for a larger MVD (i.e., cumulus or stratocumulus) when using Table 1. In conjunction with reworking Table 1 would be the development of an improved method for correcting the calculated adiabatic LWC due to entrainment. In its present form the adiabatic LWC is adjusted by Warner's[8] empirical data based on a study of cumulus clouds. Although no new data from WISP is available at this time the authors feel that much may be discovered showing the dependence of icing on LWC and MVD independently and jointly.

Acknowledgments

We gratefully acknowledge the encouragement given to us throughout the course of this study by Richard Jeck of the Naval Research Laboratory in Washington, DC, currently with the Federal Aviation Administration Technical Center in Atlantic City, NJ. He has been a tremendous source of data, comment, and reaction.

References

[1]Luers, J., Haines, P., and Cerbus, C., "One-Dimensional Icing Forecast Model," UDRI-TR-87-138, Univ. of Dayton Research Institute, Dayton, OH, 1988.

[2]Jeck, R. K., "A New Database of Supercooled Cloud Variables for Altitudes up to 10,000 ft AGL and the Implications for Low Altitude Aircraft Icing," Rept. No. 8738, AD-A137589, Naval Research Lab., Washington, DC, 1983.

[3]Rogers, C., Hanley, J., and Mack, E. "Updating this Smith-Feddes Model;" Calspan Rept. No. 7330-1, Buffalo, NY, 1985.

[4]Newton, D. W., "A Review of the Icing Situation from the Standpoint of General Aviation," NASA Publication 2086, FAA-RD-78-109, *Aircraft Icing,* 1978, pp. 31–38.

[5]Rogers, C., and Hanley, J. T., "An Algorithm for the Increase of Liquid Water Content with Height in Fog and Water Hazes," Calspan Rept. 6711-M-1, Buffalo, NY, 1980.

[6]Jeck, R. K., Personal communication from Naval Research Lab., Washington, DC, 1989, 1990, 1991.

[7]Air Weather Service, AWS TR-80-001, March 1980, *Forecasters guide on Aircraft Icing* AD-A085490, Scott Air Force Base, IL, 1980.

[8]Warner, J., "On Steady-State One-Dimensional Models of Cumulus Convection," *Journal of Atmospheric Sciences,* 1970, pp. 1035–1040.

[9]Borovikov, A. M., et al., *Cloud Physics,* edited by A. Kh. Khrgian, pp. 276–277.

[10]Hansman, R. J., Jr., "Droplet Size Distribution Effects on Aircraft Icing Accretion," *Journal of Aircraft,* Vol. 22, No. 6, 1985, pp. 503–508.

[11]Politovich, M. K., "Microphysical Influences on Aircraft Icing," *Conference on Cloud Physics,* Chicago, IL, Nov. 15–18, 1982, American Metereological Society, Boston, MA.

[12]McGinley, J. A., Albers, S. C., McCaslin, P. T., and Smart, J. R., "Validation of the Smith-Feddes Ice Forecasting Method During a Winter Storms Program," Progress Rept., NOAA/ERL/FSL (Forecast Systems Lab.), Boulder, CO, 1990.

[13]Hoffman, H. E., and Roth, R., "Cloudphysical Parameters in Dependence on Height Above Cloud Base in Different Clouds," *Metereology and Atmospheric Physics,* Vol. 41, 1989, pp. 247–254.

[14]Newton, D. W., Personal Communication at 29th Aerospace Sciences Meeting, Reno, NV, 1991.