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AIRCRAFT ICING DURING LOW-LEVEL FLIGHTS

R. R. Rapp

A Rand Note
prepared for the
United States Air Force

Rand
SANTA MONICA, CA. 90406

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The reasons why icing may hinder low and slow flights are presented. A crude measure of the potential of icing near the ground is presented and it is shown that, by this measure, icing may be a serious problem when flying over the higher terrain of central Europe. Some suggestions for improving the measure of icing potential are given. (Author)

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PREFACE

This Note was prepared for Project AIR FORCE. as part of a study of *Weather Effects on Air Force Missions*, in response to questions about potential icing on tactical aircraft flying at low level in central Europe. Icing is not a serious problem for fast, high-flying aircraft, but tactical considerations may require that aircraft fly low and slow. Thus, the possibility of icing may have to be taken into account in planning tactical missions. The findings should be of interest to persons involved in tactical flight planning in central Europe.

SUMMARY

Recent occurrences of icing on A-10 aircraft deployed to Germany have prompted a renewal of interest in assessing aircraft icing potential and the operational prediction of icing hazard.

Icing occurs when an aircraft not equipped for anti-icing penetrates a cloud containing supercooled water drops at a speed too slow for compressive heating to preclude ice formation. The design of the airframe and operating speed of the aircraft are important aerodynamic factors in icing occurrence. The major meteorological factors are the temperatures and sizes of the cloud particles and the amount of liquid water in the cloud.

The winter season (October-April) in the southern two-thirds of Germany provides frequent conditions for potential icing encounters by aircraft flying low over the rugged terrain. A crude measure of icing potential in January shows a rapid increase in icing potential with altitude above about 1000 ft msl. If aircraft were forced to fly at about 1000 ft msl (due to terrain or other reasons), icing conditions could be expected, according to this measure, about 10 percent of the time. At 3000 ft msl, icing conditions could be expected about 50 percent of the time.

Because of the probable importance of the icing hazard to near-term tactical air operations in Germany, the major past efforts to develop statistical and operational prediction techniques for icing hazard were reviewed. They were found to be deficient in two respects: first, their physical basis is shaky; and second, their spatial resolution is insufficient for practical application to tactical air in Germany.

A recent Air Force workshop (May 1979) outlined a research program to improve the aircraft icing prediction capability. While it recommended most of the necessary ingredients, it is felt that two aspects of the problem remain inadequately addressed:

1. The space scale of the investigations should be reduced to a scale commensurate with terrain and cloud variability in Germany.
2. The time history of clouds should be investigated with respect to the rate at which supercooled water drops change to ice particles.

I. INTRODUCTION

The old problem of aircraft icing has returned to haunt the new Air Force with the operational introduction of the A-10 aircraft into the NATO theater. The A-10 (and the OV-10, as well) have no anti-icing or deicing gear. A number of icing occurrences have been reported in flights over German terrain, at least one (in April 1979) resulting in engine damage. The problem could be greatly exacerbated in combat, where flights through ice-producing clouds might not be as easily avoided as on peacetime training missions. Aircraft operated at relatively low speeds and at low altitudes over rugged German terrain are particularly vulnerable to icing hazards.

This Note summarizes a quick assessment of past and recent work in quantifying aircraft icing potential and predicting icing occurrences. The special circumstances of low-level flight in the German winter environment are examined, and some specific suggestions are made with regard to predicting icing in that environment.

The problems caused by aircraft icing were discovered soon after man learned to fly and the general understanding of the mechanism of aircraft icing was quickly obtained. The details of cloud physics and the interaction of the aircraft with cloud and rain droplets, however, are still uncertain, and much information is needed to determine the specific conditions that will cause icing on a specific type of aircraft. Serious icing occurs when supercooled water droplets impinge on some portion of the aircraft. The droplets freeze on impact and in due course build up a layer of ice, which adds weight and alters the flow of air around the aircraft. Ice layers on the wings can alter lift; ice on the wings, fuselage, and empennage alters drag; ice on control surfaces changes control characteristics; and ice on engine air intakes restricts the free flow of air to the engine.

In order for ice to form, the droplet (or drop) must be below freezing when it impacts the aircraft surface. Very small droplets may be carried in the airstream around the aircraft and never impact; thus one important factor is the degree to which an aerodynamic shape can collect water drops. The collection efficiency is a function of the size distribution of the water drops and the aerodynamic characteristics of the aircraft. Even though a droplet is supercooled in the cloud, compressive heating as it impacts the surface may heat it to above-freezing temperatures. Such heating is a function of aircraft velocity and the aerodynamic configuration of the aircraft. The severity of icing, if it does occur, is dependent on the amount of condensed water in the supercooled state that is present in the cloud. For a complete determination of the occurrence of ice it would be necessary to know:

- Collection efficiency of all parts of the aircraft as a function of aerodynamic design and speed;
- Compressive heating over all parts of the aircraft as a function of aerodynamic design and speed;
- Temperature of the cloud drops;
- Liquid water content of the cloud; and
- Size distribution of the cloud droplets.

The first two items--basically aircraft characteristics--will require numerical calculations, model tests, or flight tests of many different aircraft. The last three--the cloud parameters--will require intensive research in cloud microphysics. It is inconceivable that the cloud parameters could be measured routinely; therefore it will be necessary to estimate them from more readily available data. It is unlikely that precise estimates will ever by obtainable, but more refined estimates than the simple presence or absence of supercooled clouds may be possible. Most of the present "rules" for defining an icing condition are based on very shaky physical reasoning.(1) The best that we can do is to say there is a potential for icing if there are liquid water clouds present and the ambient temperature is below freezing.

II. THE PROBLEM IN CENTRAL EUROPE

Icing is most likely to be encountered in central Europe on low-level flights over the higher terrain elevations. Recent analyses of the problems of target acquisition and aircraft attrition indicate that low-level flight might be required to avoid enemy defenses and that slower speeds might be required to enable the acquisition and recognition of targets in time to launch missiles. This may lead to aircraft flying at low speeds in the lower part of the atmosphere where supercooled clouds of high liquid water content may be present.

Low-level supercooled stratus clouds do occur over central Europe and could be expected to have a maximum frequency on winter mornings. Table 1 shows some temperature and cloud data extracted from *WWAS* for January.[2] The last line in Table 1, labeled "Icing Potential," is simply the product of the probability of temperatures below freezing, the probability of a ceiling below 300 ft, and the number of days in January. This implies that low temperature and low ceilings are independent, which is probably a poor assumption. Unfortunately, cross tabulations of ceiling and temperature are not readily available. Despite this difficulty, the icing potential, as defined, gives an order of magnitude estimate, and the relative values indicate more frequent icing over higher elevations.

It should be noted that Kleiner Feldberg is only 22 km northeast of Wiesbaden, but is 659 meters higher. The icing potential--as defined here--is larger at Kleiner Feldberg than at Wiesbaden by a factor of five. The measure of icing potential may not be very accurate in an absolute sense, but it does give a strong indication that icing may be a more severe problem for low-level flights over the mountains than is generally estimated from broad-scale studies.

For the purposes of studying icing climatology, West Germany can be divided into three climatic zones. North of a line from Dusseldorf to Hannover to Dresden is the northern plain, which ranges between 0 and 100 meters above sea level. South of a line from Freiburg to Stuttgart,

Table 1

JANUARY CLIMATIC DATA

	Berlin	Wiesbaden	Kleiner Feldberg
Percent frequency that the minimum temperature is < 32°F	64%	65%	90%
Percent frequency that the ceiling is less than 300 ft and/or vis < 1 mi between 0600 and 0800	8.2%	16.2%	64%
Station Elevation	1603 ft (50 m)	460 ft (140 m)	2622 ft (799 m)
Icing Potential (days)	1.6 days	3.3 days	17.9 days

to Nuremberg, to Dresden lie the Swabian Alps, the Bavarian plateau, and the very high Alpine ranges. This southern region is all higher than 300 meters, and tation data are available as high as 1300 meters. Between the northern plains and the southern highlands lies a region of mountains cut by many river valleys. Peaks in the region may reach close to 1000 meters; much of the area exceeds 500 meters, but most of the settlement--and hence weather data--is in the river valleys at elevations below 300 meters. The number of days with potential icing, as defined for the last line of Table 1, was computed for January mornings from *WWAS* for 20 weather stations in the central region. Figure 1 is a plot of number of days of potential icing as a function of the elevation of the station. There is not much variation up to 300 meters, but above that level the icing potential increases dramatically. The data have been roughly approximated by:

$$\text{Icing potential} = 2.77 + 0.37\ (E-2)^2,$$

where E is elevation in hundreds of meters.

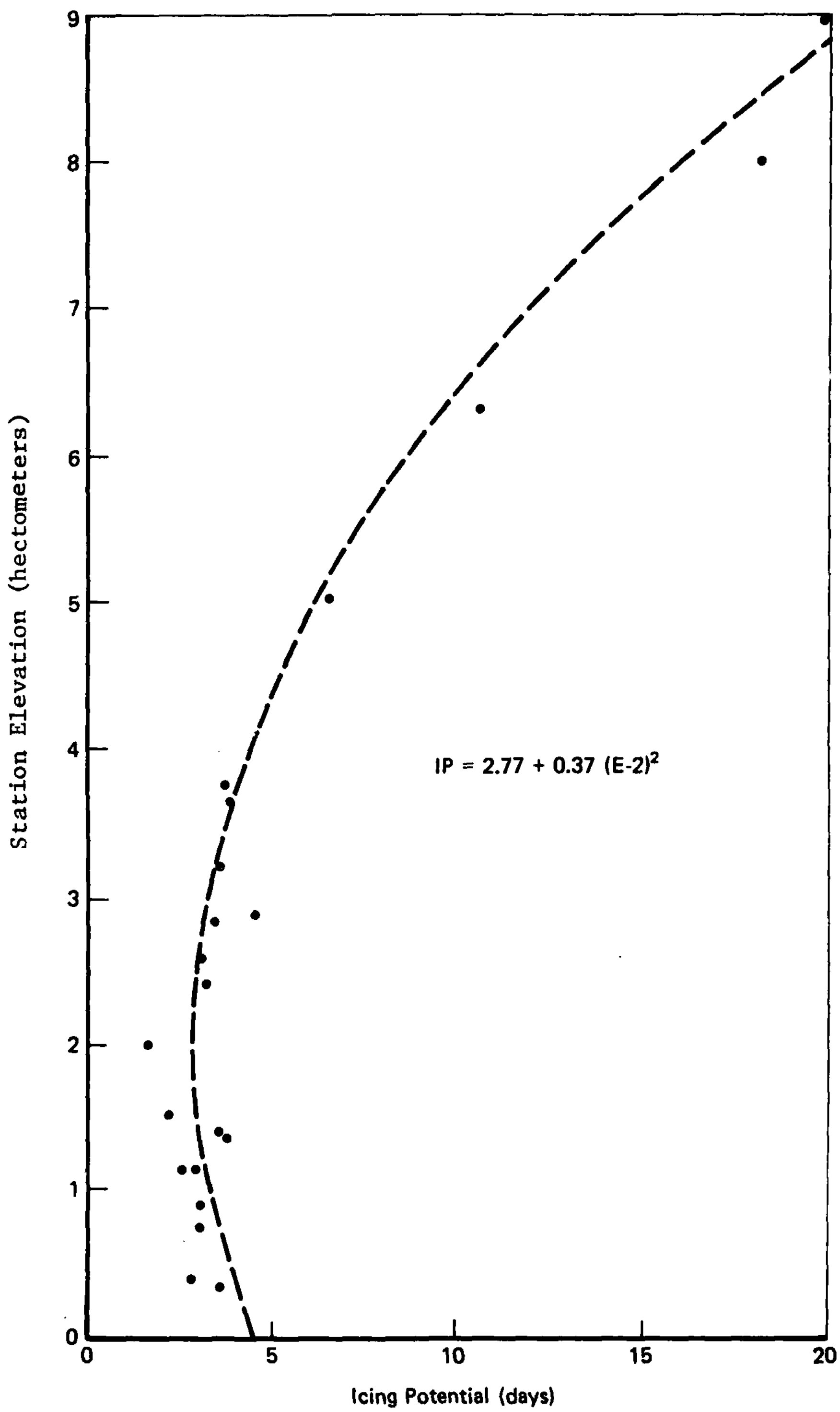

Fig. 1 — Icing potential—central Europe

III. TEMPERATURE-DEW POINT ANALYSES

Because cloud observations are very subjective, attempts have been made to relate icing probability to the temperature, T, and the difference between the temperature and the dew point, $T - T_D = \Delta T$. The basic concept behind the use of temperature and dew point was an assumption that icing would be most likely when the temperature was between the dew point and the frost point.* Recent research suggests that this is not necessarily a good assumption.[4] There is some merit to the use of these two measures because ΔT is a crude measure of liquid water content and T is a crude measure of the amount of condensed water already frozen.

The most ambitious program was an analysis of thousands of icing reports from weather reconnaissance aircraft from May 1952 through June 1955. Observations were included if the aircraft was in cloud at least 25 percent of the time and the temperature was below freezing. The studies, summarized in Ref. 1, presented tabulations of icing frequency as functions of T and ΔT in an odd fashion. For observations of T between 0 and -2°C, the cases were divided between $\Delta T = 0$ and $\Delta T > 0$. For T between -3 and -7°C, the division was between $\Delta T \leq 1$ and $\Delta T > 1$, and so on for successive 5°C increments of temperature, with the final entry of T between -28 and -32°C showing a division between $\Delta T \leq 6$°C and $\Delta T > 6$°C. This tabulation, reproduced in Table 2, obscures a weak correlation between T and ΔT and makes it impossible to correlate icing with T and ΔT.

In the warmest category, T = 0 to T = 2, there were only 17 percent of the cases with reported icing, and the ΔT breakdown showed no significant difference between $\Delta T = 0$°C and $\Delta T > 0$°C. The next temperature category, T = -3°C to T = -7°C, had the highest frequency of icing, and

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*The dew point is the temperature at which the vapor pressure of the air equals the saturation vapor pressure over water. The frost point is the temperature at which the vapor pressure of the air equals the vapor pressure over ice. The frost point is always higher than the dew point.[3]

Table 2

FREQUENCY OF AIRCRAFT ICING AS A FUNCTION OF AIR TEMPERATURE
AND AIR TEMPERATURE MINUS DEW POINT
(Spread = Temperature - Dew Point)

Air Temperature (°C)		Number of Observations	Number of Icing Cases	Percent Frequency of Icing
0 to -2	(With spread = 0°	245	41	16.7
	(With spread > 0°	49	8	16.3
	(Total	294	49	16.7
-3 to -7	(With spread ≤ 1°	1101	563	51.1
	(With spread > 1°	114	37	32.5
	(Total	1215	600	49.4
-8 to -12	(With spread ≤ 2°	1018	418	41.1
	(With spread > 2°	141	32	22.7
	(Total	1159	450	38.8
-13 to -17	(With spread ≤ 3°	1251	237	18.9
	(With spread > 3°	133	15	11.3
	(Total	1384	252	18.2
-18 to -22	(With spread ≤ 4°	772	134	17.4
	(with spread > 4°	77	7	9.1
	(Total	849	141	16.6
-23 to -27	(With spread ≤ 5°	347	38	11.0
	(With spread > 5°	35	5	14.3
	(Total	382	43	11.3
-28 to -32	(With spread ≤ 6°	160	15	9.4
	(With spread > 6°	20	0	0.0
	(Total	180	15	8.3
Grand Total		5463	1550	28.4

in this temperature category, with $\Delta T \leq 1°C$, icing was observed 51 percent of the time. The relatively low frequency of icing at the warmest temperatures might be attributable to aerodynamic heating. The failure of ice to form in half the cases near -5°C with $\Delta T \leq 1°C$ may be due to very small droplets combined with aerodynamic heating. The decrease of icing frequency at colder temperatures is probably due to the fact that most of the water has already turned to ice. According to a model for the natural glaciation of supercooled clouds,[4] the rate of glaciation increases markedly as the temperature decreases. A cloud of supercooled water with a liquid water content of 0.1 g m^{-3} would be completely converted to ice in 30 minutes at -15°C. This same cloud at -10°C would still be 99.997 percent water after 30 minutes. The amount of supercooled water available to form aircraft ice is therefore not only a function of the temperature at the moment, but also of the temperature history of the cloud from the time of condensation of the droplets. It appears, therefore, that it will be necessary to add the time-temperature history of the cloud to the list of essential cloud parameters.

Heath and Cantrell[5] applied the frequencies in the table from Ref. 1 to radiosonde data for 380 stations for which there was at least five years of data to produce an atlas of icing probability for the Northern Hemisphere. The charts, for each month at the standard pressure levels, may be useful as a guide to areas that need further study, but they do not have enough spatial or vertical resolution for use in tactical planning.

IV. RESEARCH NEEDS

A workshop was held in May 1979 to outline the research necessary to improve the capability to assess the severity of the aircraft icing problem, provide a method for predicting the probable occurrence of icing, and study possible countermeasures to reduce the impact of ice formation on aircraft. The research program was documented by Jackson[6] and appears to cover most of the research necessary to study the cloud and aircraft parameters listed in Section I. There are two problems which, in my opinion, are not sufficiently well covered by the proposed research plan. The first of these omitted problems is the space scale of the proposed investigations, and the second is the time history of the cloud formation. The ETAC contribution to the Icing Workshop[6] was an outline of a method for inferring liquid water content of clouds depicted on AFGWC's 3-D nephanalysis. An ingenious algorithm has been devised to estimate the liquid water content of the cloud layers depicted in the 3-D nephanalysis by using the analyzed synoptic charts. The nephanalysis has a spatial resolution of about 40 km and the synoptic analysis has a resolution of about 320 km. By using clouds and temperature rather than temperature and dew point, it stands a good chance of improving on the Heath and Cantrell atlas, but it would not be able to resolve the small-scale changes over the central German region where terrain elevation can change markedly over distances of 25 km. Because it uses ambient air temperatures together with synoptic cloud picture, the technique will not include any cloud dynamics. There will be no means, therefore, to distinguish between clouds that are continually being created--and hence rich in unglaciated droplets--and older clouds that may have the same condensed water content and the same temperature but are almost completely glaciated.

In order to provide the information needed to plan tactical aircraft flights in an area such as central Europe, it will be necessary to understand the mechanism of the formation of the clouds which could cause icing. Figure 1 shows how the occurrence of low temperature and near-surface clouds increases with elevation. A first step in improving the icing potential index would be a cross tabulation of temperature and low cloudiness for stations at various elevations in the area.

A more ambitious program might include measurements of the cloud physics parameters in central Europe. Measurement of liquid water content, temperature, and particle size distribution as a function of terrain elevation and synoptic situation could be accomplished by small research aircraft. The data from such flights could be combined with standard observations and analyses to construct an empirical model for the cloud parameters necessary to determine the probability of icing. These parameters, combined with the appropriate aircraft characteristics, would then serve as a basis for estimating the fine-scale variations of ice over central Europe.

In summary, aircraft icing is dependent on the aerodynamic design and the speed of the aircraft. Research to establish the effect of these parameters is in the planning stage, and the plans appear to be good.[6] Aircraft icing also depends on the temperature, liquid water content, droplet size distribution, and age of the cloud. Plans for the operational estimation of these parameters are, in my opinion, inadequate, largely because the spatial resolution of the proposed estimates will not provide the requisite detail. A preliminary analysis suggests that the meteorological conditions for icing may exist more than 30 percent of winter mornings over regions with elevations of 500 meters. Moreover, the terrain in central Europe is such that terrain elevation can change by several hundred meters over horizontal distances of a few tens of kilometers. It is suggested that the measurement of the appropriate cloud parameters over various terrain elevations in central Europe could lead to the development of forecast rules and an icing climatology with the requisite spatial resolution.

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