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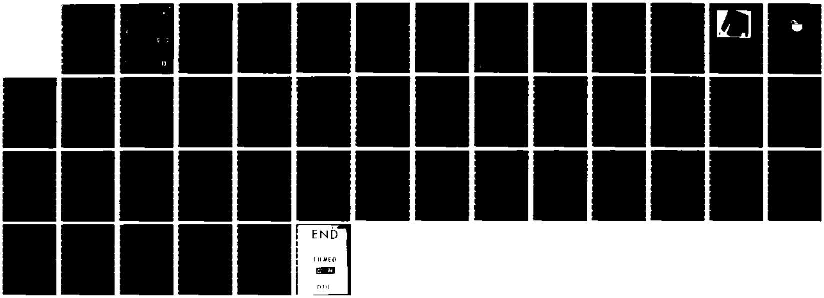

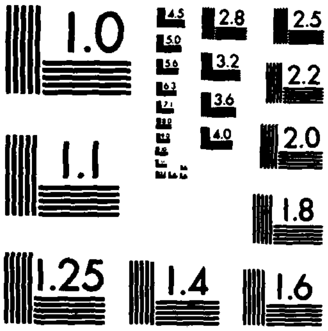

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Analysis of AFGL Aircraft Icing Data

IAN D. COHEN, Capt, USAF

5 July 1983

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METEOROLOGY DIVISION PROJECT 6670
AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MASSACHUSETTS 01731

AIR FORCE SYSTEMS COMMAND, USAF

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> During the winters of 1979-80 and 1980-81, data on aircraft icing were gathered by flying an MC-130E aircraft into areas in which icing was forecast. The occurrence or lack of icing was recorded both by a human observer and by a Rosemount Ice Detector. Records from 25 flights were used.

The results of visual observations of icing taken during flight program were compared to the results indicated by two forecast methods, one developed by the Air Weather Service (AWS) and one developed somewhat later by the Air Force Global Weather Central (AFGWC). Nowcasts were made (Contd)

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20. Abstract (Contd)

using those methods based on radiosonde data taken near the flights. Icing was observed in about 70 to 80 percent of the cases in which heavy or moderate icing was indicated, and 30 to 40 percent of those in which no icing was forecast. Nowcasts of light icing had varying success. Generally, the nowcasts called for more intense icing than was observed.

The results of the ice detector were compared to the visual observations. They correlated well, although they were not in complete agreement, especially in cases of light icing.

The data were examined as a function of altitude and temperature. Icing was reported at altitudes from 3000 to 22,000 ft (.9 to 6.7 km). The AWS forecast methods worked best below 10,000 ft (3.0 km). Icing occurred at temperatures ranging from +2° C to -21° C. Success of the forecasting methods appeared to be independent of temperature.

Preface

This report is part of a study of aircraft icing begun in 1979. Since then, many people have contributed their time and talent to the program. Mr. Donald Grantham, assisted by Mr. Paul Tattelman, supervised the data gathering. They and the author, among others, spent many hours forecasting the development of storms and deciding when and where to look for icing.

The aircrews and maintenance personnel of the *4950th Test Wing* at Wright-Patterson AFB, Ohio, provided excellent support. Without their willingness to work long and hard, often at night and on weekends, we could not have gathered the data needed for this research.

The project crews from AFGL also put in many long and difficult hours. Their work in operating and maintaining the meteorological instrumentation was essential to the success of this project. Much of the data analysis was done by Ms. Nancy Kobb.

Special thanks are due to Mr. Morton Glass, whose many suggestions helped us prepare this report. He also reviwed the manuscript. Dr. Arnold Barnes also made many useful suggestions. Mr. Irving Gringorten and Mr. Charles Burger provided valuable advice and assistance regarding skill scores.

Computer products used for this report were prepared by Digital Programming Services, Inc. Mrs. Carolyn Fadden typed the manuscript, and Ms. Barbara Main prepared the line drawings.

Finally, I wish to acknowledge the leadership and support of Mr. Iver Lund, who began this effort.

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1. INTRODUCTION

The advent of sophisticated aerospace vehicles that travel in the lower atmosphere has reawakened interest in the problem of aircraft icing. The Air Force Geophysics Laboratory (AFGL) is one of several organizations examining this problem.

AFGL equipped an MC-130E aircraft with cloud physics instrumentation. This aircraft was used to measure particle size distribution and liquid water content of clouds ranging from the dense stratocumulus associated with large scale storm systems to subvisible cirrus clouds. Barnes, Cohen, and McLeod (1982)[1] describe the aircraft and its instrumentation.

In October 1979, a Rosemount Icing Detector was installed near the left wing tip. Glass and Grantham (1981)[2] explain how this device works and compare its

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(Received for publication 30 June 1983)

[1] Barnes, A.A. Jr., Cohen, I.D., and McLeod, D.W. (1982) Investigations of Large Scale Storm Systems, AFGL-TR-82-0169, Final Report, AD A119862.

[2] Glass, M., and Grantham, D.D. (1981) Response of Cloud Microphysical Instruments to Aircraft Icing Conditions, AFGL-TR-81-0192, AD A112317.

results to those of other instrumentation. Glass (1982)[3] further examines the ice detector and its response to supercooled water. Studies by Norment (1979),[4] (1980a),[5] and (1980b)[6] show how the location for the ice detector was selected and how well it sampled the free air conditions.

Data gathering flights began in November 1979 and lasted for two winters. Table 1 lists the flights used in this report; Appendix A gives a list of data passes. In some cases, data for two or more projects were gathered on the same flight. The flight program was completed in April 1981.

The flights were designed to achieve the following goals:

(1) To test the ice detector in a variety of conditions,

(2) To verify forecasts of icing made with conventional techniques,

(3) To further examine temperature and altitude ranges where icing occurs,

(4) To relate occurrence, type, and intensity of icing to drop size distributions and liquid water content of clouds, and

(5) To study the relation between icing and the synoptic weather patterns.

The first and fourth of these goals were examined in a previous report.[2] The fourth and fifth will be studied further in a future report. This report will look again at the first and will also examine the second and third of these purposes.

Most conventional forecast techniques use a rawinsonde sounding to provide temperature and moisture profiles. Therefore, most of our data were taken within 30 nm of the rawinsonde station and within one hour of rawinsonde observation times.

All flights were made under conditions in which icing was likely to occur. In many cases, the expected icing was observed; however, in some, there was little or none.

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[3] Glass, M. (1982) Droplet spectra and liquid water content measurements in aircraft icing environments, Preprints, Conference on Cloud Physics, Chicago, Ill., 14-18 Nov 1982, pp 400-403, AFGL-TR-82-0344, AD A122516.

[4] Norment, H.G. (1979) Airflow Effects on Riming Measurements by a Wing-Tip-Mounted Ice Detector on the MC-130E Research Airplane, AFGL-TR-79-0194, AD A077019.

[5] Norment, H.G. (1980a) Calculation of Water Drop Trajectories To and About Arbitrary Three-Dimensional Bodies in Potential Airflow, NASA Contractor Report 3291.

[6] Norment, H.G. (1980b) Calculated Effects on Water Drop Flux Measurements of an Extended Mounting for an Ice Indicator Mounted on the Wing Tip of the MC-130E Research Airplane, Final Report, AFGL Contract F19 628-80-M-0008.

2. INSTRUMENTATION

The instrumentation on the aircraft served three purposes:

(1) To measure the icing the aircraft experienced,

(2) To describe the microphysical aspects of the clouds that the aircraft penetrated, and

(3) To record meteorological and geographical parameters such as temperature, altitude, and location.

2.1 Observations of Icing

Visual observation and an icing detector were used to describe icing conditions.

The in-flight meteorologist made the visual observations. From his station, he could visually detect any accumulation of ice on the windshield, the leading edge of the wing, the spinners of the propellers, or the instrument pods. He communicated with other crew members to detect ice in other locations.

The "visual hydrometeor probe," known as the "Snowstick," was also useful. The snowstick is a metal rod about 2.5 cm in diameter located near the flight meteorologist's station. It extends from inside the airplane through a hole in the fuselage to a point about 0.5 m beyond the skin of the airplane. By observing how fast ice forms on the snowstick, the observer can estimate the rate of ice accumulation. Ice can usually be removed from the snowstick by drawing it into the airplane. For this project, it was primarily used to characterize the nature and intensity of ice forming on the aircraft. Figure 1 shows the snowstick as the observer sees it.

The written notes taken by the in-flight meteorologist and voice tape recordings made during the flights described the observations on icing occurrence, rate, and type.

A Rosemount Ice Detector, Model 871FA (see Figure 2), was mounted near the right wing tip. The instrument is used by several commercial and military aircraft to warn of icing. It detects ice with a probe that vibrates at a high frequency. Ice accumulating on the probe changes the frequency of the vibrations. A known mass of ice will change the frequency by a given amount. When this frequency change reaches a predetermined value, a heater is triggered. The heater turns off automatically when the ice is melted, and the cycle is repeated as long as icing conditions persist. The number of cycles observed in a given period indicates icing intensity. Calibration factors provided by the manufacturer and the true air speed of the aircraft can be used to determine the thickness of ice accumulated on the airplane per nautical mile.

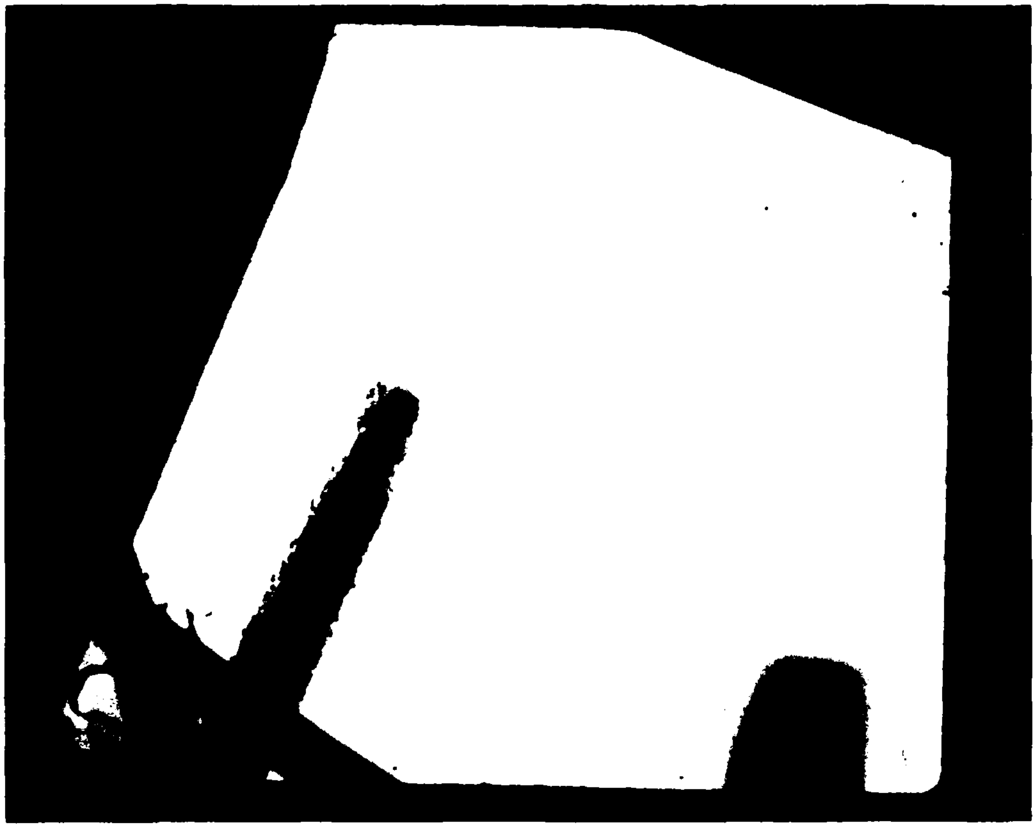

Figure 1. The Snowstick as seen by the Mission Director. This photograph (taken during an earlier mission) shows how ice can accumulate on the snowstick

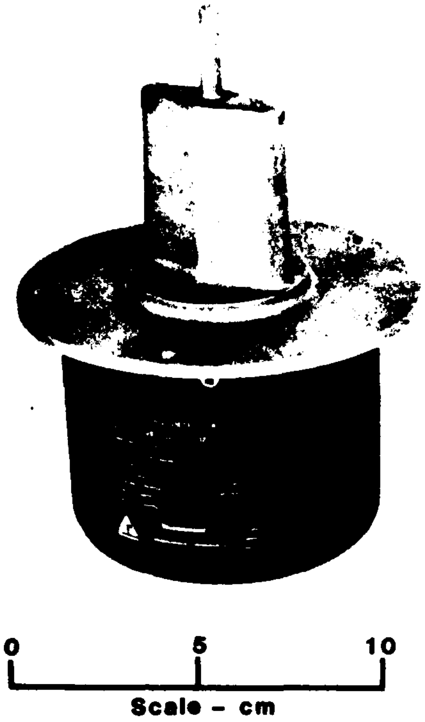

Figure 2. The Rosemount Ice Detector, Model 871FA

2.2 Microphysical Measurements

Liquid water content, particle size, and particle type may be related to the occurrence and rate of icing. Several instruments measure these values. A Johnson-Williams Liquid Water Content Meter (J-W) and an Axial Scattering Spectrometer Probe (ASSP) provided liquid water content data. The ASSP measures particle sizes. From this information, liquid water content is calculated. Comparisons done by Glass and Grantham[2] and Breed and Dye (1982)[7] show that, in an all-liquid environment, the J-W and ASSP compare quite favorably.

The ASSP, in conjunction with cloud and precipitation probes, provided information on particle size distributions. One- and two-dimensional probes, manu-

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[7] Breed, D.W., and Dye, J.E. (1982) In-cloud comparisons of FSSP and JW probes during CCOPE, Preprints, Conference on Cloud Physics, Chicago, Ill., 14-18 Nov 1982, pp 282-285.

factured by Particle Measuring Systems, Inc. (PMS), supplied additional information on sizes and shapes of particles. Glass and Grantham[2] explain the operation and use of these instruments.

2.3 Meteorological Instruments

A Rosemount Total Temperature Probe, a Cambridge Dew Point Hygrometer, and an Inertial Navigation System (which included continuous observations of position, wind direction, and wind speed) provided standard meteorological data. The various instruments on the aircraft are described in earlier AFGL reports, including Barnes, Cohen, and McLeod[1] and Varley (1978).[8]

3. FORECAST TECHNIQUES NOW IN USE

The Air Weather Service's Forecasters' Guide on Aircraft Icing (1980)[9] represents the current philosophy on the forecasting of aircraft icing. Most of the information in that report came from observations and research made during the 1950s. Techniques using icing diagrams such as Figure 3 have been the primary source of aircraft icing forecasts. Hilsenrod (1979)[10] and Jeck (1981)[11] have noted that we now have more information available and can reexamine the forecasting problem.

This report compares the results obtained by two current methods of icing nowcasts with aircraft observations. Both methods involve analysis of an upper air sounding. We will examine whether the conditions that are supposed to produce icing actually do. The rawinsonde soundings closest in time and space to the flight were examined by two methods: the Skew-T method and the method developed by the Air Force Global Weather Central (AFGWC).

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[8] Varley, D.J. (1978) Cirrus Particle Distribution Study, Part I, AFGL-TR-78-0192, AD A061485.

[9] Anon (1980) Forecasters' Guide on Aircraft Icing, AWS/TR-80/001.

[10] Hilsenrod, A. (1979) Summary report, Icing Forecasting Committee, NASA Workshop on Aircraft Icing, Cleveland, Ohio, 19-21 July 1978, NASA Conference Publications 2086, FAA-RD-78-109, pp 93-100.

[11] Jeck, R. (1981) Progress on low altitude cloud icing research, Proc. Fifth Annual Workshop on Meteorological and Environmental Inputs to Aviation Systems, Tullahoma, Tenn., December 1981, NASA Conference Publications 2192, FAA-RD-81-67, pp 59-63.

3.1 The Skew-T Method

The Skew-T method is described in the Forecasters' Guide.[9] It is a manual technique designed to provide a quick short-range forecast. Given only the rawinsonde sounding, the forecaster can evaluate icing conditions using temperature, dewpoint, height of cloud base, and stability of the atmosphere. The diagram shown in Figure 3 can be superimposed on a standard USAF Skew-T log P diagram (see Figure 4) on which the rawinsonde sounding has been plotted. To use the method, the forecaster first determines whether the sounding is stable or conditionally unstable. If it is stable, rime ice is considered likely. If unstable, clear ice is expected. The upper limit of clear ice is considered to be -25°C (the heavy dotted line on Figure 3). The upper limit of rime icing is the isotherm corresponding to the temperature at which the dewpoint curve intersects the rime-icing scale in the upper left-hand corner of Figure 3 after Figure 3 has been superimposed on the sounding plotted on a chart like that of Figure 4. This is done by placing the bottom of Figure 3 at either the cloud base or the lifting condensation level (LCL) indicated by the sounding. Figure 3 is placed so that the 0°C mark is on the 0°C isotherm at the cloud base or LCL in Figure 4. Figure 5, which is taken from the Forecasters' Guide,[9] illustrates the result. If the altitude for which the forecast is to be valid is within the potential area of icing, and if the dewpoint spread indicates it will be in cloud, then the intensity of the icing can be read off the chart using rules set forth in the Forecasters' Guide.[9] If a frontal inversion is present, the temperature and altitude help determine the intensity of the icing; if no frontal inversion is present, a vertical line drawn at the LCL replaces the temperature as an indicator of the intensity.

In this study, the Skew-T method was used to analyze the icing potential of the soundings closest to the times during which icing flights occurred. The result is a "nowcast," an analysis of the current probability of icing. Although a nowcast may be of only limited operational use, it is valuable in determining how well forecast methods will work. Nowcasts were made for each level at which aircraft icing information was available. The nowcasts were compared to the actual observed icing. The results will be discussed later in this report.

3.2 The AFGWC Method

The Air Force Global Weather Central (AFGWC) has developed a simplified version of the Skew-T method. As Priselac (1979)[12] explains, the AFGWC method

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12. Priselac, E.P. (1979) Preparation of the Icing Forecast, WF Procedure 312, Forecasting Service Division, Air Force Global Weather Central (AFGWC), Offutt AFB, Nebr., 28 Sept 1979.

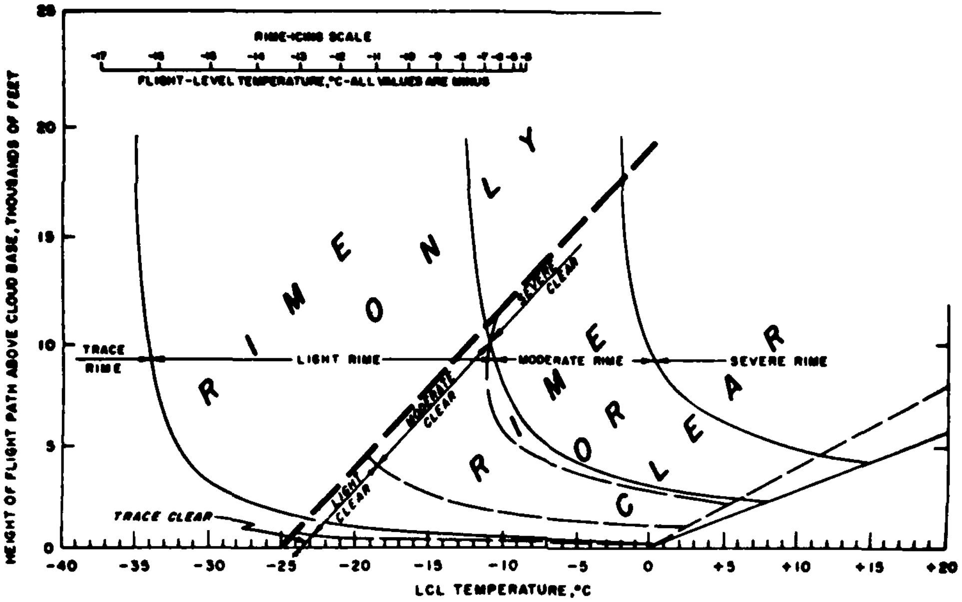

Figure 3. USAF Icing Diagram. This diagram, taken from Figure 3C of AWS-TR-80-001, is used in conjunction with a standard USAF Skew-T diagram to forecast icing. In the AFGL study, the word "heavy" is used instead of the word "severe"

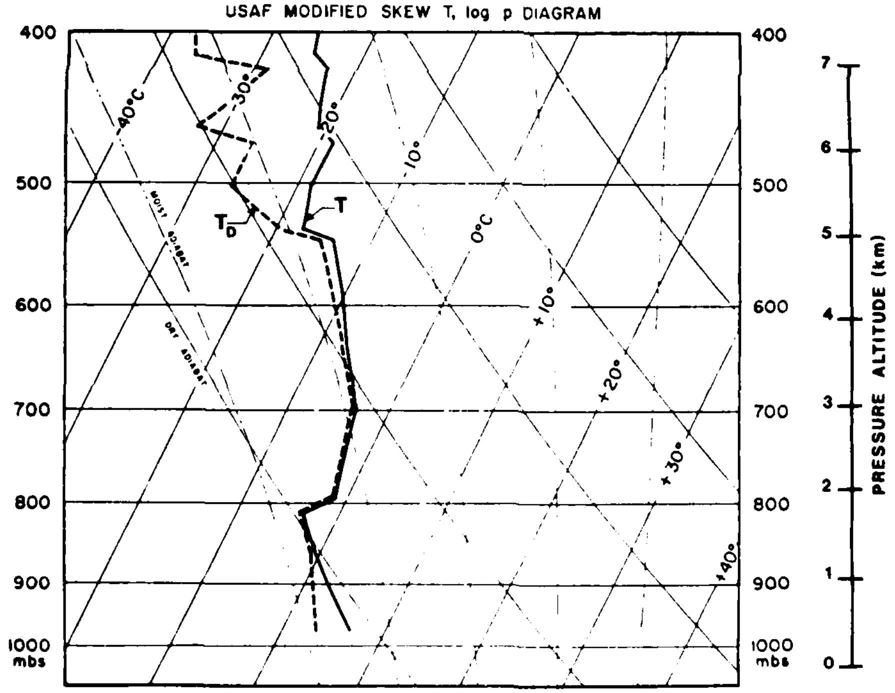

Figure 4. USAF Skew-T Log P Diagram. Horizontal lines are isobars. Lines which slope to the left are isotherms

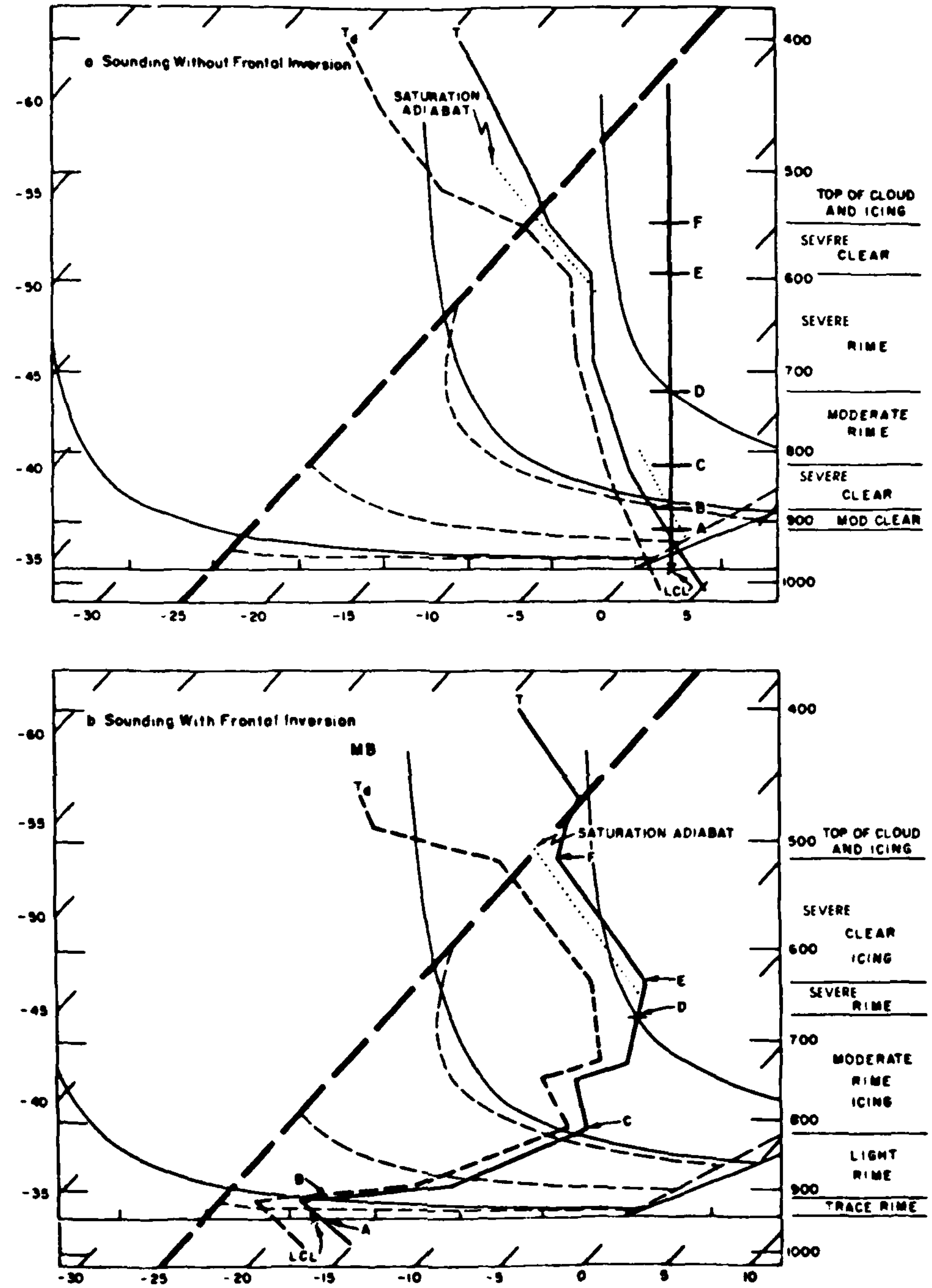

Figure 5. Icing Diagram Superimposed on Plotted Sounding. This diagram, Figure 5 of AWF-TR-80-001, results when figure 3 is superimposed on a plotted sounding

provides for an automated forecast of icing probabilities based on information derived from attachment 1 of the procedure. The procedure also provided a nowcast with results similar to those of the Skew-T method. Although the results of these nowcasts were similar in many cases, they were not similar in all. These nowcasts were also compared to the actual observed icing. These results will also be discussed later in this report.

4. THE FLIGHT PROGRAM

AFGL began conducting icing flights in November 1979. The flight program continued until April 1980, was resumed in November 1980, and was completed in April 1981. Twenty-five flights provided the data for this report. Table 1 lists these flights.

A period of at least 3 minutes during which the aircraft gathered data at a constant altitude will be referred to as a "pass." A set of data taken as the aircraft passed through a given altitude during a descent will be referred to as a "point."

Data gathered during 20 of the flights were prepared specifically for this program. The other five flights involved portions of spiral descents, as described by Lo and Passarelli (1982),[13] that penetrated layers of cloud with potential for icing. While passes as such were not flown on these flights, the altitude and temperature were recorded at 1000-ft intervals, and observations of icing were recorded.

Flights specifically designed to provide icing data were planned to be at the selected radiosonde station at approximately 2300Z or 1100Z, that is, 1 hour before the official time of the observation. This provided 2 hours to gather data. We tried to locate our sampling area within 30 nm of the station. These requirements were modified if maintenance delays, air traffic control requirements, or the availability of sufficient clouds at the appropriate altitudes made it necessary to do so. Most of the passes were within 50 nm and 2 hours of the radiosonde observation. Data outside of these limits were included if the nearest available sounding appeared to be representative of the clouds sampled by the aircraft.

Once the sampling area had been selected (preferably downwind of the radiosonde launch point), a sampling pattern was established. The aircraft flew a "racetrack" pattern, flying for at least 3 minutes, then turning and flying in the opposite direction, thus completing a closed loop, the straight legs of which were oriented parallel to the wind.

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[13] Lo, K.K., and Passarelli, R.E. (1982) The growth of snow in winter storms: An observational study, J. Atmos. Sci. 39:697-706.

TABLE 1. Flights Used in Icing Study From 1979 to 1981

Number	Date	Type	Location	Radiosonde*	Altitudes (1000 ft)	Number of Passes
79-49	6 Dec 79	Icing	Huntington, W. Va.	HTS	5-17	12
79-50	11 Dec 79	Icing	Peoria, Ill.	PIA	6-16	7
79-51	16 Dec 79	Icing	Flint, Mich.	FNT	4-11	7
80-01	20 Jan 80	Icing	Dayton, Ohio	DAY	3-12.9	5
80-02	21 Jan 80	Icing	Salem, Ill.	SLO	3-10	6
80-03	22 Jan 80	Icing	Greensboro, N.C.	GSO	7-17	6
80-04	28 Jan 80	Spiral	Dayton, Ohio	DAY	3.5-8.2	-
80-05	2 Feb 80	Icing	Seattle, Wash.	UIL	6-12	4
80-09	24 Feb 80	Spiral	Hoquiam, Wash.	UIL	9-13	-
80-14	3 Mar 80	Icing	Quillayute, Wash.	UIL	2.8-11	7
80-16	8 Mar 80	Icing	Kennebunk, Maine	PWM	9-16	8
80-18	10 Mar 80	Icing	Buffalo, N.Y.	BUF	5-14	11
80-24	8 May 80	Icing	Denver, Colo.	DEN	10-24	9
80-33	24 Oct 80	Icing	Green Bay, Wis.	GRB	6-11	6
			Flint, Mich.	FNT	9-14	6
80-34	27 Oct 80	Spiral	Peoria, Ill.	PIA	13-19	-
80-35	5 Dec 80	Icing	Dayton, Ohio	DAY	11-12	2
80-38	17 Dec 80	Icing	Flint, Mich.	FNT	5-12	8
81-02	29 Mar 81	Icing	Richmond, Ind.	DAY	9-13	5
81-05	9 Apr 81	Icing	Albany, N.Y.	ALB	6-17	15
81-06	14 Apr 81	Spiral	Boston, Mass.	PWM	8.5-20	-
81-07	17 Apr 81	Icing	Portland, Maine	PWM	11-19	6
81-08	18 Apr 81	Icing	Portland, Maine	PWM	14-17.7	6
81-09	23 Apr 81	Icing	Albany, N.Y.	ALB	9-22	18
81-10	28 Apr 81	Spiral	Albany, N.Y.	ALB	5-14	-
81-11	29 Apr 81	Icing	Portland, Maine	PWM	8-15	8

*Locations of Radiosonde Stations are listed in Appendix B.

During a pass, the aircraft maintained level flight at an indicated airspeed of 150 knots ± 5 knots. Three minutes was the minimum time required for a pass. Thus, a pass covered at least 10 nm. This would give the icing detector enough time to complete several cycles if significant icing was occurring. A pass could be extended to increase the amount of data gathered, adjusting the dimensions of the racetrack if necessary. This was most often done in cases where the cloudiness at the flight level was not continuous. During a pass, particle size distributions, J-W liquid water content values, temperature, dewpoint, wind velocity, and icing (both visual and ice detector) were monitored. The data represent an average for the pass.

Data were taken at altitude intervals of 1000 or 2000 ft. The Mission Director decided which interval to use before each mission, depending on how thick the area of potential icing was. The interval was often modified in flight if conditions did not match the forecast.

During spiral descents, temperature, dewpoint, wind, and visual observance of icing were recorded every 1000 ft. Only visual icing data were used for spiral descents. Also, the temperature values are instantaneous rather than averages. The spirals did provide a vertical profile of the atmosphere, and those that traversed areas of potential icing added useful data to the study.

Because most of the flights operated from Wright-Patterson AFB, Ohio, data from the Great Lakes area and the North Central Plains states predominate. Eight flights originated in Massachusetts and sampled icing conditions in the Northeast. The remainder were taken during deployments for other programs, thus giving us three flights in the Puget Sound area of Washington State and one flight in Colorado.

5. COMPARISON OF NOWCASTS WITH FLIGHT DATA

The visual observations from the aircraft can now be compared with nowcasts from the radiosonde data. These nowcasts can indicate the kind of icing a C-130 may encounter, given the atmospheric conditions. In this section, we will use the observer's comments to determine whether icing was occurring. Intensity and type of icing will be discussed further in the next section.

The Mission Director served as an in-flight observer. During data passes, he noted whether or not ice was forming on the exterior surfaces of the aircraft. The most common locations for icing formation were the windshield, the leading edge of the wing, the "spinner" in the center of the propellers, and the snowstick. The icing detector was used as a tool to help determine if icing was occurring, but the observer did not base his decision solely on the detector. Later, we will see how the observer's visual observations compared with the data provided by the icing detector.

On 20 flights, 162 data passes were made. The five flights with spirals were usually analyzed at 1000-ft intervals and provided 44 additional data points.

5.1 Comparison of Visual Observations with Skew-T Nowcasts

Table 2 compares the results of the visual observations of icing with the results of Skew-T nowcasts on those flights in which passes were made. The table shows that while the intensity may vary, a nowcast of icing does indicate about a three-in-four chance of encountering icing. When the Skew-T called for no icing, there was icing in 43 percent of the cases. Situations in which icing could not be expected and was not nowcast (for example, clear air, temperatures above about $+6^{\circ}$C or below about -30°C, etc) were not included. In general, the nowcasts called for more intense icing than was observed, but this may be due to the type of aircraft and its speed. Different airplanes will generally be affected differently by icing from a given cloud.

Table 3 was compiled in the same manner as Table 2, but all data (spirals and icing flights) were included. The results were similar to those in Table 2. The additional data very slightly improved the statistics of the Skew-T forecast method. In this case, 75 of the 103 instances when icing was nowcast had icing observed, while only 39 of the 103 instances when no icing was expected had any icing to report.

Thus, while the Skew-T could use some refinement, it does point out those combinations of temperature, humidity, and altitude in which icing is most likely to occur.

5.2 Comparison of Visual Observations with the AFGWC Method

While the AFGWC method is similar to the manual Skew-T analysis, the nowcasts do differ, especially in values of intensity. Tables 4 and 5 compare visual observations with the results of the AFGWC method. In either case, a nowcast of moderate or heavy icing seems to indicate that some icing will occur. Light-icing nowcasts do poorly, only verifying about half the time. The AFGWC method seems to yield an intensity of moderate icing most frequently. Almost four out of five of these cases had icing. A nowcast of heavy icing occurred only once; in that instance, light icing was reported. For the C-130 aircraft, this seems reasonable because, although that particular aircraft never encountered heavy icing, a smaller aircraft in the same situation might have.

TABLE 2. Aircraft Icing Observations vs Skew-T Nowcasts for 162 Icing Passes

OBSERVED ICING	NOWCASTS				
	Heavy	Moderate	Light	Trace	None
Heavy	0	0	0	0	0
Moderate	8	3	2	0	6
Light	20	19	3	1	19
Trace	2	4	4	0	5
None	13	7	5	1	40
Cases with Icing	30	26	9	1	30
Total Cases	43	33	14	2	70
Percent with Icing	70	79	64	50	43

TABLE 3. Aircraft Icing Observations vs Skew-T Nowcasts for 206 Data Points and Passes

OBSERVED ICING	NOWCASTS				
	Heavy	Moderate	Light	Trace	None
Heavy	0	0	0	0	0
Moderate	9	3	2	0	7
Light	25	22	3	1	26
Trace	2	4	4	0	6
None	13	9	5	1	64
Cases with Icing	36	29	9	1	39
Total Cases	49	38	14	2	103
Percent with Icing	73	76	64	50	38

TABLE 4. Aircraft Icing Observations vs AFGWC Nowcasts for 162 Icing Passes

OBSERVED ICING	NOWCASTS				
Observed	Heavy	Moderate	Light	Trace	None
Heavy	0	0	0	0	0
Moderate	0	12	4	0	3
Light	1	36	12	0	13
Trace	0	9	3	0	3
None	0	17	19	0	30
Cases with Icing	1	57	19	0	19
Total Cases	1	74	38	0	49
Percent with Icing	100	77	50	-	39

TABLE 5. Aircraft Icing Observations vs AFGWC Nowcasts

OBSERVED ICING	NOWCASTS				
Observed	Heavy	Moderate	Light	Trace	None
Heavy	0	0	0	0	0
Moderate	0	13	4	0	4
Light	1	43	13	0	20
Trace	0	9	3	0	4
None	0	17	25	0	50
Cases with Icing	1	65	20	0	28
Total Cases	1	82	45	0	78
Percent with Icing	100	79	44	-	36

The addition of the 44 data points obtained in spirals did not significantly alter the results obtained from the 162 icing passes. Rather, they seemed to emphasize the same categories.

Although the intensity of the icing was a matter of the observer's judgement, it is interesting to note that no single individual tended to report more or less intense icing than another. The icing detector helped give the observer a "feel" for intensity of icing, and some semiquantitative rules about icing on the snowstick helped to standardize intensity observations.

5.3 Statistical Evaluation of the Nowcasts

As Tables 2-5 show, the forecast methods do have an effect on accuracy, but it is small and difficult to measure.

A method developed by Gringorten and Boehm (1982)[14] was tried. This method provides some weight for results that are near, but not equal to, the verification value. Unfortunately, it did not apply in this case because it was designed to evaluate a continuum of values, and the finite number of possibilities presented in this study distorted the scores.

A "skill score" can show how to best interpret these methods. The skill score described by Panofsky and Brier (1958)[15] was used. This skill score was used in this case, although it only gave credit for a correct forecast. Thus, a nowcast of light icing was incorrect if either no icing or moderate icing was observed.

The skill score is defined by the following equation:

$$S = \frac{R - E}{T - E} \tag{1}$$

where S = the skill score
R = the number of correct forecasts (or nowcasts)
T = the total number of forecasts (or nowcasts)
E = the number of correct forecasts which can be attributed to chance, climatology, etc

In this case, E is determined by multiplying the total number of nowcasts in each category by the total number of observations in the equivalent category, adding the results, and dividing by the total number of cases in the sample.

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[14] Gringorten, I.I., and Boehm, A.R. (1982) The B-G System of Evaluating Forecasts, AFGL-TR-82-0006, AD A118735.

[15] Panofsky, H.A., and Brier, G.W. (1958) Some Applications of Statistics to Meteorology, Pennsylvania State University, University Park, Pa.

This method was first applied to Tables 2-5 as they appear. In addition, the following four combinations of categories were tried:

(1) Observed heavy icing = moderate; nowcast trace = none. Since nowcasts generally called for more intense icing than observed, here each nowcast was verified by an observation of the next higher intensity (for example, forecast moderate icing was verified by light icing, etc), except heavy icing or no icing, which were verified by the same category.

(2) Moderate icing vs light icing vs no icing. Heavy and moderate icing were one category, light and trace another, and no icing was the third.

(3) Icing vs no icing with a nowcast of light interpreted as no icing. Since nowcasts of moderate or heavy icing appeared more likely to result in icing, nowcasts of heavy and moderate were verified by all observations of icing, while nowcasts of light or trace were verified by observations of no icing.

(4) Icing vs no icing. Any nowcast of icing, regardless of intensity, was verified by any observed icing. A nowcast of no icing was verified only by an observation of no icing.

The results are summarized in Table 6. They show that both methods have dubious skill at predicting intensity. If we use the next lower intensity to verify the nowcast, the skill scores improve significantly. They show more skill when used to predict the occurrence of icing, as noted by the skill scores of methods (3) and (4). In the case of the Skew-T method, we find a straight icing to icing and no icing to no icing correlation is best. For the AFGWC method, however, we can improve the skill scores by interpreting a nowcast of light or trace as an indication of no icing.

The addition of the 44 data points from spirals (Table 3 vs Table 2 and Table 5 vs Table 4) consistently improved the skill scores by 2 to 6 points. The reason for this is not known.

6. INTENSITY AND TYPE OF ICING

As has been shown, both methods had problems predicting intensity. They tended to predict more intense icing than was observed. Both methods predicted moderate or heavy icing more frequently than light or trace.

[illegible] nowcast method did not include trace as a possible intensity and [illegible] a trace only twice, a trace of icing will be considered [illegible].

[illegible] the number of times each of four intensity values were [illegible] nowcasts indicating each value. As the solid line shows, [illegible] exceeded light only 21 out of 206 times, while both

Table 6. Icing Skill Scores

Method	Categories		Skill Scores			
	Nowcast	Observed	Table 2	Table 3	Table 4	Table 5
Unmodified	H/M/L/T/N	H/M/L/T/N	.07	.10	.09	.11
(1)	H/M/L/T, N	H, M/L/T/N	.21	.24	.15	.21
(2)	H, M/L, T/N	H, M/L, T/N	.12	.15	.09	.11
(3)	H, M/L, T, N	H, M, L, T/N	.27	.32	.33	.38
(4)	H, M, L, T/N	H, M, L, T/N	.29	.35	.27	.30

Note: The letters H, M, L, and T mean heavy, medium, light, and trace, respectively. N indicates no icing. Categories are separated by a solidus (/), with each nowcast category being verified only by the corresponding observation category.

forecast methods called for greater-than-light icing more frequently than for light icing.

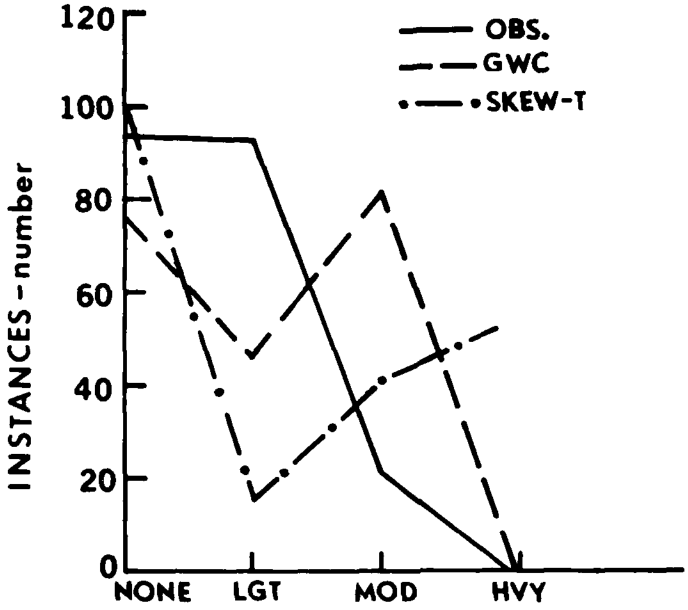

Figure 6. Observed Number of Instances of Various Intensities of Icing Compared With Number of Nowcasts

The Skew-T method rarely indicated light icing, although it frequently forecast no icing. When it did call for icing, the intensity was at least moderate and frequently heavy. Of the 103 times that the method predicted icing, almost half called for heavy icing.

In contrast, the AFGWC method indicated heavy icing only once and predicted moderate icing many times more than it was observed. The dearth of indications of light icing seems puzzling, especially since this category was the one most frequently observed. This intensity is also the one most frequently reported by pilots.

Table 7 compares the forecasts with the observations in another way. Here, heavy icing has been assigned a value of 3; moderate icing, 2; and light (or trace of) icing, 1. Thus, we can see how far from correct the nowcasts were. Again, both methods called for heavier icing than was observed, but the Skew-T nowcasts varied much more in both directions than the AFGWC nowcasts. Again, the frequency of nowcasts of heavy icing from the Skew-T method seems unusually high. When the Skew-T method called for heavy icing, the AFGWC method would often call for moderate icing. In many of these instances, the result was light icing.

Table 7. Comparison of Forecast (Nowcast) Intensity With Observed Intensity

Difference of Categories (Forecast-Observed)	Skew-T		AFGWC	
	Cases	Percent	Cases	Percent
+3	15	7	0	0
+2	37	18	18	9
+1	41	20	77	37
0	73	35	78	38
-1	33	16	28	14
-2	7	4	4	2
-3	0	0	0	0

Types of icing considered include rime, mixed, and clear. The Skew-T method does not forecast mixed icing. Table 8 shows comparison of observations of and Skew-T forecasts for rime and clear icing. Rime icing was observed more often than expected. This may partially be an observing problem, since spotting and identifying clear ice on the aircraft extremities is difficult. A forecast of clear ice was an excellent sign that some icing would result; only 3 of the 26 cases in which clear ice was expected reported no ice. In all three cases, ironically, the forecast was for heavy, clear icing.

The AFGWC method forecast rime ice more often than the Skew-T method. Table 9 shows the comparison of observations of rime ice with AFGWC nowcasts. Over half of the entire data set consisted of forecasts of rime icing. Over half of those verified; rime icing was observed. Only 3 forecasts of clear ice were included, as opposed to 26 using the Skew-T method. Two of the three forecasts of clear ice verified; the third resulted in rime ice.

As Tables 7, 8, and 9 show, both forecast methods do reasonably well in predicting the existence of icing, but both have problems identifying intensity and type. This is partially due to observation problems, since the intensity and type of icing may vary from aircraft to aircraft and from observer to observer. Closer examination of the microphysical and synoptic aspects of the problem, however, may help improve these phases of icing forecasting.

Table 8. Observed Icing Type vs Nowcasts Using Skew-T Method

TYPE OBSERVED	NOWCAST				
	NONE	RIME	MIXED	CLEAR	TOTAL
NONE	65	24	0	3	92
RIME	33	43	0	20	96
MIXED	1	7	0	2	10
CLEAR	3	4	0	1	8
TOTAL FORECASTS	102	78	0	26	206

Table 9. Observed Icing Type vs Nowcasts Using AFGWC Method

TYPE OBSERVED	NOWCAST				
	NONE	RIME	MIXED	CLEAR	TOTAL
NONE	50	39	3	0	92
RIME	27	61	7	1	96
MIXED	1	7	2	0	10
CLEAR	0	5	1	2	8
TOTAL FORECASTS	78	112	13	3	206

7. ICE DETECTOR RESULTS

The ice detector provided semiquantitative estimates of ice intensity and was used as a tool by the observers as they made their estimates. The complete analyses, however, were not available to the in-flight meteorologist. Thus the visual data is the result of a decision based on several sources of information, of which the ice detector was only one. The observer knew only if the ice detector was or was not cycling. In this section, we will compare the intensity as measured by the observer to that measured by the ice detector.

There are several ways to interpret the data from the ice detector. The method we will use is to compare the number of cycles that the ice detector completes per nautical mile. This gives a result which is independent of the aircraft speed and the calibration factor necessary to convert the number of cycles into a measure of thickness.

As Glass and Grantham[2] note, there is a linear relation between the rate of cycling and the liquid water content of the air through which the airplane is flying. The rate of cycling (R_A) of the probe on the C-130 aircraft is related to the liquid water content (LWC) by this formula:

$$R_A = -0.1836 + 9.6\,(\overline{LWC}) \tag{2}$$

For any given aircraft traveling at a given true air speed, the rate of accumulation of ice on a surface will be related to the liquid water content by a linear relationship.

Ice detector results for the five flights in which spiral patterns were flown are not included in this section. Ice detector results from two other flights were not available for this analysis. Therefore, the data presented here are based on 18 of the 25 flights. Ice detector data were available for 140 of the data passes included in the sample.

The results of the 140 data points are summarized in Table 10. Although the human observer and the ice detector did not always agree, there was some correlation between them. The ice detector did not cycle at all in 41 of the 57 cases in which no ice was reported by the observer. In only five cases did the ice detector cycle more than once in 10 nm (the approximate length of a pass) when no ice was reported. In some cases, an accumulation of water or snow on the ice detector may have modified the vibration of the sensor, causing the instrument to cycle. In both cases where the ice detector indicated .21 cycles/nm and no icing was observed, there was icing reported at other levels. This not only makes it

Table 10. Ice Detector Cycling Rate Compared With Observed Ice

	OBSERVATION					
CYCLING RATE (cycles/nm)	NO ICE	TRACE ICING	LIGHT ICING	MODERATE ICING	HEAVY ICING	ALL OBSERVATIONS
No. Cases	57	9	56	18	0	140
Cases-.00	41	4	22	0	0	67
Cases-.01-.10	11	1	6	2	0	20
Cases-.11-.20	3	3	12	4	0	22
Cases-.21-.30	2	0	3	5	0	10
Cases-.31-.40	0	1	4	1	0	6
Cases-.41-.60	0	0	6	4	0	10
Cases-.61-.80	0	0	3	1	0	4
Cases- .80	0	0	0	1	0	1
Maximum rate (cycles/n/m)	.21	.37	.78	.99	-	.99
Minimum rate	.00	.00	.00	.10	-	.00
Mean rate	.031	.098	.224	.326	-	.126
Median rate	.00	.07	.10	.26	-	.06

more difficult for the observer to detect additional accumulation, but it also could cause a misinterpretation of the ice detector data.

The detector did not detect a trace of icing on 4 of 10 occasions, and did not detect light icing in 20 of the 56 cases in which it was reported. Twelve of those 20 occurred on the same flight (81-09), suggesting problems with the ice detector on that particular flight. On that same flight, the ice detector also indicated icing on two of the three passes when the observer did not.

Observations of a trace of icing corresponded to a variety of ice detector readings, but only once did a reading exceed .20 cycles/nm. Light icing seemed to correspond to about .10 to .35 cycles/nm, but at times values as large as .78 were recorded. These large values showed no particular pattern; therefore, they could be related to different problems, including the problem of defining exactly how much ice must accumulate before it is no longer called light.

The 18 cases of observed moderate icing, a relatively small number, showed the largest variety of ice detector readings. Moderate icing is even more difficult to identify than light icing. Also, since the icing passes lasted a finite amount of time, cases of intermittent cloudiness could occur. Thus, although moderate icing may have occurred for 1 minute of a 3-minute pass, no icing (and thus no cycling of the ice detector) may have taken place during the other 2 minutes of the pass. This may explain why the mean value of our icing cases differs so much from the median value. A similar effect may have affected the light category, but the low value for the median in that case is probably the result of the questionable data obtained on flight 81-09.

The data show that although the icing detector does a good job of sensing icing and can give a semiquantitative estimate of its intensity, it is not perfect. Therefore, pilots must still be aware of the dangers of icing, and forecasters still must forecast it.

8. TEMPERATURE AND ALTITUDE RANGE OF ICING OCCURRENCES

Passes ranged in altitude from 2000 to 24,000 ft (0.7 to 7.1 km). Table 11 shows the accuracy of the nowcasts at different altitudes. The majority of nowcasts and occurrences were between 5000 and 19,000 ft (1.4 and 5.8 km). Both methods seemed to do well below 10,000 ft (3.0 km). Both methods seemed weaker at altitudes higher than 10,000 ft (3.0 km). In this series of flights, icing was reported at 22,000 ft (6.9 km) and could be found at any altitude below this.

The altitude used for this portion of the study is the pressure altitude given by the aircraft's altimeter. Therefore, values of 18,000 ft and higher are pressure altitudes (18,290 ft = 500 mbar regardless of the height of that pressure surface).

Table 11. Accuracy of Nowcasts at Different Altitudes

Altitude (1000 ft)	Skew-T Fcst/Observed				AFGWC Fcst/Observed				Total	Skew-T	%	AFGWC	%
	No/No	No/Yes	Yes/No	Yes/Yes	No/No	No/Yes	Yes/No	Yes/Yes					
24	1	0	0	0	1	0	0	0	1	1	100	1	100
23	1	0	0	0	1	0	0	0	1	1	100	1	100
22	0	0	0	1	0	0	0	1	1	1	100	1	100
21	0	1	0	1	0	1	0	1	2	1	50	1	50
20	1	0	0	1	1	0	0	1	2	2	100	2	100
19	4	1	0	1	4	1	0	1	6	5	83	5	83
18	2	1	1	1	2	1	1	1	5	3	60	3	60
17	3	3	4	2	3	3	4	2	12	5	42	5	42
16	1	2	3	4	1	2	3	4	10	5	50	5	50
15	2	4	2	8	2	4	2	8	16	10	63	10	68
14	2	4	0	5	2	2	1	6	11	7	64	8	73
13	3	5	3	5	1	1	5	9	16	8	50	10	63
12	3	6	4	6	1	4	6	8	19	9	47	9	47
11	5	5	1	7	1	4	5	8	18	12	66	9	50
10	4	2	1	10	1	1	4	11	17	14	82	12	71
9	7	1	1	6	5	1	3	6	15	13	87	11	78
8	6	0	3	7	6	0	3	7	16	13	81	13	81
7	7	1	1	4	6	0	2	5	13	11	85	11	85
6	3	1	1	4	3	1	1	4	9	7	77	7	77
5	4	0	2	2	4	0	2	2	8	6	75	6	75
4	2	0	0	1	2	0	0	1	3	3	100	3	100
3	1	2	0	1	1	2	0	1	4	2	50	2	100
2	1	0	0	0	1	0	0	0	1	1	100	1	100
TOTALS	63	39	27	77	49	28	42	87	206	140	68	136	66

Table 12. Accuracy of Nowcasts at Different Temperatures

Temp. Range	Skew-T Fcst/Observed				AFGWC Fcst/Observed				Total	Skew-T	%	AFGWC	%
	No/No	No/Yes	Yes/No	Yes/Yes	No/No	No/Yes	Yes/No	Yes/Yes					
≤ -20.0	5	2	0	1	4	2	1	1	8	6	75	5	63
-18.0-19.9	2	1	0	1	2	1	0	1	4	3	75	3	75
-16.0-17.9	3	1	0	2	2	1	1	2	6	5	83	4	67
-14.0-15.9	4	3	5	2	2	3	5	4	14	6	43	6	43
-12.0-13.9	4	4	6	5	4	4	6	5	19	9	47	9	47
-10.0-11.9	2	3	3	7	2	2	3	8	15	9	60	10	67
-8.0-9.9	1	1	2	13	1	0	2	14	17	14	82	15	88
-6.0-7.9	3	4	3	7	2	3	4	8	17	10	59	10	59
-4.0-5.9	6	6	5	15	3	2	8	19	32	21	66	22	69
-2.0-3.9	6	6	2	9	1	4	7	11	23	15	65	12	52
-0.0-1.9	6	1	2	7	4	1	4	7	16	13	81	11	69
±0.0+1.9	7	1	0	3	6	1	1	3	11	10	91	9	82
+2.0+3.9	8	0	0	0	8	0	0	0	8	8	100	8	100
+4.0+5.9	3	0	0	0	3	0	0	0	3	3	100	3	100
≥ +6.0	0	0	0	0	0	0	0	0	0	0	-	0	-
Totals*	60	33	28	72	44	24	42	83	193	132	68	127	66

*13 cases were omitted due to lack of temperature data.

Below 18,000 ft, the values are approximately the height of the aircraft above mean sea level.*

Table 12 shows the accuracy of nowcasts at different temperatures. Icing was experienced at temperatures between +2° C and -21° C. These temperatures are "true" temperatures as opposed to the "total" temperatures recorded by the aircraft system. While certain instrument errors [see Glass and Grantham (1981),[2] p. 13, including footnote] are present, the temperatures should be within a degree of the actual air temperatures.

In contrast to the altitude (Table 11), the temperature (Table 12) does not seem to affect the accuracy of the nowcasts. Although one category (8.0-9.9) did verify better than the others, this is probably only a coincidence; neighboring values do not show a similar trend. Both methods achieved high percentages at the extreme temperatures, but this is because of several cases in which icing was neither observed nor expected. Neither method did particularly well at identifying those rare cases in which icing did occur at these temperatures.

9. SUMMARY

The forecasting of icing is at best an inexact science. There are, however, some guidelines that a forecaster can follow. Both the Skew-T and the AFGWC forecast methods can point a forecaster in the right direction. While neither is sufficient in itself, both usually identify situations where icing is likely to occur.

Icing intensity and type are extremely hard to pinpoint, partially because of difficulties in definition and identification. In adequate light, one can identify the type of icing on an aircraft windshield easily; however, if one tries to tell whether a patch of ice on a wing or engine 40 ft from the observer is rime or clear, it becomes more difficult. If the airplane is in clouds at night, it is often impossible. Under similar meteorological conditions, intensity can vary from aircraft to aircraft. Again, however, forecast methods can give an idea of what is to be expected. Forecast intensity values cannot be taken literally, but must be adjusted to compensate for different types of aircraft and their speeds.

The AFGWC method was generally closer to the observed intensity. The Skew-T method often called for heavy icing, a condition that was never observed. This was forecast only once by the AFGWC method. Although the AFGWC method was only slightly more accurate in predicting the correct intensity, it was

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*Aircraft altimeters are usually set at 29.92 when flight is at 18,000 ft or higher. Below this altitude, an altimeter setting, determined by the local surface pressure, is applied to correct for the difference between pressure altitude and geometric altitude.

considerably more successful in predicting the intensity to within one category. The AFGWC method predicted the intensity to within one category 183 of 206 times; the Skew-T method succeeded in only 147 cases.

Neither method forecast the type of icing accurately. Clear and mixed icing were the exception, both in forecasts and observations, but forecasts of clear or mixed icing only rarely agreed with the observations.

The Rosemount Ice Detector gives a good indication of whether ice is forming and a fair indication of its intensity. It can be a useful tool in icing research as well as operational flying. It can extend the ability of a pilot to sense icing, but it cannot replace a trained pair of eyes. The air crew must still make the final determination of the type and intensity of icing.

The empirical forecast methods seem to work best at altitudes below 10,000 ft (3.0 km). They do not show a marked preference for any particular temperature range.

Current forecast methods leave much room for improvement. Work by Jeck (1982)[16] among others to establish a data base should lead to improved forecasting techniques. Varley (1980)[17] and Cohen (1981)[18] have looked at large scale storms and have shown just how widespread the potential for icing is. While icing forecasts will probably never be perfect, much can be done to improve them.

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Appendix A

Flight Data for 206 Data Points

The following pages list all aircraft data used in this report. Icing Flights are indicated by pass numbers; each line represents a pass. The temperature represents an average of the pass. For Spiral Flights, each line represents a data point. Pass numbers and icing detector values are not given for those flights. Temperatures represent an instantaneous value.

The following abbreviations are used:

ALT	Altitude (1000s of feet)
TEMP	Temperature in degrees celsius
SKT	Icing types and intensities indicated by the Skew-T method
GWC	Icing types and intensities indicated by the AFGWC method
VIS	Visual observations of the Mission Director
ICD	Average number of cycles of the Rosemount Icing Detector per nautical mile

Icing Intensity:	T	Trace
	L	Light
	M	Moderate
	H	Heavy
Icing Types:	R	Rime
	C	Clear
	M	Mixed

PASS	ALT	TEMP	SKT	GWC	VIS	ICD
Flight 79-49						
1	5	-1.0	MR	MR	TR	.17
2	7	-2.0	MR	MR	LR	.09
3	9	-3.7	HR	MR	LR	.47
4	11	-6.3	HR	MR	LM	.38
5	13	-10.2	HR	MR		.07
6	15	-14.7	HR	LR	LM	.48
7	17	-15.9				.04
8	16	-13.4	HR	LR		.17
9	14	-8.4	HR	MR	LM	.51
10	12	-5.5	HR	MR	LM	.62
11	10	-5.3	MR	MR	LM	.05
12	8	-2.8	MR	MR	LR	Missing
Flight 79-50						
1	6	+5.3				.00
2	8	+2.4				.00
3	10	-1.3	HC	LR	LR	.00
4	12	-5.0	HR	LR	LR	.00
5	14	-9.2	HR	MR	LR	.24
6	15	-11.4	HC	MR	MR	.29
7	16	-13.3			MR	.46
Flight 79-51						
1	4	-1.8	LR	MR	TR	.15
2	6	-4.1	MR	MR	LR	.49
3	7	-5.9	MR	MR	LR	.78
4	8	-7.4	HC	MM	MR	.54
5	9	-5.7	HC	MM	LR	.12
6	10	-7.9			MR	.63
7	11	-5.8				.00
Flight 80-01						
1	12	-12.7	LR	LR	TR	.37
2	12.6	-13.8	LR	LR	LR	.42
3	12.9	-12.6	LR	LR		.00
4	3	-7.3			LR	.31
5	3	-7.6			LR	.34
Flight 80-02 (No ice detector data available)						
1	3	+0.7				
2	5	+2.2				
3	7	-0.7	MR	MR		
4	8	-2.5	MR	MR		
5	9	-5.3	HR	LR		
6	10	-5.6	HC	HC	LR	

PASS	ALT	TEMP	SKT	GWC	VIS	ICD
Flight 80-03						
1	15	-9.3	HR	MR		.00
2	17	-12.7	HR	LR		.00
3	13	-5.9	HR	MR		.00
4	11	-3.4	HR	MR	LR	.09
5	9	-0.5			TR	.07
6	7	+3.3				.00
Flight 80-04 (Spiral)						
	8.2	-15.2	MR	LR		
	6.8	-11.6	MR	LR		
	5.1	-12.5				
	4.6	-11.9				
	4.0	-12.3				
	3.5	-10.3	MC	LR	LR	
Flight 80-05						
1	12	-7.9			LR	.06
2	10	-4.7		MC	MC	.13
3	8	-2.2	HC	MC	LC	.65
4	6	+0.9	HC		LR	.00
Flight 80-09 (Spiral)						
	13	-12.1	HC	MR	LR	
	12	-9.1	HC	MR	LR	
	11	-7.0	HC	MR	LR	
	10	-4.9	HC	MR	MR	
	9	-3.7	HC	MR	LR	
Flight 80-14						
1	2.8	+4.1				.08
2	5	+1.0				.08
3	7	-2.2		MR	TR	.00
4	8	-4.0	HR	MR		.00
5	11	-9.8	HR	MR	LR	.14
6	10	-8.0	HR	MR	LR	.11
7	8	-2.9	HR	MR	MR	.10
Flight 80-16						
1	16	-14.5	HC	LM	LM	.00
2	15	-12.8	HC	LM	MR	.10
3	14	-10.4		LR	MR	.16
4	13	-8.2		LR	MR	.23
5	12	-6.6		LR	LR	.00
6	11	-4.8		LR		.00
7	10	-2.7		LR		.00
8	9	-1.3		LR		.21

PASS	ALT	TEMP	SKT	GWC	VIS	ICD
Flight 80-18 (No ice detector data available)						
1	5	-2.5	MR	MR		
2	6	-4.2	MR	MR	TR	
3	7	-5.9	MR	MR	TR	
4	8	-7.6	MR	MM	TR	
5	9	-10.0	HR	MR	LR	
6	10	-11.8	HR	MR	TR	
7	11	-13.5	HR	MR		
8	12	-15.3	HR	LR		
9	13	-17.6		LR		
10	14	-20.2		LR		
11	5	-2.1	MR	MR	MR	
Flight 80-24						
5	24	-29.3				.00
6	23	-26.8				.00
7	21	-21.9			TR	.00
8	19	-16.9				.00
9	18	-15.0	HC	MR		.00
10	17	-12.3	HC	MR		.00
11	16	-6.0	MR	LR		.00
12	15	-10.1	MR	LR	LR	.00
13	16	-10.1	HC	LR	TR	.00
Flight 80-33						
1	6	0.0		LR	TR	.00
2	7	-1.1		LR		.00
3	8	-1.6	HC	MR	MR	.32
4	9	-4.2	HC	MM	MR	.21
5	10	-5.8	HR	MR	MR	.27
6	11	-5.9			LR	.18
7	9	-2.0		LR		.10
8	10	-3.5		LR		.00
9	11	-5.2		LR		.00
10	12	-6.3		LR		.00
11	13	-8.0	HR	LM	LR	.00
12	14	-9.8	HC	LR	LR	.00
Flight 80-34 (Spiral)						
	19	-21.5				
	18	-19.7				
	17	-17.4			TR	
	16	-15.7			LR	
	15	-12.9			LR	
	14	-10.6			LM	
	13	-8.2	HC	MM	LM	

PASS	ALT	TEMP	SKT	GWC	VIS	ICD
Flight 80-35						
1	11	-3.4			LR	.17
2	12	-2.1			LR	.25
Flight 80-38						
1	5	-2.8	LR	MR		.00
2	6	+0.2	LR	MR	TR	.12
3	7	-0.7	LR	MR	TR	.00
4	8	-1.9	MR	MR	LR	.37
5	9	-4.0	MR	MR	LR	.49
6	10	-5.7	MR	MR	MR	.45
7	11	-7.9	MR	MR	MR	.99
8	12	-8.3	MR	MR		.00
Flight 81-02						
5	13	-5.3				.09
6	12	-4.3			LR	.16
7	11	-3.1			LR	.29
8	10	-1.2	MR	MR		.21
9	9	+0.7				.00
Flight 81-05						
1	17	-17.0	LR	MR	LR	.06
2	16	-15.3	TR	MR		.08
3	15	-13.6				.00
4	15	-13.6				.00
5	12	-7.8				.00
6	11	-6.6			TR	.00
7	10	-3.6				.00
8	9	-1.3				.00
9	8	-1.0				.00
10	7	+0.1				.00
11	7.5	-1.1				.00
12	7.5	+0.1				.00
13	8	-1.3				.00
14	7	+1.2				.00
15	6	+2.0				.00

PASS	ALT	TEMP	SKT	GWC	VIS	ICD
Flight 81-06 (Spiral)						
	19	-14.9			LR	
	18	-13.7			MR	
	17	-11.8			LR	
	16	M				
	15	-7.6				
	14	-5.9				
	13	-4.2		LR		
	12	-2.6		LR		
	11	0.0		LR		
	10	M		LR		
	9	+2.1				
	8.5	+3.6				
	20	-17.7				
	19	-15.4				
	18	-13.8				
	17	M				
Flight 81-07						
1	19	-19.4				.00
2	17	-14.9	HC	LM		.00
3	15	-10.9	HR	LM		.00
4	12	-5.5	HR	LM		.00
5	11	-4.5		LM	LC	.07
6	11.2	M		LM	LR	M
Flight 81-08						
1	17	-20.0			LR	.00
2	15	-14.1			MR	.11
3	15	-10.5			LR	.21
4	14	-12.1			LR	.00
5	17.7	-20.3				.00
6	15	-15.0			LR	.16
Flight 81-09						
1	17	-12.2	MR	MR		.18
2	16	-10.9	MR	MR	LC	.00
3	15	-8.6	MR	MR	LC	.00
4	13	-4.4	LR	MR		.00
5	12	-3.3	LR	MR	MM	.45
6	11	-1.0	LR	MR	LC	.00
7	10	+0.4	TR	MR	LR	.00
8	9	+2.2				.13
9	17	-14.0	MR	MR	LR	.00
10	18	-14.8	MR	MR	LR	.00
11	19	-15.9	MR	MR	LR	.00
12	20	-17.7	MR	MR	LR	.00
13	21	-19.3	MR	MR	LR	.00
14	22	-21.5	MR	MR	LR	.00
15	16	-11.2	MR	MR	LR	.00
16	15	-9.4	MR	MR	LR	.00
17	14	-7.5	MR	MR	LR	.06
18	13	-5.5	LR	MR	MM	.13

PASS	ALT	TEMP	SKT	GWC	VIS	ICD
Flight 81-10 (spiral)						
	5	+2.8				
	6	M				
	7	M				
	8	M				
	9	M				
	10	M	MR	MR	LR	
	11	M	MR	MR	LR	
	12	M			LR	
	13	M			LR	
	14	M				
Flight 81-11						
1	15	-9.2	HR	LR	LR	.13
2	14	-6.5	HR	MR	LR	.09
3	13	-5.0		MR	LR	.05
4	12	-3.0		MR	LR	.11
5	11	-1.2		MR		.07
6	13	-5.2		MR	LC	.14
7	15	-9.2	HR	LR	MC	.26
8	8	+4.8				

Appendix B

Radiosonde Stations Used in This Report

ALB	Albany, N.Y.
BUF	Buffalo, N.Y.
DAY	Dayton, Ohio
DEN	Denver, Colo.
FNT	Flint, Mich.
GRB	Green Bay, Wis.
GSO	Greensboro, N.C.
HTS	Huntington, W.Va.
PIA	Peoria, Ill.
PWM	Portland, Maine
SLO	Salem, Ill.
UIL	Quillayute, Wash.