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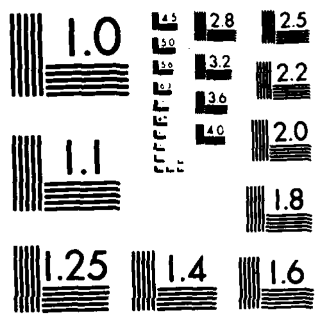
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MICROWAVE MONITORING OF AVIATION ICING CLOUDS

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Final Report
For the Period 20 January 1983 - 30 November 1983

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A field demonstration of passive microwave radiometers was used to assess the usefulness of remotely-sensed cloud properties for the purpose of providing aviation icing hazard advisories. The microwave system measured air temperature profiles, from surface to 10,000 feet, cloud liquid water content, and cloud base altitude. Radiosondes provided temperature air truth, a ceilometer provided cloud base air truth, and pilot reports provided icing condition air truth.

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20. Abstract

Temperature profiles from the microwave remote sensing system agreed with radiosonde temperature profiles to an RMS accuracy that was predicted prior to the field experiment from simulation calculations. Integrated water vapor content measurements agreed with radiosonde values, indicating that microwave integrated liquid water content values were also valid. Microwave-generated cloud bases were in fair agreement with ceilometer values. Icing advisories from the microwave system correlated with the rate of pilot reports of icing conditions. The false alarm rate was nil, and the "hit rate" was good.

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MICROWAVE MONITORING OF AVIATION ICING CLOUDS

1. INTRODUCTION

Clouds of supercooled liquid water droplets continue to be an aviation icing safety hazard for certain categories of aircraft. Accurate forecasts for this hazard still elude us. It is even difficult to obtain accurate knowledge of present conditions. The process of assessing present conditions is called "nowcasting." Better nowcasting would improve aviation operations, and it would also improve forecasting accuracy.

An investigation by Hogg and Guiraud (1980) showed a promising correlation between microwave-measured integrated cloud liquid water content and pilot reported icing encounters for a 24-hour period, near Stapleton Airport, Denver, Colorado. The system used in that experiment did not measure overhead temperature profiles, so 12-hourly radiosonde temperature profile information had to be relied on for inferring the super-cooled properties of the cloud layer.

The work reported here is an attempt to evaluate a more complete set of remote sensors for the improvement of nowcasting. A field demonstration was conducted with a system of passive microwave radiometers, supplemented by an infrared radiometer, that can be used to determine cloud temperature as well as integrated liquid water content. These cloud properties are then used to infer the icing hazard potential of the cloud layer.

For some years the Jet Propulsion Laboratory has been operating a system of passive microwave remote sensors. This system is housed in a van, called MARS: "Mobile Microwave Atmospheric Remote Sensing System." MARS determines the following meteorological properties:

1) altitide temperature profiles, surface to 10,000 feet,
2) line-of-sight water vapor content (ie, precipitable water vapor),
3) line-of-sight liquid water content (ie, cloud water burden),
4) cloud base temperature, and altitude.

During previous deployments of MARS we have demonstrated the retrieval of properties 1 through 3, above. This experiment was our first attempt to measure cloud base. It was also our first field operation in a "winter" setting (snow, freezing rain, etc).

2. DESCRIPTION OF THE EXPERIMENT

During March, 1983, MARS was operated at Buffalo, NY, at the Greater Buffalo International Airport. MARS was located next to the National Weather Service radiosonde (RAOB) launching site. Pilot reports of cloud icing conditions were collected in collaboration with the Federal Aviation Administration (FAA) Flight Service Station, also located at the Buffalo Airport.

Buffalo was chosen as a site for this experiment partly as a result of discussions with personnel at the NASA Lewis Research Center, LeRC. An aircraft field experiment which they had been conducting for several years showed Buffalo to be a favored location for encountering icing conditions during the late winter months. Also, Buffalo was within range of the home base for the LeRC research icing aircraft (at Cleveland, Ohio), and arrangements were made to attempt coordinated LeRC aircraft overflights in order to provide air truth calibrations for the MARS system.

2.1 MARS System Description

MARS consists of passive microwave radiometers, operating at the frequencies 22.23, 31.4, 54.0, 55.3, and 57.5 Gigahertz (GHz). Each radiometer is sequenced through its own set of elevation angles, from zenith to close to the horizon. An infrared radiometer (8-14 microns) is used to monitor zenith IR brightness temperature, for the purpose of deducing cloud base altitude. Outside air temperature, barometric pressure, and relative humidity are monitored. This sensor system is controlled by a Hewlett-Packard 9825 desktop computer. This computer also performs data acquisition, data recording, and real-time analysis and display. Data cycles are completed every 2 minutes. Monitor displays show air temperature versus altitude and icing hazard information. These images can be transmitted via phone to standard remote terminals, as was done on several occasions during the Buffalo experiment. Figure 1 is a photograph of the MARS van during the Buffalo deployment.

2.2 Preparation for Field Trip

Since MARS had never operated in cold weather, the radiometer subsytems had to be "winterized." An infrared radiometer was purchased, and was calibrated in a refrigerator/oven chamber. Software was developed that enabled real-time displays of icing conditions on a monitor display of altitude/temperature profiles.

A magnetic tape of Buffalo RAOBs was obtained from the NWS National Climatic Center, in Ashville, North Carolina. This data consisted of February and March RAOBs for the 4-year period 1977 to 1980. Computer simulations were conducted to obtain retrieval coefficients for converting observed quantities to desired meteorological properties. The concepts underlying retrieval coefficient derivations, and procedures for their calculation, are described by Staelin (1966), Westwater and Strand (1968), Westwater (1972), Westwater et al (1975), and Decker et al (1978).

2.3 Field Experiment

The MARS van was set-up at the Buffalo Airport March 3, 1983. Preliminary observations showed the presence of "radio frequency interference" in the 57.5 GHz radiometer. One interfering signal had a 20-second repetition rate, which suggests that the source of the interference was the WSR-57 weather radar, located less than a mile away. Shielding was improvised, which solved the problem.

Observations began March 5. Icing conditions did not exist for several days. In fact, on March 7 a record "high temperature for date" was broken by 16 degrees Fahrenheit (76 degF versus 60 degF). The weather for this particular March was unusual. The first half of the month was warmer than average, and the second half was colder. On March 25, a record low temperature was tied (5 degF). March 30 was the last observation date. Appendix A is a NWS summary of weather conditions for Buffalo during March, 1983.

PIREPs were obtained from the FAA Flight Service Station and the NWS Forecast Office, both located at the airport. FAA personnel stated that this particular March was sparce for icing conditions.

Because of the generally recognized poor prospects for aviation icing conditions, every effort was made to operate MARS in marginal weather. We discovered that useable data could be obtained in light rain, and when it was snowing (provided the air temperature was sufficiently cold that the snow wasn't "wet"). Observations during these marginal weather conditions were accomplished by manually wiping off the microwave radomes between 10-minute data cycles.

RAOB data were provided to us approximately an hour after RAOB launch. Surface observation data, including ceilometer and cloud layer information, was also provided by the NWS.

The original experiment plan included overflights of MARS by a specially-instrumented aircraft operated by NASA's Lewis Research Center, LeRC, located in Cleveland, Ohio. The aircraft was instrumented to measure 1) ice accretion rate, 2) cloud liquid water concentration, LWC, 3) drop size distribution, and 4) outside air temperature. These cloud properties are ideal input for characterizing icing conditions, and our intent was to provide some high quality air truth comparisons for the MARS nowcast advisories. We deliberated by phone with LeRC personnel on a daily basis about the potential usefulness of an overflight (whenever icing conditions had been forecast). On every occasion it was decided "not to fly," either because the prospects for icing in the Buffalo area were too vague, or because rain was forecast, or because there were higher priority flights scheduled for the Cleveland area.

2.4 *Vapor/Liquid Measurements*

Microwave observables were converted to line-of-sight contents for water vapor and liquid water, V and L, using well-established algorithms (Staelin, 1966; Toong and Staelin, 1970; Westwater, 1978; Snider et al, 1980; and Gary, 1981). A simple equation is used to relate each desired property (V or L) to the observables. The constants which appear in these equations were obtained from plots of zenith sky brightness temperature (corrected for "saturation"), T1 and T2 (22.23 and 31.4 GHz), versus vapor content. The final set of retrieval coefficients can be summarized:

$$V = C1 + C2*T1 + C3*T2$$
$$L = C4 + C5*T1 + C6*T2$$

where:

C1 = -0.125	C2 = 0.0661	C3 = -0.03463
C4 = -178	C5 = -6.35	C6 = 20.78

Comparisons between MARS-generated vapor content and RAOB-derived vapor content showed good agreement. The RMS difference between the two is 0.064 cm (clear weather) and 0.094 cm (coudy, rain, snow weather). If it is assumed that RAOBs have errors of 5 or 10%, then MARS errors for water vapor content are also 5 or 10%. RAOBs don't measure liquid water concentration, so no evaluation of accuracy could be made for MARS-generated integrated liquid water content. However, since the liquid and vapor properties are closely related to the same microwave observables, it can be said that the good water vapor performance indicates that the liquid water measurements were also good.

2.5 Statistical Retrieval Preparations

A statistical algorithm is used to convert observables to desired meteorology properties. Publications by Westwater and others (1) describe the formalism of this technique. Briefly, there are 21 MARS observables (Table 1) and 24 physical properties to be retrieved. A set of 22 retrieval coefficient numbers are needed to convert the observable set to any given physical property (a constant term and 21 observable multipliers are used). To retrieve all 24 physical properties, therefore, a 22x24 matrix of retrieval coefficients is needed. This report will not describe how the coefficients are prepared, as this is adequately documented in the literature (Westwater and Strand, 1968; Westwater et al, 1975).

Prior to the Buffalo field observations, several candidate 22x24 retrieval coefficient matrices were prepared. One matrix set was calculated from only clear weather RAOBs, another from cloudy/warm RAOBs, and another from cloudy/cold RAOBs, etc. It was discovered, in the middle of the Buffalo observations, that the cloudy/warm and cloudy/cold coefficients did as good a job of portraying overhead conditions as any of the other candidates. All subsequent reduction of data has been performed using these coefficients. A novel interpolating scheme is used: when air temperature is warmer than +10 degC, the "warm" retrieval products are used; when air temperature is colder than -10 degC, the "cold" retrieval products are used; and when air temperature is between -10 degC and +10 degC, an interpolation of the two retrieval products is used.

2.6 T(h) Refinement

There's no such thing as a perfectly calibrated radiometer. Nor is there a perfectly calibrated RAOB system. In order to compare performance of one system with the other, an intercomparison adjustment of one system relative to the other must be applied. The requirment is to impose one calibration adjustment algorithm to the observables of one system uniformly for the entire data set under evaluation (i.e., the adjustment algorithm may not vary from day to day, etc.). The procedure for deriving this set of calibration adjustments is to compare observed quantities with theoretical predictins of what should have been observed. Empirical correlations produce the adjusting equations. Once derived for a particular system, these calibration adjustment equations should be suitable for all observations with the system, including future uses of the system. Such "one time" calibrations against a chosen air truth standard is common practice by users of remote sensing systems.

For this experiment, there are 28 occasions when RAOBs and MARS data overlap in the required manner. Of these, 15 were clear weather situations. These 15 RAOB/MARS comparisons have been used to determine "calibration adjustment equations," which have been applied to subsequent reductions of all MARS data. Dependencies of required correction upon the temperature of the radiometer's ambient calibrating target were used in almost all equations (implying that our hot and ambient calibration targets were radiating at slightly different temperatures than assumed).

(Ideally, only cloudy RAOB conditions would be used for deriving MARS calibration equations, since the cloudy conditions are the intended time of use for MARS. However, since RAOBs don't specify the quantity of liquid water in a cloud layer, RAOBs for cloudy occasions cannot be used for calculating predicted observables; therefore, the cloudy RAOBs cannot be used for calibrating MARS. Consequently, the clear sky RAOBs were used for this purpose.)

Fig 2 is a plot of MARS-derived altitude temperature profiles (incorporating the "calibration adjustment equations") for the overall coldest and warmest dates. Also plotted in this figure are the corresponding RAOB-measured temperature profiles. Good agreement between the MARS and RAOB profiles is apparent.

A statistical analysis has been performed on the MARS versus RAOB temperature profiles for the 28 comparisons that are available. Fig 3 is a plot of RMS difference (MARS minus RAOB) for a selection of altitudes. The dotted line is a pre-experiment prediction of RMS performance. The "predicted" and "actual" are in good agreement. This implies that the information content of the observables has been properly extracted by the retrieval process that converts observables to desired physical properties.

Figure 3 also says something about the altitude regime for which MARS temperature profiles add useful information. Above 10,000 feet, there is almost no difference between the RMS performance (MARS minus RAOB) and the inherent variability above Buffalo (RAOB minus average RAOB). Below 10,000 feet, the improvement can be dramatic, such as at 2000 feet, where there is a nine-fold improvement.

2.7 Cloud Properties

Several properties of the overhead clouds are of interest for aviation icing. Cloud base, cloud top, liquid water concentration within the cloud layer(s), total amount of liquid water in the overhead cloud layer(s), temperature of the cloud droplets, and drop size distribution. MARS observables contain information that is statistically correlated with cloud base, LWC, total amount of liquid water in the clouds, and temperature of the cloud liquid. Cloud top information is only weakly correlated with MARS observables, and drop size distribution information is completely lacking.

Comparisons of cloud base altitudes is often confounded by the existence of multiple layers. Frequently, there was a lowest layer with a coverage that was "scattered," the next higher layer was "broken," and the third layer was "overcast." Under these conditions the MARS-derived cloud base would vary considerably, with time scales corresponding to the passage of clouds. In order to minimize the effects of rain and snow accumulation on the IR sensor's window, the IR sensor was pointed "off-zenith," at an elevation angle of approximately 45 degrees. This hampered comparisons of NWS-measured cloud bases and MARS-derived cloud bases when there were 2 or more cloud layers. A comparison of cloud base altitudes has been performed on a selected data set (for one-layer cloud conditions). The results of this comparison can be summarized by stating that MARS-derived cloud base altitudes have an accuracy of "500 feet orthogonally added to 20% of the indicated cloud base altitude." For example, a MARS-generated cloud base altitude of 4000 feet will have an accuracy of about 1000 feet.

Cloud liquid water burden is measured with high confidence by MARS. It is derived "deterministically," as described in section 2.4. Liquid water concentration, LWC, can be deduced by dividing liquid burden by cloud thickness. Cloud thickness is obtained from cloud base and cloud top information. Since cloud top is a weakly-constrained retrieved property, cloud thickness is not well known from MARS observables. Hence, LWC is a weakly-constrained retrieved property. This is especially true when there are multiple layers of clouds. Nevertheless, LWC can still be calculated, and it is included in the real-time (and replay) panels showing temperature profiles and icing conditions. One of the intended uses of the over-flights of the Lewis Research Center aircraft was to compare LWC measured by MARS with that measured in situ.

2.8 Icing Nowcasting

One method for calculating icing hazard potential is to assume that it is proportional to LWC, and that it decreases monotonically in going from a temperature just below freezing to a temperature of approximately -40 degC. At this coldest temperature only the very smallest droplets of water can remain in the liquid phase (the larger droplets freeze, and do not contribute to icing hazard). For this study we have adopted the following equation for "icing hazard potential," IHP, at altitude h:

$$IHP(h)=LWC(h)*(T(h)+40degC)/40.$$

Because of the inherent uncertainty of cloud top retrievals, described in the preceding paragraph, we have chosen to retrieve IHP using a statistical algorithm. To do this, we calculated IHP profiles for each RAOB in the March 1977-1980 archive, using the above equation. These icing properties were then correlated with MARS observables, and retrievable coeff ients were determined that allowed conversion of observables to icing perties (using statistical procedures identical to those that were used convert observables to temperature profiles).

One additional assumption had to be made in order to calc IHP(h) in the manner just described. Since RAOBs don't measure LWC(h) algorithm had to be devised for estimating this parameter. We assumed that, for any specified level in a cloud, LWC is equal to the difference between the vapor concentration at that level and the vapor concentration immediately below the base of the cloud, multiplied by a number which we chose to be 0.50. There are physical arguments why this relationship should hold, which won't be presented here (Fletcher, 1962). Aircraft measurements have indicated that the multiplier factor is between 0.25 and 0.70, with the exact value depending on cloud type, age, etc, in ways that are not entirely understood (Malkevich et al, 1981).

The concepts just described were used to determine retrieval coefficients for converting MARS observables to integrated-IHP (called "icing exposure"), lowest altitude where IHP>0 (called "icing base"), and altitude of maximum IHP (called "icing peak altitude"). This information is retrieved in real-time (and during post-analysis) and is included in the video display of altitude temperature profiles. Figure 4 is an example of such a display. The "icing exposure" value of 8 is the largest value encountered during the Buffalo experiment.

Figure 5 shows plots of icing exposure (integrated IHP) for two dates. The upper panel is for March 28, the date that generated the largest value of icing exposure. Because of rain, the MARS system was shut down at 1731. The lower panel is for March 22, when the sky was overcast and the air temperature was below freezing, but when MARS icing exposures were low in value. It was not obvious in looking at the sky why icing exposure should be low, but according to MARS there was an insufficient amount of liquid water in the clouds to pose an icing hazard.

2.9 PIREP Comparisons With MARS Icing Advisories

The correlation of icing hazard predicted by MARS was confirmed by the frequency of icing PIREPs for the two dates represented in Figure 5. The positive icing PIREP times are shown in the upper part of each panel. March 22 and 28 disinguish themselves as high and low icing condition dates by either the PIREP or MARS icing exposure criteria quite unambiguously.

There is a question about the lack of hour-to-hour MARS-PIREP correlation on March 28. Prior to 1600 EST there is little indication of serious icing problems, yet there are two nearby PIREPs for icing. It is possible, but can't be proven, that the clouds to the south of Buffalo (where the PIREPs originated) contained more liquid water than at the MARS site.

As good as the correlation is, in this figure, between MARS icing advisory and PIREP incidence, something more objective and subject to statistical assessment is needed.

The 169 hours of MARS data were grouped by time of day into one of 5 periods: 06-11, 11-16, 16-20, 20-01, and 01-06 Eastern Standard Time. There were 45 such occasions of data belonging to one of these periods. For each of these 45 data groups an assessment was made concerning the existence of preconditions for icing. This was based on the criteria of surface air temperature and sky overcast condition. If, at any time during this period, it was colder than +5 degC, and if the sky was either "broken" or "overcast," the period was assigned to the "icing precondition" category. The other periods were assigned to the "non-icing precondition" category. There were 21 data groups in the "icing" category, and 24 data groups in the "non-icing" category. These groups are listed in Table II.

Also tabulated in Table II, for the "icing" category data groups, is a summary of PIREP information. PIREPS were segregated by distance from the Buffalo Airport, with a 50 mile criterion for "close" versus "far." PIREPS farther than 100 miles were not used. PIREP coverage was not complete, due to inadequate communication between MARS personnel and FSS personnel, and in any future experiment this will have to be given greater attention. Because of this incomplete coverage, it was necessary to normalize the number of PIREPS by the number of hours of PIREP coverage. This PIREP rate is included in Table II, for the "close" and "far" distance zones. Standard errors for PIREP rate have been calculated, and are also included in the tabulation.

Consider, first, the 21 data groups which satisfy the surface-based preconditions for icing. The groups were categorized two ways: according to their frequency of PIREPs, and according to their MARS-generated icing exposure. The upper panel of Figure 6 shows the number of groups in each of the subcategories. The "scoring box" has six sub-boxes. The occurence of data groups in these sub-boxes fits a pattern which can be stated:

1) when MARS says icing exposure is low, PIREP frequency is low,
2) when MARS says icing exposure is medium, PIREP frequency is mixed,
3) when MARS says icing exposure is high, PIREP frequency is high.

The lower scoring box in Figure 6 is for the data groups for which surface-based icing preconditions do not exist. There is no PIREP data for this group (I felt silly asking FAA for icing PIREP data when the temperature was in the 50's to 70's, or the sky was clear), and the PIREP frequency can safely be assumed to be zero. On only two occasions did MARS generate non-zero icing exposure for this data subset. These two occasions were for March 23 and March 29, when the sky cover was "broken" clouds, and the surface air temperature was below freezing, ie, when, in fact, there may have been intermittent icing overhead. (In retrospect, perhaps "broken" cloud cover conditions should be included as a permissible pre-condition for icing.) The pattern which this scoring box shows can be stated:

1) when there is little chance for icing, based on visual observations of sky coverage, and surface air temperature is warm, MARS says that icing exposure is very low,
2) under these same conditions, MARS never says that icing exposure is high,
3) under conditions when there are scattered clouds, and air temperature is cold, MARS can say that icing exposure is medium.

The patterns in both scoring boxes is consistent with what is desired in the way of icing forecast performance from a remote sensing system.

3. CONCLUSIONS

A passive microwave remote sensing system was successfully operated at the Buffalo Airport during 20 days of March, 1983. The remote sensor system, called MARS, succeeded in measuring precipitable water vapor and temperature profiles (from surface to 10,00 feet), as validated by radiosonde air truth comparisons. Crude cloud base altitude measurement capability was demonstrated. Icing exposure values for 45 groups of data in 6-hour blocks correlate well with the frequency of icing PIREPs (from a region closer than 100 miles). False alarms are virtually nil, and the "hit rate" is good.

There is nothing incompatible with the position that a system like MARS can provide automated aviation icing hazard advisories. However, it should be pointed out that there were no air truth overflights with instrumentation for documenting the MARS determined cloud properties, and there were only 73 hours for which surface-based preconditions for icing existed (colder than +5 degC, sky cover either broken or overcast). Part of this low icing hour data base can be attributed to the inability of MARS to operate in medium and greater rain (or wet snow conditions). Future improvements can be considered that may allow such all-weather observing.

It is prudent to say that the MARS system is still unproven, as an aviation icing advisory tool, inspite of its successful performance to date. What is needed is a more comprehensive evaluation, covering more hours of potential icing, more severe icing conditions, and documented with specially-instrumented aircraft overflights.

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TABLE I

OBSERVABLES

1)	Tb	57.0 GHz	5	deg elevation
2)	Tb	"	8	"
3)	Tb	"	14	"
4)	Tb	"	20	"
5)	Tb	"	30	"
6)	Tb	"	46	"
7)	Tb	"	90	"
8)	Tb	55.3 GHz	36	"
9)	Tb	"	42	"
10)	Tb	"	50	"
11)	Tb	"	90	"
12)	Tb	54.0 GHz	36	"
13)	Tb	"	42	"
14)	Tb	"	50	"
15)	Tb	"	90	"
16)	Integrated water vapor			
17)	Outside air temperature			
18)	Relative humidity			
19)	Barometric pressure			
20)	Integrated liquid water			
21)	IR temperature			

RETRIEVABLES

1)	Air temp, surface	
2)	"	100 ft
3)	"	200 ft
4)	"	300 ft
5)	"	500 ft
6)	"	700 ft
7)	"	1000 ft
8)	"	1300 ft
9)	"	1600 ft
10)	"	2000 ft
11)	"	2500 ft
12)	"	3200 ft
13)	"	4000 ft
14)	"	5 kft
15)	"	7 kft
16)	"	15 kft
17)	"	20 kft
18)	"	25 kft
19)	Max Icing Hazard, IHmx	
20)	Altitude of IHmx	
21)	Integrated IH	
22)	Lowest altitude for Icing	
23)	Cloud top altitude	
24)	Cloud top base	

TABLE II

ICING PRE-CONDITION DATA GROUPS

Date	Sky Cov	Hrs MARS Data	Max IHP	Hrs PIREPs	#PIREPs <50,<100	PIREPS/Hr <50	PIREPS/Hr <100
9a	DZL	2.0	3.3	-	-	-	
9n	RAIN	2.0	2.0	-	-	-	
10a	DZL	0.5	5.0	1	1,1	1.0#1.0	1.0#1.0
11a	SNO	5.0	2.0	1	0,0	0.0#0.7	0.0#0.7
11m	OVC	4.0	2.4	-	-	-	
11p	OVC	2.5	1.3	1.7	2,3	1.2#0.7	1.8#0.8
12a	OVC	4.0	1.4	3	2,4	0.7#0.4	1.3#0.5
12m	BKN	2.5	0.0	3	0,0	0.0#0.2	0.0#0.2
18m	RAIN	6.0	0.4	5.5	0,0	0.0#0.1	0.0#0.1
20a	OVC	5.0	2.0	5	0,5	0.0#0.1	1.0#0.3
20m	OVC	5.0	1.4	5	0,6	0.0#0.1	1.2#0.4
20p	OVC	3.0	0.9	1	1,2	1.0#1.0	2.0#1.2
21m	SNO	1.0	0.8	5	1,1	0.2#0.2	0.2#0.2
22a	OVC	5.0	1.5	4	0,0	0.0#0.2	0.0#0.2
22m	SNO	5.0	0.8	5	0,1	0.0#0.1	0.2#0.2
22p	SNO	3.0	0.7	3	0,0	0.0#0.2	0.0#0.2
23m	BKN	5.0	0.2	-	-	-	
27a	RAIN	3.5	1.9	-	-	-	
28m	OVC	4.0	1.1	2.5	2,2	0.8#0.5	0.8#0.5
28p	RAIN	1.5	8.0	4	2,6	0.5#0.3	1.5#0.5
28e	OVC	3.0	4.3	-	-	-	

NON-ICING PRE-CONDITION DATA GROUPS

Date	Sky Cov	Hrs MARS Data	Max IHP
5p	CLR	0.5	0
7p	CLR	0.5	0
17a	CLR	5.0	0
17m	Cir	0.8	0
17p	Cir	3.0	0
23a	CLR	5.0	0
23p	SCT	3.0	0.2
24a	CLR	5.0	0
24m	CLR	5.0	0
24p	CLR	3.0	0
25a	CLR	5.5	0
25m	CLR	5.0	0
25p	CLR	2.5	0
26a	CLR	5.5	0
26m	CLR	5.0	0
26p	Cir	4.0	0
26n	Cir	5.0	0
29e	SCT	4.0	1.3
29a	CLR	6.0	0
29m	CLR	5.0	0
29p	CLR	4.0	0
29n	CLR	5.0	0
30e	CLR	5.0	0
30a	CLR	4.0	0

CLR = clear; CIR = cirrus; SCT = scattered; BKN = broken; OVC = overcast
SNO = snow; DZL = drizzle; 9a = March 9, AM (06-11 EST);
p = PM (16-20 EST); n = night (20-01 EST); e = early AM (01-06 EST)
m = mid-day; # = plus or minus

FIGURE CAPTIONS

Figure 1
Photograph of MARS van, as it was configured at Buffalo in March, 1983. The box with "RFI blinders" at the left is the 57.5 GHz radiometer. The middle box houses the 54.0 and 55.3 GHz radiometers. The box on the right houses the 22.23 and 31.4 GHz radiometers. (The people, from left to right, are Tom Osborn, Richard Denning, Noboru Yamane, and Bruce Gary.)

Figure 2
These two samples of "retrieved" and "RAOB" temperature profiles correspond to the overall warmest and coldest of the 28 MARS/RAOB comparisons that were made in Buffalo.

Figure 3
These plots summarize MARS temperature profiling performance. The dotted lines are pre-experiment predictions of performance, and the solid lines are actual performance. The left-side plots are "MARS minus RAOB" RMS differences. The right-side plots show variability with respect to the average temperature profile for Buffalo for March.

Figure 4
The three panels are altitude temperature profile plots of the same data for three different altitude scales. The top panel is for surface to 22,000 feet, the middle panel is for surface to 7300 feet, and the bottom panel is for surface to 2200 feet. A Centigrade temperature scale is shown along the bottom. The "O" symbol is MARS-generated air temperature, and the ":" symbol is RAOB measured air temperature. A pattern of blanks denote a dry adiabatic lapse rate, fixed to the surface air temperature. Clouds are represented by the slash symbol.

The upper-right box of information gives OAT (outside air temperature), VAP (water vapor burden), LIQ (liquid water burden), IR (8-14 micron infrared sky brightness temperature), and LWC (liquid water concentration, averaged for the cloud layer). The lower-left information box gives icing-related information. ICING EXPOSURE is the height integral of icing hazard (defined in text, and scaled to produce values of 0 to 10 for a typical month), CLD TOPS (cloud tops, feet above surface), ICING PK (altitude of maximum icing hazard, feet), ICING BS (lowest altitude where icing is predicted to be present, feet), and CLD BS (ceiling altitude, feet).

Figure 5
Plots of MARS-generated icing exposure versus time for two dates. Pilot reports for icing (for the period indicated) are either closer than 50 miles (filled circle) or between 50 and 100 miles (open circles).

Figure 6
Scoring boxes are used to compare MARS predictions of icing and PIREP confirmations.

FIGURE 1

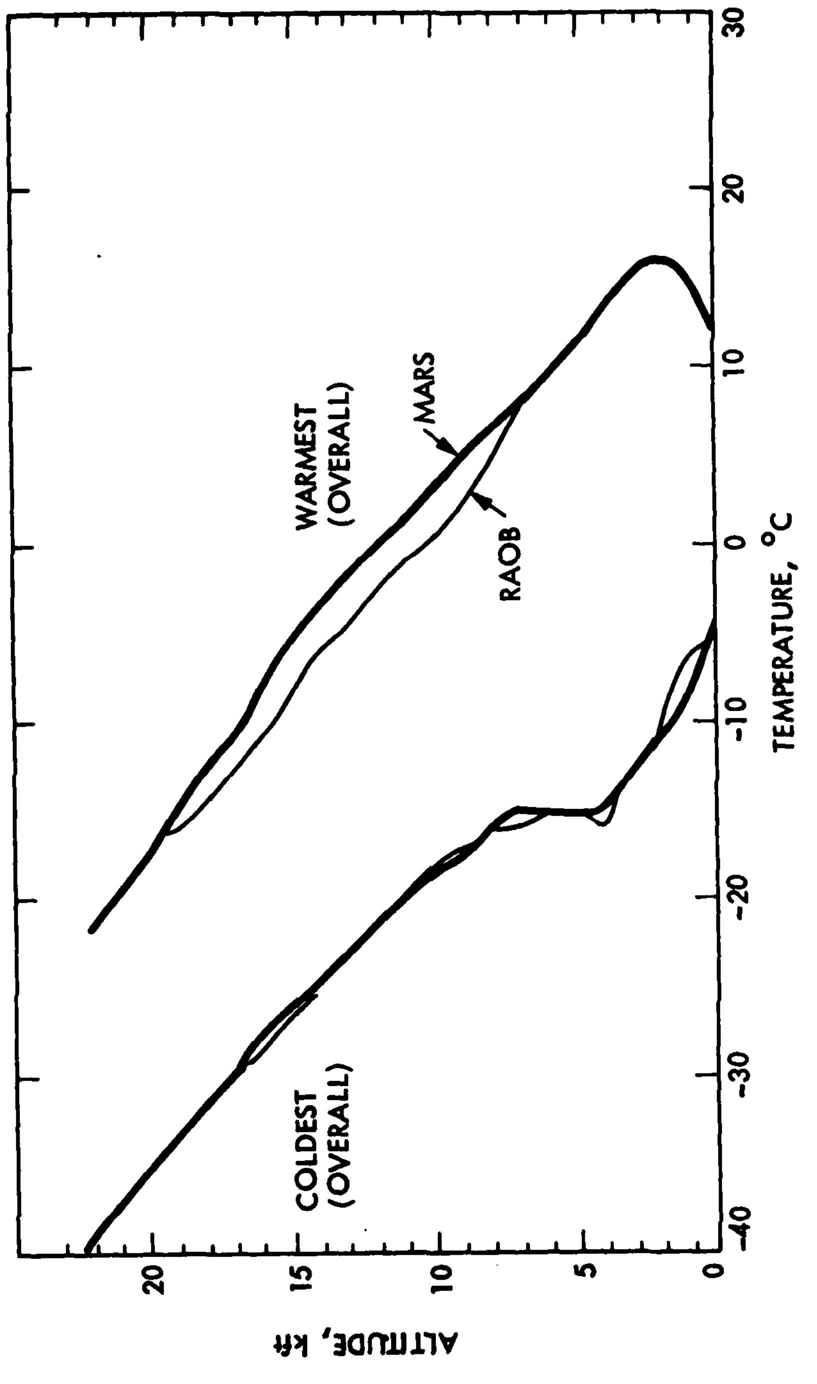

WARMEST (OVERALL)
MARS
RAOB
COLDEST (OVERALL)
-40
-30
-20
-10
0
10
20
30
TEMPERATURE, °C
0
5
10
15
20
ALTITUDE, kft

FIGURE 2

PERFORMANCE SUMMARY

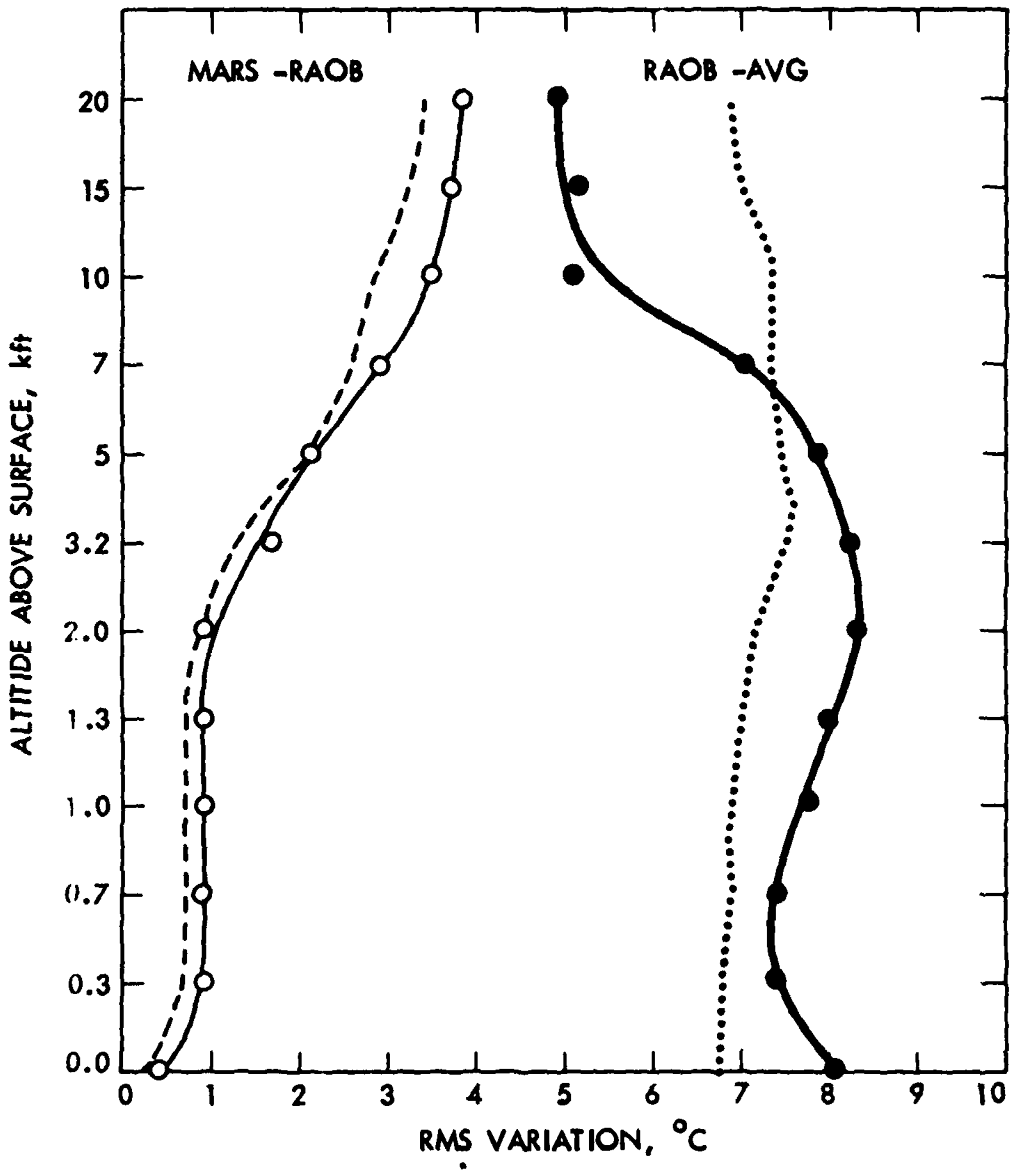
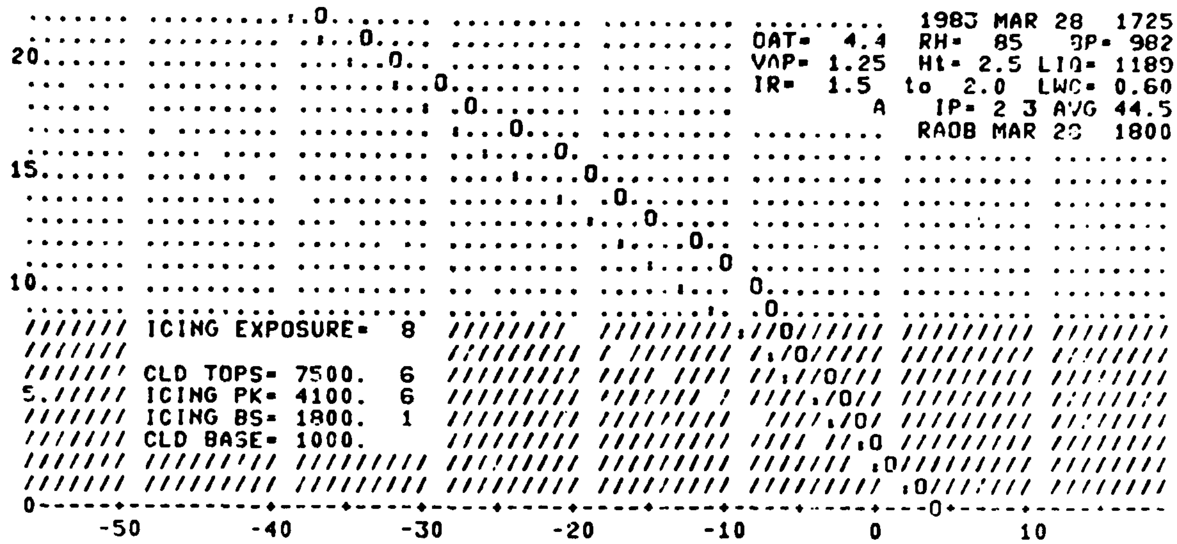
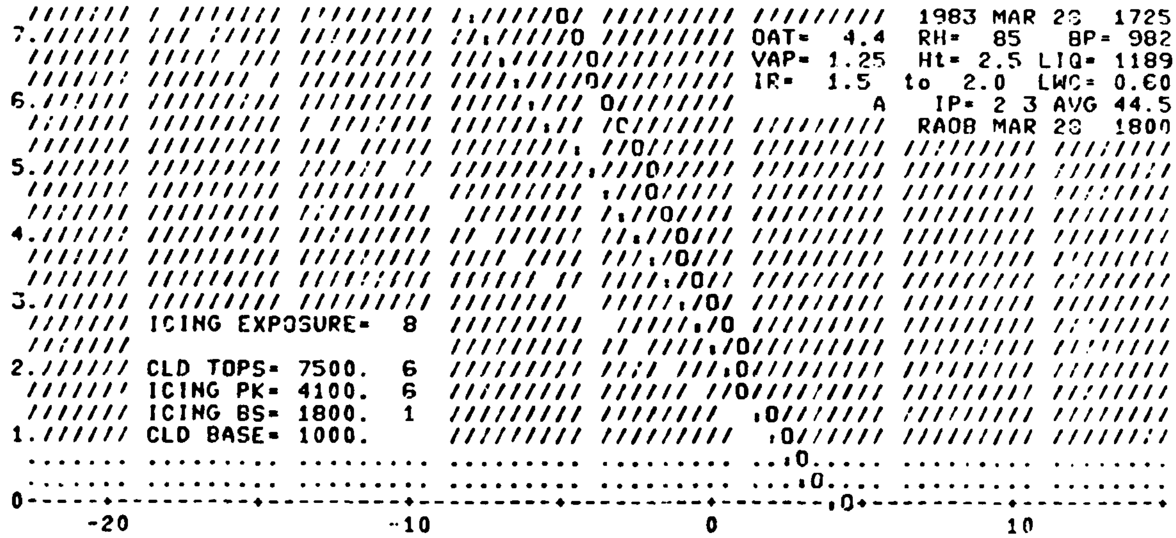


FIGURE 3


1983 MAR 28 1725
OAT= 4.4 RH= 85 BP= 982
VAP= 1.25 Ht= 2.5 LIQ= 1189
IR= 1.5 to 2.0 LWC= 0.60
A IP= 2 3 AVG 44.5
RAOB MAR 28 1800
ICING EXPOSURE= 8
CLD TOPS= 7500. 6
ICING PK= 4100. 6
ICING BS= 1800. 1
CLD BASE= 1000.
20
15
10
5.
0
-50 -40 -30 -20 -10 0 10


1983 MAR 28 1725
OAT= 4.4 RH= 85 BP= 982
VAP= 1.25 Ht= 2.5 LIQ= 1189
IR= 1.5 to 2.0 LWC= 0.60
A IP= 2 3 AVG 44.5
RAOB MAR 28 1800
ICING EXPOSURE= 8
CLD TOPS= 7500. 6
ICING PK= 4100. 6
ICING BS= 1800. 1
CLD BASE= 1000.
7.
6.
5.
4.
3.
2.
1.
0
-20 -10 0 10

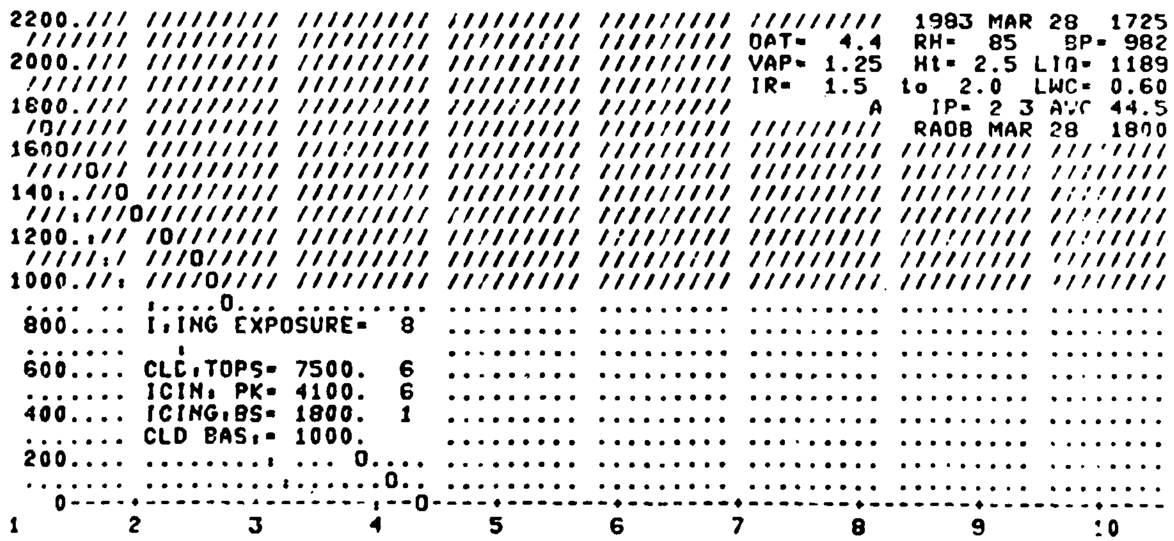
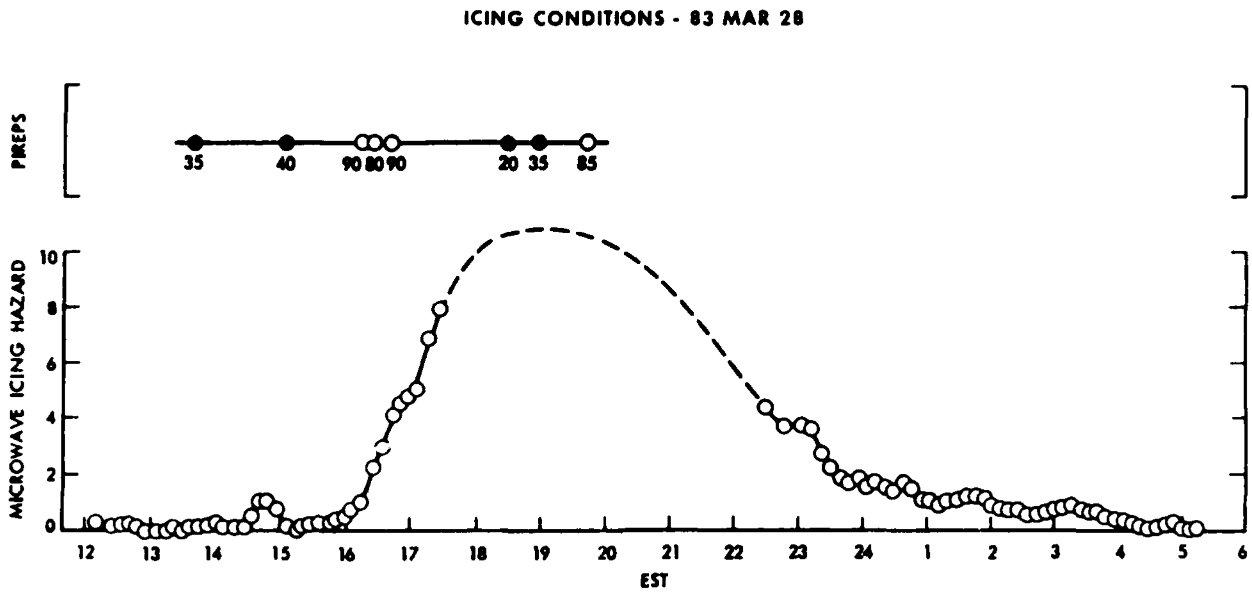

1983 MAR 28 1725
OAT= 4.4 RH= 85 BP= 982
VAP= 1.25 Ht= 2.5 LIQ= 1189
IR= 1.5 to 2.0 LWC= 0.60
A IP= 2 3 AVG 44.5
RAOB MAR 28 1800
ICING EXPOSURE= 8
CLD TOPS= 7500. 6
ICING PK= 4100. 6
ICING BS= 1800. 1
CLD BASE= 1000.
2200.
2000.
1800.
1600
1200.
1000.
800....
600....
400....
200....
0
1 2 3 4 5 6 7 8 9 10

FIGURE 4


ICING CONDITIONS - 83 MAR 28
PIREPS
35
40
90 80 90
20 35
85
MICROWAVE ICING HAZARD
10
8
6
4
2
0
12 13 14 15 16 17 18 19 20 21 22 23 24 1 2 3 4 5 6
EST

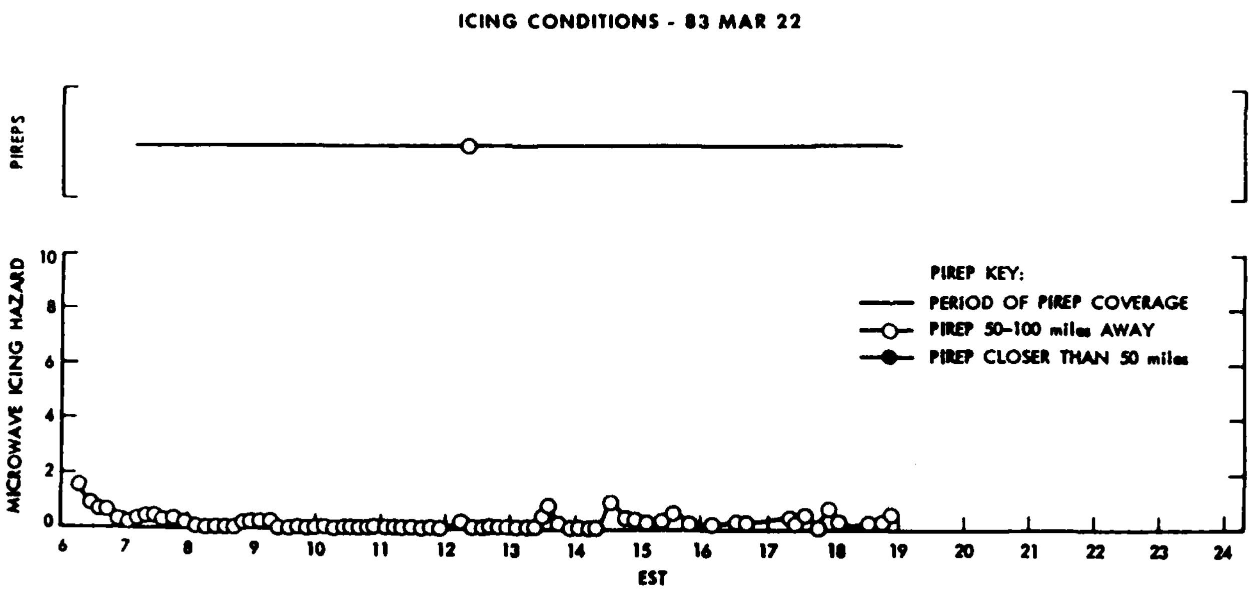

ICING CONDITIONS - 83 MAR 22
PIREPS
MICROWAVE ICING HAZARD
10
8
6
4
2
0
PIREP KEY:
PERIOD OF PIREP COVERAGE
PIREP 50-100 miles AWAY
PIREP CLOSER THAN 50 miles
6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
EST

FIGURE 5

SCORING BOXES

WHEN PRECONDITIONS FOR ICING EXIST

MICROWAVE-PREDICTED ICING HAZARD POTENTIAL	PIREPS/HOUR 0.0-0.1	PIREPS/HOUR > 0.1
3-10	0	2
0.5-3.0	3	8
0.0-0.5	2	0

WHEN PRECONDITIONS FOR ICING DON'T EXIST

MICROWAVE-PREDICTED ICING HAZARD POTENTIAL		
3-10	0	-
0.5-3.6	2	-
0.0-0.5	23	-

FIGURE 6

WS FORM F-6 APPENDIX A - NATIONAL WEATHER SERVICE SUMMARY OF SURFACE OBSERVATIONS FOR BUFFALO DURING MARCH, 1983.

U. S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL WEATHER SERVICE

STATION: BUFFALO, N. Y. (Greater Buffalo International Airport)

MONTH: March | YEAR: 1983

PRELIMINARY LOCAL CLIMATOLOGICAL DATA

LATITUDE: 42° 56' N | LONGITUDE: 78° 44' W | GROUND ELEVATION (ft): 705 FT | STANDARD TIME: Eastern

Day (1)	Temp °F Maximum (2)	Minimum (3)	Average (4)	Departure from normal (5)	Degree days (Base 65°) Heating (6a)	Cooling (6b)	Precipitation (In.) Total (water equivalent) (7)	Snowfall, ice pellets (8)	Snow, ice pellets or ice on ground at 07E (9)	Wind Average speed (m.p.h.) (10)	Fastest mile Speed (m.p.h.) (11)	Direction (12)	Sunshine Total (Min.) (13)	Percent of possible (14)	Sky cover sunrise to sunset (Tenths) (15)	Weather occurrences (16)	Peak gust Speed (MPH) (17)	Dir (18)	Time (EST) (19)	Lake Erie Temp (20)
1	53	26	40	+12	25	0	0	0	0	6.2	09	NE	548	81	10		15	NE	1411	34
2	47	29	38	+10	27	0	.01	0	0	8.2	10	SW	413	61	4	1,8	20	SW	1403	34
3	46	35	41	+13	24	0	.01	0	0	10.2	15	240	314	46	8	1,8	22	SW	1518	34
4	52	35	44	+15	21	0	.14	0	0	10.6	16	100	190	26	10	1	23	E	1839	34
5	67	35	51	+22	14	0	T	0	0	11.6	17	090	628	92	3	1	26	E	1549	35
6	62	47	55	+26	10	0	.14	0	0	10.7	18	170	291	42	10	1	30	S	1323	35
7	76	45	61	+32	4	0	0	0	0	8.3	15	140	572	83	7		23	SW	2112	35
8	61	46	54	+24	11	0	.02	0	0	10.7	17	130	206	30	10		24	SE	0014	36
9	48	41	45	+15	20	0	.63	0	0	7.0	14	210	0	0	10	1	18	SW	1153	36
10	41	36	39	+8	26	0	.26	T	0	10.3	16	020	0	0	10	1	23	NE	2132	36
11	36	30	33	+2	32	0	.11	(.8)	T	12.0	15	N	0	0	10	1	23	N	2151	37
12	41	26	34	+3	31	0	0	0	T	13.1	18	NW	435	62	7		26	NW	1520	37
13	45	23	34	+2	31	0	0	0	0	12.0	18	SW	701	99	0		25	SW	1600	36
14	51	31	41	+9	24	0	T	0	0	7.1	09	SW	12	2	10		17	SW	1443	36
15	43	34	39	+7	26	0	T	0	0	12.5	13	W	4	1	10	1	23	W	1518	37
16	55	33	44	+11	21	0	0	0	0	7.6	15	E	602	84	3		22	E	1433	37
17	61	30	46	+13	19	0	0	0	0	9.5	16	SE	652	91	6		22	SE	2012	37
18	54	34	44	+10	21	0	.34	0	0	12.2	17	SE	273	38	10	1	26	SE	1130	37
19	55	36	46	+12	19	0	.66	0	0	15.2	34	SW	20	3	10	1	45	SW	2214	37
20	36	25	31	-3	34	0	T	T	0	16.3	20	W	3	0	10		32	W	0148	37
21	30	23	27	-8	38	0	(.77)	3.9	T	12.9	24	E	0	0	10	1,4,6	35	E	0503	38
22	24	14	19	-16	46	0	(.15)	2.0	3	15.9	22	W	41	6	10	1,6,9	32	W	1902	38
23	25	10	18	-18	47	0	.01	.2	6	15.3	21	W	433	59	6	6,9	31	W	1646	38
24	21	9	15	-21	50	0	0	0	5	7.8	10	W	740	100	1	6	18	NW	1043	36
25	30	5	18	-18	47	0	0	0	3	5.0	09	NE	743	100	0	6	17	NE	1005	36
26	40	10	25	-12	40	0	0	0	2	7.8	11	E	746	100	4	6	17	NE	1627	36
27	42	29	36	-1	29	0	.42	T	T	10.1	15	S	0	0	10		25	S	1633	36
28	44	32	38	20	27	0	.13	T	T	13.0	20	SW	8	1	10	1	29	SW	1233	36
29	32	21	27	-11	38	0	0	0	0	13.2	17	NW	732	97	1		28	NW	1016	36
30	37	20	29	-10	36	0	0	0	0	5.9	08	N	607	80	6		15	N	1406	36
31	46	23	35	-4	30	0	0	0	0	8.2	07	E	613	81	8		18	E	1446	36
SUM	1401	873	—	—	868	0	(3.20)	(6.9)	—	327.0	—	—	10527	—	224	—	—	—	—	—
AVG	45.2	28.2	—	—	—	—	—	—	—	10.6	Fastest	Direction	Possible	%		—	Fastest	Direction	Date	—
										MISC. →	34	SW	22209	47	7.2	—	45	SW	19	—

TEMPERATURE DATA

AVERAGE MONTHLY 36.7
DEPARTURE FROM NORMAL +3.7
HIGHEST 76 ON 7
LOWEST 5 ON 25
NUMBER OF DAYS WITH -
MAX 32° OR BELOW 6
MAX 90° OR ABOVE 0
MIN 32° OR BELOW 19
MIN 0° OR BELOW 0

HEATING DEGREE DAYS (Base 65°)
TOTAL THIS MONTH 868
DEPARTURE FROM NORMAL -152
SEASONAL TOTAL 5122
DEPARTURE FROM NORMAL -823

COOLING DEGREE DAYS (Base 65°)
TOTAL THIS MONTH 0
DEPARTURE FROM NORMAL 0
SEASONAL TOTAL 0
DEPARTURE FROM NORMAL 0

PRECIPITATION DATA

TOTAL FOR THE MONTH 3.20 IN
DEPARTURE FROM NORMAL +.23 IN
GREATEST IN 24 HRS .86 ON 18-19

SNOWFALL, ICE PELLETS
TOTAL FOR THE MONTH 6.9 IN
GREATEST IN 24 HRS 3.9 ON 21-22
GREATEST DEPTH ON GROUND 6 ON 23,24

PRESSURE DATA
HIGHEST SEA-LEVEL 30.50 IN. ON 26
LOWEST SEA-LEVEL 29.21 IN. ON 21

WEATHER

NUMBER OF DAYS -
CLEAR (Scale 0–3) 6
PARTLY CLOUDY (Scale 4–7) 7
CLOUDY (Scale 8–10) 18
WITH 0.01 INCH OR MORE PRECIP 15
WITH 0.10 INCH OR MORE PRECIP 10
WITH 0.50 INCH OR MORE PRECIP 2
WITH 1.00 INCH OR MORE PRECIP 0

SYMBOLS USED IN COLUMN 16

1 = FOG
2 = FOG REDUCING VISIBILITY TO ¼ MILE OR LESS
3 = THUNDER
4 = ICE PELLETS
5 = HAIL
6 = GLAZE OR RIME
7 = BLOWING DUST OR BLOWING SAND REDUCING VSBY TO ⅝ MILE OR LESS
8 = SMOKE OR HAZE
9 = BLOWING SNOW
X = TORNADO

MAXIMUM PRECIPITATION

Δt (Minutes)	5	10	15	20	30	45	60	80	100	120	150	180
PRECIPITATION (Inches)	.05	.08	.08	.08	.08	.08	.14	.15	.18	.23	.26	.29
ENDED DATE	5	5	5	5	5	5	5	19	19	19	19	19
TIME	0812	0814	0814	0814	0814	0814	0815	0125	0145	0202	0232	0215

* LAST OF SEVERAL OCCURRENCES; ® FASTEST OBSERVED 1-MINUTE WIND SPEED
3/5: HIGH OF 67°F EQUALED RECORD HIGH FOR DATE SET IN 1976.
3/7: HIGH OF 76°F EXCEEDED RECORD HIGH FOR DATE OF 60°F SET IN 1973 AND EXCEEDED HIGHEST SO EARLY FOR SPRING OF 72°F.
3/25: LOW OF 5°F EQUALED RECORD LOW FOR DATE SET IN 1974.

WS FORM F-6 SUPERSEDES WS FORM F-6 (9-76) WHICH SHOULD BE USED UNTIL EXISTING STOCK IS DEPLETED ★ U.S. GOVERNMENT PRINTING OFFICE 1978 -885-010 1130