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ICING CHARACTERISTICS OF LOW ALTITUDE, SUPERCOOLED LAYER CLOUDS

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16. Abstract

A limited amount of new data has been obtained on the icing environment during initial airborne measurements aimed at developing environmental icing criteria for use in certifying helicopters for flight into icing conditions. Supercooled cloud characteristics are reported for 12 icing events encountered at temperatures from -10°C to 0°C at altitudes from 3500 to 6500 ft above the surface of Lake Erie and Lake Michigan. Recorded droplet size spectra from a Particle Measuring Systems' Axially Scattering Probe (ASSP) were used to compute droplet mass (volume) median diameter (MMD) and, in addition to a Johnson-Williams LWC Indicator, the liquid water content (LWC). A review of available historical data from 1944-1950, upon which the atmospheric icing standards of Appendix C, FAR 25 were based, reveals that data obtained from measurements of ice accretion on multidiameter cylinders are subject to a number of significant errors of both signs. These probable errors, which will continue to be evaluated, may be responsible for the conclusions that: 1) the historical LWC values are generally larger than those observed in the flights described in this report; 2) the historical MMDs appear to be generally too small for all values of LWC; and 3) the historical droplet size distributions are unreliable, as is acknowledged in the later historical literature.

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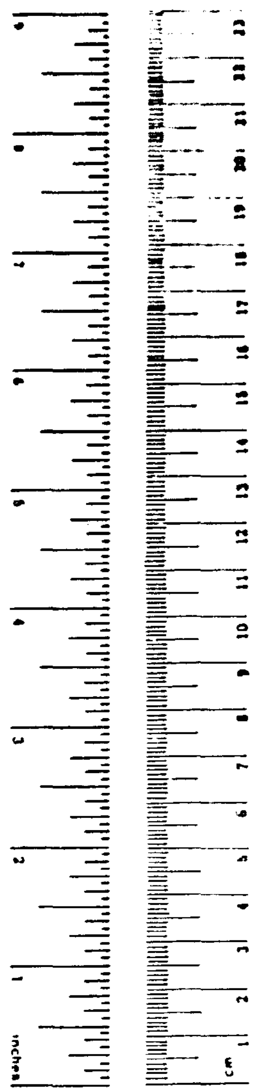
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

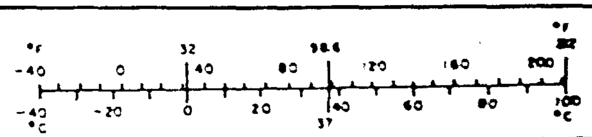
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

... see NBS Misc. Publ. 286 ...



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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I. INTRODUCTION

The use of helicopter aircraft is becoming increasingly widespread by the armed services as well as by many civilian activities, especially government and industry. A growing number of gas and oil drilling operations on remote, offshore rigs, for example, are being serviced by helicopters. With this growing use and importance, there is a strong interest among users and manufacturers in the production of helicopters with IFR capability and certification for flight in at least some types and degrees of adverse weather. A type of adverse weather of major concern in the northern latitudes is the presence of supercooled, wintertime clouds in which some amount of aircraft icing may always be expected.

The Federal Aviation Administration (FAA) presently certifies for all weather flight only those helicopters which have a demonstrated capability for flight in maximum icing conditions as specified in the Federal Aviation Regulations[1], Part 25 (FAR-25), Appendix C. This document contains the airworthiness standards for transport category airplanes and is currently applicable to helicopters.

The design standards included in FAR-25 for protection against aircraft icing were drawn up for fixed wing aircraft capable of altitudes of 10,000 ft and above. Thus, to meet these standards an aircraft must be protected especially against specified maximum loadings of supercooled, cloud liquid water content (LWC) which the FAA and the aviation community suspect may be too stringent for slow flying aircraft at altitudes below 5000 ft where most helicopter operations take place. Also, the present standards are based on icing data collected during the period from about 1944 to 1950. Since the concerns at that time were for high flying aircraft, much of these supporting data were obtained at altitudes well above 5000 ft. In addition, because new cloud physics instrumentation has evolved in the meantime there is a general desire to have these old data reviewed for accuracy as well as for applicability to helicopter operations. It would seem desirable then to collect additional data at low altitudes to help reevaluate the existing data base and, if possible, to document the effects of local meteorological processes, such as lake effects, for example, on icing conditions in major operating areas for helicopters.

From the user's and manufacturer's point of view there is, in addition to these same concerns, a possibility that regulations may be amended so that helicopters may be "partially" certified for flight into various degrees of icing conditions, depending on the design of the craft and the effectiveness of its ice protection equipment. "Partial" certification could mean permission to fly into supercooled clouds for specified lengths of time depending on the forecasts or on the LWC and OAT the helicopter encounters during flight, for example. Alternately, partial certification could possibly be written in terms of a maximum, instantaneous or continuous LWC which is not to be exceeded for a given type of helicopter.

In the latter case the permissible altitudes and Outside Air Temperature (OAT) to which the craft may fly could possibly be determined in at least one of the following three ways. First, if sufficiently accurate and complete icing climatologies (helicopter icing susceptibility vs altitude, OAT and LWC) exist, then perhaps exceedance probabilities could be used to define operational limits on altitude alone. Secondly, if appropriate on board LWC or icing rate sensors were used along with cockpit readouts or warning devices, the helicopter could continue in flight at unrestricted altitudes or OAT until the LWC limit were approached. Once the limit was approached the pilot would have to follow corrective maneuvers, such as flying to cloud free layers or to altitudes of reduced LWC, or to temperatures above freezing until accumulated ice melts away. The assumption would be that cloud conditions and the local terrain will permit corrective maneuvers to take place. The third possibility is one that should be at least supplemental to the first two options. That is, if reliable and accurate forecasts of supercooled LWC can be made for a range of altitudes along the flight path of interest, then the pilot could limit his altitude, terrain permitting, to levels at which the ambient LWC is less than the certification limit.

The problem with these three approaches is that at the present time there are substantial uncertainties in the climatologies, the instrumentation, and the forecasting methods, as they apply to helicopters.

The concerns with the existing climatologies (icing data bases) have already been described. Secondly, there appears to be some uncertainty as to whether currently available LWC meters and icing rate detectors will give reliable results when flown on helicopters.

Concerning the forecasting procedures, there are several problems to be considered. Current practice calls for specifying the type of icing to be expected (rime, clear, or mixed) and the severity in relative terms (trace, light, moderate, or severe). It should be noted that these terms have conventionally been defined in relation to the operational effects on reciprocating engine, straight wing transport aircraft. The AWS Forecaster's Guide[2] defines these terms as being strictly applicable only to the C-54 and C-118 aircraft. Otherwise, what may be moderate icing for one aircraft may be severe for another, depending on the design and ice protection capabilities of each aircraft. There is an evolving opinion that a preferable procedure would be to have each helicopter or aircraft certified in terms of a range of LWC and OAT combinations. Then, if forecasts were in terms of LWC and OAT over the altitudes and flight paths of interest, the pilot of a particular craft could readily determine whether or where he could fly. Unfortunately, present ice forecasting techniques are apparently unable to specify quantitative LWC values. Reportedly, part of the problem is that when icing is forecast many aircraft are grounded, especially helicopters, so that there is little opportunity to verify or refine forecasts with feedback from pilots.

In view of these circumstances, the FAA has requested the Atmospheric Physics Branch of the Naval Research Laboratory to study some of these problems. In particular, prescribed tasks are:

1. Obtain observations on the icing environment below 10,000 ft. and especially below 5000 ft. using an instrumented aircraft.

a) Obtain data on LWC, droplet size distributions and OAT at temperatures below 0°C and associated altitude and location over land and coastal areas of the northeast U.S. and the Great Lakes areas of the U.S.

b) Temperature of the "skin" of the aircraft shall be reported to determine the effects of the temperatures of the airframes on the accumulation of ice. The effects of going from an environment above 0°C to one below 0°C, and vice versa, shall be noted.

c) Observation of snow and ice associated with LWC and droplet size distributions will be obtained.

d) The type of cloud and location in the cloud will be noted at the time LWC, droplet size spectra, and OAT are obtained.

e) Available standard and research instrumentation shall be used to obtain the desired data.

2. The existing data base on the icing environment will be reviewed to assess the accuracy and applicability to helicopter operations.

3. A review of the instrumentation presently available or in development shall be made. The cost and benefits of using the instruments operationally will be analyzed and reported.

In partial fulfillment of these tasks, the remainder of this report is devoted to the review of the existing data base and to the presentation of the limited results from initial measurements aboard an NRL research aircraft during March, 1979.

II. EXISTING DATA BASE

A. Summary of Data Sources for Current Design Standards for Aircraft Ice Protection.

References 3 through 12 in the bibliography are reported to contain cloud characterization data in icing conditions. Not all of these references were available for study in the preparation of this report and no attempt has been made to include data obtained outside the United States.

Of the available references, six [4,6-10] contain data from layer clouds below 6000ft in which the altitude and geographic location of the measurements are included. Only one of these reports[4] gives information on cloud base height, cloud layer thickness, and height of the measurements above cloud base. The geographical locations and types of instruments used for the measurements in these reports are listed in Table 1. All of the LWC data from these references for layer clouds below 6000ft have been plotted against alititude, OAT, and MMD and are shown in Figs. 1,2, and 3, respectively. Data from the NRL flights of March 1979 are also plotted in these Figures for comparison. As will be discussed in section IV of this report, these LWC values initially observed by NRL reside in the low end of the range of reported LWC values and the NRL mass median diameters are larger than the average of the previously reported data.

Later reports, such as Lewis et al (1952)[13] and Hacker et al (1951),[14] do not contain information on individual measurements since the authors are more concerned with generalizing the accumulated data for use in arriving at icing design standards.

Table 1. SUMMARY OF AVAILABLE SOURCES FOR ICING DATA IN LAYER CLOUDS BELOW 6000 FT PRESSURE ALTITUDE.

	Data	Cloud	Instrumentation	Used for	Measurement of:		Ice	No. of
Ref.	Year	Locations	LWC	Mean Dia.	Max Dia.	Size Distrib.	Meter	Samples
4	1944	MSP	DP	--	AI	--	--	4
6	1946	OR	2,4RMC	2,4RMC	AI	4RMC	--	3
7	1946-47	NE,MO, TN,OH, IN	4RMC	4RMC	AI	4RMC	--	31
7	1946-47	LE,OH, LM,MN	4RMC	4RMC	--	4RMC	RD	37
8	1947-48	LE,NY, OH,LM	4RMC	4RMC	--	4RMC	--	27
9	1948	LM,IN	4RMC	4RMC	AI	4RMC	RD	6
10	1948-49	IN,LE, LM,LS, MSP,MN	4RMC	4RMC	--	4RMC	RD	77
10	1949-50	LE,OH	5RMC	5RMC	AI	5RMC	RD	28

Explanation of Symbols:

Cloud locations: MSP=Minneapolis, St. Paul; OR=Oregon; NE=Nebraska; MO=Missouri; TN=Tennessee; OH=Ohio; IN=Indiana; LE=Lake Erie; LM=Lake Michigan; MN=Minnesota; LS=Lake Superior; NY=southwestern New York.

Instrumentation: DP=dewpoint sensor; 2RMC= 2 cylinder Rotating Multicylinder probe; AI=Area of Impingement technique with fixed diameter cylinder; RD=Rotating Disk icing rate meter.

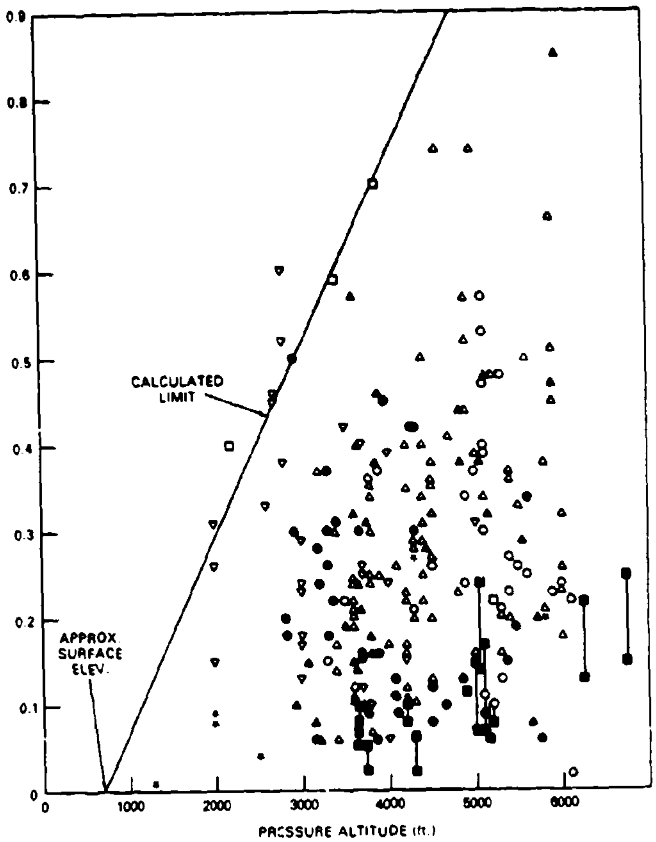

FIGURE 1. INDICATED LWC VS. ALTITUDE IN SUPERCOOLED LAYER CLOUDS BELOW 6000 FT.

□ - W. Lewis (Ref. 4), using dewpoint sensor, 1944. (Note data points tend to be high.)

○ - W. Lewis (Ref. 7), using 4RMC method in strato Cu over the midwest-Great Plains area, 1946-47.

● - D. Kline (Ref. 7), using 4RMC method in stratus and strato Cu in the Great Lakes area, 1946-47.

▲ - D. Kline (Ref. 8), using 4RMC in stratus and Strato Cu in the Great Lakes area, 1947-48.

★ - W. Lewis and W. Hoecker (Ref. 9), using 4RMC in Great Lakes area, 1948.

△ - D. Kline (Ref. 10), using 5RMC method in strato Cu in Minnesota and the Great Lakes area, 1948-49.

▽ - D. Kline (Ref. 10), using 5RMC in Great Lakes area, 1949-50.

■—■ - R. Jeck, NRL measurements in stratus and strato Cu over Lake Erie and Lake Michigan, March 1979. The upper symbol (■) is the LWC indicated by a Johnson-Williams LWC meter and the lower symbol (■) is the LWC computed from the droplet size distribution indicated by the PMS-ASSP.

The straight line labeled "Calculated Limit" is the theoretical maximum LWC, taken from Bowden et al (Ref. 23) for a cloud formed by adiabatic cooling with cloud base at ground level.

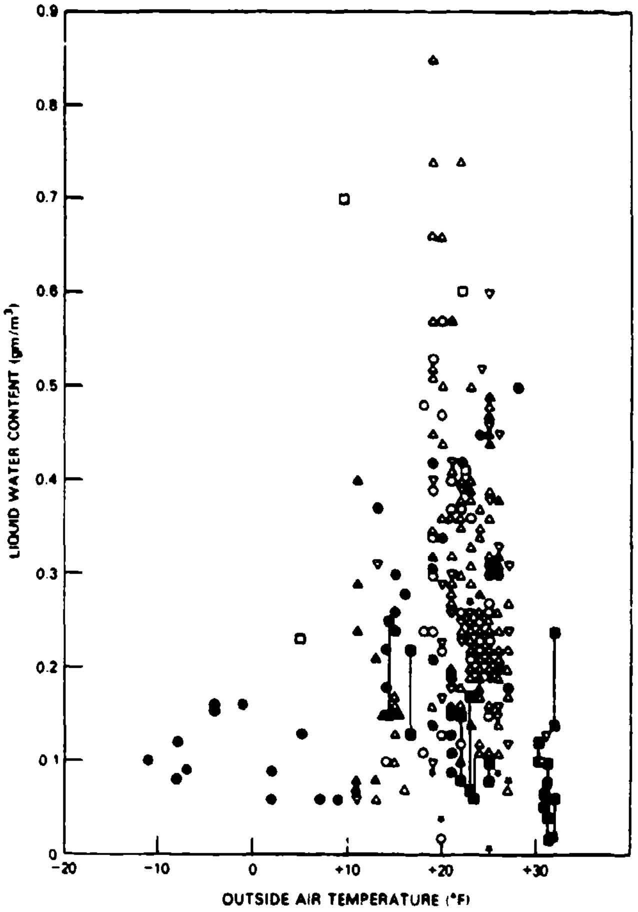

FIGURE 2. INDICATED LWC VS. OUTSIDE AIR TEMPERATURE IN LAYER CLOUDS BELOW 6000 FT.

- □ - W. Lewis (Ref. 4), using dewpoint sensor, 1944. (Note data points tend to be high.)
- ○ - W. Lewis (Ref. 7), using 4RMC method in strato Cu over the midwest-Great Plains area, 1946-47.
- ● - D. Kline (Ref. 7), using 4'MC method in stratus and strato Cu in the Great Lakes area, 1946-47.
- ▲ - D. Kline (Ref. 8), using 4RMC in stratus and Strato Cu in the Great Lakes area, 1947-48.
- ★ - W. Lewis and W. Hoecker (Ref. 9), using 4RMC in Great Lakes area, 1948.
- △ - D. Kline (Ref. 10), using 5RMC method in strato Cu in Minnesota and the Great Lakes area, 1948-49.
- ▽ - D. Kline (Ref. 10), using 5RMC in Great Lakes area, 1949-50.
- ■—■ - R. Jeck, NRL measurements in stratus and strato Cu over Lake Erie and Lake Michigan, March 1979. The upper symbol (■) is the LWC indicated by a Johnson-Williams LWC meter and the lower symbol (■) is the LWC computed from the droplet size distribution indicated by the PMS-ASSP.

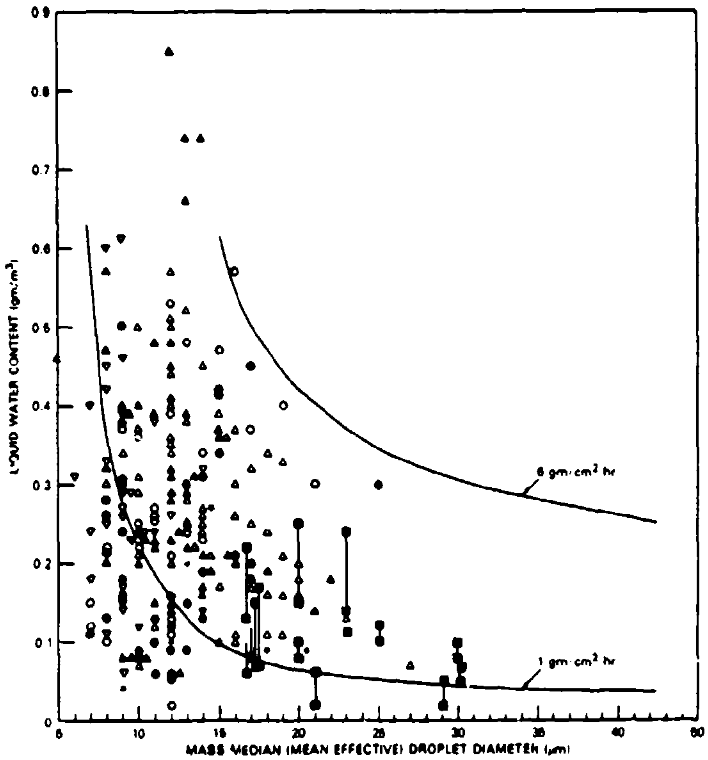

FIGURE 3. INDICATED LWC VS. MASS MEDIAN DROPLET DIAMETER IN LAYER CLOUDS BELOW 6000 FT. The smooth curves are computed water accretion rates (taken from Lewis et al (Ref. 7), for a 3-inch dia. cylinder moving at 200 mph at 10,000 ft.

- □ - W. Lewis (Ref. 4), using dewpoint sensor, 1944. (Note data points tend to be high.)
- ○ - W. Lewis (Ref. 7), using 4RMC method in strato Cu over the midwest-Great Plains area, 1946-47.
- ● - D. Kline (Ref. 7), using 4RMC method in stratus and strato Cu in the Great Lakes area, 1946-47.
- ▲ - D. Kline (Ref. 8), using 4RMC in stratus and Strato Cu in the Great Lakes area, 1947-48.
- ★ - W. Lewis and W. Hoecker (Ref. 9), using 4RMC in Great Lakes area, 1948.
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- ∇ - D. Kline (Ref. 10), using 5RMC in Great Lakes area, 1949-50.
- ■—■ - R. Jeck, NRL measurements in stratus and strato Cu over Lake Erie and Lake Michigan, March 1979. The upper symbol (■) is the LWC indicated by a Johnson-Williams LWC meter and the lower symbol (■) is the LWC computed from the droplet size distribution indicated by the PMS-ASSP.

B. Instrumentation Used for Cloud Characterization Measurements During the Period of 1944-1950.

1. Liquid Water Content (LWC).

The earliest measurements[3,4] by the National Advisory Committee for Aeronautics (NACA)-Ames Laboratory in 1944-45 made use of a dewpoint meter to determine LWC. The method consisted of measuring the dewpoint of cloud air samples that had been heated sufficiently to evaporate all of the cloud droplets in the sample. The difference between the dew point temperature of the heated sample and the OAT (the dewpoint temperature of the saturated air in the cloud) was used to compute the cloud LWC.

By the winter of 1946-47 the NACA laboratories had switched to the rotating multicylinder (RMC) method[15] which Lewis[6] referred to at that time as being the most accurate and dependable procedure thus far developed. The first RMC probe consisted of only two cylinders 1/8 in. and 1 inch in diameter. Shortly before the end of their measurements for the 1946-47 winter they replaced this probe with a four cylinder RMC with diameters of 1/8, 1/2, 1-1/4, and 3 inches. This latter probe continued to be the principal LWC device for the remainder of their measurements, although Kline[10] used a five cylinder probe in 1949-50.

The four cylinder RMC device is about 18 inches long with the cylindrical sections stacked end-to-end to form the probe. The entire probe is exposed through a hole in the fuselage and is maintained perpendicular to the airstream while it is rotated at about 20 rpm to obtain a uniform ice deposit.

After a timed interval of exposure, usually one to five minutes, the RMC is withdrawn into the cabin and the cylinders are stored for a later determination of accumulated ice mass. Theoretical relations involving droplet diameter, cylinder diameter, collection efficiencies and airspeed are used to derive the average LWC encountered during the exposure.

2. Mass (Volume) Median Droplet Diameter

The mass median diameter (MMD) or median volume diameter (MVD) is defined as that droplet diameter for which there is as much water in drops larger than the MMD as there is in drops smaller than the MMD. Until the RMC came into use the NACA measurements did not contain any information on MMD. With the two cylinder RMC probe it was possible to make an estimate of the variable termed the "Mean-Effective" Diameter, MED, once a droplet size distribution was assumed. The MED is equal to the MMD if the assumed size distribution is equal to the actual distribution. With the four cylinder RMC probe one could infer approximate size distributions and a better estimate of the MMD than was possible with the two cylinder RMC.

3. "Maximum" Droplet Diameter.

Lewis[4,6] made use of one other technique to help derive some information about droplet diameters. This technique involved the use of a four to to six inch diameter cylinder that was covered with sensitized blueprint paper. This probe was extended into the air stream for a few seconds such that the impinging droplets wetted a strip on the upwind side of the cylinder. Droplet trajectory theory then relates the width of this wetted strip to a corresponding droplet diameter for a given airspeed and cylinder diameter. The particle diameter determined in this way was termed the "Maximum Droplet Diameter" by Lewis and gives the size of the largest droplets that are present in sufficient number to affect the blueprint paper. This technique does not give any information on drop size distributions, however.

4. Droplet Size Distribution

Droplet size distributions were never directly measured in these NACA flights but were only inferred from the four cylinder RMC technique once it came into use. Usually one of several "stock" size distributions was selected as the most representative for a given case, based on the RMC measurements[6,7,10].

5. Icing Rate Meters

No sensor for measuring the rate of ice accretion was used on the NACA flights until a rotating disk device was installed by Kline for use during the 1946-47 and following winters[7,10]. This probe gives an indication of the icing rate in inches per hour collected on the edge of the disk. The results were not converted to LWC as in the RMC measurements since the density of the ice and the collection efficiency of the disk were inadequately known. Kline used rotating disks principally to provide a continuous record of the icing rate so that intense, short term events could be detected and measured. This permitted tabulation of maximum icing rates in addition to the averages obtained from the RMC method. Kline pointed out that the rotating disk meters were calibrated against the RMCs and were therefore affected by any errors that may have applied to the RMCs during the measurements.

C. Accuracy and Sources of Error in the Measurements from the Period 1944-1950.

1. Rotating Multicylinder Method and the Determination of LWC.

Lewis[6] originally estimated the probable error in deriving LWC from a two-cylinder (1/8 in. and 1 in. dia.) RMC probe at about 6%, due to combined uncertainties in timing the exposure, measuring the airspeed, estimating the density of the accreted ice, and in weighing the iced cylinders. In a later report[7], however, Lewis disclosed that the actual air velocity at the location of the multicylinder probe outside the fuselage was measured to be 12% greater than the aircraft indicated airspeed. Lewis' results published thereafter were computed with the correct air velocity, but results by Kline[7] on a different aircraft were not, since exact air velocity measurements had not been attempted on that aircraft. An underestimation of air velocity, and therefore of the total volume of air sampled, would lead to an over-estimation of LWC.

By the year 1952 as many as thirteen possible sources of error were recognized in the measurement of LWC with the RMC method[13]. One of the more significant sources of error was understood by this time to be the problem of "runoff" of water from the probe due to incomplete freezing of the supercooled droplets upon impaction. In 1951, Ludlam[16] published an analysis of the thermal processes occurring at the surface of a cylinder in a droplet bearing airstream when the effects of convection, evaporation and latent heat are taken into account. He then computed as a function of OAT, the maximum LWC that is theoretically possible in cumulus clouds with cloud base temperatures of +5°C or +20°C, and the fraction of this theoretical maximum LWC that could be measured without runoff errors when 0.35cm and 15cm diameter cylinders are used. A recent treatment by Kleuters et al[17] presents the results in a more universally applicable way. The incomplete freezing is described by a variable called the freezing fraction, f, in the heat balance equation, and is a function of OAT, LWC, airspeed and cylinder diameter. For a given airspeed and cylinder diameter, the combinations of OAT and LWC for which $f=1$ (i.e., exact balance of the thermal processes and 100% freezing of the droplets to ice with a temperature of $0^{\circ}C$) define the "Ludlam" limit. When the OAT and/or LWC is larger than this limit, then $f<1$ and incomplete freezing with "runoff" is expected to occur. The error thus increases with increasing OAT, LWC, airspeed or cylinder diameter. Figure 4 has been taken from Kleuters et al[17] and shows the computed Ludlam limits for several cylinder diameters at an airspeed of 100 m/sec. The implication is that at this airspeed, for example, indicated LWC obtained from the RMC method will always be underestimated for an OAT greater than about $-5^{\circ}C$. For lower temperatures, the errors will depend on cylinder diameter and on the actual LWC. The errors are likely to be less in layer clouds with relatively low LWC than in large convective clouds with greater LWC.

After this "runoff" problem became known, Lewis examined the data used for the major statistical analysis presented in his 1952 report[13] and concluded that not more than about 5% of the cases were close enough to the Ludlam limit to be suspect. Lewis conceded that it was not possible to make a reliable estimate of the total accuracy of LWC from the RMC method but, in his opinion, a statistical analysis drawn from the available data was expected to be "reasonably reliable".

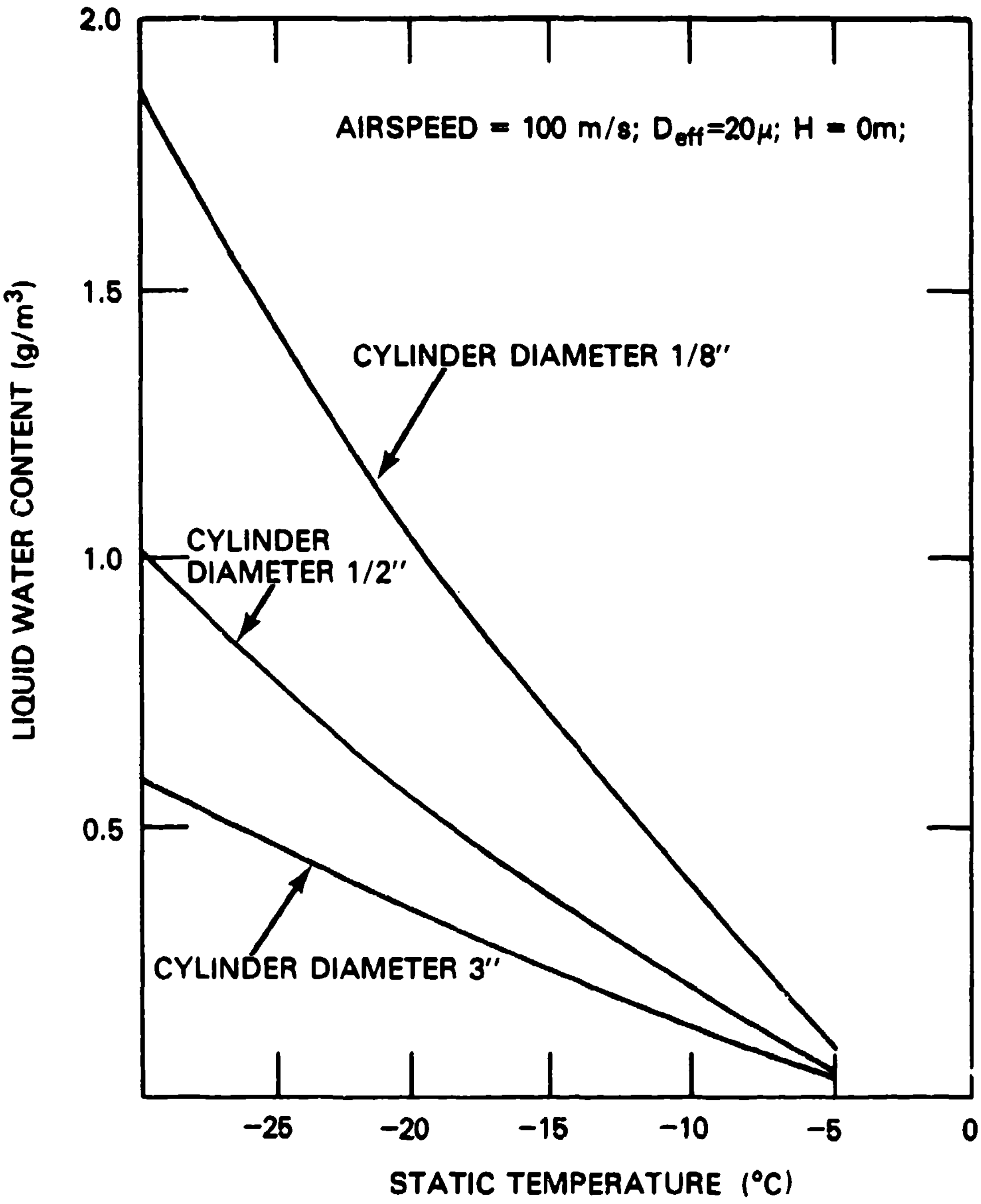

FIGURE 4. COMPUTED UPPER LIMITS ON LWC AND OAT FOR OBTAINING RELIABLE LWC DATA FROM ICE ACCRETION ON CYLINDERS AT 100 m/sec. (From Kleuters et al, Ref. 17). The curves also assume an effective droplet diameter (D_{eff}) of 20 µm and sea level conditions (H=0m).

By the winter of 1948 Lewis[9] had installed a continuously recording "cloud indicator" to document more exactly the actual length of time the aircraft was within continuous cloud during exposure of the RMC. This additional information permitted the computation of LWC averaged only over that portion of the RMC exposure interval during which the aircraft was actually in cloud. Previous LWC computations were averaged over the entire exposure which often included some intermittent, clear air space between cloud layers or cells. Needless to say, this improved method of computation yielded greater values of LWC compared to previous results. In Ref. 9, Lewis tabulates LWC values computed from both methods and the results show increases of up to 100% in the LWC from the more accurately determined cloud exposure intervals.

The data obtained by Lewis after the cloud indicator came into use were almost entirely from cumuliform clouds at altitudes above 6000ft. Although there are practically no data from which to determine the corresponding increase in LWC for layer clouds, the tendency of these clouds to be more continuous than cumuliform types suggests that the previous computations of LWC may not have been seriously underestimated due to lack of a cloud indicator.

Concerning the representativeness of LWC values reported by Lewis, it should be noted that particular efforts were made to obtain RMC data during the periods of most rapid ice formation. Knowing that the maximum LWC generally lies just below the top of a layer cloud, it is presumed that most of Lewis' measurements took place there. However, no information on position within cloud layers has been reported by Lewis in any of the publications that were available for the present study, except for Lewis' first report on the subject.[4] This means that his LWC data will probably indicate <u>maximum</u> values adequately well for layer clouds but will overestimate the average LWC encountered along paths well below the top of the cloud layer.

2. <u>Droplet Size Distributions, "Mean-Effective" Diameter (MED), and "Maximum" Droplet Diameter (MDD)</u>.

In 1947, after two seasons of collecting data with the RMC method supplemented by the area of impingement (AI) technique, Lewis et al[7] reported considerable uncertainty in determining the droplet size distributions from these methods. They found the AI data often yielded a MDD that was nearly equal to the MED simultaneously obtained from the RMC. This implied that the droplet size spectra were peaked near the MED and were very narrow in contrast to the relatively broad spectra frequently indicated by the RMC method alone. Lewis also mentions that in a few cases the indicated MDD was <u>smaller</u> than the indicated MED ----- a completely contradictory result. They concluded[7,9] that one or both of these methods must be regarded as completely unreliable for obtaining droplet size distributions until further tests could be performed. However, they were still of the opinion that the MEDs indicated by the RMC method were "fairly accurate".

By 1952 Lewis modified this latter assertion by stating that RMC measurements of droplet diameter were quite accurate and reliable for small droplets but become increasingly inaccurate as the drop size increases. He also pointed out that large positive errors are more probable than large negative errors, especially at large values of droplet diameter. The result of these errors is reported to be an exaggeration of the probability of occurrence of large droplet sizes. Lewis felt that measurements in the eastern United States were probably unaffected since clouds formed in continental air masses have relatively small drop sizes. On the other hand, their Pacific coast data were thought likely to be considerably influenced because of the larger drop sizes present in clouds associated with clearer maritime air masses.

3. Conlusion.

In summary it can be seen that there are sufficient sources of error in the use of the RMC method and in the computation of the LWC to cast some doubt on the accuracy of the published results. Because some errors increase the computed LWC while others decrease it, there is difficulty in determining what the net effect, if any, will be. Compared to the initial NRL results, some of the historical LWC data may be high but the NRL data are too few at this time to make any strong generalizations.

On the other hand, the historical MMD values do appear to be consistently smaller than those resulting from the NRL measurements.

III NRL PROJECT DESCRIPTION FOR MARCH, 1979.

This section of the report contains the details related to the initial data collecting flights conducted aboard an NRL research aircraft during the late winter of 1978-1979. The instruments and sensors available for those flights are described and the methods for computing LWC and MMD from the droplet size spectra are given. The general weather situation and cloud types and distributions in the Great Lakes and Atlantic Seaboard target areas are then recounted for the week of March 5-9 when the aircraft was available for this project. Finally, the recorded measurements of LWC, OAT and droplet number density, N, are presented in graphical form along with values of LWC and MMD computed from the measured droplet size spectra. These data are accompanied by a detailed chronology of pertinent visual observations, including the occurrence of icing events, during the flights.

In this interim report, the use of visual descriptions of icing events rather than quantitative measurements with ice detectors or icing rate meters is a result of the late start of this project near the end of the 1978-79 winter season. The limited preparation time for these initial flights and the long lead time for delivery of commercial ice detectors prevented their use at this time.

A. Instrumentation.

1. Probes and Sensors.

a) - PMS Axially Scattering Spectrometer Probe (ASSP).

i) - Description.

This cloud droplet sizing instrument is a single particle, optical counter manufactured by Particle Measuring Systems (PMS), Inc.[18] The probe is an in-situ type originally designed for airborne use. It is mounted outboard of the fuselage, as shown in Fig. 5 for this project, and has the advantage that the 3 cm diameter sampling aperture is an unobstructed, flow-through type open to the airstream so that equal windspeed (isokinetic) sampling may be achieved. The sampling aperture is also 50cm out along the airfoil-shaped probe enabling it to be kept away from any disturbed flow near the fuselage or other appendages. Isokinetic sampling avoids the possible loss or modification of droplets that may otherwise occur when ducting is used to bring sampled air to a sensitive volume in the interior of a sensor.

The ASSP is used to obtain as a function of time and aircraft position the total droplet number density (number per cm^3) and the droplet size spectrum (number per cm^3 per μm radius interval vs. droplet diameter between the limits of 3 and 45μm diameter. This size range is divided into 15 droplet size categories, or channels, resulting in a nominal size resolution capability of 3 μm diameter.

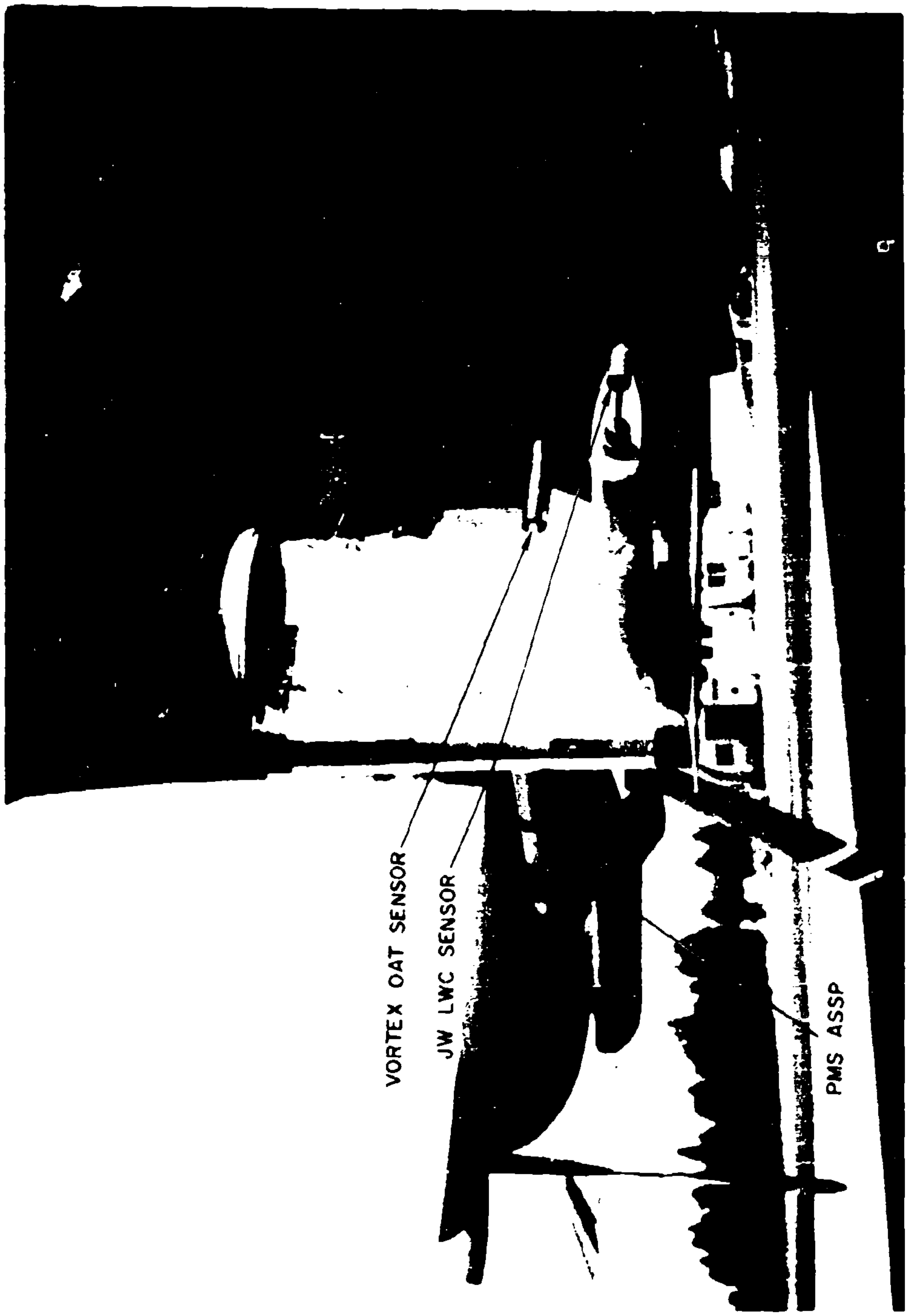

FIGURE 5. VIEW OF INSTRUMENT POD UNDER THE EC-121 AIRCRAFT, AND SHOWING THE ASSP, JOHNSON-WILLIAMS LWC SENSOR, AND VORTEX THERMOMETER.

The probe operates on the principle of scattered light by droplets passing through an illuminating beam generated by a He-Ne laser housed within the probe. The intensity of light scattered into a detector in the tip of the probe is a function to the radius of the passing droplet as originally described by Mie.[19] The pulses of scattered light are converted to voltage pulses in the detector, categorized into one of the 15 size channels by a pulse height analyser, and accumulated as "counts" in one of 15 corresponding registers in an accompanying data display system. The sizing accuracy claimed by the manufacturer is ±10% of the indicated diameters.

During the flights of March, 1979, droplet counts were allowed to accumulate for 10 second intervals before being automatically recorded on the data logging system. The number densities and size distributions were thus an average over flight paths about 800 meters long, corresponding to 10 second sampling intervals at an airspeed of about 165 kt.

From the raw droplet counts one may derive the droplet size distribution expressed by

$$\frac{dn}{dr_i} = \frac{N_i}{VW_i}, \tag{1}$$

for example, where $\frac{dn}{dr_i}$ is the number of droplets per cm^3 per μm radius interval at a diameter corresponding to the ith size channel, N_i is the recorded droplet count in the ith size channel during the sampling interval, V is the volume (cm^3) of air aspirated through the sensitive portion of the laser beam during this time, and W_i is the width of the ith size channel in terms of particle radius.

One may then compute the total liquid water content (LWC) associated with the measured droplet size distribution from the relationship

$$LWC(gm/m^3) = \frac{4\pi\rho}{3} \int_{r_{min}}^{r_{max}} r^3 \frac{dn}{dr} dr \cong \frac{4\pi\rho}{3 \times 10^6} \sum_i \frac{N_i}{V} r_i^3, \tag{2}$$

where $\rho = 1$ gm/cm^3 is the density of water, and r_i is the radius in μm corresponding to the ith size channel.

The volume or mass mediam diameter (MMD) is then easily computed by summing incremental LWC contributions, channel-by-channel, until the sum equals half of the computed total LWC. The droplet diameter associated with the size channel at which this occurs is the MMD.

Finally, the total droplet number density (No./cm^3) may be computed from

$$N = \int_{r_{min}}^{r_{max}} \frac{dn}{dr} dr = \sum_i \frac{N_i}{V}. \tag{3}$$

ii) - Performance During the March 1979 Missions

Although the probe contains internal heating elements to prevent icing along the main strut, there were several occasions during the flights when ice apparently accumulated within the sampling aperture and interfered with operation of the probe. This interference was evidenced during periods of noticeable ice accretion on the aircraft by recognizably abnormal decreases in droplet count rate leading to a complete cessation of counts. Once the aircraft descended to levels where the OAT was warmer than 0°C the ice-related interference disappeared after a few minutes and measurements could be resumed. These several periods of interference were noted and eliminated from consideration in the data processing.

The probe is calibrated for spherical water droplets and its response to non-spherical ice particles is unknown. There was no evidence that ice particles were encountered during the March mission, however, so no ambiguities in data interpretation are anticipated from this problem.

On some occasions there were a significant number of counts in all 15 size channels, indicating that the droplet distribution continued beyond the 45 μm diameter limit of detection for this probe. In these cases, the computed values of LWC, N, and MMD will be erroneously low. Data points subject to significant errors of this type are enclosed in parentheses in the data plots to follow.

On other occasions the pilots were reporting "rain" or "light rain" from the appearance of the moisture seen on the windshield at the time. The droplet sizes associated with this "rain" are not known but it is possible that they were well beyond the range of the ASSP. In such a case the reported LWC based on the ASSP (and on the Johnson-Williams LWC indicator as well) will obviously be underestimated.

b) - Johnson-Williams LWC Indicator

i) - Description

The JW model LWH Indicator used for this project is a hot wire type of probe. Impinging cloud droplets are evaporated on the heated wire, thus cooling the wire and decreasing its resistance. The change in resistance, which is a function of the LWC of the cloud, is detected by a balanced bridge circuit. The bridge output signal is available for recording or for visual readout on a panel meter with a scale of 0-1.5 gm/m^3. The response is reportedly deficient for droplets larger than about 30 μm diameter so that LWC associated with rain, drizzle, and other large droplets will be underindicated.[20] The LWC sensor is shown in place on the pod below the aircraft fuselage in Fig. 5.

ii) Performance During the March 1979 Missions

Noise and drift in the recorded JW output signal were two major difficulties that persisted throughout the flights. Troubleshooting procedures failed to reveal the cause of the noise and drift and therefore no improvements could be made in the signal quality. The noise amplitude was equivalent to about 0.5 gm/m^3 in terms of LWC and appeared to be a positive contribution riding on top of the actual dc LWC signal. Drifts of up to $\pm$1 gm/m^3 sometimes occurred both inside and outside of clouds. It is not known whether these drifts were related to possible ice accretions on the unheated (non de-iced) sensor housing and inlet aperture.

The JW-LWC data shown in the following sections have been corrected as well as possible for the noise by subtracting off what are judged to be the positive going noise spikes during a given sampling period. Corrections for drift are probably less reliable but are made by adding or subtracting a constant or linear, time varying correction from the indicated LWC such that the corrected LWC is near zero outside of a given cloud and never goes negative within the cloud.

Otherwise, the accuracy of the JW system has been reported [21] to be ±20% for droplets smaller than about 30 μm diameter.

c) - Outside Air Temperature (OAT) Probe.

The sensor used for this project was an ML-471/AMQ-8 Vortex Thermometer also known as the Bendix-Friez model 521777-1 Vortex Thermometer. The sensor was originally designed at NRL[22] to provide an indication of the free air temperature surrounding an airplane in flight. The design makes use of the cooling effect at the center of an air vortex to overcome the dynamic heating due to the plane's speed. Air entering the probe housing is deflected in a helical path by a spinner vane. The temperature at the center of the vortex formed behind the spinner vane is the same as the temperature of the free air since the cooling effect is equal and opposite to the effect of dynamic heating. The temperature sensitive element is located at the center of this vortex and therefore measures the actual free air temperature. The temperature sensitive element forms part of a bridge circuit the output of which is developed into a digital, temperature indicating readout and into an analog output suitable for recording.

The sensor housing is not de-iced so interference from ice accumulation is possible under extreme conditions. No signs of improper functioning were seen during any of the missions, however.

The sensor is shown in place on the pod below the aircraft fuselage in Fig. 5.

2. Data Logging and Processing System.

A Hewlett-Packard model 9825A Desk Computer served as the principal data logging device. The raw droplet counts accumulated in the ASSP data display system were read out in digital form along with the time-of-day every 10 seconds, and were periodically stored on a magnetic tape cassette in the Desk Computer. Voltage signals from the JW-LWC indicator, the Vortex Thermometer, an altimeter and an event marker were scanned, digitized and sent to the Desk Computer by a HP model 6940B Multiprogrammer device immediately after each readout of the droplet data. These data were included as part of the records stored on the cassette. About 1/2 second was required to record the combined droplet and analog voltage record at the end of each 10 sec interval.

Computer programs written for the HP 9825A were used at a later time to convert the digitized signal voltages to corresponding values of LWC, OAT, Altitude and Event Number. Additional program codes were used to compute droplet number density, LWC, and MMD from the raw droplet counts recorded in the 15 size channels of the ASSP.

A Brush, 6-channel analog chart recorder also provided a complementary, continuous record of altitude, OAT, LWC (as indicated by the JW sensor) and droplet count rate (as indicated by an analog output from the ASSP data display system).

A view of these recording systems and other instrument readout and control devices located in the aircraft cabin are shown in Fig. 6.

3. Aircraft.

The available aircraft for the missions of March 1979 was a Lockheed EC-121 "Super Constellation". This four engine, propeller driven plane had long been a reliable member of the NRL research aircraft fleet and could be prepared and outfitted with the required sensors, cabling, and readout equipment in a minimum amount of time. An overall view of the plane is shown in Fig. 7. The plane is equipped with pneumatic de-icing boots on the leading edges of the wings, and tail sections and has alcohol based anti icing protection for the propellers. The flights required an onboard crew of 5 or 6 Navy personnel plus one project scientist (the author). The plane was based at Patuxent River (MD) Naval Air Station. The airspeed was typically 165kt along data collection paths in the clouds.

The location of the project sensors on a pod penetrating the underside of the fuselage (Fig. 5) was dictated by the convenient availability of a large, removable camera port there. This location was reasonably close to the nose of the aircraft and was unobstructed once the landing gear were retracted after the plane became airborne. The large radome aft of the sensor pod under the fuselage was judged to be too remote to influence the airstream at the location of the pod. Other possible probe locations, such as under a wing, would have required more time for aircraft modification than was available if measurements were to be obtained before the end of the 1978-79 winter.

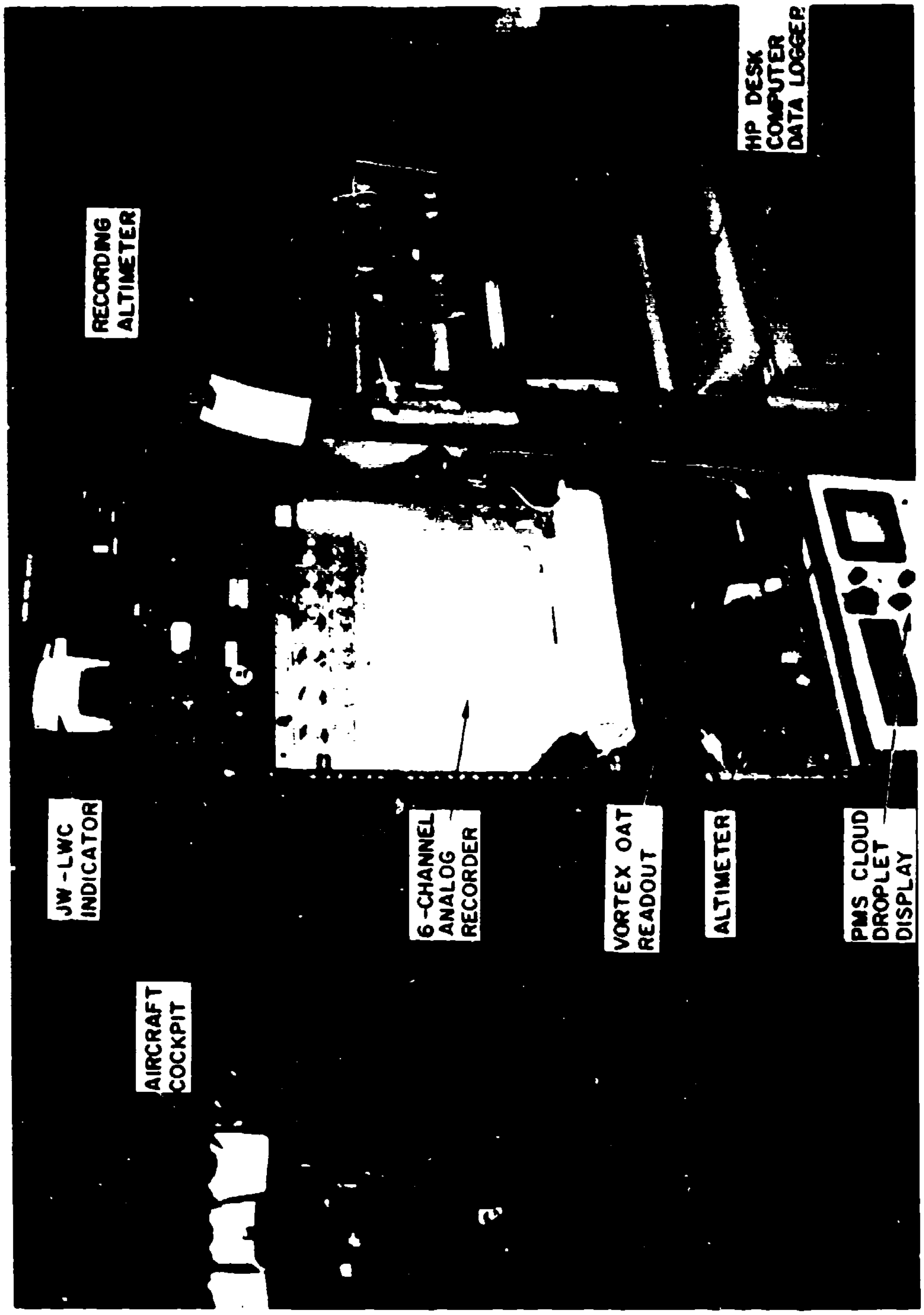

FIGURE 6. VIEW OF THE INSTRUMENT READOUT AND RECORDING SYSTEMS AT THE SCIENTIFIC OBSERVER STATION IN THE AIRCRAFT CABIN.

FIGURE 7. OVERALL VIEW OF NRL'S LOCKHEED EC-121 RESEARCH AIRCRAFT.

B. Overall Weather Picture for the Week of March 5-9, 1979.

The aircraft was available and prepared for project flights during the week of March 5-9. Reference to the daily weather maps in Figs. 8-11 will show that the main, upper altitude, synoptic feature for this period was a nearly stationary major wave structure centered over the Great Lakes. On the surface the major feature was a slowly advancing cold front along the Atlantic seaboard. Moist, southerly flow ahead of the cold front provided considerable cloudiness and precipitation as well as warm temperatures as far north as Nova Scotia. This condition persisted until March 7 when the front finally drifted out to sea. This cold front region shows up prominently on the satellite images in Figs. 12-17.

The absence of freezing temperatures below 5000 feet along the Atlantic seaboard eliminated this region from consideration for project flights until March 8. On the other hand, selected weather station reports, soundings, and prognoses for the eastern Great Lakes on March 6 were showing extensive cloudiness and subfreezing temperatures below 5000 feet. This information guided the choice of Lake Erie as the target area for March 6. Station reports from Buffalo, Erie, and Cleveland are listed in Table 2. The satellite images in Figs. 12 and 13 clearly show this region of cloudiness as a large, disk shaped mass moving slowly northeastward ahead of a vast, clear area behind the cold front.

By the next day this region of cloudiness had moved on north from Lakes Erie and Ontario and had been replaced by the aforementioned fair weather regime that was following it. However, as the surface weather maps show, a weak, low pressure system associated with a new cold front had formed and was bringing low level cloudiness and some precipitation to the northern Illinois and Lake Michigan vicinity on March 7. Selected station reports, soundings and prognoses for this area directed the choice of Lake Michigan as the target area for this day. Station reports for Muskegon, Green Bay, and Chicago Midway Airport are given in Table 3. The satellite images in Figs. 14 and 15 clearly show this region of cloudiness.

On May 8, only uninteresting, partly cloudy conditions remained throughout most of the Great Lakes so attention was turned again to the eastern seaboard region. Station reports, soundings, and prognoses revealed a chance for suitable icing conditions around an apparent occlusion along the northern reaches of the prominent cold front that had been along the eastern seaboard the earlier part of the week. The target area of cloudiness was moving rapidly northeastward from New England by the time the aircraft was able to depart Patuxent River Naval Air Station on this day. The plane chased the cloud system nearly to Canadian territory at the mouth of the Bay of Fundy between Nova Scotia and New Brunswick. By the time the plane arrived in this vicinity, only thin, receding clouds and warmer than freezing temperatures were remaining. The synoptic maps in Fig. 11 and the satellite images in Figs. 16 and 17 depict the situation.

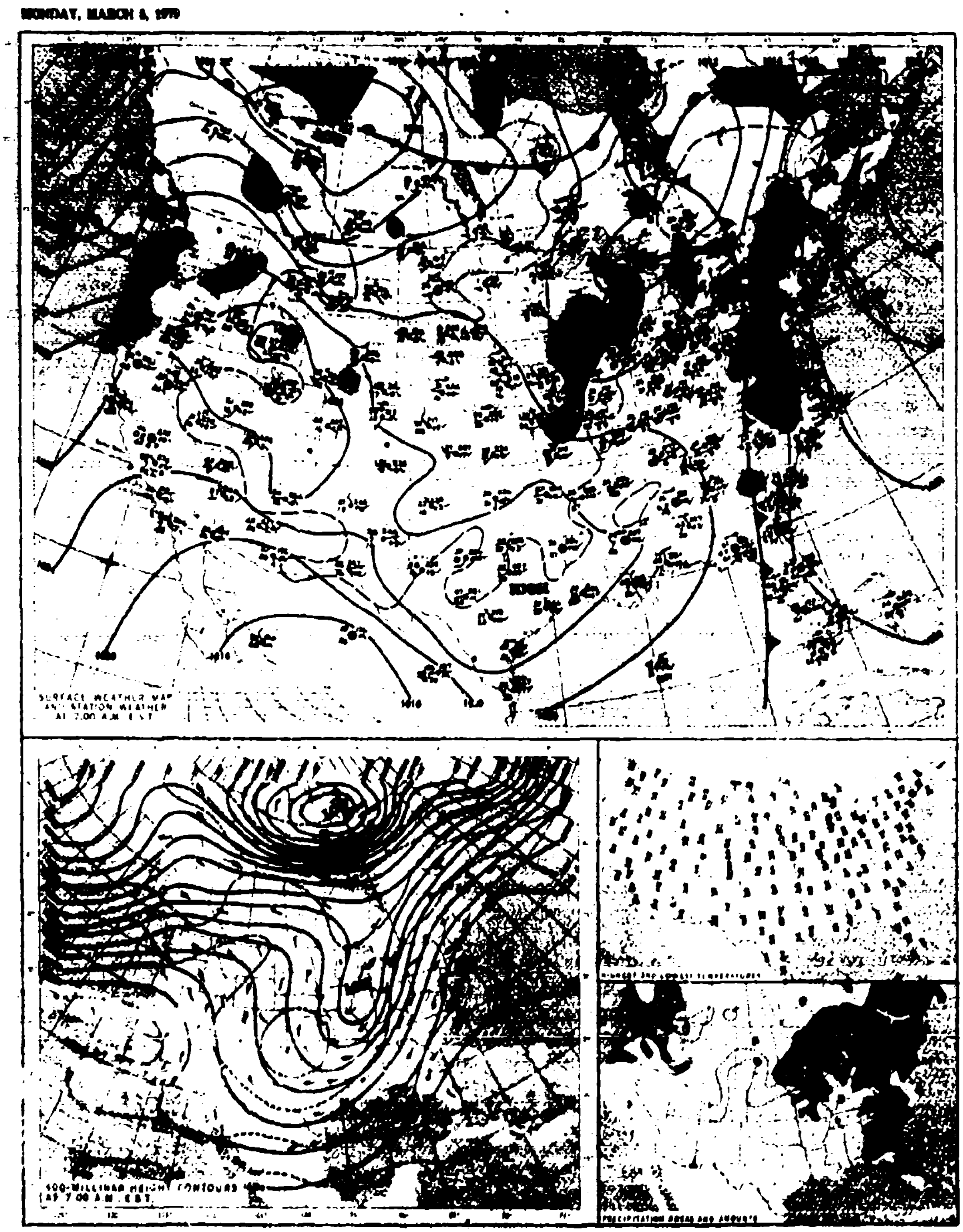

FIGURE 8. SURFACE WEATHER MAP AND 500 mb HEIGHT CONTOURS FOR MARCH 5, 1979. Maps taken from U.S. Dep't of Commerce (NOAA-EDS) "Daily Weather Maps," available from U.S. Gov't Printing Office, Washington, DC 20402.

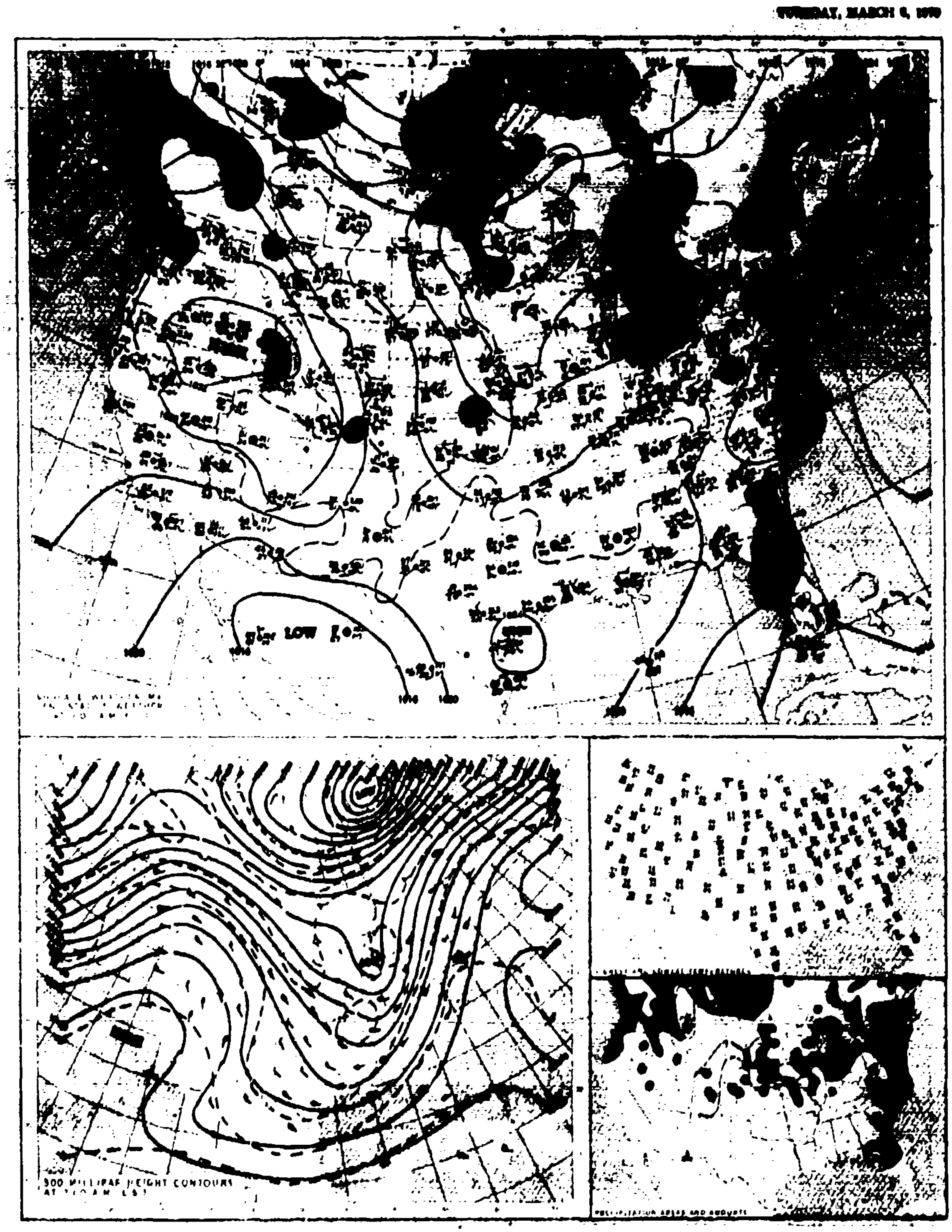

FIGURE 9. SURFACE WEATHER AND 500 mb HEIGHT CONTOURS FOR MARCH 6, 1979.

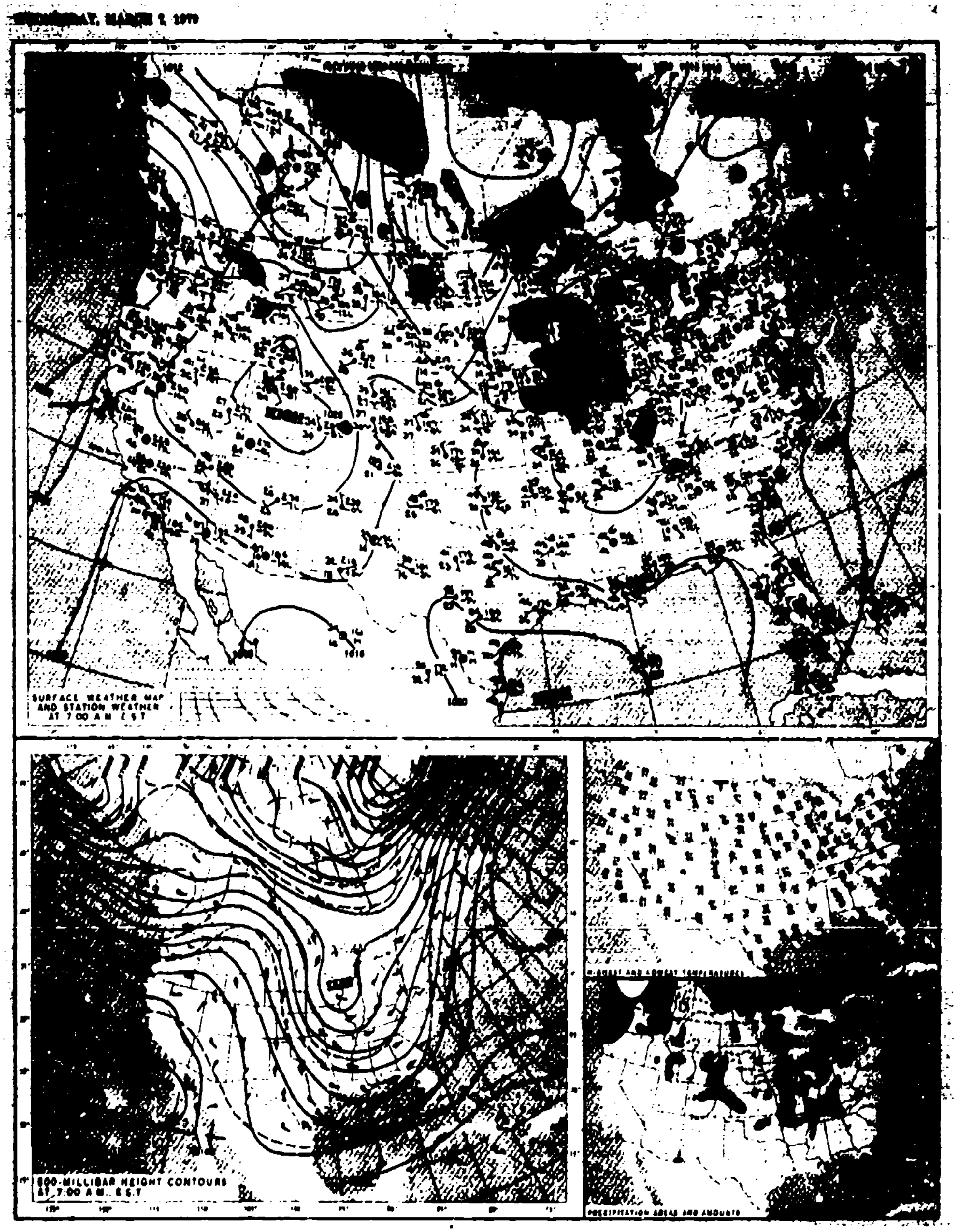

FIGURE 10. SURFACE WEATHER AND 500 mb HEIGHT CONTOURS FOR MARCH 7, 1979.

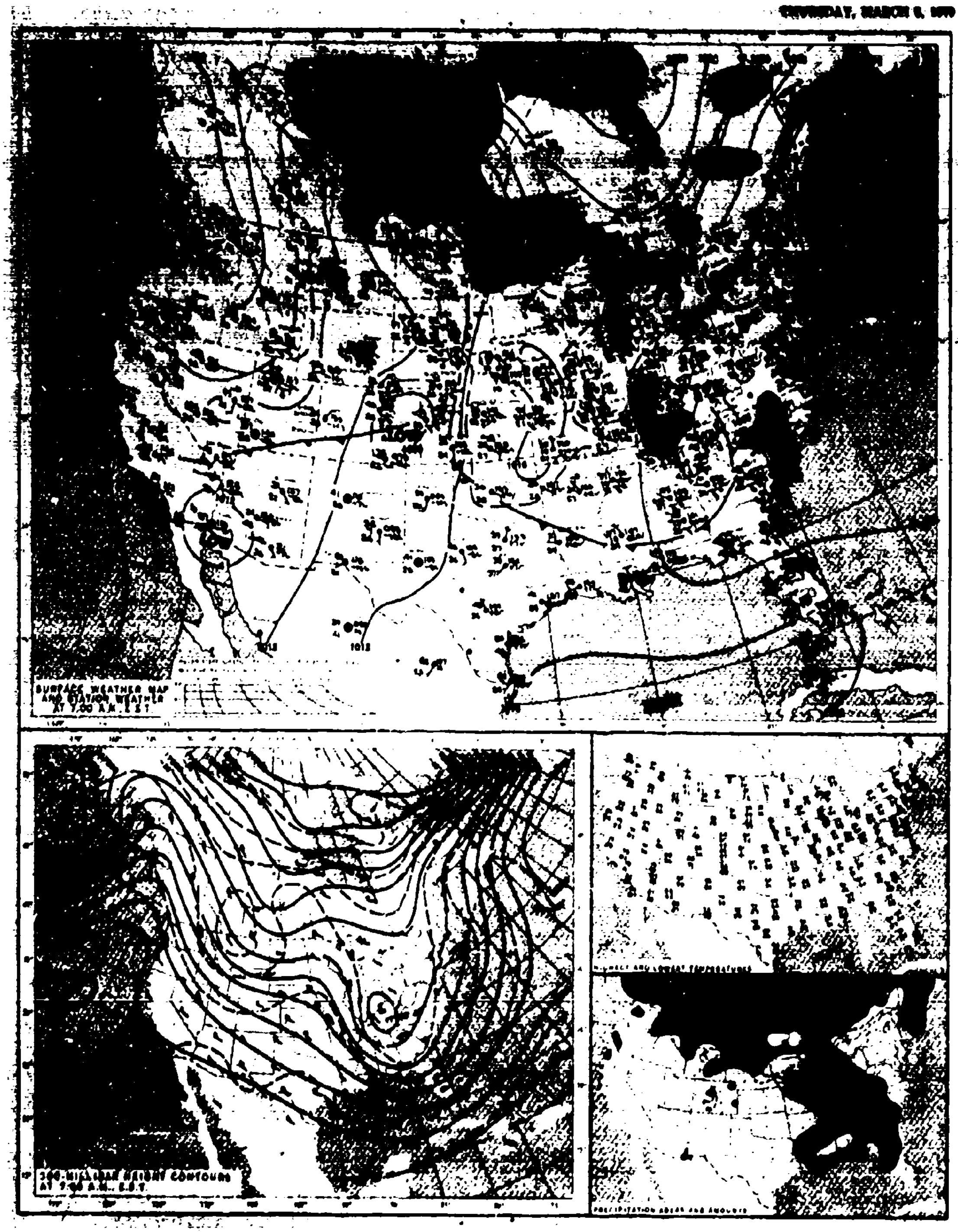

FIGURE 11. SURFACE WEATHER AND 500 mb HEIGHT CONTOURS FOR MARCH 8, 1979.

FIGURE 12. SMS - GOES PHOTO IN VISIBLE WAVELENGTHS AT 1330 E.S.T., MARCH 6, 1979. Photos courtesy of Mr. Vernon Lindsay, Meteorologist in charge of Central Flow, Weather Service Unit, National Weather Service/FAA, Washington, DC.

FIGURE 13. SMS - GOES PHOTO IN THE INFRARED AT 1400 E.S.T., MARCH 6, 1979.

FIGURE 14. SMS - GOES PHOTO IN VISIBLE WAVELENGTHS AT 1430 E.S.T., MARCH 7, 1979.

FIGURE 15. SMS - GOES PHOTO IN THE INFRARED AT 1600 E.S.T., MARCH 7, 1979.

FIGURE 16. SMS - GOES PHOTO IN VISIBLE WAVELENGTHS AT 1230 E.S.T., MARCH 8, 1979.

FIGURE 17. SMS - GOES PHOTO IN THE INFRARED AT 1300 E.S.T., MARCH 8, 1979.

TABLE 3: TELETYPE AVIATION WEATHER REPORTS FOR MARCH 7, 1979

Time (E.S.T.)	Report Type	Sky and Ceiling (Heights in feet)	VSBY (mi)	Weather and Obstructions to Vision	Sea Level Pressure (mb)	AT (°F)	DP (°F)	WDIR (deg)	WSPD (kt)	Remarks
				Reports from Green Bay, WI (GRB)						
0900	RS	indef. 300 Obscured	1/2 to 1	Light snow	1010.2	30	22	030	16	
1000	SA	Ptly.obscured M 400 OVC	1 1/2	Light snow	1010.7	30	22	030	17	
1100	SA	M 400 OVC	1 1/2	Light snow, fog	1011.2	28	24	030	18	Snow Very Light
1200	SA	M 500 OVC	1 1/2	Light snow, fog	1011.6	28	25	030	14	
1300	RS	M 700 OVC	1 1/2	Light snow, fog	1012.1	29	26	030	17	
1400	SA	M 700 OVC	3	Light snow, fog	1012.1	29	26	030	18	
1700	SA	M 600 OVC	3	Fog	1012.9	29	27	030	17	
1700	UA	Cessna 310 aircraft over GRB, flight level unknown, overcast at 6000 ft; trace of light clear icing on aircraft.								
1800	SA	M 600 OVC	4	Fog	1013.6	30	26	030	15	
1900	SA	M 1100 OVC	4	Fog	1014.2	30	26	030	16	
2100	SA	M 800 OVC	4	Fog	1014.2	29	26	030	02	
				Reports from Muskegon, MI (MKG)						
0900	RS	M 700 OVC	3	Light drizzle, fog	1009.5	34	32	130	06	
1000	SA	M 900 OVC	5	Lt rain, haze, fog	1009.5	34	21	120	05	Precip. very light.
1100	RS	Scatt.900, M2000 OVC	6	Haze	1009.8	35	41	120	05	Some snow
1200	SA	M2000 OVC	6	Haze	1010.1	35	30	130	04	
1300	SA	M2000 OVC	6	Haze	1010.1	36	30	070	04	
1400	SA	M2100 OVC	6	Haze	1009.8	36	30	160	03	
1500	SA	M1900 OVC	6	Haze	1009.9	37	30	100	04	
1700	SA	M2500 OVC	6	Haze	1009.7	35	31	300	03	
1800	SA	M2200 OVC	5	Haze	1011.1	35	32	310	04	
1900	SA	M3800 OVC	2 1/1	Fog, Haze	1011.5	34	33	330	04	
2000	SA	M5000 OVC	4	Fog, Haze	1011.8	34	32	320	05	
				Reports from Chicago Midway Airport (MDW)						
0900	RS	M 400 OVC	1 1/2	Light drizzle, fog	1009.5	34	32	130	06	
1000	RS	M 400 OVC	3	Light drizzle, fog	1008.2	33	32	180	05	
1100	RS	M 500 BKN 900 OVC	3	Light drizzle, fog	1008.6	34	33	170	05	
1200	SA	M 500 BKN 1000 OVC	2 1/2	Fog	1009.0	34	33	190	05	
1300	RS	M 800 OVC	3	Fog	1009.0	35	34	190	05	
1400	RS	M 1000 OVC	3	Fog	1009.0	35	34	180	06	
1500	SA	M 1000 OVC	4	Fog	1009.0	36	34	190	03	Higher clouds visible.
1700	SA	M 1600 OVC	5	Fog	1009.7	36	33	000	00	

TABLE 2: TELETYPE AVIATION WEATHER REPORTS FOR MARCH 6, 1979

Time (E.S.T.)	Report Type	Sky and Ceiling (Heights in hundreds of feet)	VSBY (mi)	Weather and Obstructions to Vision	Sea Level Pressure (mb)	AT (°F)	DP (°F)	WDIR (deg)	WSPD (kt)	Remarks
		Reports from Buffalo, NY (BUF)								
0900	SA	M24 BKN 37 BKN 55 OVC	6	Haze, fog	1016.5	36	33	200	7	
1000	SA	M21 BKN 31 OVC	7		1016.5	37	30	230	0	
1100	SA	SCT 30 OVC	6	Haze	1016.4	38	31	240	6	
1200	RS	SCT 25 M 45 OVC	6	Haze,	1015.4	39	31	230	9	
1300	SA	SCT 28 M 35 OVC	6	Haze	1015.0	40	29	240	17	Some rain
1400	RS	M 25 BKN 33 OVC	7	Lt.rain showers	1014.2	38	31	240	13	
1430	UA	Boeing 727 15 mi.west of Rochester at 6000 ft; Light rime icing on aircraft								
1500	RS	SCT 8 & 15 E 23 OVC	2 1/2	Lt.drizzle		35	31	260	2	
1600	SA	M 10 BKN 15,24, & 33 OVC		Lt.snow		33	30	250	3	Some drizzle
1700	RS	SCT 9 M 15 BKN 25 OVC	2 1/2	Lt.snow, fog	1015.0	33	31	250	11	
		Reports from Erie, PA (ERI)								
0900	SA	M 50 OVC	5	Haze	1016.5	35	30	200	11	
1000	SA	SCT 24 M 60 OVC	6	Haze	1017.1	35	29	200	3	
1200	RS,SP	M 5 BKN 26 BKN 60 OVC	6	Lt.rain, haze	1016.1	38	31	220	16	
1300	RS	SCT 6 M23 OVC	4	Lt.snow, haze	1016.3	30	30	270	10	Some rain
1400	RS	SCT 19 M34 OVC	3	Lt.snow, haze	1015.8	32	31	240	5	
1500	RS	M 11 BKN 30 OVC	2 1/2	Lt.drizzle, fog	1015.8	32	31	270	8	Lt. snow
1600	SA	SCT 11 M 40 OVC	4	Lt.drizzle, fog	1016.1	32	31	270	9	Lt. snow;pcpn.very light.
1700	RS	SCT 7 M 32 OVC	3	Lt.drizzle, fog	1016.1	32	30	270	6	Lt. snow;pcpn.very light.
		Reports from Cleveland, OH (CLE)								
0900	SP	SCT 8 M 16 OVC	2 1/2	Lt. snow showers	1016.9	35	31	230	15	
0920	UA	Piper aircraft (P28), 8 mi.west of Akron at 2000 ft.,moderate rime icing, rime covered windshield								
1000	SA	M25 OVC	4	Lt. snow showers	1016.9	35	31	230	13	Pcpn. very light.
1100	SA	M24 OVC	7		1016.5	38	30	230	16	
1100	UA	Cessna 310 aircraft over CGF, flight level unk; OVC based at 3000 ft, top at 6500; trace of rime ice during southbound climb.								
1200	SA	M24 OVC	7		1016.2	37	30	220	20	Ceiling ragged.
1300	SA	M24 OVC	7		1016.2	38	30	240	14	Ceiling ragged.
1400	SA	M24 OVC	7		1015.7	40	30	220	19	Ceiling ragged.
1500	SA	M26 OVC	6	Haze	1015.7	40	29	260	14	Ceiling ragged.
1600	SA	M31 OVC	10		1015.7	41	30	230	11	Breaks in OVC to West
1700	SA	M34 OVC	9		1015.6	41	29	230	10	Sml.Brks. OVC, few CU.

Note: Standard weather report notation is borrowed for these Tables. The abbreviations are as follows: SA= normal hourly report, RS= Record Special report, UA= Upper Air report, SP= Special report. M= measured ceiling, BKN= broken, OVC= overcast, SCT= scattered. VSBY= visibility, AT= Air Temperature, DP= Dew Point Temperature, WDIR= wind direction, WSPD= wind speed.

C. Naval Research Laboratory Flights of March, 1979.

The following chronicles contain commentaries on cloud conditions and other pertinent visual observations made by the onboard scientist (the author) and the pilots during the data collection periods. The "event" number corresponding to each comment or observation also appears as an encircled symbol along the time base of the indicated figure in which LWC, MMD, N, OAT, and altitude are plotted for that time interval. Since no ice detector or icing rate sensor was available for these initial flights, the report lacks quantitative ice accretion data to relate to recorded values of the other variables. Thus, the icing "data" in this report consists of visual observations supplemented by several photographs of the more notable icing events. Most of the observations on the occurrence of "moisture", "rain", and icing were made by the pilots from their vantage point in the cockpit. "Moisture" and "rain" were subjective distinctions based on the size of the droplets impacting at the moment on the windshield. During the flights the pilots kept the windshield heaters continually energized on the "low" setting of the three-position, high-low-off, control switch. This kept the windshields ice-free except for an occasional light slush which was noticeable during some of the icing events. However, the windshield wipers appeared to be unaffected by this mild heat source and consequently they were readily susceptible to ice accretion, an extreme example of which is shown in Fig. 28. Since the wipers were seldom used, and thus were stationary, they served as reasonably good visual ice detectors which were in constant view of the pilots. Unless otherwise noted, the icing events reported by the pilots in the following chronicles are all based on conditions observed at the moment on these wiper blades. The pilots' observations are distinguished from those of the onboard scientist by the inclusion of the word "pireps" in the following chronicles. The altitudes listed in the figures are in terms of feet above the average, local surface elevation. The indicated airspeed was generally maintained at a nominal 165 kt. References to icing events are underlined for easier recognition.

1. Flight of March 6, 1979: Lake Erie Vicinity.

Enroute from Pax River N.A.S. to the planned target area along the south shore of Lake Erie, the aircraft followed a clear air path at 8000 ft pressure altitude between two distinct, widespread cloud layers. The lower layer was stratus or stratocumulus with a well demarked layer top estimated from the aircraft to lie at an altitude between 5000 and 7000 ft a.s.l. During the first half of the transit this lower layer was associated with the cold front lying inland and parallel to the Atlantic coastline. During the second half of the transit to the west of the cold front, the lower layer appeared to be part of the target cloud mass lying over the eastern Great Lakes. The ground was obscured 95-100% of the time by these lower layers during entire transit. The upper cloud layer appeared to be a stratus type which provided 100% overcast to the east of the cold front. Later, as noted from aboard the aircraft at about 1150 E.S.T. and from a position about 60 miles SE of Buffalo (BUF), NY, the upper layer appeared to be cirrus or cirrostratus which provided about 30% sky cover in the two northern quadrants at this time and location. There were no clouds above the lower layer in the SW quadrant at this time. The initial descent into the target clouds (the lower status layer) began near BUF at about 1210 E.S.T. During the data collection portion of the mission the aircraft was cleared for various altitudes along the airway V-14 above the Lake Erie shoreline between BUF and Erie, Pennsylvania.

Event	Time (E.S.T.)	Alt. (Ft.)	OAT (°C)	Refer to Fig.	Description
					Descending Profile Through Cloud Layer
A	1215	5900	-9.7	18	Pireps "some rime" forming on aircraft at ~200 ft below cloud tops during first descending profile 14 mi. E or SE of BUF.
B	1216	5600	-8.4	18	Pireps "light rime" at ~500 ft below cloud tops during first descending profile.
					Level Flight near Cloud Base to Study Short and Long Term Icing Conditions There
3	1219	4200	-5.5	21	Pireps "moisture now and maybe snow at cloud base about 14 mi west of BUF.
C	1223	4400	-5.8	21	Pireps no moisture on the windshield and no additional icing occurring at the moment; still in and out of cloud near cloud base.
D	1224	4500	-5.7	21	Pireps "some moisture" on windshield.
4	1227	4500	-5.7	21	Pireps "visible moisture now; enough to make a trace of ice." Aircraft in continuous, thin cloud just above cloud base 23 mi west of BUF.
5	1228:40	4500	-5.4	21	Pireps "still in a bit of moisture" in cloud as above.
6	1229:40	4500	-5.0	21	Pireps "still in a bit of moisture" causing a bit of "rime ice" in cloud as above.

The following section, from event number 7 through 34, occurs during a malfunction of the data logging system followed by an ice-induced, temporary disablement of the ASSP droplet probe. No information is available from the droplet probe or the JW-LWC meter during this period. The event descriptions and approximate altitude and OAT are still included, however, because some significant icing occurred during this time and the commentary is a useful reference in understanding subsequent event descriptions.

Event	Time (E.S.T.)	Alt. (Ft.)	OAT (°C)	Refer to Fig.	Description
					Continue Level Flight near Cloud Base
8	~1234	4500	~-5	-	Pireps "still some light moisture visible" at 38 mi west of BUF still in continuous cloud as above.
9	~1236	4400	~-5	-	Aircraft in intermittent cloud.

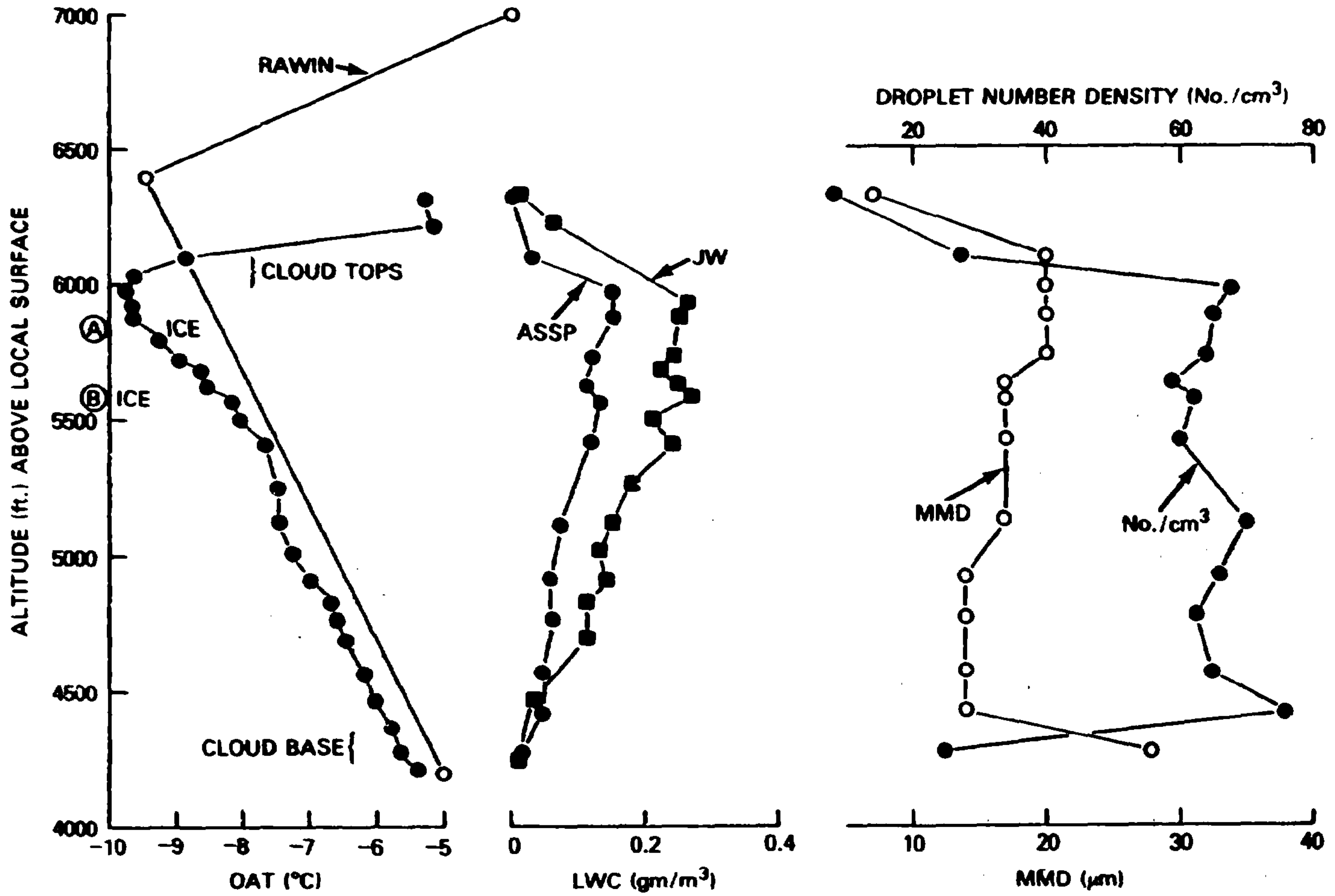

FIGURE 18. FIRST DESCENDING PROFILE THROUGH STRATUS AT 1214-18 E.S.T., ON MARCH 6, 1979 AT A POSITION 14 MI. SOUTHEAST OF BUFFALO, NY. The MMD, LWC, (except for JW-LWC), and number density are derived from the ASSP (3-45 μm dia. range) measurements. The Rawin OAT data are from the 0700 E.S.T. sounding at Buffalo. The JW-LWC data have been corrected by subtracting apparent noise and drift from the recorded signal but the accuracy of the corrected values is not known. The encircled letters along the ordinate indicate the altitude at which the pilots reported (A), "some rime", and (B), "light" rime.

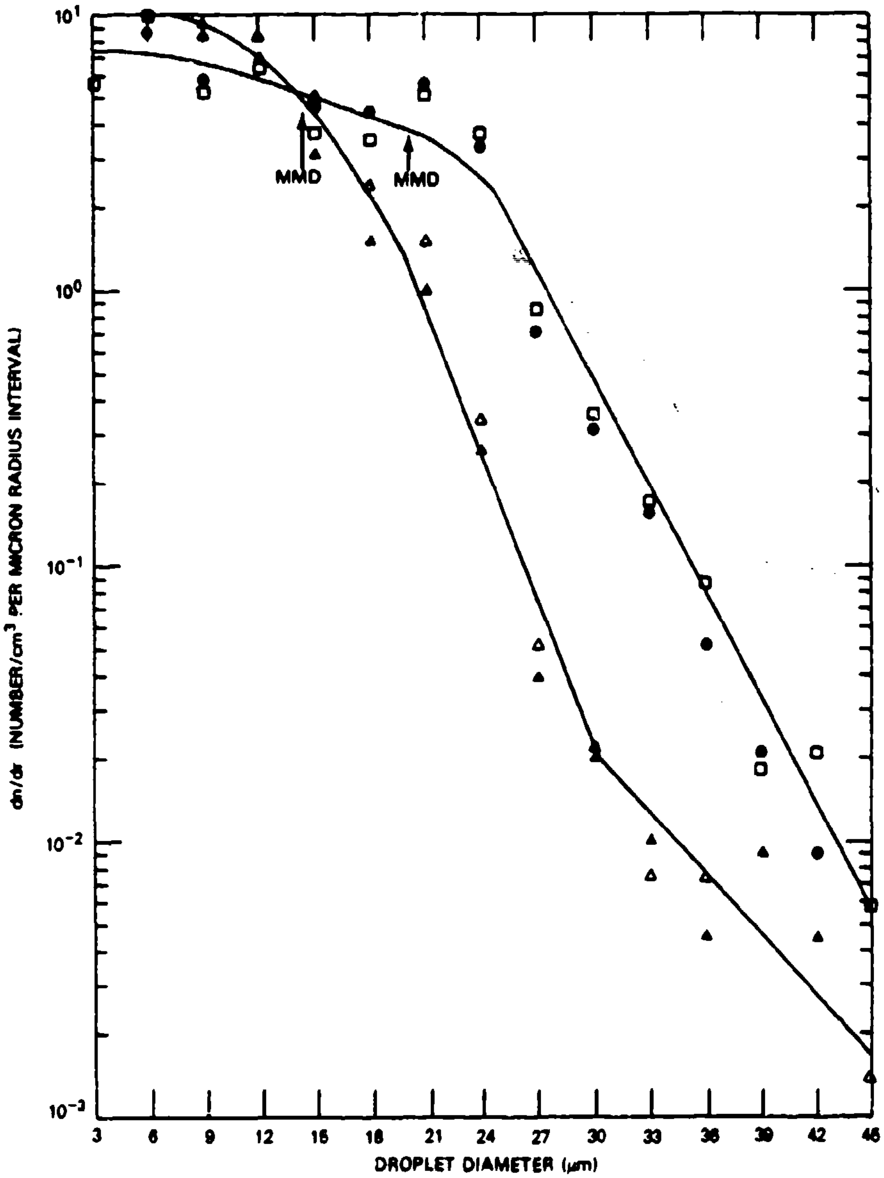

FIGURE 19. DROPLET SIZE DISTRIBUTIONS IN THE STRATUS LAYER DEPICTED IN FIG. 18. Data are from the ASSP (3-45 μm dia. range) measurements.

● - at 6000 ft } and maximum LWC (0.15 - 0.23 gm/m^3) just below
□ - at 5900 ft } the cloud tops.

△ - at 4770 ft } and low LWC (0.06-0.12 gm/m^3) just above cloud base
▲ - at 4570 ft }

The lines are arbitrary, smooth curves drawn through the datum points.

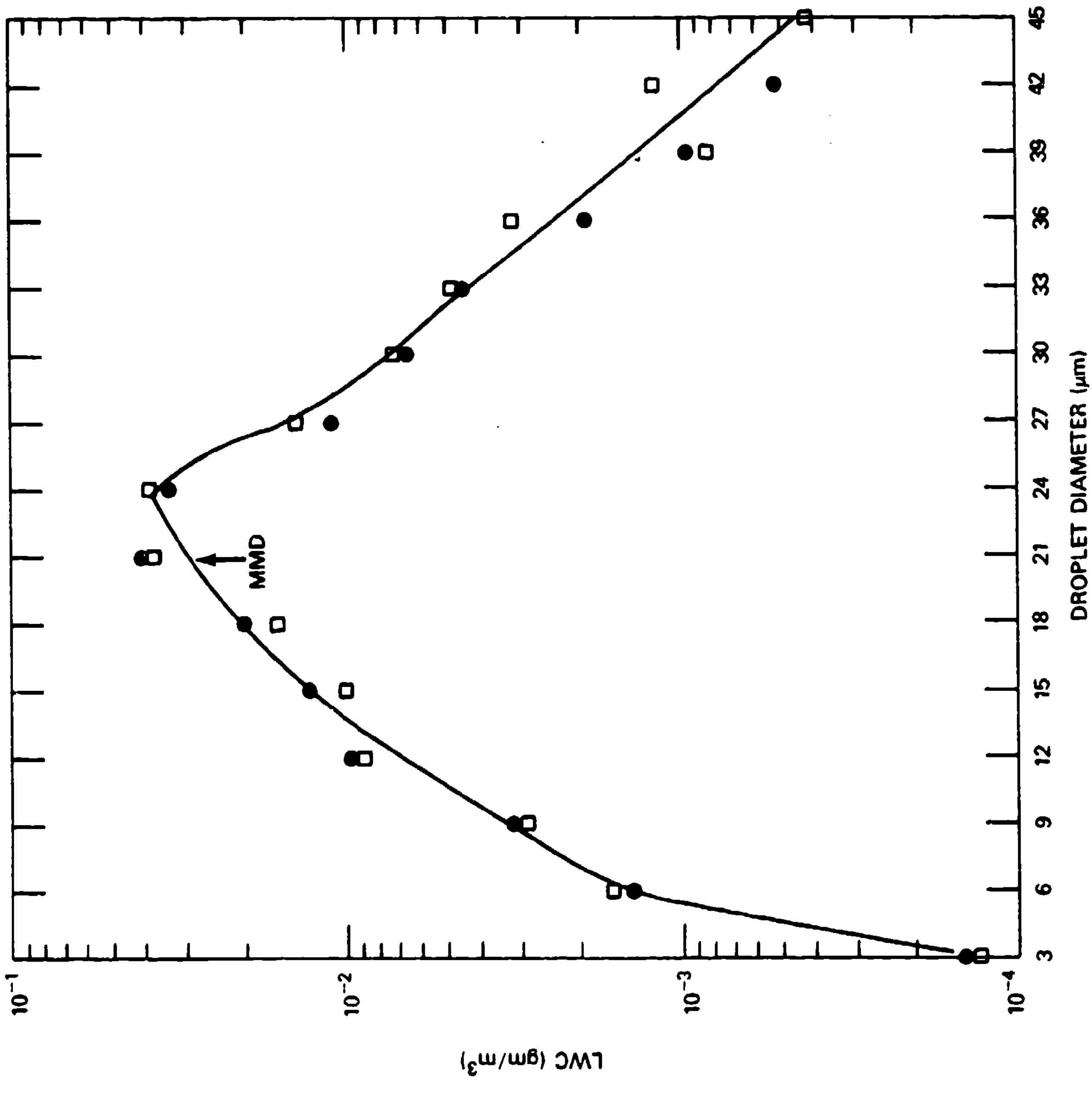

FIGURE 20. LWC CONTRIBUTIONS FROM THE TOTAL DROPLET POPULATION IN EACH OF THE 15 INDIVIDUAL SIZE CHANNELS OF THE ASSP. Data apply to the stratus layer depicted in Fig. 18.

● - at 6000 ft } and maximum LWC (0.15-0.23 gm/m^3) just below
□ - at 5900 ft } cloud tops.

The solid line is an arbitrary smooth curve drawn through the datum points.

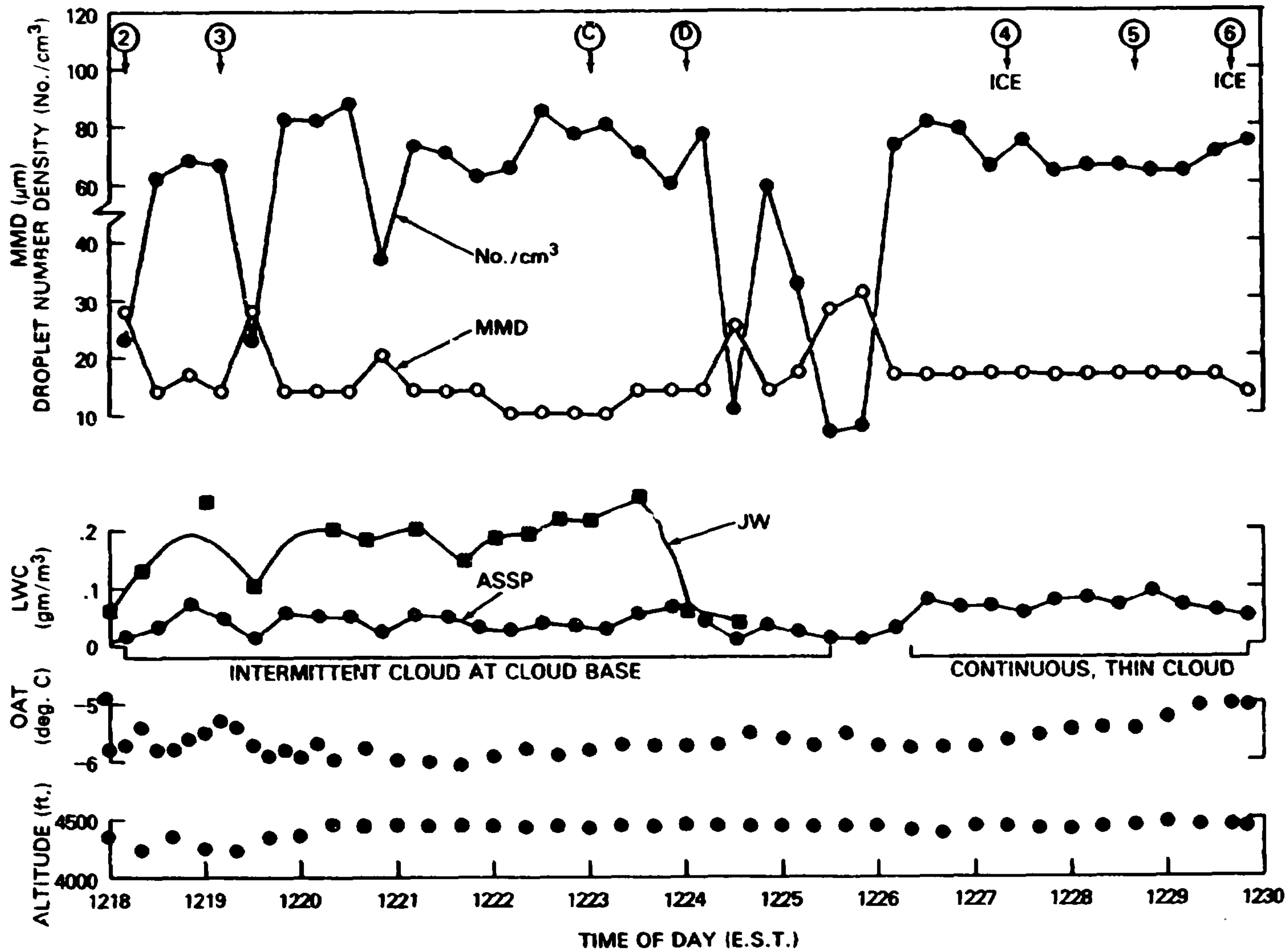

FIGURE 21. LEVEL FLIGHT AT CLOUD LAYER BASE NEAR 4500 FT TO DETERMINE THE ICING CHARACTERISTICS AT, AND JUST ABOVE, CLOUD BASE. The flight path is approximately from BUF to a point about 31 miles west of BUF on the first pass toward Erie. MMD, LWC, and number density are derived from the ASSP, (3-45 μm dia. range) except for the JW-LWC. The latter data have been corrected by subtracting apparent noise and drift but the accuracy of the corrected values is not known. The encircled numbers along the time base refer to visual observations (events) described in the text.

Event	Time (E.S.T.)	Alt. (Ft.)	OAT (°C)	Refer to Fig.	Description
12	~1243	4500	~-5	-	Aircraft back in continuous cloud again. Pireps "some moisture now and forming a bit of rime".
14	1248	4500	~-4	-	Pireps "still see moisture with icing" still in continuous cloud.
15	1249	4500	~-4	-	Pireps "still see moisture with icing". Data from ASSP beginning to degrade probably due to ice accumulation in the sampling volume. Still in continuous cloud, presumably just above cloud base.
16	1252	4500	~-3	-	Pireps "rime is still accumulating and is pretty heavy now". From the scientific station in the aircraft, rime can be seen along the leading edge of the wings and the engine cowling where it has the appearance of about 1/8 inch accumulation of impacted snow. Still in continuous cloud. ASSP now unusable due to apparent interference of ice with laser beam.

Increase Flight Level by 500 ft and Proceed in Continuous Cloud To Study Short and Long Term Icing Conditions at this Elevation Within the Cloud.

Event	Time (E.S.T.)	Alt. (Ft.)	OAT (°C)	Refer to Fig.	Description
17	1258	5000	~-5°	-	Aircraft starting 180° turn near Erie. Side windows have accumulated a thin layer of ice specks. Windshield in cockpit is layered with "snow". Still in continuous cloud.
18	1259	5000	~-5	-	Pireps "moisture is heavier now," still in continuous cloud.
22	1309	5000	~-4	-	Aircraft in intermittent cloud. Cloud base has risen to 5000 ft at this time and position (43 mi east of Erie).
23	1310	5000	~-4	-	Pireps back in continuous cloud and "picking up moisture again".
24	1313	5000	~-5	-	Pireps clouds thinning again; aircraft in intermittent cloud again.

Event	Time (E.S.T.)	Alt. (Ft.)	OAT (°C)	Refer to Fig.	Description
	Descend to Warmer Temperature to Thaw out Droplet Probe, Observe Rate of Shedding of Accumulated Rime Ice, and to Note any Precipitation Below Cloud Base.				
26	1322	5000	~-4	-	Aircraft starting 180° turn at 3 mi. south of BUF and starting descent to 3400 ft. Begin second pass from BUF to Erie.
27	1323	4100	~-2	-	Aircraft just below cloud base. Airspace between cloud base and ground is noticeably hazy. Rime is disappearing from the side windows but is still present on the wings and engine cowlings.
28	1327	3400	~-2	-	No moisture or new icing now at, or just below cloud base.
30	1335	3400	~-3	-	Pireps aircraft is back in clouds but "very little moisture" observed now on windshield.
31	1336	3400	~-3	-	Pireps "trace of moisture now." Aircraft seems to be in a nearly cloud free zone between two cloud layers. Puffs of cloud can be seen passing near the aircraft but the ground is totally obscured by intervening cloud at this time.
32	1346	3400	~-3	-	Pireps "beginning to pick up some moisture now" at about 29 mi east of Erie.
34	1348	3400	~-3	-	Pireps "possible light snow now, maybe some rain mixed in." From the scientific observers station one can see 1- to 3-inch wide splotches of rime intermittently dislodging and flying off the wings and engine cowlings.
36	1353:30	3500	-4.2	22	Droplet probe is now ice-free and operative again. Aircraft has been in continuous cloud for last 7 mi. Ground is still obscured. Pireps "rain now, and forming a little <u>ice</u>." OAT is lower and some ice still remains on wings and cowlings.

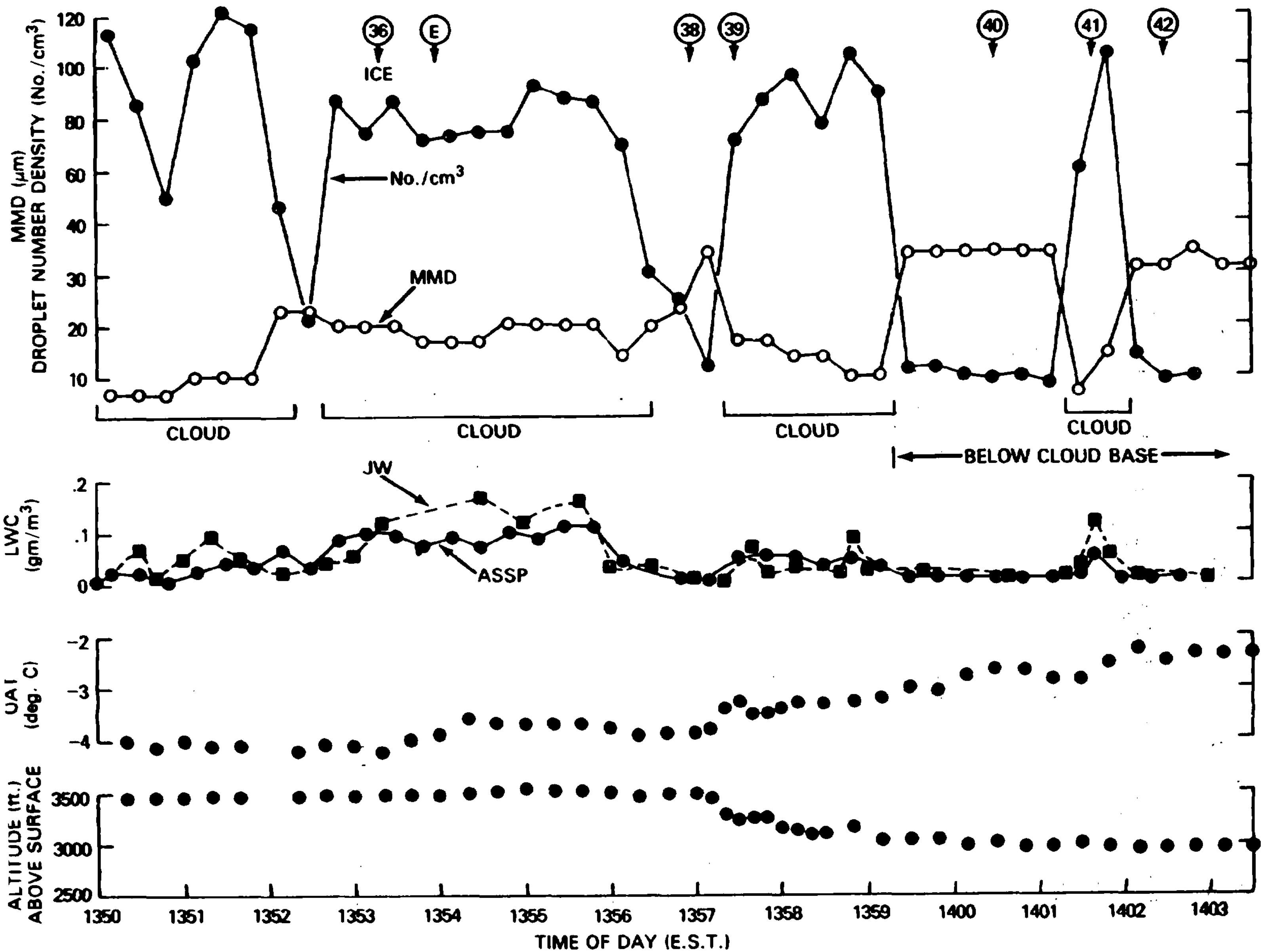

FIGURE 22. VARIABLE ALTITUDE PATH ABOVE AND NEAR THE STRATUS CLOUD BASE NEAR ERIE.

Event	Time (E.S.T.)	Alt. (Ft.)	OAT (°C)	Refer to Fig.	Description
E	1354	3500	-3.9	22	Cloud is noted to be relatively dense at this time.
	Descend to Look for Cloud Base and Warmer Temperature Again to Observe Rate of Meltoff of Accumulated Ice on Wings and Cowlings.				
38	1357	3500	-3.9	22	Aircraft exits cloud just as begin descent to look for cloud base. The ground is now visible at present position about 6 mi east of Erie.
39	1357:30	3200	-3.3	22	Aircraft starting 180° turn at 5 mi east of Erie and continuing descent to 3000 ft. This begins the second pass from Erie to BUF.
40	1400	3000	-2.7	22	Pireps "some rain" below cloud base. The visibility in the airspace between cloud and ground is noticeably low in all directions. Low VSBY due to snow?
41	1401:40	3000	-2.8	22	Pireps "rain heavier now" as aircraft passes through brief cloud, still generally below cloud base.
42	1402:30	3000	-2.4	22	Pireps "precip. very light now." Thin layer of rime still persists on the leading edge of the wings and the engine cowlings with a maximum thickness of perhaps 1/8" to 1/4". Aircraft is still just below cloud base.
44	1407:40	3000	-2.4	-	Ground now obscured by a lower cloud layer estimated at perhaps 1000 ft below the aircraft.
	Begin Period of Multiple Ascents and Descents to Determine Present Distribution of Cloud Layers and to Obtain Icing Data in Existing Layers.				
45	1412:20	3000	-2.7	23	Start ascent to 4500 ft at position 38 mi west of BUF.
46	1413:10	3300	-3.2	23	Enter cloud base (of second of three separate cloud layers in this vicinity at this time).

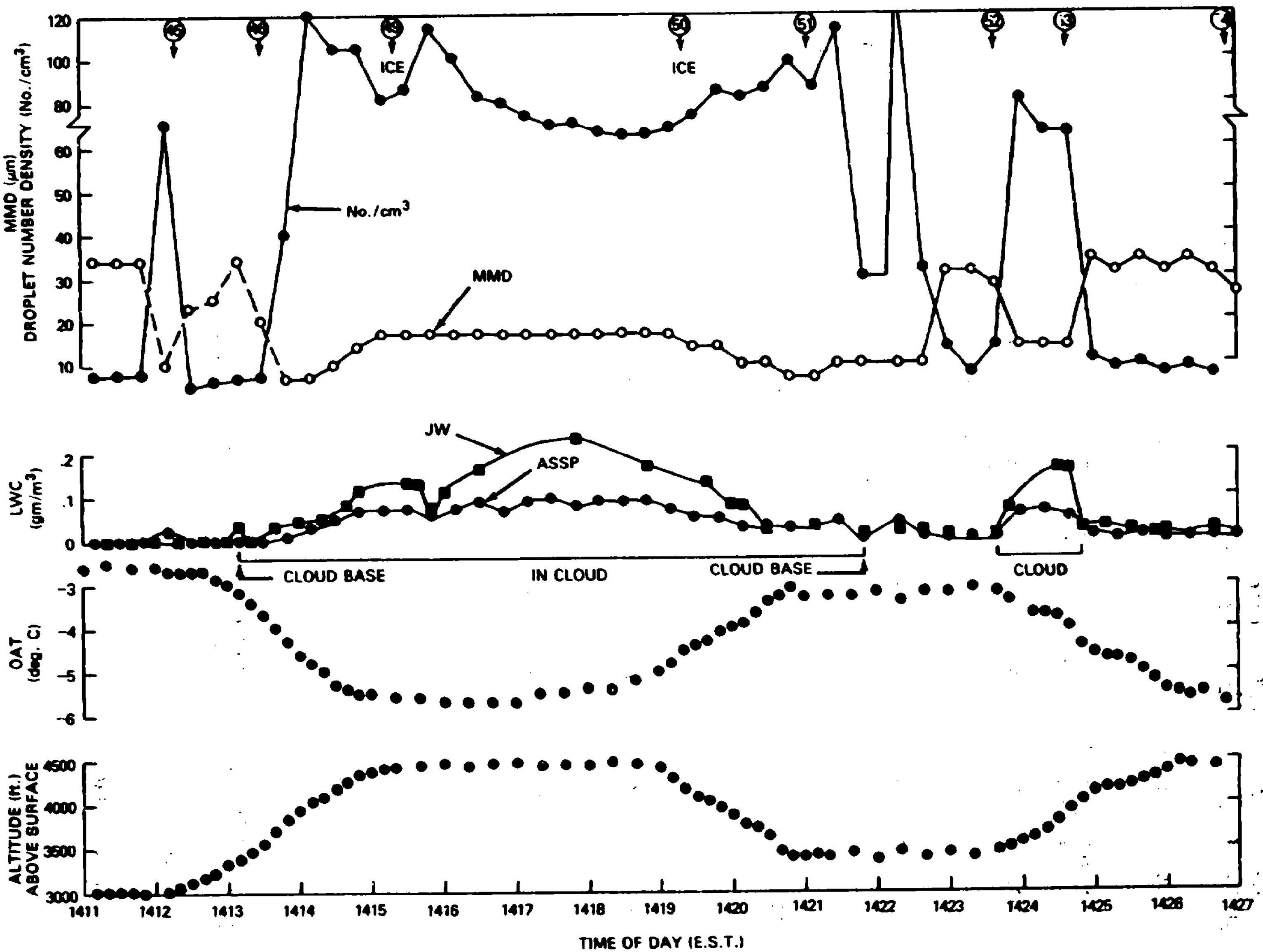

FIGURE 23. PROFILE FROM BELOW CLOUD BASE UP TO 1000 FT ABOVE THE STRATUS CLOUD BASE AT ABOUT 38 MILES WEST OF BUFFALO DURING THE FINAL PASS FROM ERIE TO BUFFALO.

Event	Time (E.S.T.)	Alt. (Ft.)	OAT (°C)	Refer to Fig.	Description
49	1415:20	4400	-5.6	23	Begin short period of level flight at about 4400 ft. (approx. 1000 ft above cloud base). Pireps "trace of moisture and light ice streaking."
50	1419:20	4200	-4.5	23	Descending toward 3400 ft at this time. Pireps "moisture and (rime) icing" occurring.
51	1421	3400	-3.3	23	Aircraft just above cloud base. Lower cloud layer is not present at this location and ground is visible now. Rime on wings and cowlings cowlings appears to be thicker now - perhaps up to 1/4" accumulation. Pireps "slight moisture now but no new icing occurring."
52	1423:40	3500	-3.2	23	Start ascent back to 4400 ft. Position is 8 mi west of BUF. Aircraft is just below cloud base at the moment.
53	1424:40	3900	-4.7	23	Pireps "some moisture" at this time. The ground is coming into view again even though the aircraft is still ascending. Thus, cloud base appears to be rising rapidly near BUF.
54	1427	4400	-5.6	23	Aircraft still below cloud base at this altitude and position 13 mi south of BUF at the completion of the final data run for the day. Aircraft starting transit back to Pax River.

2. Flight of March 7, 1979: Lake Michigan

Enroute from Pax River N.A.S. to the target area across the mid-section of Lake Michigan, the NRL aircraft followed a clear air path at about 10,000 ft pressure altitude. At the 1415 E.S.T.departure time, the only cloud in the vicinity of Pax River was a thin sheet moving to the northeast and out to sea, with the trailing edge of the cloud overhead at this time. Otherwise the sky was cloudless with good vertical and horizontal visibility during the transit into Ohio. At about 1530 E.S.T., near Belleaire, Ohio, the aircraft entered under the eastern edge of a cloud sheet that was associated with the extensive cloud system covering the Lake Michigan target area. As the aircraft continued in transit on a northwesterly heading at 10,000 ft, the OAT gradually dropped from -6°C to -10°C along with a gradually worsening horizontal and vertical (aircraft-to-ground) visibility. By 1558h, the visibility was obscured in all directions with neither the ground nor the horizons being visible. The aircraft was not in cloud at this time, but was in a heavy haze. By 1615h the aircraft began encountering puffs of cloud at 10,000 ft with distinct clouds visible now at an estimated 1000 ft below the aircraft. At this time, no moisture had yet been observed on the wings or on the windshield.

By 1620h the aircraft was in intermittent cloud with snow being reported by the pilots. No moisture or ice had yet appeared on the aircraft surfaces. The visibility appeared to be nearly zero in all directions.

By 1622h rime ice (or impacted snow) was becoming noticeable on the leading edges of the wings and on the tip of the propeller hubs. The OAT at this time was -10°C. The cloud remained nearly continuous until about 1635h when the aircraft broke out into what appeared to be a thin, clear area between cloud layers. The photograph in Fig. 24 was made at about 1632h to show the rime accumulation during this interval.

From 1635h until the beginning of the descent into the target cloud layer near Muskegon (MKG) at 1655h, the aircraft remained in this semi-clear (some intermittent clouds) area. The top of the lower cloud deck was now estimated to be 1000 ft or more below the aircraft while the upper deck, now a thin, broken layer, was estimated to be some 1000 ft above the aircraft. The lower deck of stratus or stratocumulus provided 100% cloud coverage at that level and was the target cloud for data collection purposes.

The data collection portion of this mission was conducted in several passes across central Lake Michigan following airways V450, V26-55, and V55 between Muskegon,MI, and Manitowoc, WI. The initial descent into the lower stratus deck began at about 1702h at about 4 mi southeast of MKG.

The following chronicle describes cloud conditions, icing events, and other pertinent visual observations made during the mission in the target clouds.

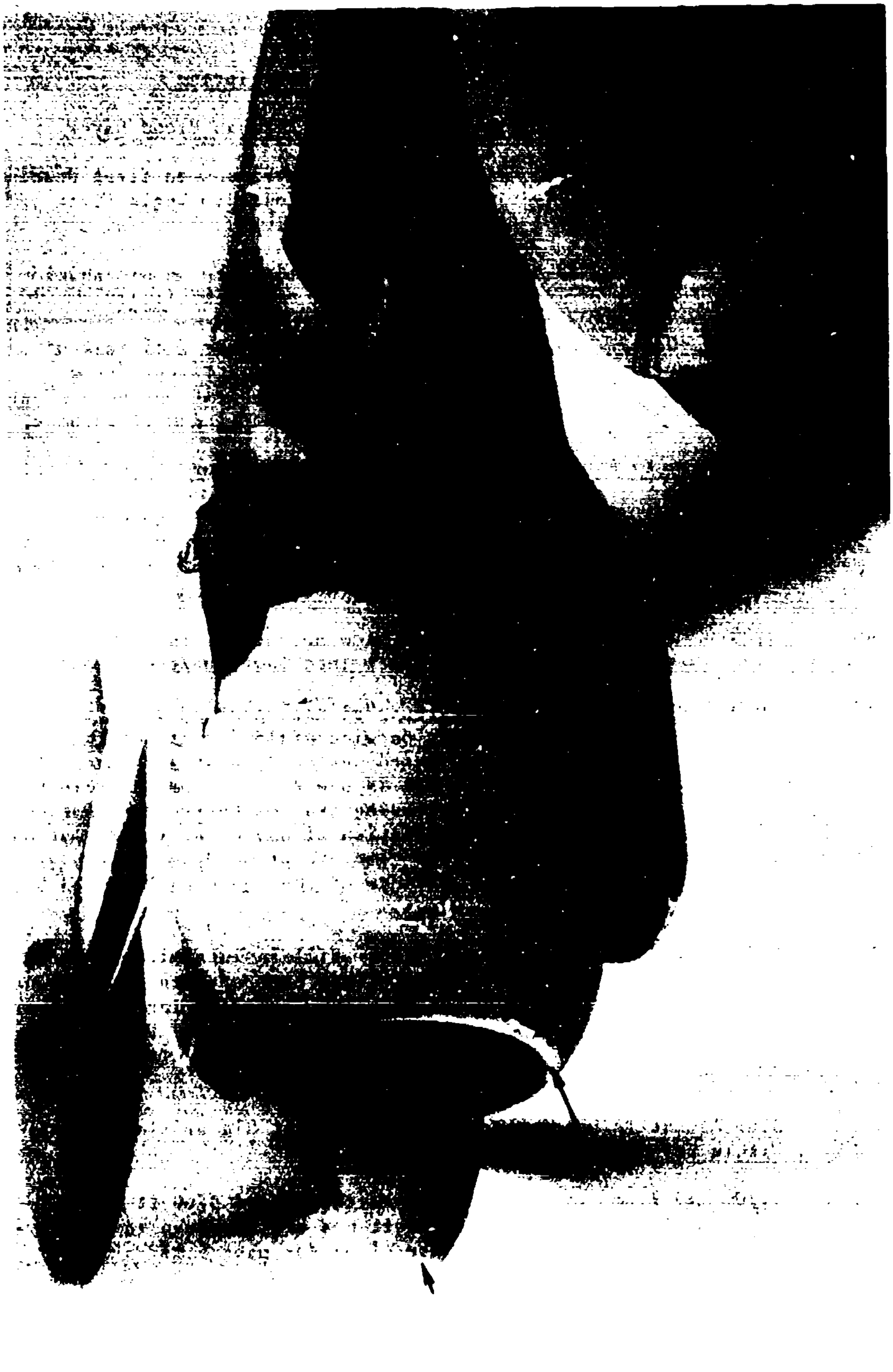

FIGURE 24. PHOTO OF RIME (OR IMPACTED SNOW) ACCUMULATED AT 10,000 FT DURING TRANSIT TO LAKE MICHIGAN ON MARCH 7.

Event	Time (E.S.T.)	Alt. (Ft.)	OAT (°C)	Refer to Fig.	Description
					Descending Profile Through Cloud Layer
7	1702:40	[illegible]0	-3.2	25	Enter cloud layer top on first descent into target clouds to begin first pass across L. Michigan.
8	1705:20	3700	0.0	25	Pireps "some moisture on windshield and starting to stick" (ice).
9	1708:30	2700	-0.4	25,26	Aircraft located 6 or 7 mi east of eastern shoreline. Pireps "some moisture on windshield but no ice" at this altitude just below cloud base.
Flight near Cloud Base to Study Short and Long Term Icing Conditions There.					
10	1710:10	2700	-0.1	26	Aircraft just crossing eastern shoreline. Surface of lake seen to be open water at this location. Pireps "light rain" now at cloud base.
11	1711:40	2700	-0.2	26	Start slow ascent toward 3200 feet to get back into lower part of cloud layer.
12	1714:10	3000	-0.4	26	Pireps "slight rain and clear ice forming on windshield. Rime that had accumulated during transit at higher altitudes is now gone. From the scientific observing station there is no noticeable indication of any clear ice formation at this time except perhaps for the wet appearance of the de-icing boots on the wings.
13	1716:50	3150	-0.3	26	Aircraft still in intermittent cloud base. Cloud base appears to be about 400 ft higher over the lake than over adjacent land near MKG. Pireps "intermittent light rain and clear ice on the windshield."
		Slow Ascent To Observe Icing Conditions at Higher Elevations Within the Cloud Layer.			
14	1721	3150	+0.7	26	Start ascent toward 3700 ft level. Aircraft has already been in relatively dense cloud for past 5 mi.

The following section, from event 15 through 19, occurs during a period when data was accidentally erased on the data logging system. No information is available from the cloud droplet probe or the JW-LWC meter during this period.

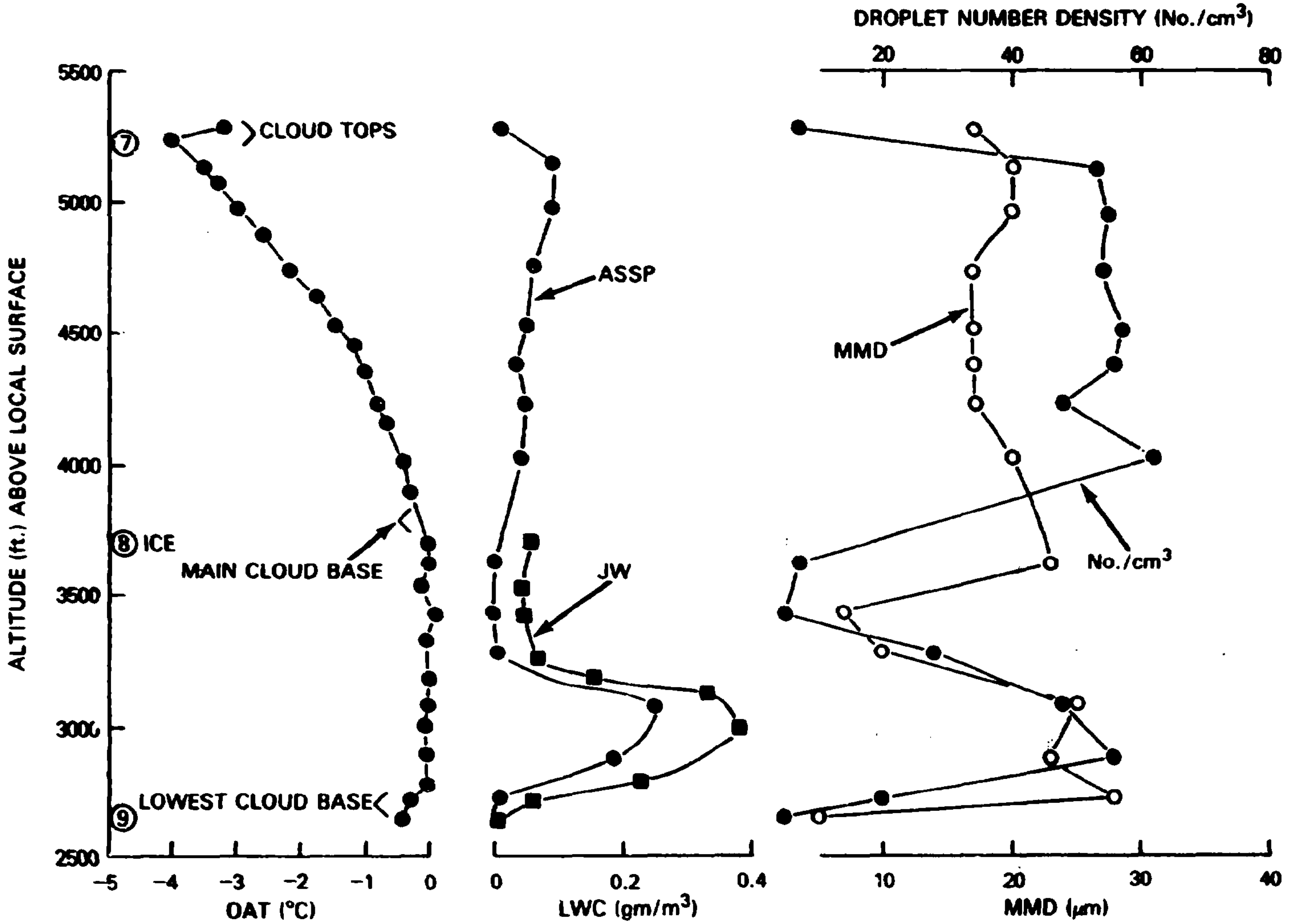

FIGURE 25. FIRST DESCENDING PROFILE THROUGH TWO CLOUD LAYERS BELOW 5500 FT AT 1702-08 E.S.T. NEAR MUSKEGON ON MARCH 7, 1979. The MMD, LWC (except for JW-LWC), and number density are derived from the ASSP (3-45µm dia. range) measurements. The JW-LWC data have been corrected by subtracting apparent noise and drift from the recorded signal but the accuracy of the corrected values is not known. The encircled numbers along the ordinate refer to visual observations (events).

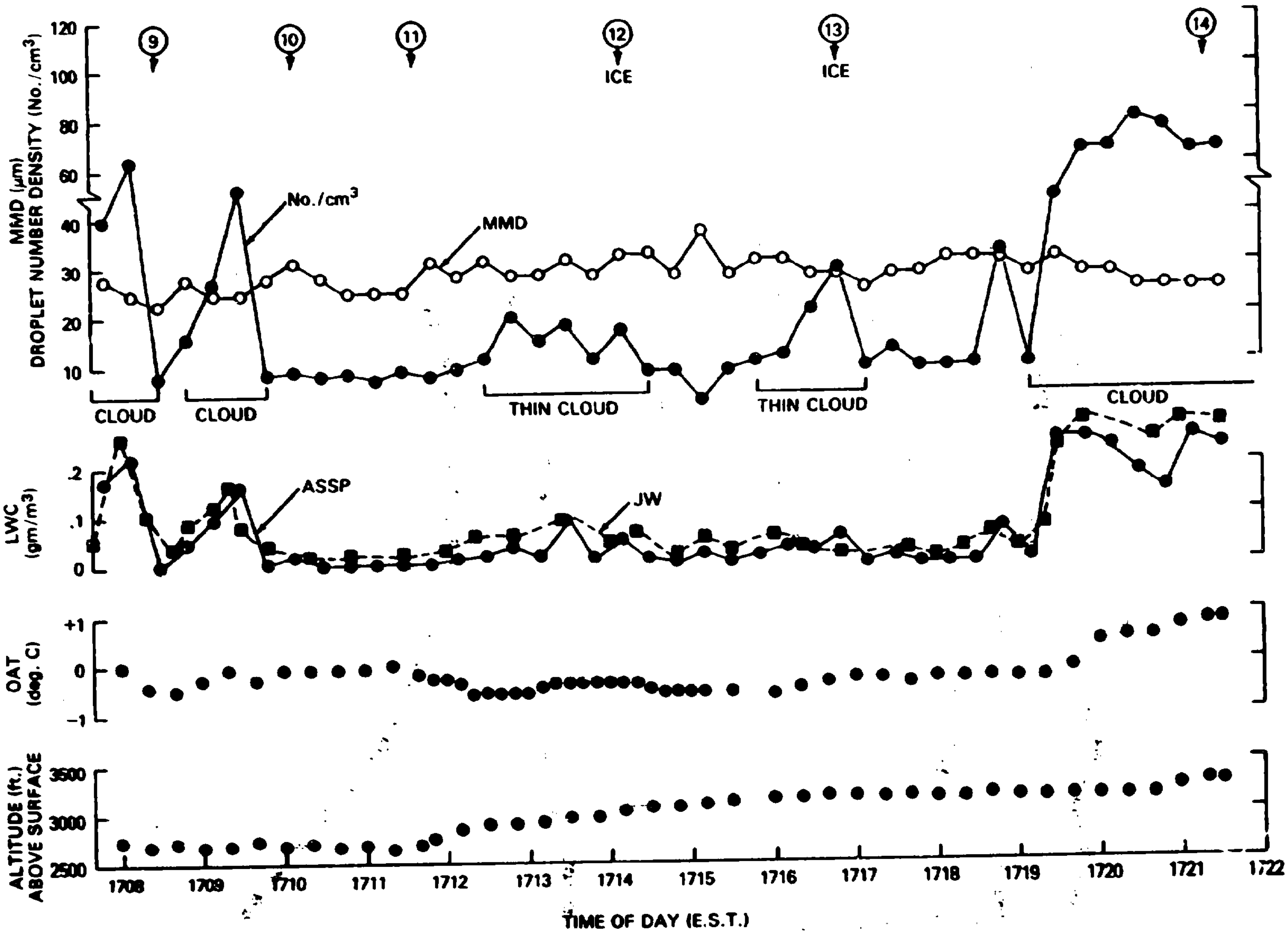

FIGURE 26. VARIABLE ALTITUDE PATH AT AND ABOVE THE STRATUS CLOUD BASE OVER LAKE MICHIGAN WEST OF MUSKEGON.

Event	Time (E.S.T.)	Alt. (Ft.)	OAT (°C)	Refer to Fig.	Description
15	1723:20	~3300	~0	-	Aircraft is still in cloud and lake is no longer visible below. A slight line of rime is present on the leading edge of the wings. The rime appears to be peeling off or is being knocked off in blotches 1-3 inches wide. Pireps "still noting light precipitation."
16	1726:30	~3400	~0	-	Slight turbulence noted for the first time. Aircraft still in continuous cloud over the lake. Pireps "still a trace of precipitation."
17	1730	~3600	~0	-	Wing de-icer boots activated for the first time to free wings of clear ice accumulation. Observed ice turn from clear to milky white and blow off here and there as the boots expanded. An estimated 1/4" of "slushy" appearing ice can be seen on the engine cowlings at this time. Pireps "no precipitation at this time" although aircraft is still in cloud. Aircraft position is 43 mi southeast of Green Bay and 5 mi east of the western shoreline of L. Michigan Heading is still NW toward Manitowoc along airway V450. Start ascent toward 4000 ft.
18	1732:30	~4000	~+0.5	-	Pireps "precipitation getting a bit heavier now." Aircraft beginning turn along western shoreline toward airway V26-55, some 10 mi to the north.
19	1740:00	4050	+0.5	27	Aircraft is now heading back east toward MKG along airway V26-55. Aircraft still in cloud and pireps "intermittent moisture". Start ascent toward 4400 ft level.
20	1742:40	4350	+0.2	27	Pireps "very slight trace of moisture".
21	1744:10	4400	+0.4	27	Aircraft now in and out of shallow cloud billows above average top of this principal cloud layer. (Another layer remains at higher altitudes). Pireps "intermittent moisture". Photo (Fig. 28) of ice aggregation on windshield wiper made at this time.

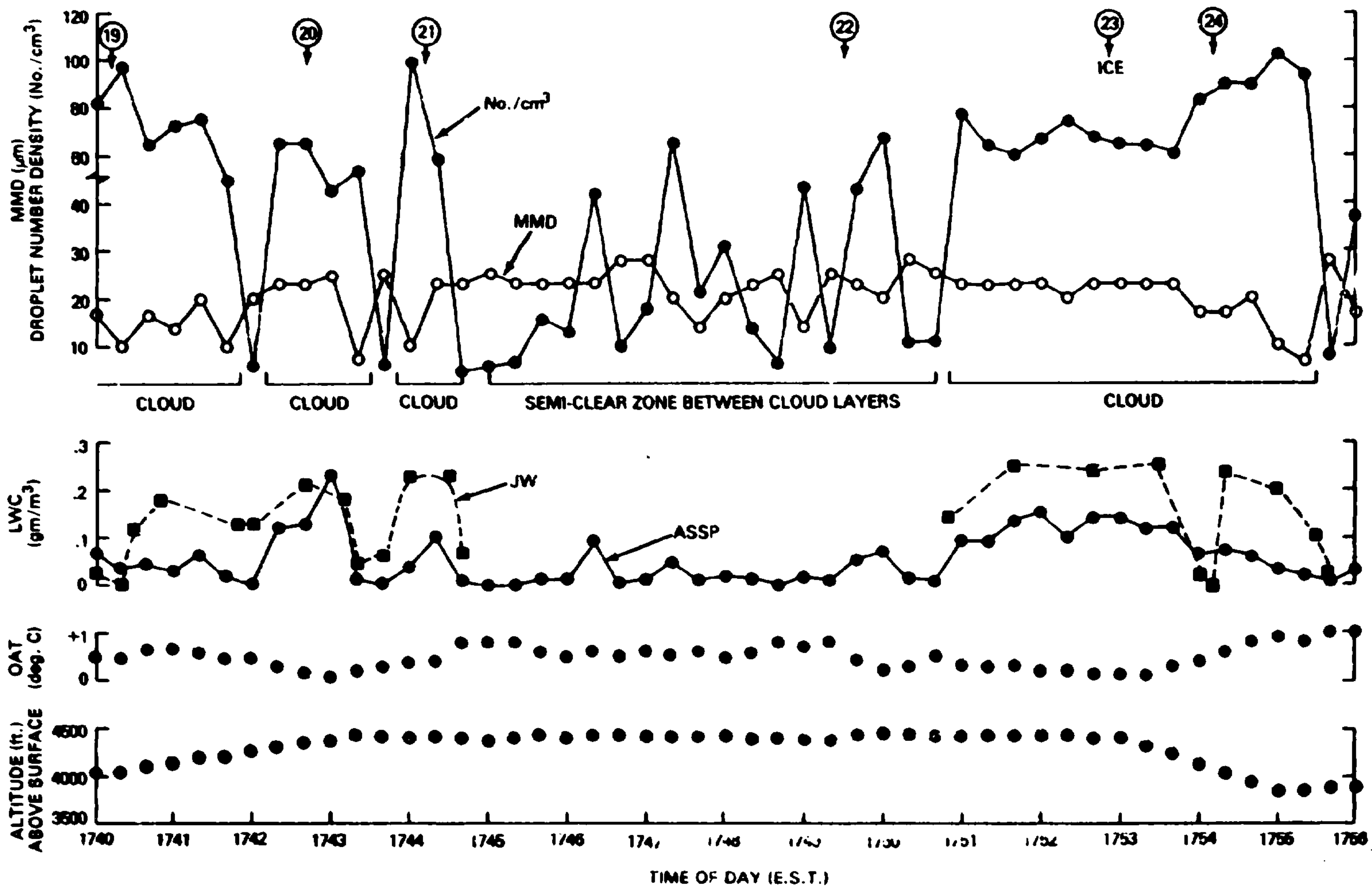

FIGURE 27. FLIGHT PATH AT, AND JUST BELOW, THE TOP OF THE PRINCIPAL CLOUD LAYER ALONG THE WESTERN HALF OF AIRWAY V26-55 OVER LAKE MICHIGAN.

Event	Time (E.S.T.)	Alt. (Ft.)	OAT (°C)	Refer to Fig.	Description
22	1749:30	4400	+0.6	27	Aircraft is now in a semi cloud-free area between cloud layers. Pireps still noting "precipitation" which apparently is falling from the overhead cloud deck.

Slow Descent to Determine Thickness of Cloud Layer at this Time and to Examine Repeatablity of Icing Conditions Observed During Preceding Ascent.

Event	Time (E.S.T.)	Alt. (Ft.)	OAT (°C)	Refer to Fig.	Description
23	1752:50	4400	+0.1	27	Aircraft has been back in continuous cloud for last 6 miles. Pireps "some ice" at this time. Start descent toward 3900 ft level.
24	1754:00	4150	+0.4	27	Pireps "heavier precipitation" in the cloud layer at this altitude.
25	1756:30	3900	+1.2	-	Begin additional 500 ft descent in cloud.
26	1757:30	3600	+1.3	-	Aircraft at cloud base - lake is visible below. Pireps "still some moisture".

Maintain Flight Level at Cloud Base Until Turn Around Point near MKG.

Event	Time (E.S.T.)	Alt. (Ft.)	OAT (°C)	Refer to Fig.	Description
27	1759:40	3500	+1.4	-	Pireps "a bit of moisture" in 1-2 mile wide, intermittent cloud parcels at cloud base.
28	1800:30	3525	+1.3	-	Aircraft crossing eastern shoreline heading SE along airway V55. Snow covered ground is visible below. Visibility is good in the downward direction and moderate in horizontal directions. Aircraft still just below cloud base.
29	1802:40	3550	+1.9	-	Pireps more "moisture" noticeable on windshield during penetrations of 1-2 mile long cloud parcels at cloud base.

Slow Ascent Back Into Cloud Layer.

Event	Time (E.S.T.)	Alt. (Ft.)	OAT (°C)	Refer to Fig.	Description
30	1807:40	3500	+1.8	29	Start turn to west to re-enter airway V450 at a position 18 mi NW of MKG. Begin ascent toward 4000 ft level in cloud layer.
31	1809:10	3600	+1.6	29	Aircraft entering cloud base.

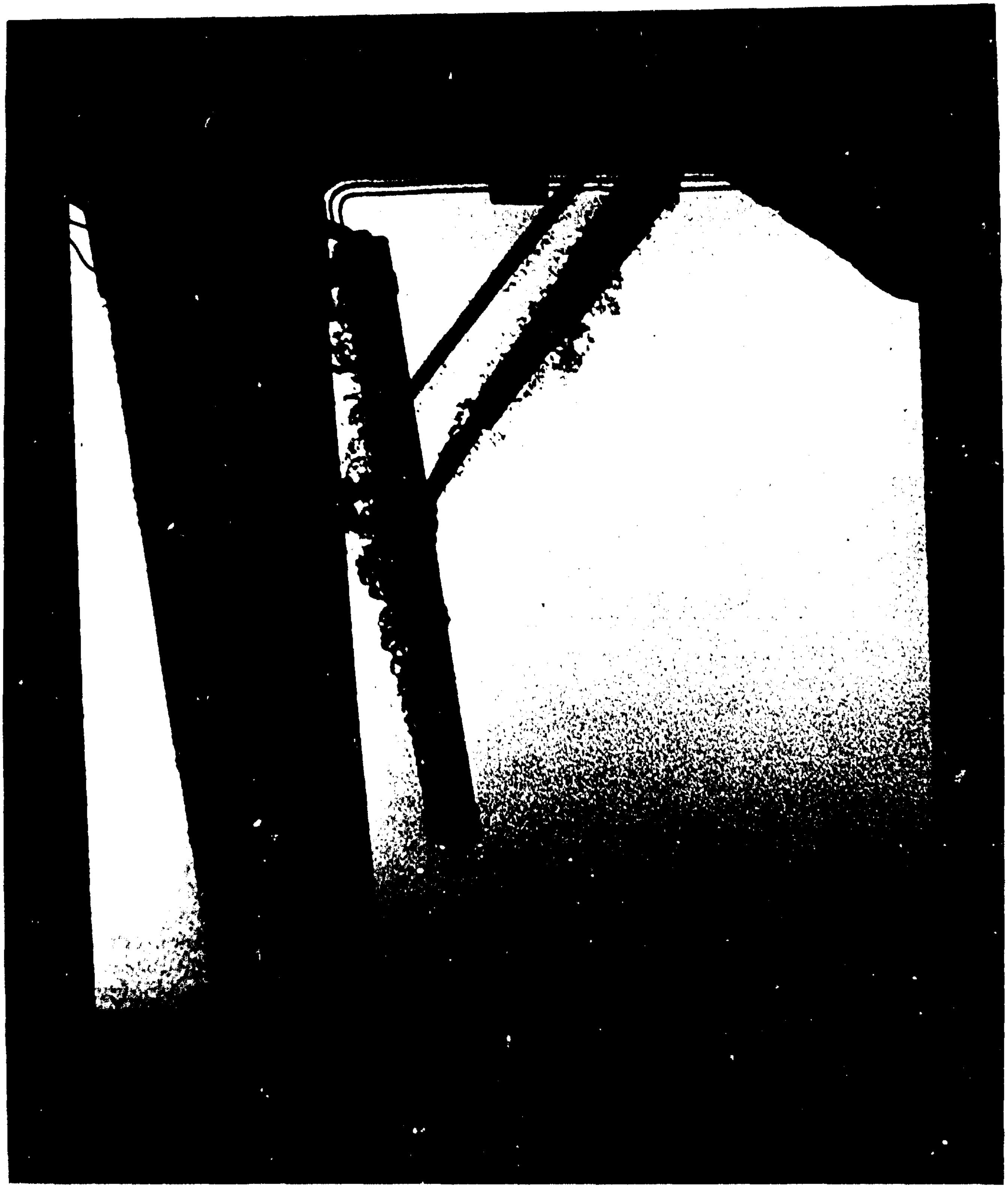

FIGURE 28. PHOTO OF ACCUMULATED ICE ON WINDSHIELD WIPERS AT 1744 E.S.T. DURING THE MARCH 7 MISSION.

Event	Time (E.S.T.)	Alt. (Ft.)	OAT (°C)	Refer to Fig.	Description
32	1810:00	3850	+0.7	29	Aircraft well into cloud now but pireps "no visible moisture" noted yet on windshield.
33	1811:30	3975	+0.6	29	Pireps "trace of moisture" noted on windshield at this altitude.
34	1813:10	3975	+0.7	29	Pireps "cloud more dense now and a bit more moisture" being observed on windshield. Ice still clinging to wiper blades and some ice is still on engine cowlings. Unable to determine visually whether any clear ice was still present on wings so pilots activated de-icer boots to fracture, and thereby reveal presence of any ice. Observed only a slight amount of ice as evidenced by the small degree of "whitening" seen during the boot expansion.
35	1816:40	4000	+0.2	29	Begin additional 500 ft ascent in cloud.
36	1818:20	4275	-0.4	29	Pireps "light icing now" noted on windshield.
37	1819:50	4475	-0.8	29	Pireps "some moisture and icing" noted at this time. ASSP droplet probe beginning to show signs of data degradation due to apparent ice interference with laser beam in sampling volume.
38	1820:50	4450	-0.9	29	Thin line of rime ice noticeable now on leading edge of wings. Rime is breaking off in blotches. Some mixed ice is quite evident on cowlings, and has the appearance of rough nuggets of about 1/4" diameter embedded in frozen slush. Some turbulence now too.

The following section, from event 39 to 42, occurs while the droplet probe was out of order due to apparent ice accumulation in the sampling volume.

Event	Time (E.S.T.)	Alt. (Ft.)	OAT (°C)	Refer to Fig.	Description
39	1824:10	4475	-1.1	-	Pireps "still a little moisture collecting on windshield and forming a little clear ice."
40	1825:40	4475	-1.0	-	Begin additional 500 ft ascent in cloud layer.

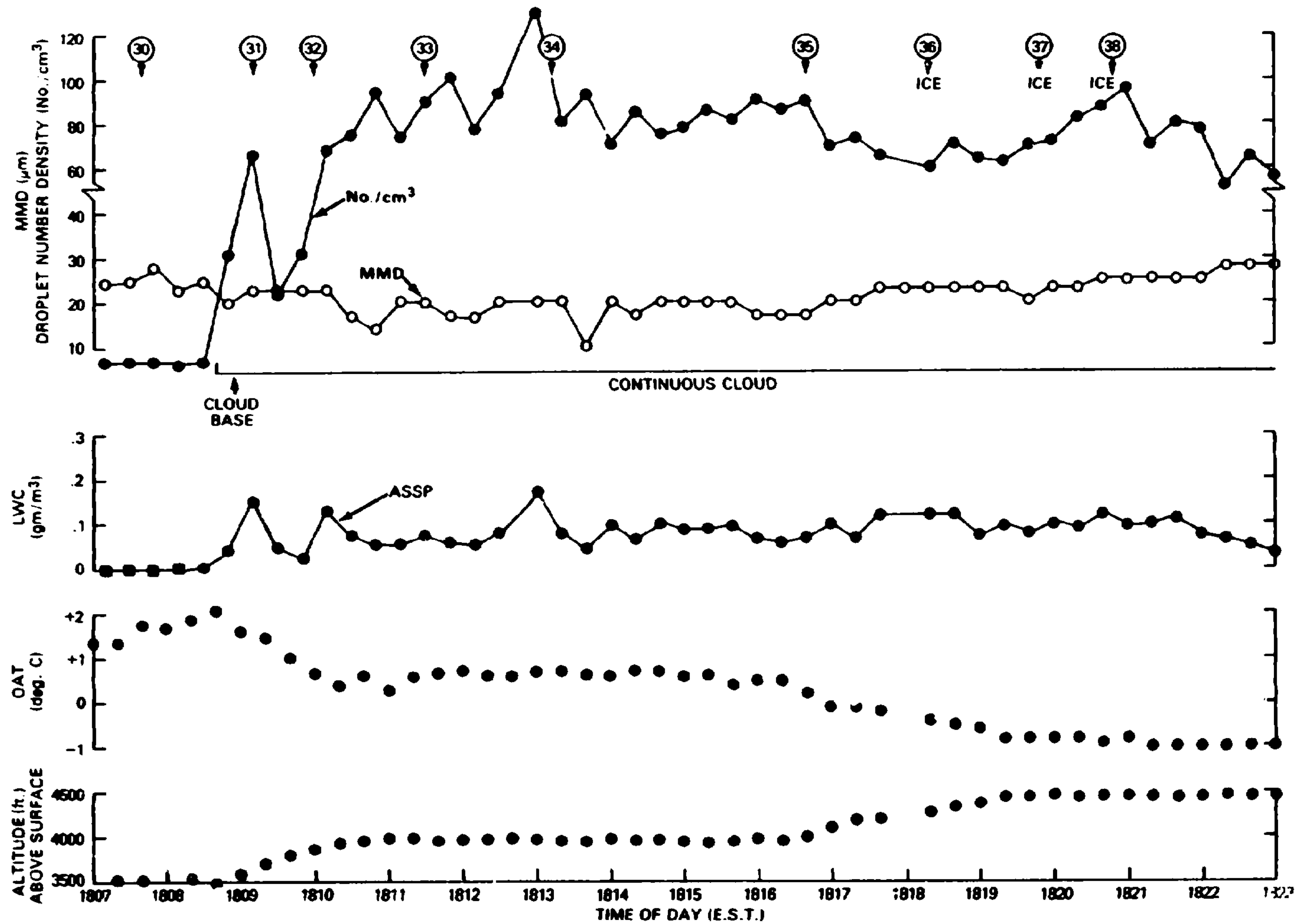

FIGURE 29. VARIABLE ALTITUDE FLIGHT PATH IN LOWEST 1000 FT OF STRATUS LAYER OVER EASTERN LAKE MICHIGAN ALONG AIRWAY V450.

Event	Time (E.S.T.)	Alt. (Ft.)	OAT (°C)	Refer to Fig.	Description
41	1828:40	4750	-1.9	-	Pireps "still seeing moisture forming on windshield and the icing rate has increased a little."
	Descend to Non Freezing Temperatures at 1600 ft Above Surface to Thaw Out Droplet Probe and Observe Rate of Ice Meltoff from Aircraft.				
A	1832:30	~4900	~-2	-	Begin descent toward 1600 ft.
B	1834:30	~3400	~+1.5	-	Photo (Fig. 30) made of present accumulation of ice on wings and cowlings. Ice thickness on cowling is estimated to be 1/2" to 1" now.
C	1835:20	~3100	~+1.5	-	Pireps "ice coming loose from windshield wipers now".
D	1839	1600	+1.3	-	Aircraft is already heading back toward MKG on second NW-SE pass over lake. Present position is 35 mi SE of Green Bay. Aircraft well below cloud.
E	1840	1600	+1.3	-	Large pieces of ice can be seen blowing off of engine cowlings now.
F	1841	1600	+1.3	-	Some turbulence is noticeable again at this time. The surface of the lake, over 50% covered with ice floes, is visible below.
42	1842:00	1600	+1.3	-	Droplet probe still not operating properly, but wings and cowlings are completely ice free now.
	Slow Ascent Through Cloud Layer for Final Ascending Profile.				
43	1844:00	1600	+1.8	-	Begin slow ascent along NW-SE heading, starting at a position about 70 mi NW of MKG.
45	1848:20	3050	-1.0	-	Pireps "moisture" seen on windshield now" but aircraft is not in cloud yet. Lake can still be seen below.
46	~1850	~3400	-0.8	-	Pireps "light moisture" observed, but aircraft still not in cloud.
47	1852:30	3900	-1.5	-	Aircraft encountering some cloud fragments which appear to be part of

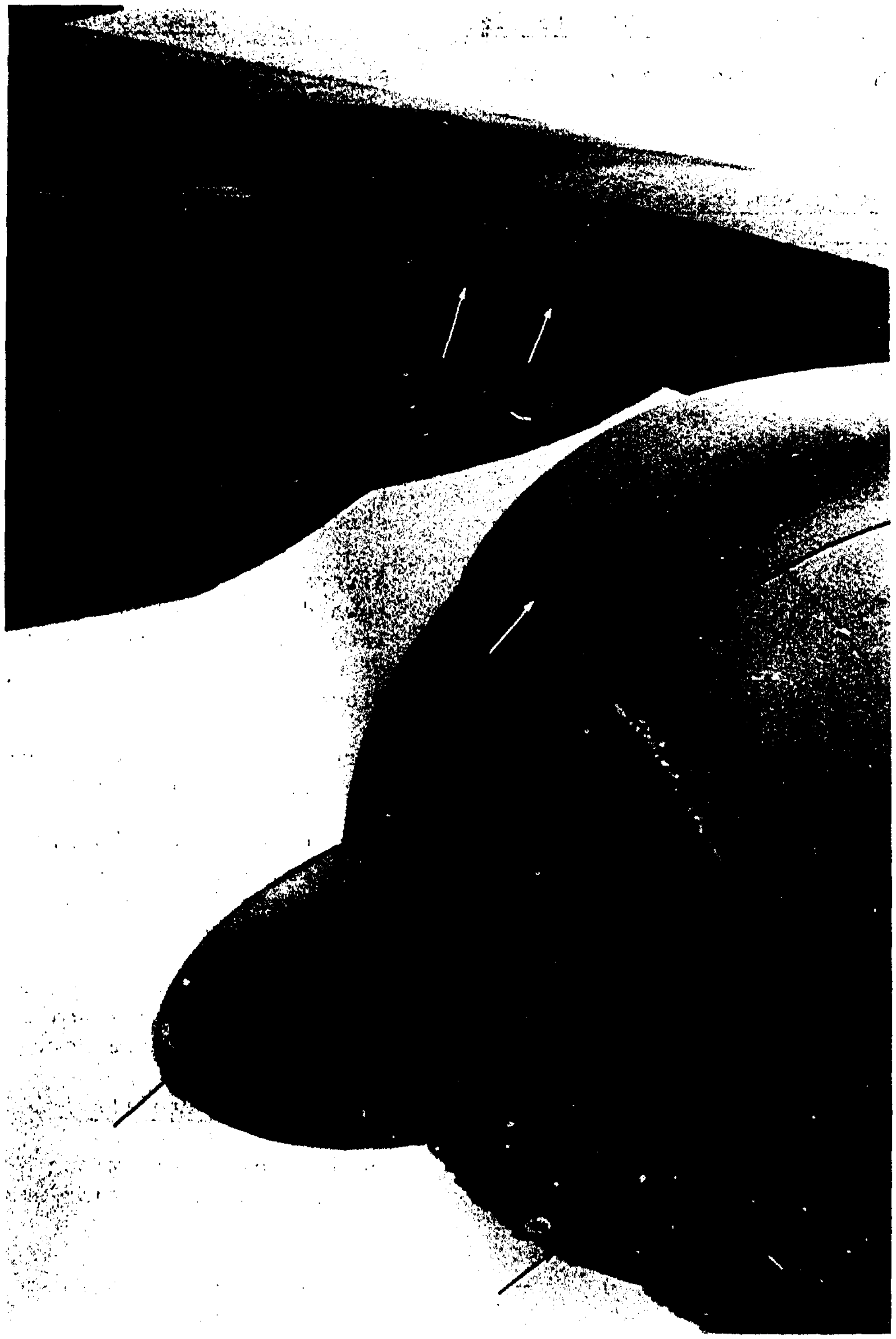

FIGURE 30. PHOTO OF ACCUMULATED ICE ON ENGINE COWLING AT 1834 E.S.T. Ice on cowling is visually estimated to be one-half to one inch thick. Arrows indicate noticeable accretions.

Event	Time (E.S.T.)	Alt. (Ft.)	OAT (°C)	Refer to Fig.	Description
					of a thin, broken layer below the main cloud deck at this time and location. Sky becoming darker as dusk progresses.
G	1853:40	4200	-2.3	-	Aircraft entering cloud base.
48	1856:30	4875	-3.6	-	Pireps "moisture" and light icing" now.
49	1858:30	5275	-3.3	-	Aircraft just breaking out of nearly smooth top of cloud layer. Cloudless sky is above. Begin nearly level flight just above cloud layer.
50	1900:50	5400	-2.8	-	Pireps "moisture and ice" forming intermittently as aircraft penetrates occasional shallow billows projecting above layer.
					Slow Descent Through Cloud Layer for Final Descending Profile
51	1902:20	5225	-2.8	-	Begin slow descent starting at 39 mi NW of MKG. Slight amount of rime noticeable now on wings and cowlings.
52	1903:20	4800	-2.1	-	Pireps "very light moisture in cloud now".
53	1904:50	4150	-0.9	-	Aircraft at cloud base already - snow covered ground is visible below. The stratus layer at this location near MKG is considerably thinner, and cloud base is higher compared to earlier passes. End of data collection for this mission.

IV Summary of Results

A) Comparison of Initial NRL Measurements with Historical Data.

1. Liquid Water Content

Examination of the data plotted in Figs. 1, 2, and 3 shows that the NRL data fall well within the lower half of the range covered by the historical data for layer clouds below 6000 ft. pressure altitude. The principal reason for this result is presumably that the reported historical data are intentionally representative of the upper levels of layer clouds where the LWC is a maximum, since an object of those early studies was to determine the maximum icing conditions that aircraft could encounter during flight. The NRL data are intentionally from various levels within the cloud layers that were encountered and may be low, relative to the historical data, for that reason.

Another impediment to intercomparison with the NRL data and to further use of the historical data for helicopter icing studies is the lack of information about cloud layer thicknesses and cloud base temperatures in the historical data. The vertical distribution of LWC in layer clouds as a function of layer thickness and base temperature, for example, may be a useful way to organize the data for low altitude helicopter applications in addition to the less informative presentations such as in Figs. 1, 2, and 3. Lewis' first report on LWC measurements (Ref. 4) did follow this approach but it was abandoned in all later reports in favor of the more familiar statistical presentations.

The spread in the error limits in the NRL liquid water content data is due principally to uncertainties in the data from the particular Johnson-Williams unit used during these missions. The abnormally high level of noise and drift in the JW-LWC signal made it unusable some of the time. Even after the JW-LWC signal had been corrected as well as possible, the indicated LWC was still generally greater than that derived by computation from the measured droplet size distribution. Since the largest droplet that can be measured by the ASSP is 45 μm diameter, the LWC values derived from the ASSP will be underestimated when there is a significant amount of liquid water in drops larger than this size. Thus, the ASSP-derived data may be taken as a lower limit for the LWC while the corrected Johnson-Williams data may possibly serve as an estimated upper limit to the LWC present at a given time.

2. Incidences of Icing vs OAT.

The principal comment to be made here is that, as can be seen from Fig. 2, the majority of recorded icing events have occurred at air temperatures in the relatively narrow range from +20°F to +27°F. In fact, the historical data show a cutoff at +27°F. This may reflect a decision by the earlier investigators to disregard measurements taken at warmer temperatures in order to avoid errors from runoff due to incomplete freezing of impacted droplets on the rotating multicylinders.

The NRL data include two occurrences of icing at temperatures of +31°F and +32°F. These occurrences were based on observations by the pilots of the NRL aircraft and, although the ice formation was soft at these warmer temperatures, the effects were noticeable on the windshield wipers and these icing events were thus valid ones. The rotating multicylinders would have yielded no reliable LWC information for these events because of runoff errors. Note that icing rate meters which respond to the net accumulation of ice would still be useful for research purposes in these cases.

3. Mass Median Droplet Diameters (MMD).

Reference to Fig. 3 will show that the values of MMD obtained from the NRL measurements are larger than for the majority of icing events studied by the earlier investigators. This is an interesting result for several reasons. One is that it implies that the rotating multicylinder method systematically underestimates the MMD, assuming that the clouds encountered during the NRL flights are typical of those studied by the earlier investigators, and assuming that the high resolution droplet size spectra from the ASSP are accurate and free from unknown systematic errors themselves.

A second reason is that the amount by which the MMD is underestimated by the multicylinder method is all the more remarkable if the measurements were made in the upper levels of a given layer cloud where the MMD (as well as the LWC) are generally a maximum.

A third point to be made is that the NRL measurements have shown in a number of cases, principally at, or just below cloud base, that large values of MMD, e.g., greater than about 30μm, occur simultaneously with low values of droplet number density. Such cases may be seen in Figs. 18, 21, 22, and 23 of this report. One of these cases where icing was observed simultaneously is plotted at 30 μm MMD in Fig. 3 corresponding to a LWC of approximately 0.09 gm/m^3. Although such cases represent relatively low values of LWC and icing rate, the fact that they occur near cloud base makes it significant for present interests where one can imagine helicopters being flown just below cloud base in order to maintain altitude without losing visibility.

One aspect of this particular example (near Event 12, Fig. 26) that calls for further study, however, is the fact that the pilots were reporting light rain at the time. This may imply freezing rain as the important factor in this case, and the LWC and MMD would be even greater than indicated by the ASSP.

B) Other Observations and Conclusions.

1. Visual Icing Threshold on the EC-121 Aircraft.

When one examines the data for the cases where the pilots were reporting the occurrence of ice, principally from observations of the unheated windshield wiper blades, the following conclusions appear to hold.

a) - The pilots were unable to detect any ice formation unless the LWC (as derived from the ASSP data) was at least 0.08 to 0.10 gm/m^3 and the associated cloud was at least two miles wide.

b) - For these cases the MMD and droplet number density were always greater than 17 µm and 60 cm^{-3}, respectively, except for the one case at cloud base where light rain was reported and the indicated N was 30 cm^{-3} or less.

c) - For the cases where the OAT was sub freezing and the aircraft was in cloud but no icing was reported by the pilots, the LWC was less than the 0.08-0.1 gm/m^3 "threshold" and the MMD was smaller (10-14 µm) while N was very large. That is, the cloud consisted only of many small droplets at those times.

2. Variability of Cloud Conditions

During both the missions reported here, considerable variability was noted in cloud base height, cloud layer thickness, and in the number of distinct layers as a function of position and time. In such circumstances, it can be appreciated that the prediction of icing severity and extent at a given location or altitude would be difficult except perhaps for forecasting the worst icing conditions to be expected for a given period.

3. Rain as a De-Riming Agent

On three occasions (Event 34 of March 6 and Events 15 and 38 of March 7) accumulations of rime ice on the leading edges of the wings were seen to be breaking away in one- to three- inch wide blotches. In all three cases the OAT was near, or slightly below, freezing such that one may expect de-icing to occur anyway. However, the pilots were also reporting light rain at these times which may mean that some combination of mechanical and thermal processes associated with the impaction of relatively large droplets onto a rimed surface at near-freezing temperatures may help dislodge the accumulated rime.

4. Data Needed for Helicopter All Weather Certification

If anti-icing or de-icing equipment is to be designed for all weather protection of helicopters, then the maximum expected icing rates, LWC, and MMD will have to be determined, as in the past, for clouds within some specified altitude limits.

The historical data (Fig. 1) show that the liquid water content encountered in layer clouds at altitudes less than 5000 ft above the surface will be less than 0.6 gm/m^3 for over 95% of the cases. The initial data collected by NRL does not challenge this upper limit for LWC except for the uncertainty associated with occurrences of "rain" which imply that droplets were present with sizes larger than were detectable by the apparatus in use at the time.

However, the NRL data do suggest that the mass median diameters arrived at by the earlier researchers with the rotating multi-cylinder probes are generally too small. Additional measurements are needed to verify this contention and to assess the contribution of the frequently observed "rain" to the total LWC. Future NRL flights will include a PMS Optical Array Probe (OAP) for determining size spectra of droplets between 20 and 300 μm diameter.

References

1. Federal Aviation Regulations, Part 25, Airworthiness Standards: Transport Category Airplanes, DOT/FAA, Washington, D. C. (1974).

2. "Forecaster's Guide on Aircraft Icing," Air Weather Service Manual 105-39, U.S.A.F. (1969).

3. J.K. Hardy, "Measurement of Free Water in Cloud under Conditions of Icing", NACA ARR 4111 (1944).

4. W. Lewis, "Icing Properties of Noncylonic Winter Stratus Clouds", NACA TN 1391 (1947)

5. W. Lewis, "Icing Zones in a Warm Front System with General Precipitation", NACA TN 1392 (1947).

6. W. Lewis, "A Flight Investigation of the Meteorological Conditions Conducive to the Formation of Ice on Airplanes", NACA TN 1393 (1947).

7. W. Lewis, D.B. Kline, and C.P. Steinmetz, "A Further Investigation of the Meteorological Conditions Conducive to Aircraft Icing," NACA TN 1424 (1947).

8. D.B. Kline, "Investigation of Meteorological Conditions Associated with Aircraft Icing in Layer-Type Clouds for 1947-48 Winter", NACA TN 1793 (1949).

9. W. Lewis and W.H. Hoecker, Jr., "Observations of Icing Conditions Encountered in Flight During 1948", NACA TN 1904 (1949).

10. D.B. Kline and J.A. Walker, "Meteorological Analysis of Icing Conditions Encountered in Low Altitude Stratiform Clouds," NACA TN 2306 (1951).

11. W. Rasmussen, et al., "Thermal Anti-Icing Tests, DC-6", United Airlines Report F-81-14 (1947).

12. D. North, "Icing Test Flights of Curtiss No. 124171-1 Propeller De-Icing Shoes on DC-6 Airplane NX90725," American Airlines Report DC-6-1934X14 (1948).

13. W. Lewis and N.R. Bergun, "A Probability Analysis of the Meteorological Factors Conducive to Aircraft Icing in the United States," NACA TN 2738 (1952).

14. P.T. Hacker and R.G. Dorsch, "A Summary of Meteorological Conditions Associated with Aircraft Icing and a Proposed Method of Selecting Design Criterions for Ice Protection Equipment," NACA TN 2569 (1951).

15. I. Langmuir and K.B. Blodgett, "A Mathematical Investigation of Water Droplet Trajectories," General Electric Report, (July 1945).

16. F.H. Ludlam, "The Heat Economy of a Rimed Cylinder," Quart. J. Roy. Met. Soc., 77, 663 (1951).

17. W. Kleuters and G. Wölfer, "Some Recent Results on Icing Parameters," proc. of Sept. 1977 meeting Of the NATO Advisory Group for Aerospace Research and Development, Ottawa, Canada; report No. AGARD-AR-127.

18. Particle Measuring Systems (PMS), Inc., 1855 South 57th Court, Boulder, Colorado 80301.

19. G. Mie, Ann. Phys., 25, 377 (1908).

20. R.G. Knollenberg, "Comparative Liquid Water Content Measurements of Conventional Instruments with an Optical Array Spectrometer", J. Appl. Met., 11, 501-8 (1972).

21. J.E. Dye and D.W. Breed, "The Microstructure of Clouds in the High-Frequency Hail Area of Kenya," J. Appl. Met., 18, 95 (1979).

22. R.E. Ruskin and W.D. Scott, in Weather and Climate Modification, W.N. Hess, editor, John Wiley & Sons, New York (1974), p. 146

23. D.T. Bowden, A.E. Gensemer, and C.A. Skeen, "Engineering Summary of Airframe Icing Technical Data," FAA Tech Rept. ADS-4 (1964).

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