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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

Flight icing-rate data obtained in a dense and abnormally deep supercooled stratiform cloud system indicated the existence of liquid-water contents generally exceeding values in amount and extent previously reported over the midwestern sections of the United States. Additional information obtained during descent through a part of the cloud system indicated liquid-water contents that significantly exceeded theoretical values, especially near the middle of the cloud layer. The growth of cloud droplets to sizes that resulted in sedimentation from the upper portions of the cloud is considered to be a possible cause of the high water contents near the center of the cloud layer. Flight measurements of the vertical temperature distribution in the cloud layer indicated a rate of change of temperature with altitude exceeding that of the moist adiabatic lapse rate. This excessive rate of change is considered to have contributed to the severity of the condition.

INTRODUCTION

Measurements of the meteorological characteristics of supercooled clouds obtained by the NACA and other organizations during flights in icing conditions have permitted tentative specifications of liquid-water contents, droplet sizes, and cloud temperatures for use in the design of aircraft thermal ice-protection systems. A more reliable specification of typical and, in particular, probable maximum extent

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[1]U. S. Weather Bureau Meteorologist assigned to work in collaboration with the NACA Lewis laboratory staff in icing research program.

and severity of icing conditions is dependent upon the continued accumulation of flight data, preferably during routine flight operations. As additional data are gathered, the range of meteorological conditions and the variety of cloud systems surveyed will be extended.

The provision of equipment adequate for complete ice protection against the most severe conditions that nature can produce may often be impractical because of performance penalties or reduced payload. However, data indicating the meteorological characteristics of the extremely severe icing encounters are desirable to provide designers and operators with information on which to judge the limitations of available equipment and the design of future equipment, and to assist operating personnel in determining proper navigation techniques through such hazardous areas to alleviate the high rates of ice accretion. Increased reliability in flight forecasting and meteorological advisory service may also be possible as the weather situations and the atmospheric conditions that cause or are associated with potentially hazardous icing conditions are more completely understood.

Data recently obtained during an icing-research flight conducted from the NACA Lewis laboratory indicated the existence in a continuous icing condition of supercooled liquid-water contents that exceeded those previously encountered and measured during four winters of flight operations over the midwestern sections of the United States. The liquid-water content also exceeded those reported by the NACA from icing flights conducted in other geographical areas of the continental United States.

The data are presented in this report because of their possible interest and significance to aircraft designers, operators, and aeronautical meteorologists and as a contribution to the large amount of flight measurements of the physical characteristics of supercooled clouds required for an adequate statistical analysis of meteorological parameters associated with icing conditions.

APPARATUS AND PROCEDURE

The meteorological instrumentation on the research aircraft permitted continuous measurements of liquid-water content during flight and, in addition, made available data concerning the vertical variation of liquid-water content through a dense region of the stratiform cloud layer.

These data were obtained with a rotating-disk-type icing-rate meter calibrated to measure liquid-water content of icing clouds. This instrument was first developed by the Massachusetts Institute of Technology (reference 1) and consisted essentially of a rotating disk edgewise to the air stream, a feeler for measuring the thickness of ice collected on the edge, and a scraper for removing the ice after it had been measured. A photograph of the instrument in operation is given in figure 1(a). The complete instrument is shown in figure 1(b) mounted on the left side of the fuselage of the research aircraft used in this investigation.

The design of the original meter was modified and the operating characteristics were investigated by the NACA to obtain a suitable instrument for meteorological studies. The disk rotates at approximately 7 rpm, a speed which permits measurements of liquid-water content within relatively short distances along the flight path. This rotational speed combined with ice collection during only 160° of rotation gives an ice-collection time short enough to average the liquid-water content over a distance of 1000 feet at a flight speed of 180 miles per hour. Ice-thickness measurements (magnified 86 times), rotational speed of the disk, and elapsed time are all recorded on photographic film (fig. 2) through a system of lights and mirrors.

In a previous series of flight icing investigations, unpublished data obtained with this meter were compared with that obtained by the rotating-multicylinder technique described in reference 2. From these investigations, the disk was found to collect between 50 and 70 percent of the liquid water measured by the multicylinders. The values of liquid-water content presented in this report were calculated from the icing-rate measurements by using a 60-percent ice-collection relation based on the multicylinder comparison and therefore contain errors inherent in the multicylinder method.

The multicylinder technique was used during this flight to obtain measurements of droplet sizes within the icing clouds in which the liquid-water contents were being measured by the icing-rate meter.

The airspeeds and the altitudes were recorded during the flight on photographic film with two pressure capsules and mirror systems developed by the NACA for flight use. The airspeed could be read from these records to an accuracy of ±2 miles per hour and the altitude within ±50 feet. Outside air temperature was obtained with a shielded-type thermocouple developed by the NACA to measure air temperatures under icing conditions without realizing the heat of fusion from ice accretions. This temperature probe was calibrated both in the laboratory and in flight and found to have a temperature recovery in wet air of approximately 0.6 of the full dry adiabatic temperature rise.

The flight plan used to obtain the meteorological data consisted of a departure from Cleveland, Ohio, on January 4, 1951 at approximately 11:00 a. m. (e. s. t.) followed by a climb to the base of the clouds where a northeast heading was established along a flight path over the south shore of Lake Erie. A climb was then made into the icing cloud near Perry, Ohio to a pressure altitude of 5000 feet where a horizontal traverse of the cloud at an average true airspeed of 180 miles per hour was made over a distance of approximately 65 miles to a point near Erie, Pennsylvania. The traverse ended at this point because of aircraft traffic-control problems and a 180° turn was made, followed by a climb to 6000 feet (pressure altitude). A horizontal traverse was also made at this altitude to a point near the original entrance into the cloud layer where the aircraft broke out of the clouds. A slow descent was then made to obtain a detailed variation of liquid-water content through the dense cloud layer below. The flight terminated at Cleveland at approximately 12:15 p. m. (e. s. t.).

RESULTS AND DISCUSSION

The continuous record of icing rate obtained by the icing-rate meter during approximately 45 minutes of flight in the extensive supercooled cloud system was used to calculate, for each 15-second interval of time, the liquid-water content encountered in the cloud. Figure 3 is a plot of the variation of the calculated values of water content with time in the cloud at pressure altitudes of 5000 and 6000 feet. Also shown in figure 3 are the time intervals and the values of liquid-water content calculated from data obtained during two rotating-multicylinder exposures. Mean-effective droplet diameters of 9 and 6 microns for exposures 1 and 2, respectively, were calculated from the multicylinder data. Extremely wide droplet size distributions (H and G, exposures 1 and 2, respectively, based on the theoretical distributions defined in reference 3) apparently existed during the cylinder exposures. These wider theoretical distributions are usually not definitive by this technique. The absolute accuracy of the values of liquid-water contents based on icing-rate-meter data cannot be completely evaluated because of the unknown magnitude of errors inherent in the multicylinder technique on which the calibration of the icing-rate meter was based. Errors considered to be inherent in the multicylinder technique at flight speeds include loss of cloud droplets due to run-off or bounce-off, which results in measured values less than those actually existing in supercooled clouds.

The severity of the icing condition in terms of liquid-water content is summarized in figure 4. For each of the altitudes flown, the data points plotted in figure 3 were arranged so as to obtain cumulative-frequency data. Because each 15-second observation of liquid-water concentration at an average true airspeed of 180 miles per hour represents 3/4 mile flown in the cloud, the miles of flight in conditions exceeding a given water concentration were plotted rather than the conventional frequency of occurrence of specified values.

Thus, at an altitude of 5000 feet, a liquid-water content of more than 1.20 grams per cubic meter was encountered over a cumulative distance of 6 miles, whereas values exceeding 1.00 gram per cubic meter were measured over a total distance of 27 miles. A supercooled-water concentration greater than 0.60 gram per cubic meter existed over 52 miles of the total distance of 65 miles flown at 5000 feet. The average water content measured at 5000 feet was 0.86 gram per cubic meter.

Icing conditions encountered at 6000 feet (fig. 4) were less severe than those at 5000 feet. The average liquid-water content was 0.58 gram per cubic meter. The maximum liquid-water content reached 1.48 grams per cubic meter for a short distance after reversal in direction of flight and climb to the higher altitude were accomplished. The clouds encountered at the higher level were associated with a second cloud layer that merged with the lower denser, supercooled, stratiform cloud along the southern shoreline of Lake Erie.

Comparison of the meteorological data obtained during this flight with those measured during previous research flights (references 4 and 5) indicates that, in terms of distances flown in specified icing conditions, the condition reported herein exceeded values previously reported. The maximum measured average liquid-water content over a distance of approximately 65 miles reported in reference 4 was 0.73 gram per cubic meter compared with 0.86 gram per cubic meter reported herein. For the same distance, reference 5 indicated a maximum measured liquid-water content of only 0.48 gram per cubic meter.

Vertical Variation of Liquid-Water Concentrations

Information concerning the vertical variation of the meteorological variables in icing clouds is of use in studies of the structure of clouds and in the determination of navigation procedures that will reduce the rate of ice accretion to tolerable limits. Such information is of particular interest in this instance because of the severe nature of the icing encounter.

Near the termination of the flight, a descent was made through a dense portion of the lower cloud layer. The continuous record of icing rate obtained while altitude was being reduced at approximately 350 feet per minute is shown in figure 2. The horizontal distance flown in the cloud during the descent and survey was 20 miles. Liquid-water-content values calculated from the icing rate are presented in figure 5 as a function of height above the base of the cloud. No measurements of ice accretion were obtained in the lowest 200 feet of the cloud layer because of the marginal freezing-point temperature on the measuring instruments caused by kinetic and frictional heating effects.

If the assumption is made that no sedimentation or entrainment is occurring and that a cloud layer is characterized by complete adiabatic mixing, the liquid-water content at any level in the cloud may be calculated by considering an air parcel to be lifted adiabatically from the condensation level. The amount of condensate is determined by the change in saturation mixing ratio of the adiabatically ascending air parcel and may be calculated according to the formula:

$$m = (w_0 - w_1)\rho$$

where

m liquid-water content, grams per cubic meter

w_0 saturation mixing ratio at cloud base, grams of water vapor per kilogram of dry air

w_1 saturation mixing ratio at upper level in cloud, grams of water vapor per kilogram of dry air

ρ density of dry air at cloud top, kilograms per cubic meter

One curve in figure 5 was computed according to this procedure on the assumption of a moist adiabatic lapse rate by using a cloud-base temperature of 28° F, which was based on flight measurements and is in agreement with U. S. Weather Bureau radiosonde data near the flight area, obtained approximately 2 hours prior to the cloud survey. This assumption gave a temperature of 19° F at the cloud tops. However, a flight temperature measurement of 17° F at 5200 feet indicated the existence of a temperature lapse rate exceeding the moist adiabatic rate. This vertical temperature distribution would account for additional liquid-water concentrations. Another curve was therefore computed on the basis of the flight measurement of the lower temperature in the cloud tops.

Relative to the theoretical calculations based on flight data the maximum measured liquid-water concentrations near the cloud tops agree with the calculated amounts within the probable accuracy of the data. Liquid-water contents measured from near the top to the center of the cloud layer indicated the existence of water contents significantly exceeding possible theoretical values. Because of the occurrence of freezing precipitation (mixed with snow grains) at ground level near the eastern terminus of the flight area between 12:30 and 1:30 p. m. with all levels in or above the cloud layer at subfreezing temperatures, and the wide distribution of droplet sizes indicated by the multicylinders, growth of the supercooled droplets to sizes sufficient to cause appreciable sedimentation was evidently occurring. Cloud droplets falling from the upper regions of the cloud layer therefore probably increased the liquid-water contents at lower levels in the cloud. Visual observations below the cloud layer during the descent from 12:09 to 12:15 p. m. indicated that no precipitation products had reached the clear air below the cloud layer at that time.

Synoptic Weather Conditions

A weather map plotted from 1:30 p. m. (e. s. t.) U. S. Weather Bureau surface weather observations is shown in figure 6. The center of the low-pressure area with which the cold front along the eastern coastal area was associated had moved over southern Lake Huron late during the day preceding the flight. The cold front reached the western edge of the flight area by 1:00 a. m. the day of the flight, and moved eastward at approximately 35 miles per hour, decelerating slightly after passing the western Pennsylvania area. The cloud layer in which the icing flight was conducted was apparently formed by turbulent mixing in the lower levels of the atmosphere. Additional moisture was available as the air moved across Lake Erie. Available meteorological reports of cloud cover, temperature, and the lack of measurable rates of precipitation, which was shown in reference 4 to be a usable criterion for judging the existence of supercooled liquid water, indicated that the cloud layer with potential icing conditions extended to central New York state. The western edge of the overcast clouds was between Toledo and Cleveland, Ohio during the time of the flight. The total horizontal extent of this icing condition is therefore estimated to have been at least 450 miles. Its severity over other than the flight area is unknown.

A flight report within 40 miles of the area over which the data were obtained, but 1 hour earlier, indicated the existence of two cloud layers, the top of the lower layer being 5500 feet (mean sea level), which corresponded with the tops encountered during the cloud survey, but with an upper cloud layer extending to 8000 feet. The two cloud layers apparently merged over the flight area because no evidence of a discontinuity in the clouds existed during the climb to 6000 feet, though the icing rate diminished considerably as is indicated in figures 2 and 3. Icing conditions therefore probably existed through a vertical distance extending from 2600 to about 8000 feet, which equals the maximum vertical extent of icing clouds observed during the 48 encounters reported in reference 4.

SUMMARY OF RESULTS

Data obtained during flight in an unusually dense supercooled stratiform cloud system indicated an average liquid-water content of 0.86 gram per cubic meter over a distance of 65 miles which exceeded values previously reported. Values exceeding 1.00 gram per cubic meter were encountered over a cumulative distance of 27 miles at an assigned altitude of 5000 feet, and 0.60 gram per cubic meter was exceeded over 80 percent of the total distance flown.

Factors that contributed to the severity of the icing condition were considered to be (1) the movement of the air across Lake Erie, (2) the existence of a temperature lapse rate in the cloud layer in excess of the moist adiabatic, (3) the growth of cloud droplets to sizes permitting sedimentation from the upper portions of the cloud layer and thus increasing the liquid-water content of the lower levels in the cloud, and (4) the unusual depth of the supercooled clouds because of the merging of two cloud layers. This unusual vertical extent of the clouds would have, depending upon the flight procedures, necessitated extreme changes of flight altitude to avoid the icing condition completely.

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REFERENCES

1. Vonnegut, B., Cunningham, R. M., and Katz, R. E.: Instruments for Measuring Atmospheric Factors Related to Ice Formations on Airplanes. De-Icing Res. Lab., Dept. Meteorology, M.I.T., April 1946.

2. Anon.: The Multicylinder Method. Mount Washington Monthly Res. Bull., vol. II, no. 6, June 1946.

3. Langmuir, Irving, and Blodgett, Katherine B.: A Mathematical Investigation of Water Droplet Trajectories. Tech. Rep. No. 5418, Air Materiel Command, AAF, Feb. 19, 1946, (Contract No. W-33-038-ac-9151 with Gen. Elec. Co.).

4. Kline, Dwight B., and Walker, Joseph A.: Meteorological Analysis of Icing Conditions Encountered in Low-Altitude Stratiform Clouds. NACA TN 2306, 1951.

5. Lewis, William: A Flight Investigation of the Meteorological Conditions Conducive to the Formation of Ice on Airplanes. NACA TN 1393, 1947.

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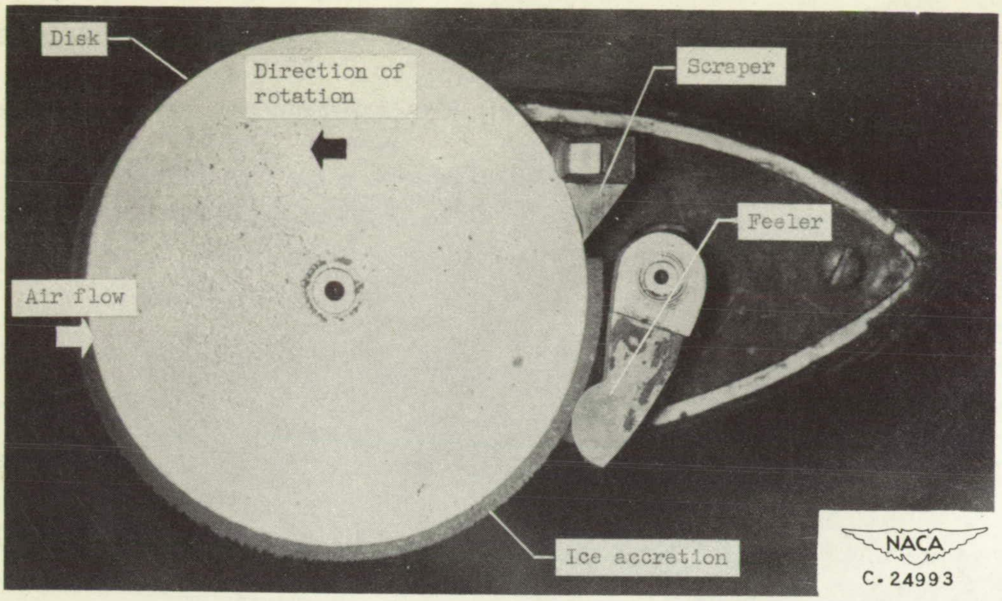
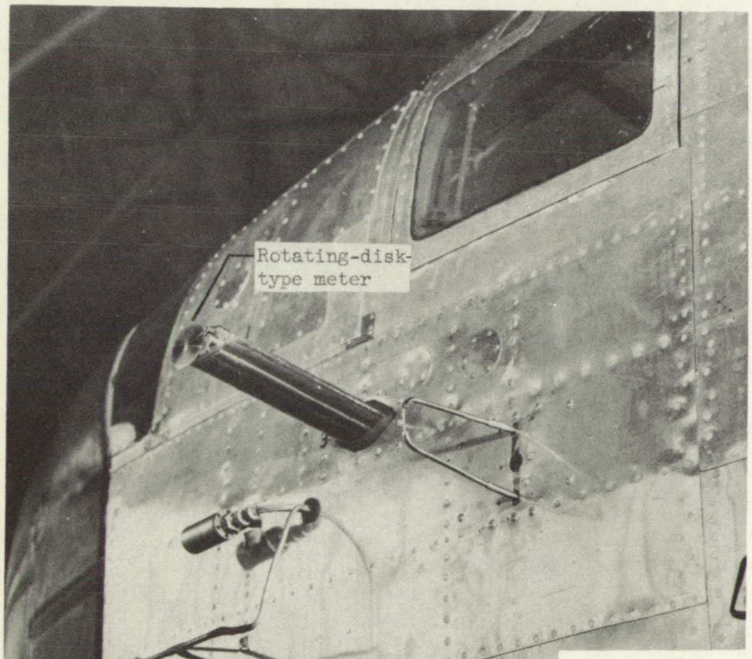


(a) Close-up showing instrument in operation.



(b) Instrument mounted on left side of fuselage of research aircraft.

Figure 1. - Rotating-disk-type icing-rate meter.

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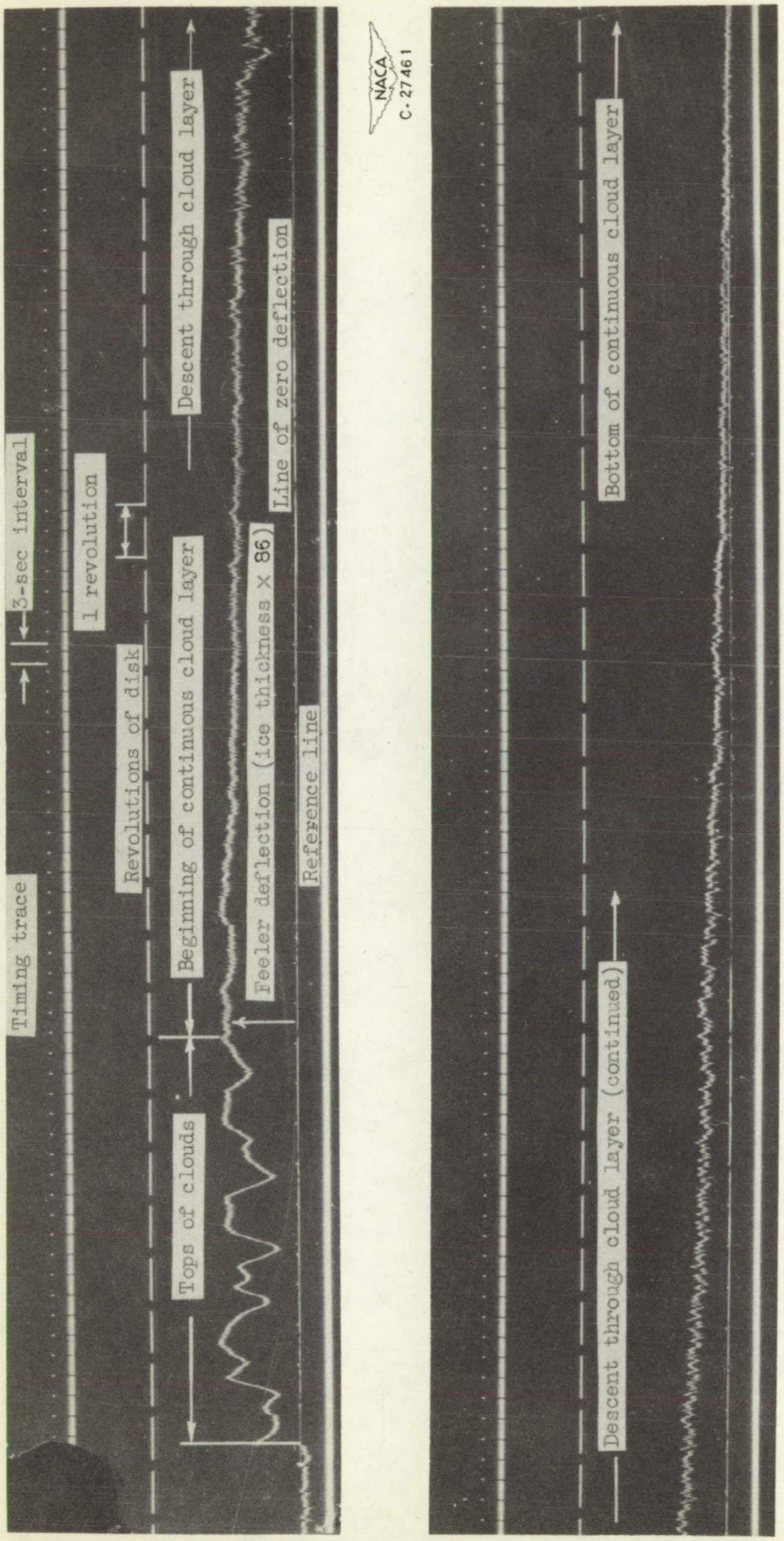

Figure 2. - Icing-rate-meter record obtained during descent through a dense supercooled stratiform cloud layer.

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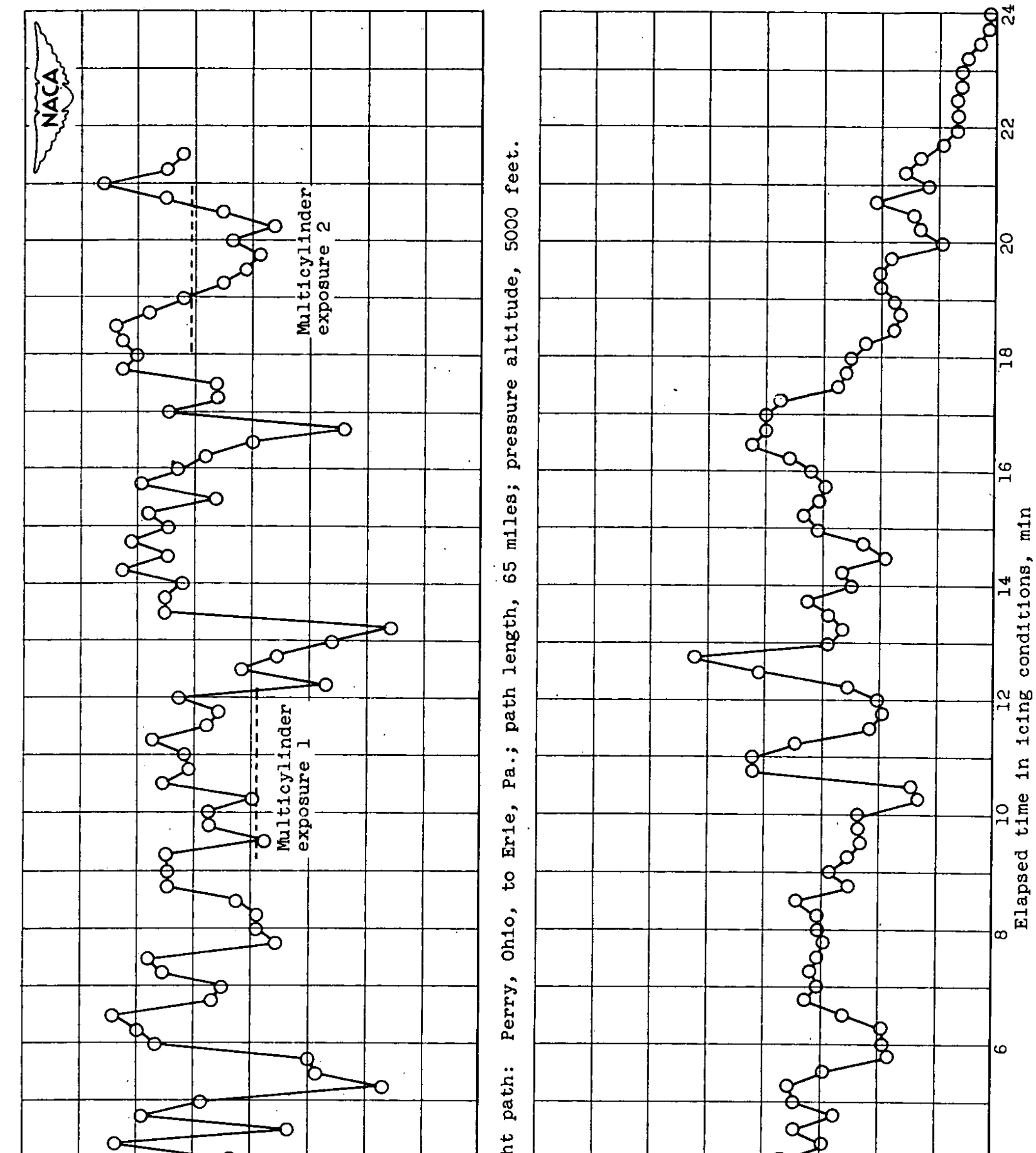

(a) Flight path: Perry, Ohio, to Erie, Pa.; path length, 65 miles; pressure altitude, 5000 feet.

(b) Flight path: Erie, Pa., to Perry, Ohio; path length, 72 miles; pressure altitude, 6000 feet.

Figure 3. - Variation of liquid-water content with icing time measured with rotating-disk-type icing-rate meter on January 4, 1951 during flight in supercooled stratiform cloud. Average true airspeed, 180 miles per hour.

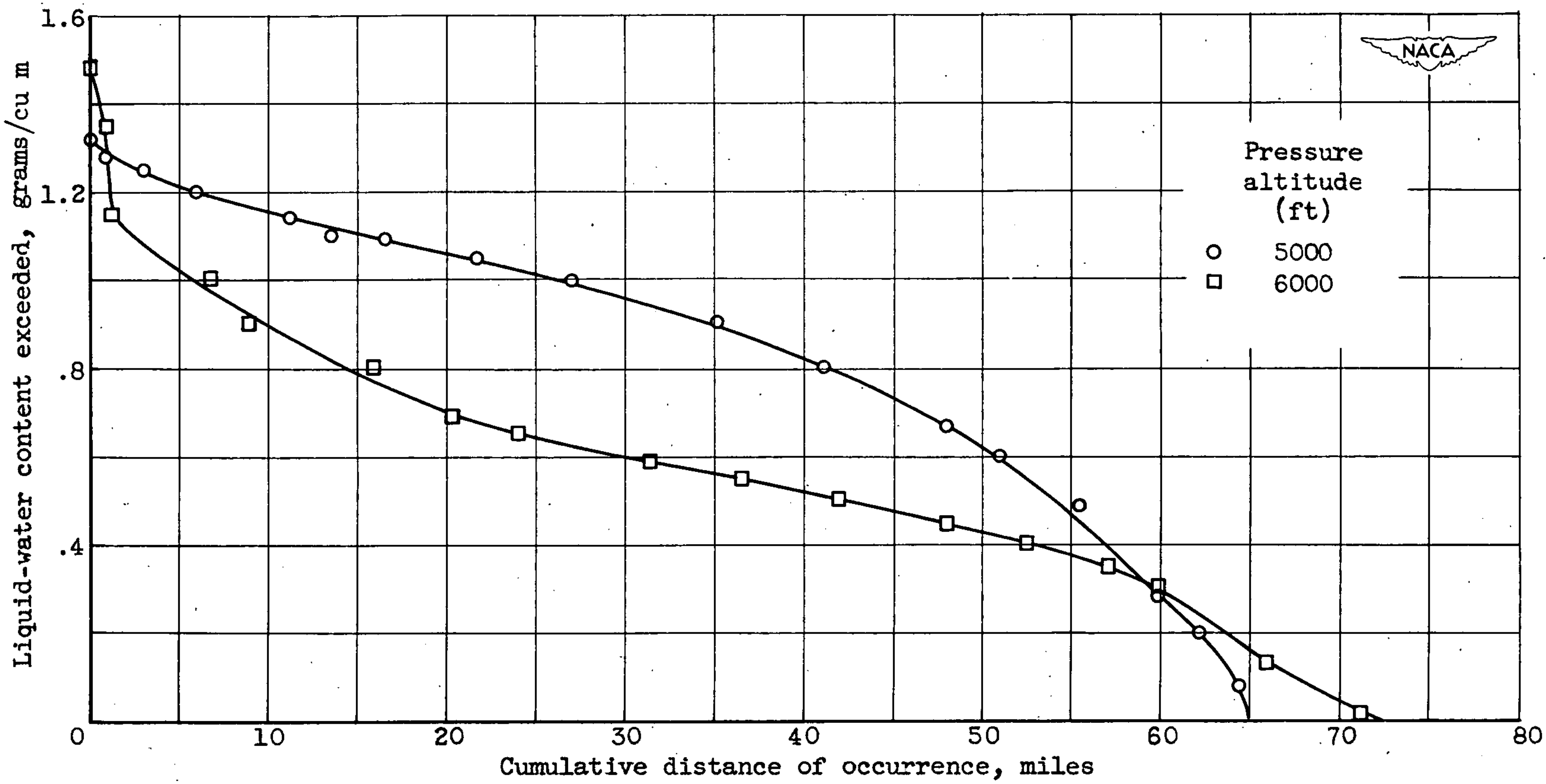

Figure 4. - Cumulative distances flown in liquid-water contents greater than indicated values, January 4, 1951. Average true airspeed, 180 miles per hour; pressure altitudes, 5000 and 6000 feet; ambient temperatures, 17° and 15° F, respectively.

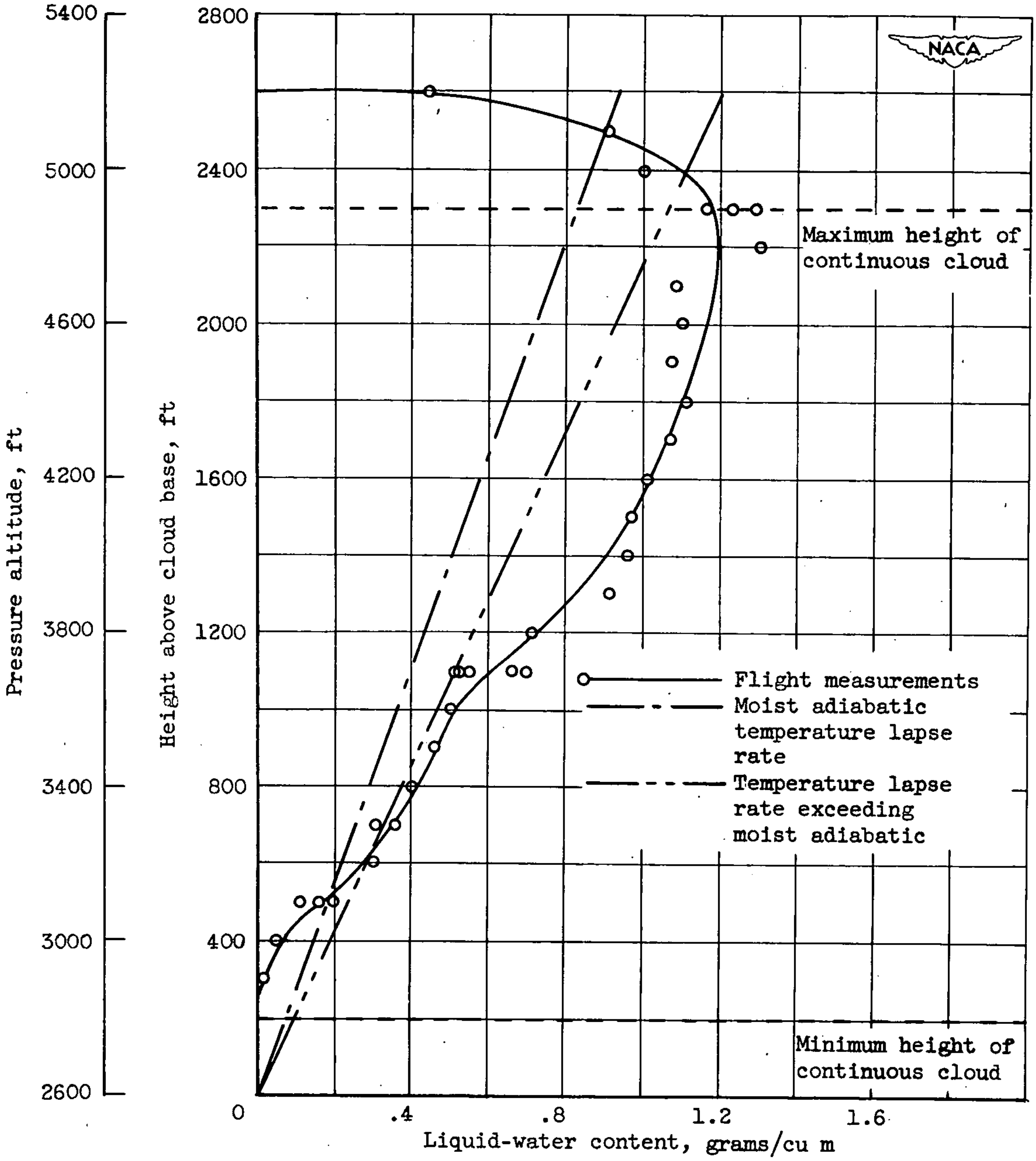

Figure 5. - Vertical distribution of liquid-water content measured on January 4, 1951 over a distance of 20 miles during descent through a dense, supercooled stratiform cloud layer. Temperature measured at cloud top and base, 17° and 28° F, respectively.

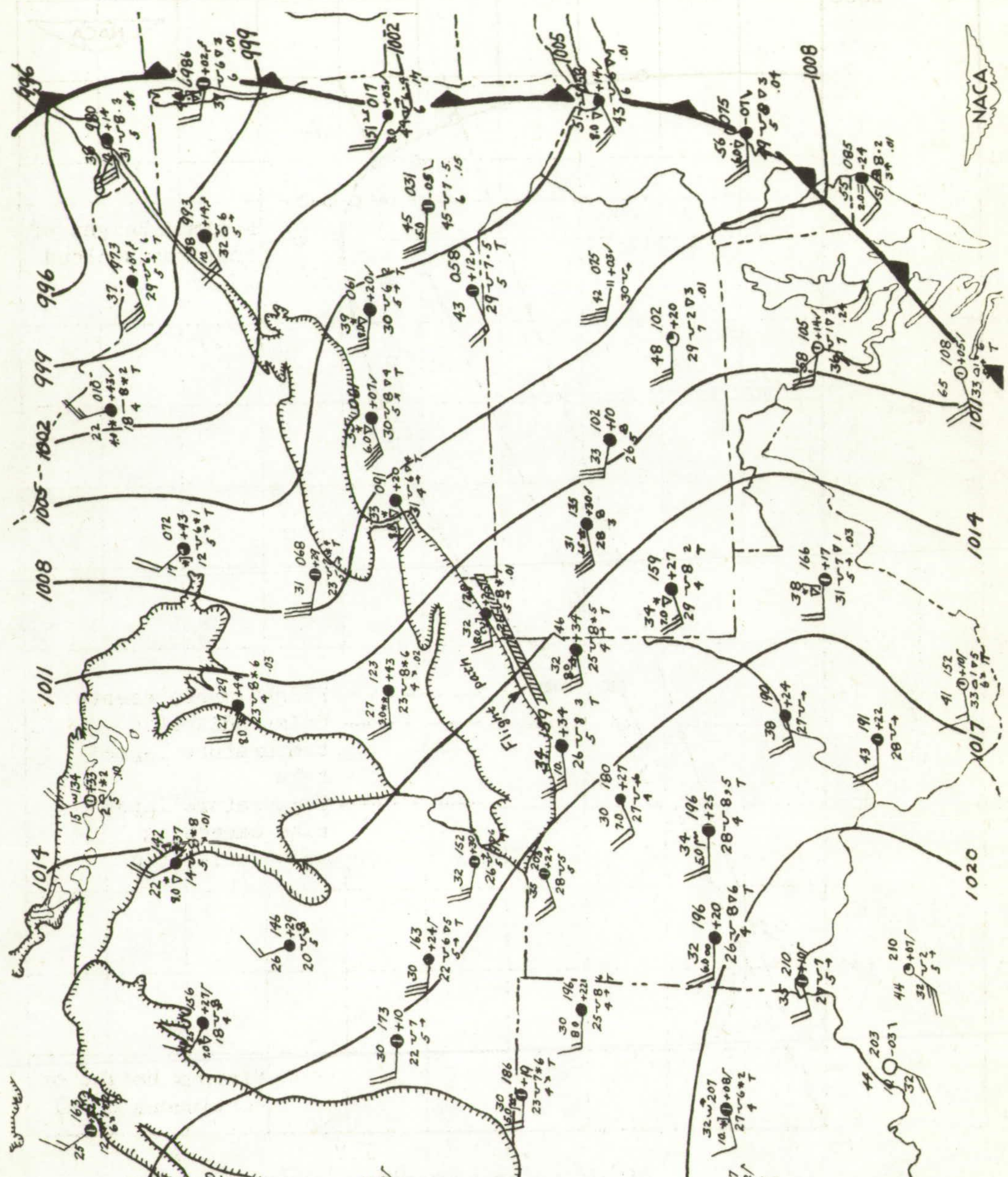

Figure 6. - Weather map of Great Lakes area for 1:30 p.m. (e.s.t.) January 4, 1951. Data are plotted in accordance with conventions of international synoptic weather code.