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TECHNICAL NOTE 2306

METEOROLOGICAL ANALYSIS OF ICING CONDITIONS ENCOUNTERED IN LOW-ALTITUDE STRATIFORM CLOUDS

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SUMMARY

Liquid-water content, droplet size, and temperature data measured during 22 flights in predominatly stratiform clouds through the 1948-49 and the 1949-50 winters are presented. Several icing encounters were of greater severity than those previously measured over the same geographical area, but were within the limits of similar measurements obtained over different terrain within the United States. An analysis of meteorological conditions existing during the 74 flights conducted for four winters indicated an inverse relation of liquid-water concentration to maximum horizontal extent of icing clouds. Data on the vertical extent of supercooled clouds are also presented. Icing conditions were most likely to occur in the southwest and northwest quadrants of a cyclone area, and least likely to occur in the southeast and northeast quadrants where convergent air flow and lifting over the associated warm frontal surface usually cause precipitation. Additional data indicated that icing conditions were usually encountered in nonprecipitating clouds existing at subfreezing temperatures and were unlikely over areas where most weather observing stations reported the existence of precipitation. Measurements of liquid-water content obtained during 12 flights near the time and location of radiosonde observations were compared with theoretical values. The average liquid-water content of a cloud layer, as measured by the multicylinder technique, seldom exceeded two-thirds of that which could be released by adiabatic lifting. Local areas near the cloud tops equaled or occasionally exceeded the calculated maximum quantity of liquid water.

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INTRODUCTION

One phase of the icing research program conducted at the NACA Lewis laboratory consisted of supplementing laboratory icing studies with research flights in supercooled clouds. The meteorological aspects of icing research included (1) development and testing of instruments for measuring icing conditions during flight, (2) collection of data indicating the maximum extent, severity, and frequency of conditions for which thermal anti-icing systems should be expected to provide protection, and (3) application of flight experience and meteorological data to the development of forecasting techniques usable in flight planning and navigation to avoid potentially hazardous conditions.

Sufficient in-flight measurements of icing conditions have been made by the NACA and other organizations to provide tentative design criterions for thermal anti-icing systems (reference 1). The meteorological data accumulated by the Lewis laboratory during the 1946-47 and the 1947-48 winter seasons are presented in references 2 and 3, respectively. Additional data are desirable to assure the adequacy and statistical reliability of previous information, and, if necessary, to revise or to extend proposed design conditions.

The observations made during the 1948-49 and the 1949-50 winters are presented herein. In addition, data gathered during four winters of icing research flights are presented that indicate the vertical and horizontal extent of supercooled stratiform clouds encountered and their location in relation to existing synoptic weather conditions.

APPARATUS AND METHOD

The airplanes used for research flights in icing conditions were bomber-type aircraft equipped with thermal anti-icing systems. Icing instruments installed on the airplanes for the 1948-49 winter were similar to those described in reference 3. The following instruments, designed to provide improved and more complete measurements of meteorological data, were used during the 1949-50 winter:

1. Rotating multicylinders consisting of five cylinders each 2 inches in length with diameters of 1/8, 1/2, $1\frac{1}{4}$, 3, and $4\frac{1}{2}$ inches with integral flanges and transition segments designed to reduce end effects and to provide two-dimensional flow around the cylinders

2. Impingement recorder consisting of a 6-inch-diameter cylinder around which a movable water-sensitive tape was exposed for 2 to 6 seconds; the maximum-effective droplet diameter was calculated from the observed extent of impingement

3. Cloud detector consisting of an electrically heated metallic probe for indicating presence of liquid water by measuring and recording temperature fluctuations caused by evaporation of impinging water

4. Three rotating-disk icing-rate meters installed for comparison and developmental tests

5. Shielded thermocouples for continuous recording of free-air temperature

The continuously recording icing-rate meters were calibrated against the multicylinders and provided data concerning short duration or nearly instantaneous liquid-water concentrations encountered in supercooled cloud formations. Maximum values obtained with the icing-rate meter are used in this report to supplement the measurements of icing intensity obtained over greater horizontal distances with the multicylinders.

Once a desirable flight-test altitude was established, as many consecutive multicylinder observations as possible were made to approximate a continuous record of the icing encounter. The exposure time of the multicylinders varied from 2 to 6 minutes, depending upon the rapidity with which the ice accumulated on the cylinders. The usual time lapse between consecutive multicylinder exposures was 2 to 5 minutes to permit preparation of equipment and coordination of observations.

Recent work at the Lewis laboratory has indicated that a knowledge of the size of the largest cloud droplets present in sufficient quantities to measure by the impingement method (maximum-effective droplet size) during a multicylinder exposure in some instances provided information usable for a more unique determination of theoretical droplet-size distribution curves on which the multicylinder technique is based. When possible, several observations of maximum-effective droplet size were made during each multicylinder exposure. The arithmetic average of the maximum-effective droplet-size observations was used as the representative value for the concurrent multicylinder observations during the 1949-50 winter. Use of this procedure provided data that were considered more internally consistent, but did not eliminate other suspected errors in the multicylinder method, such as changing collection efficiency due to variation in size and shape of the cylinders, loss of supercooled water because of run off or "bounce-off," and occasionally changing droplet-size distributions during single multicylinder exposures as indicated by maximum-effective droplet-size measurements. Errors of unknown magnitude might also be introduced by the presence in natural clouds of droplet-size distributions differing from the theoretical distribution used in the multicylinder method. Because the icing-rate meters were calibrated against the multicylinders, possible errors inherent in the multicylinder technique also affect the reliability of the icing-rate-meter data.

Nearly all the meteorological data were obtained in continuous icing conditions at altitudes below 10,000 feet. Flight procedures varied with existing weather conditions, traffic control problems, and the requirements of concurrent engineering tests. In general, an attempt was made to find icing near the cloud tops in off-airway regions to permit greater freedom of flight operations. Hourly airway weather reports and radiosonde data were utilized in forecasting and flight planning. Circular or rectangular flight patterns were flown depending upon cloud conditions and extent of the operating area. Occasionally, where in-flight reports of cloud state and vertical depth indicative of significant icing were available, flights were conducted on airways at an assigned altitude.

RESULTS AND DISCUSSION

The meteorological data for the 1948-49 and the 1949-50 winters are presented in tables I and II, respectively. Icing flights 1 to 12 with a total of 98 multicylinder observations are included in table I. The 1949-50 data in table II include 38 multicylinder observations of liquid-water content and droplet size measured during ten flights, which are listed as flights 13 to 22. In addition, table II includes the maximum-effective droplet-size measurements.

All icing conditions encountered were in continuous icing clouds, or were made continuous by proper navigation. Stratocumulus clouds were the predominant type investigated during the 1948-49 and the 1949-50 winters; however, on two occasions (flights 10 and 11), large cumulus clouds extended through a continuous stratocumulus layer. Flight 12 includes data measured during the only icing encounter in altostratus and altocumulus cloud systems.

Comparison of 1948-49 and 1949-50 Data with Icing Conditions Encountered during the 1946-47 and 1947-48 Winters

The following table is a summary of the meteorological conditions encountered during four winters in which icing flights have been conducted from the Lewis laboratory:

		1946-47	1947-48	1948-49	1949-50
Liquid-water content (g/cu m)	Average	0.21	0.23	0.33	0.30
	Median	.18	.19	.34	.30
	Range	.06 to .50	.05 to .57	.06 to 1.30	.06 to .60
Mean-effective droplet diameter (microns)	Average	13	13	14	10
	Median	12	12	13	9
	Range	7 to 36	5 to 22	5 to 27	6 to 14
Temperature ($^{\circ}F$)	Average	12	19	22	20
	Median	15	21	23	21
	Range	-11 to 28	9 to 26	11 to 27	10 to 31

Flights conducted during the 1948-49 and the 1949-50 winters were in clouds with higher liquid-water concentrations and warmer temperatures than those measured during the earlier phases of the flight icing research program. These results were influenced to some extent by the desire to find higher liquid-water concentrations for engineering test purposes.

An examination of the mean-effective droplet-size data indicates a significant trend toward smaller mean-effective-droplet diameters and diminished range of mean-effective droplet-size conditions in the 1949-50 data. The choice of wider theoretical droplet-size distribution curves based on maximum-effective droplet-size measurements and the small number of observations are considered to be the primary causes of this trend rather than any seasonal difference in cloud structure.

Cumulative-frequency curves of the 136 observations of liquid-water content and mean-effective droplet diameter measured in 22 flights conducted during the 1948-49 and the 1949-50 winters are presented in figure 1. The liquid-water content data indicate that 50 percent of the multicylinder observations were in clouds with water concentrations in excess of 0.30 gram per cubic meter, whereas

10 percent of the observations indicated values higher than 0.54 gram per cubic meter. The extreme value of 1.30 grams per cubic meter (flight 11) was measured over a 5-minute exposure period of the multicylinders during straight-line flight.

The mean-effective droplet-diameter measurements shown in figure 1 are comparable with those indicated in reference 3. Of the measurements made during the 1948-49 and the 1949-50 winters, 80 percent was within the range from 9 to 18 microns. A maximum mean-effective droplet-diameter measurement of 27 microns was observed.

Horizontal and Vertical Extent of Icing Clouds

Horizontal extent of continuous icing conditions. - The choice of design criterions for ice-prevention systems is influenced by operational procedures and by the duration of icing conditions that necessitate icing protection. The meteorological phase of this problem is one of determining the spatial extent of icing clouds.

Data, primarily measured in cumuliform clouds and presented in reference 4, indicate the inverse relation of the liquid-water content to the extent of the icing conditions. The additional data presented herein are primarily applicable to low-altitude stratiform-cloud conditions in which continuous flight may be expected under extreme conditions.

Of 74 flights conducted during the four winters for which in-flight data are available, 57 flights encountered a trace or more of ice. Multicylinder measurements of liquid-water concentrations obtained during each of the flights were averaged and plotted against the maximum distance flown in any one direction in icing, as shown in figure 2. In order to provide additional data in the higher ranges of liquid-water content, the distance traversed on a single heading during one multicylinder exposure was used as the extent of measured liquid-water concentrations in excess of 0.50 gram per cubic meter. Such data are only approximate because the icing severity during the interval between consecutive multicylinder observations was indeterminant except during flights when icing-rate-meter data were available. Extreme values of liquid-water content, obtainable from continuous icing-rate-meter records, were used to provide additional information on the extent of instantaneous or short-duration liquid-water concentrations. In most instances, the data in figure 2 approximate the maximum geographical extent of the continuous icing clouds. Comparison of these data with those measured over the western sections of the United States reported in reference 4 indicates substantial agreement throughout the range of maximum values encountered irrespective of the diverse geographical areas and predominantly different cloud types explored.

Inspection of figure 2 indicates that liquid-water concentrations as high as 1.30 grams per cubic meter existed over a horizontal distance of 15 miles, 0.70 gram per cubic meter for a distance of approximately 100 miles, and a maximum average concentration of 0.30 gram per cubic meter over a distance of nearly 200 miles.

Vertical extent of stratiform icing clouds. - The depth of continuous icing clouds is a factor to be considered in flight navigation to reduce the rate of ice accretion, particularly with unprotected aircraft. In order to provide information on the average and the maximum vertical extent of continous or nearly continuous icing conditions, data were obtained when feasible either by surveying the clouds or by noting the height of the cloud tops in relation to the height of the cloud bases reported by weather observing stations over the flight area. Reliable data were obtained for a total of 48 flights during four winters of icing flights. The observations were generally obtained over terrain where orographic effects were considered negligible. The maximum depth of the icing clouds was not determined as the thickness of one particular icing cloud layer in every case. Two or more cloud layers sufficiently close together, or with varying bases and tops such that icing conditions were unavoidable without frequent changes in flight altitude, were considered as one cloud layer. The maximum vertical extent of multiple cloud layers was approximately 6500 feet as indicated in figure 3. Eighty percent of the icing conditions was less than 4000 feet in vertical extent. The average observed vertical extent of stratiform icing clouds was approximately 3000 feet. Flight surveys indicated a maximum depth of 3500 feet for any single cloud layer, which is in approximate agreement with the discussion of cloud-thickness values presented in reference 2.

Criterions for Predicting Existence and Severity of Icing Conditions

Relation of icing conditions to occurrence of precipitation. - Clouds containing only ice crystals or snow cause no danger of ice accretion, except near the freezing level where rising air currents within the clouds may carry water droplets into the ice crystal clouds for several hundred feet above the freezing level. Flights through such zones may occasionally encounter wet snow, which adheres to the aircraft components.

The continued coexistence of supercooled water and ice crystals in a cloud at subfreezing temperatures requires saturated conditions with respect to liquid water in the spaces between the ice crystals. Because the saturation vapor pressure over ice is lower than over water at the same temperature, a supersaturated condition with respect to ice occurs at temperatures below 32° F. A vapor pressure gradient therefore exists in the vicinity of each ice crystal causing the crystals to grow at the expense of the supercooled cloud droplets. If the cooling rate caused by the vertical component of air movement is sufficiently great, the rate of condensation is equal to or greater than the rate of diffusion of the water vapor to the ice crystals, thus permitting the coexistence of liquid and crystalline cloud particles. Such a critical vertical velocity is near zero at the freezing level because the vapor pressure over water and ice are equal, but increases rapidly at temperatures below freezing and reaches such magnitudes as those normally existing in cumuliform cloud formations. Stratiform cloud systems (which are formed in large masses of air that are lifted slowly by the action of convergence) or winter stratocumulus (which are formed by mixing of the air in the surface turbulence layer) are usually characterized by vertical velocities of low magnitude in the absence of orographic effects. Therefore, when the crystallization process is initiated either by the introduction of ice crystals from an upper cloud layer or by spontaneous freezing of droplets within the cloud layer, the supercooled liquid-water concentration is depleted as the water vapor goes into the crystalline state.

No known method exists for determining the onset of the crystallization process in the atmosphere. Under laboratory conditions with small samples of water (reference 5), no droplets were observed to freeze at temperatures higher than 18° F. The probability of given sizes of droplets freezing spontaneously below this temperature increased as the temperature was lowered. Greater amounts of supercooling were possible as the droplet size was decreased through the range of sizes normally found in clouds.

Sample calculations in reference 6 indicate that, assuming the same amount of water in the cloud condensate, individual ice crystals are about ten thousand times as heavy and one ten-thousandth as numerous as the droplets in a liquid cloud. The weight of ice particles compared with cloud droplets contributes to relatively rapid graviational settling and permits snowflakes to fall a greater distance below the cloud bases before evaporating - usually reaching the ground as rain or snow depending upon the temperature distribution below the cloud base. Stratiform clouds composed only of water droplets seldom produce significant amounts of precipitation. Such precipitation is in the form of drizzle that can only reach the ground from an extremely low cloud height or under conditions of high relative humidity in the air beneath the cloud layer.

The presence of significant amounts of precipitation over large areas therefore indicates that the clouds are predominantly in the crystalline state and are unlikely to cause an icing hazard (except in the case of freezing rain). The use of precipitation reports for the prediction of icing danger areas for flight planning purposes is suggested in reference 7. Reference 8 mentions the observed inverse relation between the liquid-water concentrations at Mt. Washington and measured precipitation rates at a surface station several miles away. References 2 to 4 indicate qualitatively that measurable icing conditions were seldom encountered during flight through areas of precipitation, but no measurements of extent or amount of precipitation under such conditions were obtained. An exploratory flight through a precipitation area, discussed in reference 9, indicates that few supercooled cloud formations were observed.

In order to evaluate further the relation of the existence of precipitation to the physical state of extensive cloud layers, all available climatological reports over the areas flown during the four winters of icing flights were analyzed. Hourly precipitation measurements during the times of the 74 flights were obtained from references 10 and 11. Precipitation rates in excess of 0.005 inch per hour were available. Use of these data provided a more general coverage of precipitation measurements than would normally be available from regular hourly airway weather reports, but did not include instances where precipitation rates too small to measure occurred.

An average of 10 measurements of precipitation were available for each flight, varying from 2 to 35 depending upon the extent and location of the flight area. All precipitation measurements within 25 miles of the flight area were used. Where flights were conducted over any of the Great Lakes, available measurements along the shoreline were utilized. The relation of the percentage of stations reporting measurable precipitation to the average measured supercooled water concentrations in the clouds encountered is shown in figure 4. The zero range of the coordinates in figure 4 is offset to provide space to plot all the concentrated data points. Where a trace of icing was encountered, a value of 0.04 gram per cubic meter was arbitrarily assigned to the liquid-water content value; this value is the approximate lower practical limit of measurement with available instruments.

The following table is derived from figure 4 and indicates the observed occurrence of supercooled clouds in relation to the percentage of surface stations over the flight area reporting measurable precipitation during flight time:

Stations reporting precipitation (percent)	Flights encountering trace or more of ice	Flights encountering no ice
0	44	0
1 to 10	6	0
11 to 20	3	2
21 to 30	0	1
31 to 40	3	2
41 to 50	1	2
Greater than 50	0	10
Total	57	17

The available data indicate that use of precipitation reports for flight planning and forecasting is most reliable, either in cases where no precipitation is reported from stratiform clouds or where the precipitation shows evidence of covering a general area, assuming the clouds exist at subfreezing temperatures. A value of 50 percent occurrence of precipitation during which only nonicing clouds were encountered exists in the data of this report. This value is not considered to be of exact quantitative significance, but rather, is indicative of the trend of the physical state of cloud systems with the onset of precipitation conditions. Localized precipitation reports may indicate that cumuliform clouds are present or that stratiform clouds are in the transition stage from supercooled droplets to ice crystals. In such instances, the heterogeneous physical state of the clouds indicates the possibility of encountering transient icing conditions in the cloud system. The absence of precipitation is likely to be a more reliable indicator of icing in low clouds existing at subfreezing temperatures than in middle-type clouds such as altostratus and altocumulus where precipitation products can evaporate before reaching the ground. Insufficient data are available from middle cloud layers to provide an analysis of such conditions. Because the exact time and place of the onset or cessation of precipitation over an area usually is difficult to accurately predict, the use of the presence or absence of precipitation as a criterion for flight planning is most reliable for flights of short range or limited time-duration.

With the accumulation of flight and forecasting experience gained in the earlier phases of the icing research program, general precipitation areas were, whenever possible, purposely avoided to maintain a high level of efficiency in the engineering tests being conducted in icing conditions. As is indicated in the preceding discussion, this procedure resulted in a high percentage of icing encounters, but detracted from the number of meteorological survey flights in weather situations where general precipitation was occurring or was expected to occur during the time of flight. This bias in the data is of meteorological significance and should therefore be considered in the subsequent discussion.

Areas of icing encounters in relation to synoptic weather conditions. - The depletion of liquid-water content of clouds by the crystallization process and resulting precipitation suggests that areas in the proximity of an active cyclonic disturbance or low-pressure center present the least icing hazard because of the occurrence of precipitation in such regions.

The approximate midpoints of all areas traversed in search for icing conditions in supercooled clouds during four winters of experimental flights were analyzed in relation to the location of the nearest cyclonic disturbance. A plot of the azimuth and distance of the flight area from the associated low-pressure center is presented in figure 5. Of 17 flights encountering few or no supercooled droplets in clouds existing at subfreezing temperatures, 15 occurred in the northeast and southeast quadrants of the low-pressure center, which are the regions of greatest likelihood of significant general precipitation. Two-thirds of the unsuccessful icing flights were in the northeast quadrants of the associated storm area corresponding to the region of warm-front type of weather associated with developing cyclones.

The data were further related where possible to the type and location of the frontal systems that could be considered as meteorological factors contributing to the cloud formations. The distance of the midpoints of the flight areas from the low-pressure center and the perpendicular distance from the surface position of the associated fronts were used to plot the composite chart shown in figure 6. Varying frontal orientation and stages of cyclonic development should be considered in interpreting the chart. For example, in some instances no identifiable warm front existed at the time of flight into a cyclonic area. In such cases the azimuth and distance from the low-pressure center were used as in figure 5. Omitted from figure 6 are eight instances of clouds that could not be related to any pronounced frontal system, but that were caused primarily by local geographical peculiarities such as air trajectory over Lake Erie, of which the most severe continuous icing encounter in terms of liquid-water concentration and horizontal extent (flights 2 and 3) is an example.

Inspection of figure 6 indicates that with the exception of two flights all cases of nonicing clouds existed in areas of greatest probability of precipitation when considered in relation to the existing frontal pattern, or in areas of strong convergence to the east and southeast of the low-pressure center. On the basis of flight observations, the greatest likelihood of encountering clouds in the supercooled state below 10,000 feet in winter appears to exist near the periphery of precipitation areas and in the colder air masses in the northwest and southwest quadrants of a storm area where stratus and stratocumulus clouds frequently exist. Regions near the center of a low-pressure area and north of a warm front are usually characterized by precipitation and ice-crystal clouds and would therefore, on the basis of available in-flight data, cause no significant icing conditions except in the case of freezing rain.

Maximum liquid-water concentrations in stratiform clouds. - The liquid-water concentrations as measured by multicylinders in stratiform clouds are shown in reference 2 to seldom exceed one-half the amount that would be produced by adiabatic lifting through a 3000-foot interval above the condensation level. Because reliable information concerning the existing cloud thickness below the level of each icing encounter was unavailable for the computations presented in reference 2, the 3000-foot cloud thickness, which flight experience has indicated to be representative of low-altitude stratiform clouds; was chosen as the approximate maximum thickness of a continuous stratiform cloud layer although multiple icing cloud layers may exceed this thickness.

The theoretical amount of cloud condensate may be calculated if the pressure and temperature of the lower and upper extremities of a cloud layer are known or if the cloud thickness in addition to the cloud base temperature and pressure are known, provided that full adiabatic mixing within the cloud formation is assumed and that no sedimentation or precipitation of the condensate occurs. The entrainment of dryer air with the rising air currents, especially significant in cumuliform clouds, and the mixing of saturated air with the clear air at the cloud tops result in a reduction of the effectiveness of adiabatic lift within the cloud. Thus, calculations of maximum possible liquid-water content generally indicate values in excess of actual average amounts that can be measured by multicylinders. Measurements over short distances should, however, indicate values near the theoretical amounts if the distance traversed by the measuring device is of the same order of magnitude as the horizontal extent of the principal rising air currents within the clouds.

In order to provide temperature data usable for theoretical liquid-water content calculations, all flights conducted during the 1948-49 and the 1949-50 winters were screened according to the time of flight and geographical areas flown in relation to the location and time of U.S. Weather Bureau radiosonde observations. When the in-flight data coincided with the radiosonde observations made in the same cloud layers and the temperature and cloud conditions remained relatively constant, the data were used to compute the theoretical liquid-water content of the clouds.

The theoretical amount of condensation products near the cloud tops was computed according to the formula

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

where

LWC 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 cloud top, grams of water vapor per kilogram of dry air

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

When the relation

$$w = 622 \frac{e}{P-e}$$

where

e saturation vapor pressure with respect to plane water surface, millibars

P ambient-air pressure, millibars

is used with

$$\rho = 0.3484 \left(\frac{P - e}{T}\right)$$

where

T absolute temperature, $^{\circ}$K

it can be shown that

$$LWC = 216.7 \left(\frac{e_0}{P_0-e_0} - \frac{e_1}{P_1-e_1}\right)\left(\frac{P_1-e_1}{T_1}\right)$$

where the subscripts 0 and 1 refer to conditions at the cloud base and top, respectively.

The results of the calculations for 12 flights during which usable data were obtained are shown in table III. Inspection of the data indicates that the average liquid-water concentrations measured by the multicylinder method varied from one-fourth to two-thirds of the maximum theoretical values. Measurements with multicylinders provide data that are an average of the meteorological conditions over a horizontal distance varying from 5 to 20 miles, depending upon the length of exposure and flight speed. Data from the icing-rate meters used during the 1948-49 and 1949-50 winters, however, provide usable liquid-water-content data over minimum distances of 3/4 mile. The maximum liquid-water concentrations measured by the icing-rate meter are, in eight out of ten instances, in substantial agreement with the computed values within the accuracy with which the cloud height and temperature data were obtainable. Variations in cloud thickness of 500 to 1000 feet and changing temperature distributions over the flight area introduce possible errors or deviations of 15 to 20 percent in the theoretical liquid-water-content calculations.

The icing-rate-meter data for flight 2 in table III indicate the existence of liquid-water concentrations approximately 75 percent greater than the theoretical amount. A 3-minute multicylinder observation in the same conditions indicates a liquid-water concentration near the maximum theoretical value over a horizontal distance of 9 miles. This cloud formation was unique in that a temperature inversion of 14° F existed through a 1400-foot layer of air over the top of the cloud layer. Such a stable arrangement of air would greatly retard or prevent appreciable mixing of the cloud air with the unsaturated air in the vicinity of the cloud tops.

Flight 11 also indicates the existence of supercooled water concentrations approximating the maximum theoretical value over a distance of 15 miles. In this instance, the entrained air into the observed cumuliform clouds consisted partly of saturated air and liquid water because the cumuliform clouds extended through a continuous cloud layer and thus increased the liquid-water concentration above the value that would usually be encountered in such a condition. An icing-rate meter was not installed on the airplane during this flight; consequently, the maximum existing liquid-water concentration could not be determined.

The mechanism within a cloud that may occasionally cause liquid-water concentrations in excess of theoretical amounts is not at present understood. It is conceivable that such conditions could be caused by: (1) cloud droplets from the environment of an adiabatically expanding parcel being carried upward with the parcels of air that are undergoing lifting with resultant condensation of new droplets, and (2) radiation heat losses from the tops of a quiescent or stable portion of a cloud layer lowering the temperature below that caused by adiabatic lifting from the base to the cloud top, thus causing an additional amount of condensate to form in the upper regions of the cloud volume so affected.

On the basis of data obtained using rotating multicylinders, when the total ice accretion or average icing rate through stratiform clouds is of more importance for flight planning than instantaneous values, one-half to two-thirds of the theoretical liquid-water concentration appears to be a reasonable value on which to base flight forecasts. Such quantitative predictions are possible where reliable reports of cloud extent exist over areas where radiosonde data are available near the time of the proposed flight. When flights are planned through potential supercooled icing clouds with aircraft equipment that is critically affected by sudden high liquid-water concentrations, such as air-intake ducts and jet engines, the results of this investigation indicate that full adiabatic liquid-water concentrations with extremely localized regions in stratiform clouds containing at least 1.7 times the theoretical water concentrations may be expected. Such high concentrations are determined by localized and transient cloud environment and by internal circulation within the clouds, and therefore cannot be reliably predicted with information currently available to meteorologists.

SUMMARY OF RESULTS

The following results were obtained from data taken during 74 flights in search of icing conditions over the northern regions of the United States east of the Rocky Mountain area with measurements in the Great Lakes area predominating:

1. Observations of liquid-water concentrations and mean-effective droplet sizes obtained during flight in stratiform clouds at altitudes below 10,000 feet during the 1948-49 and 1949-50 winters were in substantial agreement with values previously reported. Some slight differences existed, which were attributed to measuring techniques and emphasis upon obtaining data in more severe conditions.

2. Comparison of average liquid-water contents with horizontal extent of the icing clouds indicated that values up to approximately 1.30 grams per cubic meter existed over a distance of 15 miles, 0.70 gram per cubic meter for a distance of 100 miles, and a maximum average liquid-water content of 0.30 gram per cubic meter over a distance of approximately 200 miles.

3. The maximum vertical depth of multiple layer supercooled stratiform clouds observed in flight predominantly over level terrain was approximately 6500 feet, whereas 80 percent of the icing conditions was less than 4000 feet in vertical extent. The average thickness of supercooled cloud layers so far observed is about 3000 feet. The maximum observed thickness of any one cloud layer was 3500 feet and is in approximate agreement with observations over other geographical areas of the United States.

4. In stratiform clouds existing at subfreezing temperatures below 10,000 feet, icing conditions could be expected if no precipitation were reported by ground observing stations over the cloud area. Conversely, continuous icing rarely occurred when most observing stations over the area were reporting measurable precipitation (except in the case of freezing rain).

5. In low-level clouds, the most probable icing area associated with an extratropical cyclonic disturbance was located in the northwest and the southwest quadrants of the low-pressure area. Icing conditions occasionally existed in clouds below 10,000 feet near the periphery of precipitation areas.

6. The average liquid-water content as measured by multicylinders did not exceed two-thirds of the theoretical maximum values.

7. Maximum values of icing severity measured with the rotating-disk icing-rate meter indicated that localized regions might accumulate liquid-water concentrations equal to or in excess of the adiabatic amounts.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, October 16, 1950.

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TABLE I - METEOROLOGICAL DATA OBTAINED IN

Flight	Date	Time (EST)	True air-speed (mph)	Pressure altitude (ft)	Temperature (°F)	Liquid-water content (g/cu m)	Mean-effective droplet diameter (microns)	Droplet-size distribution (a)	Cloud type	Location
1	11/22/48	1254	191	5000	19	0.16	14	A	Strato-cumulus	30 miles north of Bunker Hill, Indiana
		1303	182	4500	21	.32	12	E		
		1311	182	4700	21	.41	12	A		
		1320	182	4500	20	.36	10	A		
		1343	187	5600	20	.50	12	A		
		1350	185	4900	20	.44	12	A		
		1400	182	4900	19	.57	12	C		
2	11/23/48	1118	189	6600	17	0.88	12	A	Strato-cumulus	Southern shoreline of Lake Erie between Cleveland, Ohio and Erie, Pennsylvania
		1150	198	5900	19	.51	12	A		
		1155	190	5900	19	.45	14	D		
		1202	190	5900	19	.66	13	A		
		1208	185	5700	19	.85	12	A		
		1215	185	4600	22	.74	13	D		
3	11/23/48	1218	165	5100	19	0.34	9	E	Strato-cumulus	Over Lake Erie
		1229	167	4900	19	.52	13	A		
		1238	160	5000	19	.74	14	A		
4	3/8/49	1406	189	5800	25	0.21	14	A	Strato-cumulus	80 miles southeast of Traverse City, Michigan and northwestward across northern Lake Michigan to Green Bay, Wisconsin
		1416	195	6000	25	.32	17	A		
		1422	196	6400	23	.48	16	F		
		1427	195	6000	25	.26	16	A		
		1434	180	6400	22	.49	12	H		
		1441	195	6000	23	.24	18	C		
		1447	189	5800	23	.38	13	F		
		1453	179	5400	25	.36	15	E		
		1500	188	5500	23	.33	19	B		
		1506	185	5000	25	.39	15	E		
		1512	186	5200	25	.48	11	J		
		1518	187	5300	25	.16	19	A		
		1523	188	5300	26	.21	19	B		
		1530	184	6000	22	.18	20	B		
		1536	184	6300	22	.09	20	A		
		1544	188	5400	24	.37	16	F		
		1556	182	4000	27	.17	15	J		
		1609	171	3200	27	.37	15	J		
5	3/22/49	1200	195	4200	15	0.16	18	A	Strato-cumulus	Over Lake Superior
		1206	195	4500	15	.13	23	E		
		1211	211	3800	16	.07	27	E		
		1216	198	3400	15	.17	17	A		
		1222	198	3700	15	.10	16	A		
		1237	204	3400	13	.06	12	A		
6	3/22/49	1757	216	8700	24	0.06	16	A	Alto-stratus	Western shore of Lake Michigan
		1906	212	9300	22	.18	16	A		
7	3/25/49	1024	181	3200	27	0.07	10	A	Strato-cumulus	Vicinity of Minneapolis, Minnesota
		1122	183	4400	23	.50	10	A		
		1125	183	4500	21	.27	14	A		
		1130	182	4400	20	.34	18	A		
		1135	198	4300	21	.28	13	A		
		1140	198	4300	21	.29	12	A		
		1143	183	4500	22	.36	15	A		

[a]Size distributions are defined and discussed in reference 12.

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ICING CONDITIONS DURING 1948-49 WINTER

Flight	Date	Time (EST)	True air-speed (mph)	Pressure altitude (ft)	Temperature (°F)	Liquid-water content (g/cu m)	Mean-effective droplet diameter (microns)	Droplet-size distribution (a)	Cloud type	Location
7	3/25/49	1147	183	4400	22	0.25	13	A	Strato-cumulus	Vicinity of Minneapolis, Minnesota
		1150	184	4200	24	.17	14	A		
		1154	184	4200	24	.12	11	A		
		1157	184	4200	24	.23	12	A		
		1202	188	4200	22	.35	12	A		
		1206	188	4200	22	.40	12	A		
		1210	190	4400	23	.40	10	A		
		1214	183	4400	23	.22	11	A		
		1220	183	4400	23	.29	10	A		
		1225	184	4400	23	.31	10	A		
8	3/27/49	1400	181	3900	23	0.25	14	A	Strato-cumulus	Between Wilmar and Alexandria, Minnesota
		1406	178	4100	25	.26	14	A		
		1412	181	3800	24	.34	12	A		
		1417	181	3800	24	.25	17	A		
		1422	184	3800	22	.30	16	A		
		1429	188	3800	22	.36	12	A		
		1434	186	3800	22	.24	13	A		
		1516	188	3600	25	.11	18	A		
		1522	175	3600	26	.21	16	A		
		1527	182	3600	24	.22	13	A		
		1533	176	3600	26	.22	13	A		
		1538	182	3600	24	.24	14	A		
		1543	176	3600	26	.19	14	A		
		1548	182	3400	26	.14	12	A		
9	3/27/49	1913	186	3400	26	0.30	8	A	Strato-cumulus	25 to 100 miles east of Minneapolis, Minnesota
		1918	182	3600	25	.24	10	A		
		1923	183	4200	23	.22	10	A		
		1928	185	4500	23	.20	12	A		
		1933	175	4800	25	.23	10	A		
		1938	189	5400	23	.20	16	A		
		1943	182	3600	25	.21	14	E		
		1948	182	3600	26	.11	19	E		
		1952	184	4300	24	.20	20	A		
		1959	182	4300	25	.11	16	A		
10	4/18/49	1224	181	4500	25	0.48	16	A	Cumulus and strato-cumulus	Between Mansfield and Toledo, Ohio
		1229	192	5000	25	.44	15	A		
		1234	186	5000	25	.40	11	A		
		1240	191	4700	25	.48	14	A		
		1245	192	5000	24	.59	11	A		
		1250	192	4800	25	.46	12	A		
		1255	185	4700	25	.50	12	A		
11	4/19/49	1316	191	6400	18	0.42	8	D	Cumulus and strato-cumulus	Between Mercer and Altoona, Pennsylvania
		1332	184	7500	17	1.30	5	H		
		1350	213	7800	11	.19	8	D		
		1405	198	7200	16	.34	11	A		
		1424	198	7200	16	.70	11	B		
12	5/27/49	1453	240	7600	19	0.16	12	C	Alto-cumulus and alto-stratus	Over Lake Erie
		1508	240	8800	15	.24	7	J		
		1517	240	9000	15	.09	14	A		

TABLE II - METEOROLOGICAL DATA OBTAINED IN ICING CONDITIONS DURING 1949-50 WINTER

Flight	Date	Time (EST)	True air-speed (mph)	Pressure altitude (ft)	Temperature (°F)	Liquid-water content (g/cu m)	Mean-effective droplet diameter (microns)	Droplet-size distribution (a)	Maximum-effective droplet size (microns)	Cloud type	Location
13	12/7/49	1354	214	5000	13	0.31	14	A	--------------	Strato-cumulus	Cleveland, Ohio to Erie, Pennsylvania and return
14	1/19/50	1605	205	3000	31	0.13	14	A	--------------	Stratus	50 miles north of Norfolk, Virginia
15	1/30/50	1245	190	4000	11	0.06	9	E	--------------	Strato-cumulus	Between Cleveland, Ohio and Erie, Pennsylvania
16	1/31/50	1158 1215 1224	200 200 200	2000 2000 3000	25 21 20	0.15 .26 .23	9 9 10	B B B	14,14,14,15 15,13 --------------	Strato-cumulus	Cleveland, Ohio to Dunkirk, New York and return
17	2/7/50	1059 1107 1118 1138 1144	194 204 204 204 204	3000 3000 3000 3000 3000	22 21 20 20 21	0.24 .18 .17 .29 .29	7 7 9 9 9	D D B D D	17,14,17 19,18,18,16 15,12 18,18 20,21,17,17	Strato-cumulus	Cleveland, Ohio to Erie, Pennsylvania and return
18	2/7/50	1508 1525 1546 1551	206 206 210 190	3700 3700 3700 3700	19 19 23 22	0.40 .10 .26 .25	7 8 9 8	D A C C	15 -------------- 15,15,15,15,15 18,15,17,14	Strato-cumulus	Cleveland, Ohio to Toledo, Ohio
19	2/9/50	1443 1454 1458 1512 1523 1531 1538 1544	208 200 200 210 214 194 194 212	3700 2700 2700 2600 2800 2800 2800 2000	27 26 25 26 25 25 24 27	0.12 .45 .46 .33 .38 .60 .52 .31	10 8 9 8 11 8 9 6	C D D C E G D E	19,16,17 21,20 21,20 13,17,16,16 24,28 16,37 25,22,20,27 --------------	Strato-cumulus	Cleveland, Ohio to Mercer, Pennsylvania
20	2/10/50	1418 1423 1435	203 197 200	3700 4000 3500	24 22 21	0.24 .39 .42	10 9 8	B D D	16,16,16 19,21,20,21 17,18	Strato-cumulus	Vicinity of Mansfield, Ohio
21	3/23/50	1302 1309	178 172	4000 4200	27 26	0.24 .16	11 12	G E	23,33 --------------	Strato-cumulus	Mansfield, Ohio to Columbus, Ohio
22	3/29/50	1031 1040 1044 1049 1056 1103 1110 1115 1123 1137	196 186 185 185 185 192 186 197 197 197	7000 7000 7000 7000 7000 7000 7000 7000 7000 7000	10 12 10 10 11 11 12 13 13 14	0.30 .50 .31 .14 .32 .33 .53 .35 .43 .38	11 8 14 10 14 10 10 11 11 11	H J D A B D C B B D	19 23 -------------- -------------- 22 18 -------------- 15,16,15,15,16 -------------- --------------	Strato-cumulus	Columbus, Ohio to Huntington, West Virginia to Charleston, West Virginia to Elkins, West Virginia

[a]Size distributions are defined and discussed in reference 12.

TABLE III - MEASURED VALUES OF LIQUID-WATER CONTENT AS COMPARED WITH THEORETICAL VALUES ASSUMING ADIABATIC LIFTING

Flight (from tables I and II)	Averaged measured liquid-water content (multicylinders) (g/cu m)	Measured maximum liquid-water content		Calculated maximum liquid-water content (g/cu m)
		Multicylinders (g/cu m)	Icing-rate meter (g/cu m)	
1	0.39	0.57	0.65	0.85
2	.61	.88	1.55	.89
5	.12	.18	.34	.44
7	.28	.50	----	.41
8	.24	.36	.59	.44
10	.48	.59	.79	1.14
11	.59	1.30	----	1.43
13	.31	.31	1.13	1.30
16	.21	.26	.58	.52
17	.23	.29	.53	.43
21	.20	.24	.41	.50
22	.36	.53	1.12	1.00

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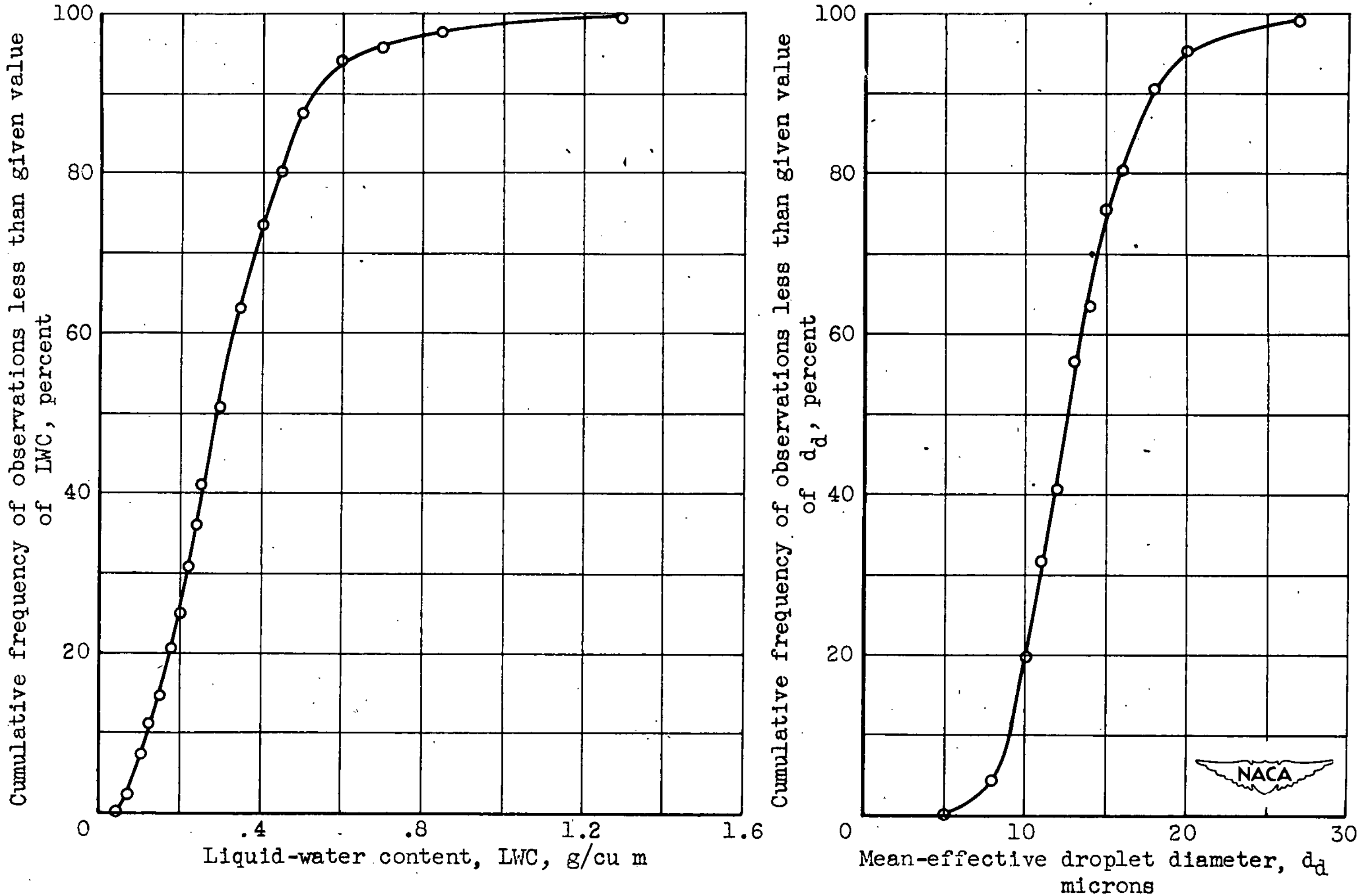

Figure 1. - Cumulative-frequency curves of 136 multicylinder observations of liquid-water content and mean-effective droplet diameter measured in supercooled stratiform clouds during 22 icing flights.

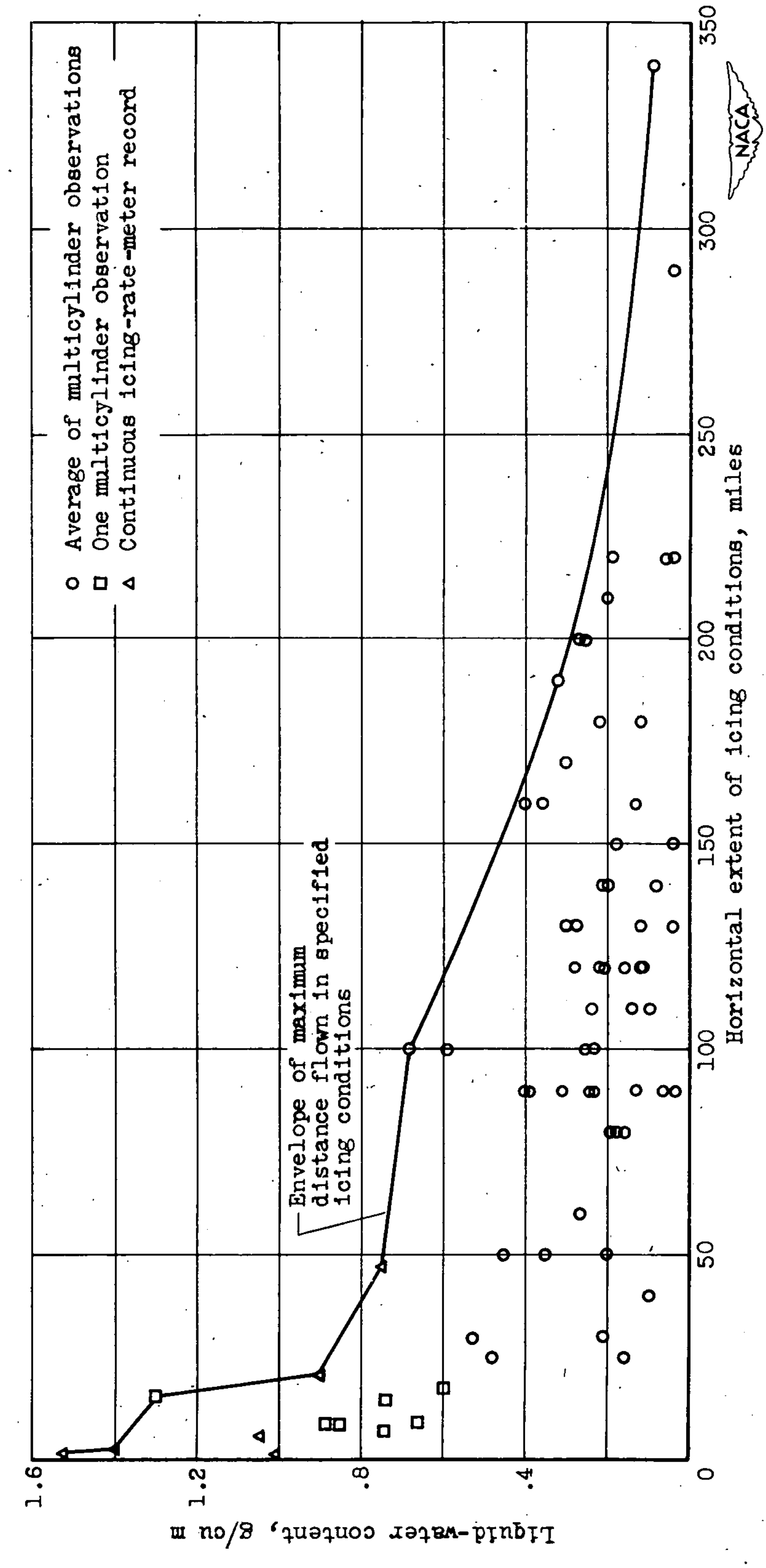

Figure 2. - Maximum distances flown during 57 icing flights in relation to average measured liquid-water content of supercooled stratiform clouds.

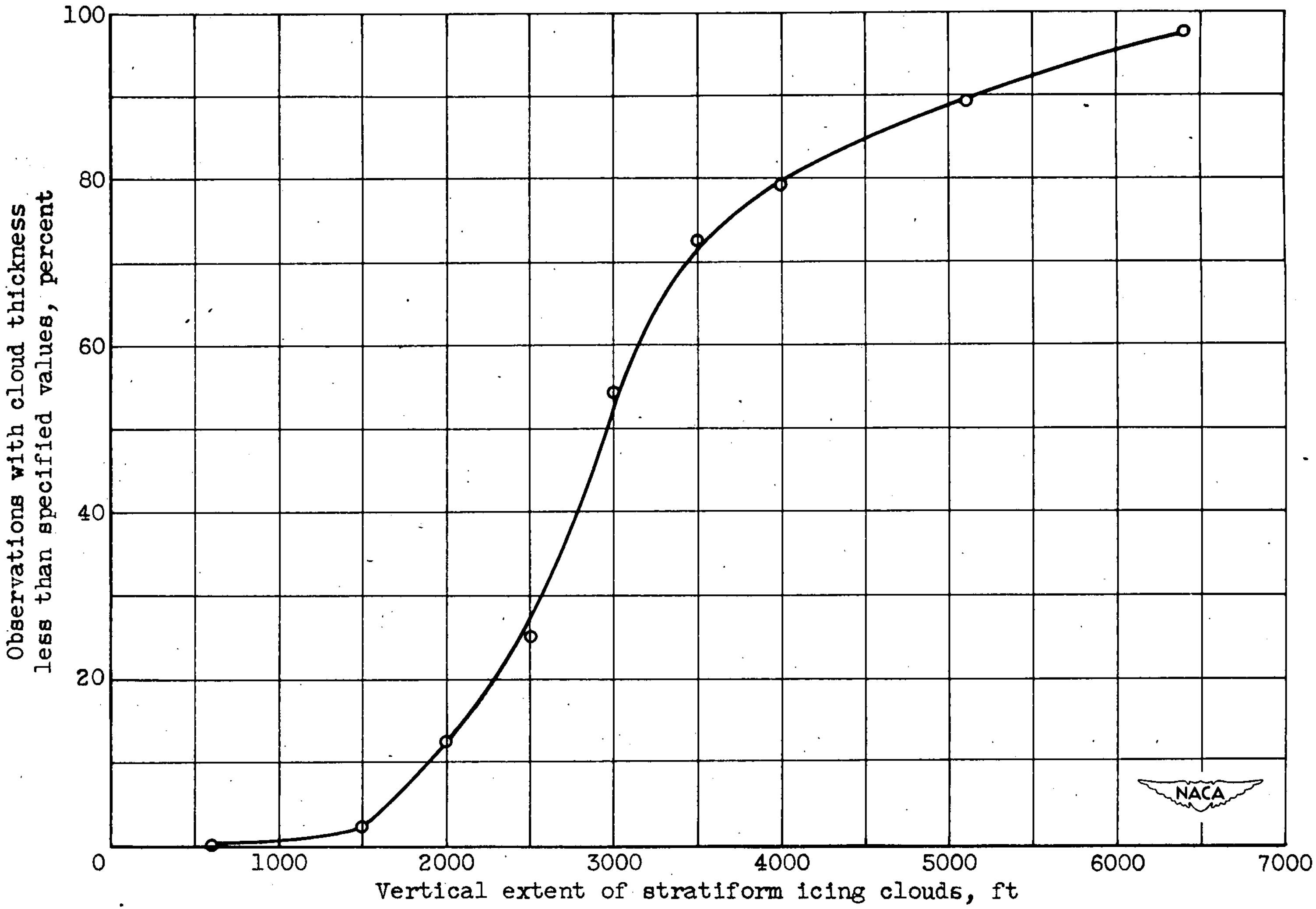

Figure 3. - Cumulative-frequency curve of cloud thickness observed during 48 icing flights in supercooled stratiform clouds.

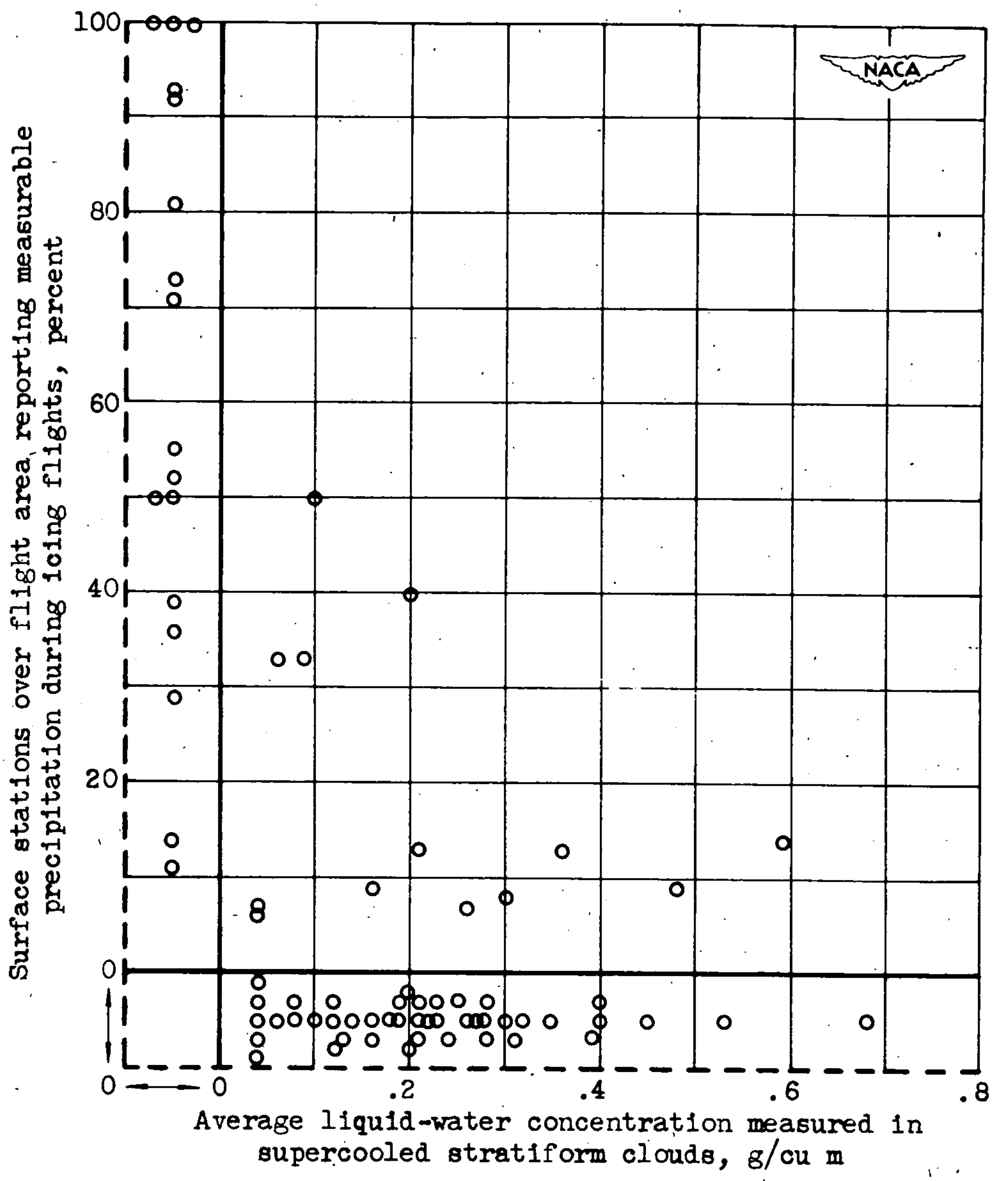

Figure 4. - Relation between percentage of surface stations reporting measurable precipitation and liquid-water concentration measured in clouds encountered during 74 icing flights.

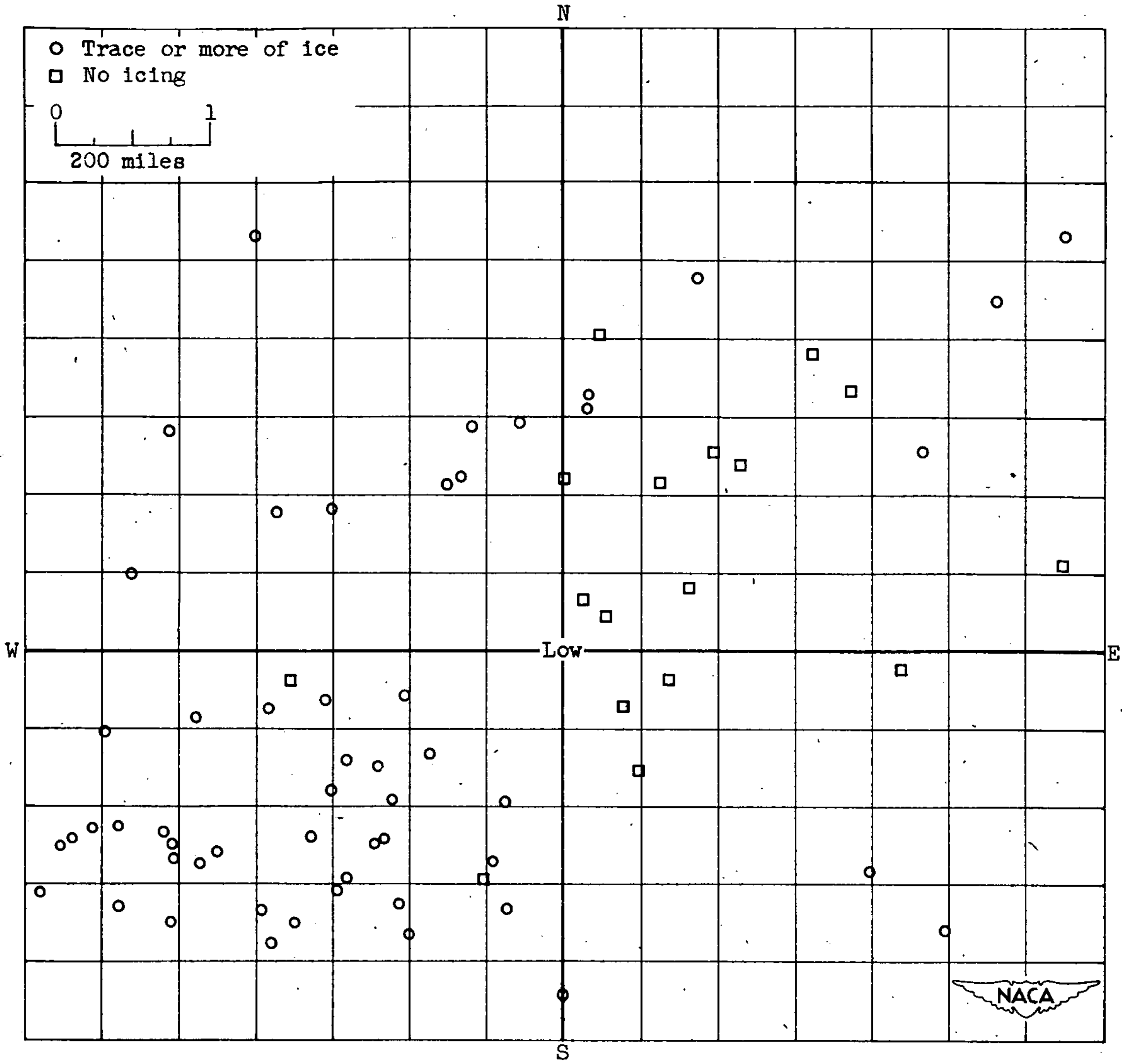

Figure 5. - Direction and distance of approximate midpoints of 70 icing flight areas as related to nearest low-pressure center.

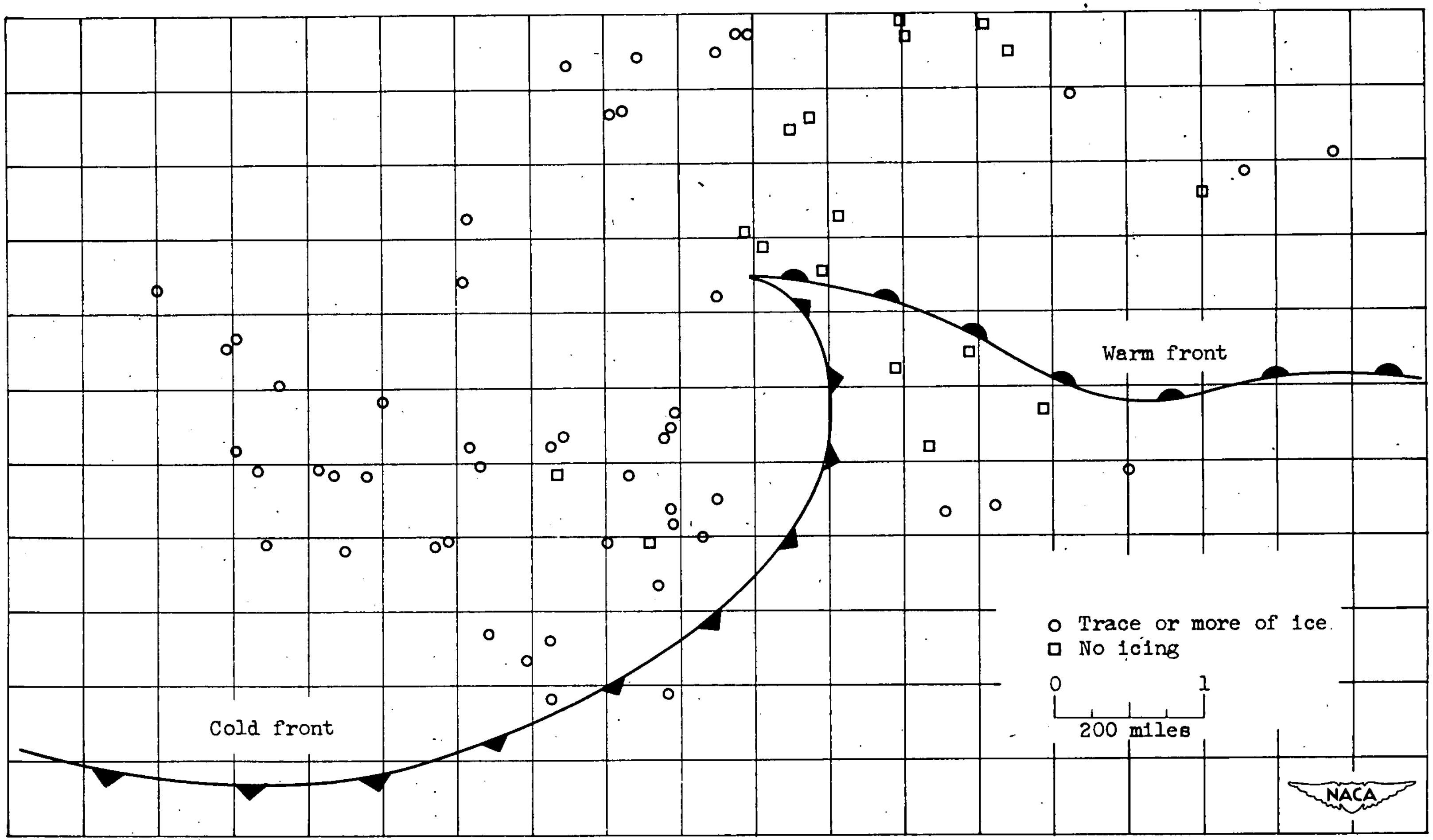

Figure 6. - Location of icing encounters in relation to nearest extratropical cyclone and associated idealized frontal pattern.