WORLD METEOROLOGICAL ORGANIZATION

TECHNICAL NOTE No. 3

METEOROLOGICAL ASPECTS OF AIRCRAFT ICING

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Secretariat of the World Meteorological Organization – Geneva – Switzerland

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ASPECTS METEOROLOGIQUES DU GIVRAGE DES AERONEFS

Résumé

Cette note technique, préparée par les soins de la Division technique du Secrétariat de l'OMM, est un résumé des rapports publiés sur les expériences effectuées récemment sur le givrage des aéronefs et autres surfaces exposées à l'air nuageux, ainsi que sur ses relations avec les propriétés des nuages.

La note débute par un bref résumé des paramètres météorologiques qui ont une influence sur le givrage des aéronefs, notamment le contenu en eau, la température ambiante et la distribution des dimensions des gouttes. Le chapitre principal décrit les recherches expérimentales récentes effectuées dans ce domaine à bord d'aéronefs, en particulier au Canada, aux Etats-Unis et en URSS. On y souligne cependant que les instruments utilisés étant sujets à certaines limitations, les résultats obtenus doivent être considérés avec quelques réserves. La note ne donne toutefois pas une description détaillée des instruments.

Le chapitre suivant passe en revue quelques expériences faites en laboratoire au Canada et en Suisse. Puis vient un résumé des recherches relatives à la physique des nuages, notamment à la formation des noyaux de glace qui jouent un rôle primordial dans le développement des précipitations.

La note traite ensuite des limitations intervenant dans les résultats des expériences faites jusqu'à présent; en effet, les mesures manquent presque totalement pour les régions tropicales, bien qu'on se soit efforcé d'obtenir des chiffres par extrapolation théorique des données obtenues dans les régions tempérées.

La note recommande enfin que des expériences soient effectuées dans d'autres parties du globe, éventuellement à bord d'avions de ligne, et que les résultats soient, à la suite d'un accord international, présentés sous une forme standard.

METEOROLOGICAL ASPECTS OF AIRCRAFT ICING

1. Introduction.

The subject of aircraft icing was discussed at the fifth session of the IMO Commission for Aeronautical Meteorology at Paris in 1950 and in paragraph 10.8.8 of the resulting recommendation it was recommended that the IMO should "study the physical characteristics of clouds with particular reference to water content, drop size and distribution, and relative composition of ice and water particles, and promote experimental research to assess the relationship of these characteristics to the effects of icing on objects exposed in cloud".

The Secretary-General of WMO was directed by Resolution 45 (EC-IV) "to collect information on experimental research on the icing of aircraft and exposed surfaces and its relation with cloud characteristics, such as water and ice content and particle size distribution" and to prepare a report on the subject.

This note is a summary of recent published papers in this field.

2. Meteorological parameters affecting aircraft icing

The rate of deposition of ice on an aircraft depends on the following meteorological factors: ambient temperature, humidity and density, liquid water content of the air, size distribution of drops and droplets. It also depends on various factors relating to the aircraft, such as the temperature of the surface, speed, attitude, geometric configuration and the past history.

An excellent review of the state of knowledge up to 1949/50 is contained in an article by W. Lewis (1). For the sake of completeness, a brief summary is given here.

The basic conditions required for ice accretion on a small object moving through the air are that the liquid water content

(1) See references at the end of publication.

shall be greater than zero and that the air temperature shall be below freezing point by at least the wet-air kinetic temperature rise corresponding to the speed of the object. For an aircraft, the position is more complicated, as the air may be cooled in places (such as the carburettor choke in a piston engine) where it is accelerated. Icing can in fact occur when the ambient air temperature is several degrees above freezing point.

Of the meteorological parameters, the two most important are the drop size distribution and the liquid water content; the former is in certain cases almost as important as the latter, at least for wing icing.

For convection clouds, the liquid water content depends on the temperature of the cloud base, the height of the object above the base, the amount of entrainment of the surrounding air, the degree of mixing, and the humidity of the surrounding air. A general consideration of these factors leads one to expect the maximum values of liquid water concentration to occur in the interior of convection clouds at a height above the base of $\frac{1}{2}$ to $\frac{3}{4}$ of the total thickness of the cloud.

In most turbulence clouds (Stratus, Stratocumulus, Altocumulus), the liquid water content increases from near zero at the cloud base to a maximum just below the top.

In the case of clouds formed by horizontal convergence (Altostratus, Altocumulus and Altostratus-Altocumulus), the liquid water content is usually very small in the main altostratus sections, which are usually composed of ice crystals. The surrounding altocumulus sections however are composed largely of water droplets.

Lewis points out the importance of the rôle played by ice crystals. The formation of ice crystals in a supercooled cloud leads rapidly to a reduction in liquid water concentration, for example from 1 gm/m^3 to about 0.1 gm/m^3 in twenty minutes or less in the case of cumulus clouds. After the formation of ice crystals in turbulent layer clouds, the liquid water concentration decreases more rapidly in the lower parts of the cloud and this leads to a gradual dissipation of the cloud from the bottom upward. If ice crystals fall into a turbulent layer cloud from an overlying cloud, the resulting precipitation may lead to the rapid dissipation of the cloud layer.

A theoretical treatment of the physics of cloud droplet formation by Howell (2) indicates that the droplet concentration is determined by the rate of cooling during the initial stage of condensation rather than by the concentration of nuclei. Uniform lifting tends to a uniform drop size distribution while evaporation decreases the number of droplets. The highest concentration is therefore to be expected in rapidly formed cumulus clouds and the lowest in altocumulus clouds formed slowly by convergence in stable air.

Another very useful general review of the meteorological aspects of aircraft icing has been published by the British Meteorological Office (3). After discussing the relevant physical properties of air and water, the various forms of ice accretion are described. This is followed by an excellent account of Langmuir's theoretical analysis (4) of the efficiency of catch of a cylinder. As an example of the application of this analysis, the report contains a graph showing the relation between the droplet size, liquid water content and rate of accumulation of ice for a cylinder 3 inches (7.6 cm) in diameter in a wind of 200 mi/hr (320 km/hr). This demonstrates clearly the importance of the droplet size at high liquid water contents. The report also considers the properties of different types of clouds, the effects of ice accretion on different parts of an aircraft and recommended flight procedure; world maps of the mean heights of the 0°C and the -40°C isothermal surfaces are given for January, April, July and October.

3. Recent experimental research

The bulk of direct recent experimental research on the meteorological parameters affecting aircraft icing has been done in Canada and the United States of America. Results are also available of an important series of measurements in the USSR (5). An attempt will now be made to summarize the main results under the headings of liquid water content, drop size distribution, temperature and extent of icing conditions.

Although details of the instruments used are not given here, it must be pointed out that many of the results are suspect owing to instrumental limitations, one of the most important being the Ludlam limit (6) for all instruments using rotating cylinders and discs. General accounts of the various instruments have been published by Pettit (7), Lewis (8) and Zaitsev (5).

3.1 Liquid water content

Values of liquid water content reported vary considerably with different types of cloud, different heights within the cloud, etc. Zaitsev (5) describes a series of investigations of cumulus clouds in which 60 flights were made through clouds at different levels. Liquid water content was measured by absorption in filter paper.

The results were tabulated as a function of height above the base of the cloud; a selection of the results is given in Table I.

TABLE I - AVERAGE DISTRIBUTION OF LIQUID WATER CONTENT IN CUMULUS CLOUDS, AFTER ZAITSEV. NUMBER OF OBSERVATIONS GIVEN IN BRACKETS

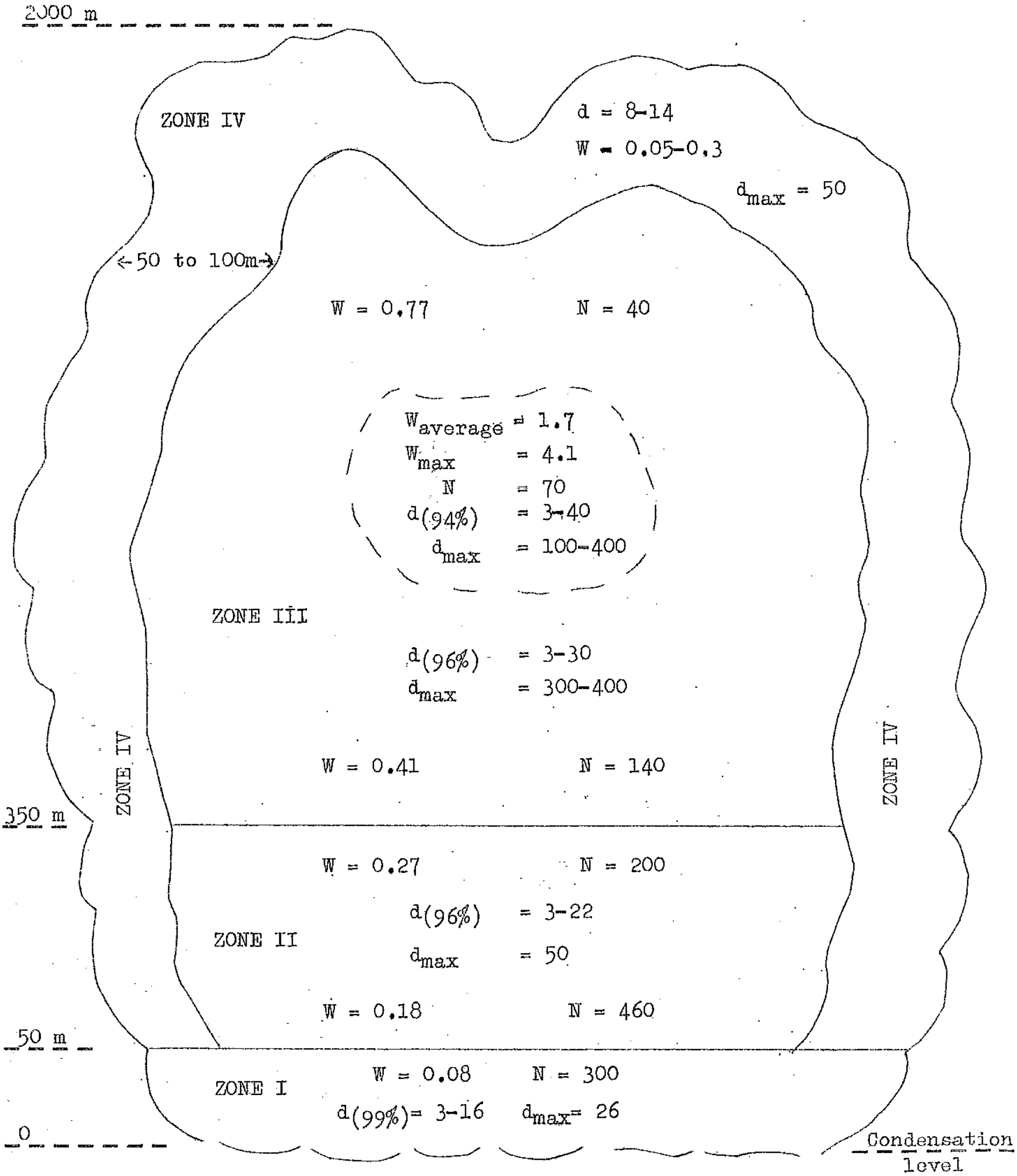
Height of middle of layer above base (metres)	Average W (gm/m^3) in dense Cu congestus	Average W (gm/m^3) in Cu humilis	Average W (gm/m^3) centre of Cu humilis and Cu congestus
150	0.33 (16)	0.17 (35)	0.23 (116)
550	0.85 (29)	0.38 (2)	0.54 (104)
950	1.70 (17)	-	0.86 (43)
1350	0.77 (3)	-	0.69 (25)

Similar measurements were made by Weickmann and aufm Kampe (9) in cumulus clouds with base temperatures between 17.5 and 24°C. They deduced the liquid water content from measurements of droplet size and visibility by an application of Trabert's formula. Up to a height of 1000 m above cloud base, their results agreed well with Zaitsev's, but their average value of liquid water content continued to increase at greater heights. This is probably because Zaitsev's observations were limited to Cumulus humilis and congestus, whereas Weickmann and aufm Kampe also took readings in cumulonimbus clouds; differences in cloud base temperature may also be an important factor (Zaitsev does not state these temperatures).

Zaitsev made some general deductions about the distribution of liquid water content in cumulus clouds which for convenience are summarized diagrammatically in Figure 1 .

Figure 1

Diagrammatic representation of distribution of liquid water content W (in gm/m3), droplet diameter d (in microns) and the droplet concentration N (no/cc) in cumulus clouds (based on Zaitsev's conclusions)



Note: $d(94\%) = 3\text{-}40$ means that 94% of the droplets have diameters between 3 and 40 μ d_{max} =400 means that droplets above 400 μ in diameter are not found

The general picture deduced supports the theoretical considerations mentioned above in Section 2.

The Canadian observations have been summarized in a recent paper by Pettit (10). Whereas the observations reported above were made at temperatures both above and below freezing point, the Canadian measurements were limited to icing conditions. The liquid water content was measured by the rotating disc technique. The results of about 1000 observations are given mainly in the form of frequency and cumulative frequency graphs of maximum liquid water content (the highest value, averaged over 13 seconds, during an icing encounter) and of average liquid water content (the average over an icing encounter of not less than 52 seconds duration). Separate graphs are given for cumuliform and stratiform clouds.

The absolute maximum value reported was 1.5 gm/m^3 (compared with 4.1 gm/m^3 measured by Zaitsev), but higher values at temperatures above about -10°C would not have been observed owing to the Ludlam limit of the instrument. The modal points of the average liquid water content curves were 0.17 gm/m^3 for cumuliform clouds and 0.10 gm/m^3 for stratiform clouds. Pettit also presents a scatter plot of maximum and average liquid water content versus temperature, which shows that the liquid water content decreases with decreasing temperature and that the peak values of maximum liquid water content are approximately twice the average values.

Observations of liquid water content in icing conditions, carried out under the auspices of the American National Advisory Committee for Aeronautics (NACA), are summarized by Hacker and Dorsch (11). The data are divided into two cloud types, stratiform and cumuliform, and are presented in the form of the observed frequency distribution of icing observations for various increments of liquid water content and heights. The average liquid water content for both cloud types increases with height to a maximum value and then decreases; the maximum values occur at about 1500 m for stratiform clouds and about 4000 m for cumuliform clouds. For any given height, the average liquid water content of cumuliform clouds is higher than for stratiform clouds. The highest value reported is 1.68 gm/m^3.

3.2 Cloud droplet size

Zaitsev (5) measured the size of cloud droplets by a direct photographic method which covers the range 2 microns (μ) to 500 μ. He found a well defined relationship, as shown in Table II (see on the following page), between the average and maximum diameter of drops in cumulus clouds and the height above the cloud base. It should be noted that his observations were not limited to icing conditions. He also reported that the droplets are smaller near the edges of the cloud than in the centre.

TABLE II - CLOUD DROPLET DIAMETERS AT VARIOUS HEIGHTS ABOVE BASE OF CUMULUS CLOUDS (AFTER ZAITSEV)

Height above base of cloud (metres)	Maximum frequency of drop diameter (microns)	Maximum diameter (microns)
Near base	4.1 to 6	26
200	9	50
600	11	(100)
800	17	(100)

Weickmann and aufm Kampe (9), using an oil-slide sampling technique capable of covering a range of droplet diameter from 4 μ to about 300 μ, measured the droplet size distribution in various types of cumuliform clouds. Their paper contains graphs showing the average droplet spectra for Cumulus humilis, Cumulus congestus and Cumulonimbus. In Cumulus humilis the droplet diameters range from 6 μ to 66 μ, whereas in the other clouds droplets were measured up to diameters of 200 μ and more. In cumulonimbus clouds it was found that the droplet spectra were narrow near the base of the cloud, and that at a height of 2000 m above base the droplet size reached its maximum value and the spectrum was very broad. In so far as they overlapped, their results agreed well with those of Zaitsev.

Aufm Kampe and Weickmann (12) have also investigated stratiform clouds and report that as the droplets in these clouds have in general more time to coalesce, the spectrum shows a tail with large droplets.

The results reported by Pettit (10) are limited to frequency and cumulative frequency distributions of volume median droplet diameter(*); these observations were also made by the oiled-slide technique. It is pointed out that many samples had to be rejected as they were obtained in conditions of mixed snow and liquid water - the oiled-slide technique used could not distinguish between droplets and melted ice crystals and snow flakes. The figures given are based on 50 samples collected during the winter. No correlation was found between droplet median volume diameter and liquid water content, while the maximum median volume diameter was 40 μ; the modal frequency was 20 μ.

The results reported in various NACA technical notes (8, 11, 13, 14) refer to observations made with rotating multicylinders. The droplet median volume diameter is deduced from the different amounts of ice collected on rotating cylinders of different diameters. In the summary by Hacker and Dorsch (11), the results are presented in the form of the frequency distributions of icing observations for various increments of droplet median volume diameter and height, separated into stratiform and cumuliform clouds.

Similar diagrams are also provided showing the frequency distribution of icing observations for various increments of liquid water content and droplet median volume diameter, grouped for the height ranges 0 to 10,000 ft. (3000 m) and 10,000 to 20,000 ft. (3000 to 6000 m). The most probable icing conditions deduced from these diagrams are assembled in Table III. (See on the following page).

3.3 Temperature

Icing has been observed over a wide range of air temperatures. As mentioned above, it may occur on certain parts of the aircraft at temperatures a few degrees above freezing point, and there are reports of ice accretion at -54°C (15) and even -60°C (16). In considering reports from commercial aircraft, it must be remembered that the thermometers are not very accurate, but even so it is quite clear that icing can occur below -40°C, the generally accepted temperature for the spontaneous formation of ice crystals (see Section 5).

Pettit (10) gives frequency and cumulative frequency curves for the temperatures of icing encounters in the Canadian investigations, but points out that the curves are biased since low

(*) The median volume diameter is the diameter for which the amount of water in all droplets of greater diameter is equal to the amount of water in all droplets of smaller diameter.

temperature encounters were preferred. 90% of all encounters occurred at temperatures above -13°C, and the modal points of the curves for both stratiform and cumuliform clouds were about -6°C.

TABLE III - MOST PROBABLE ICING CONDITIONS (AFTER HACKER & DORSCH) BASED ON NACA OBSERVATIONS

	0 to 10,000 ft. (3000 m)		10,000 - 20,000 ft. (3000 - 6000 m)	
	Liquid water content gm/m^3	Median volume diameter μ	Liquid water content gm/m^3	Median volume diameter μ
Stratiform clouds	0.19	12	0.06	15
Cumuliform clouds	0.42	21	(0.18)	(20)

In the NACA flights, as reported by Hacker and Dorsch (11), a greater range of temperature was found in encounters in stratiform than in cumuliform clouds at heights below about 2500 m. At low heights the average temperatures were lower than the corresponding temperatures of the NACA standard atmosphere, whereas at greater heights the average temperatures were slightly higher.

3.4 Extend ot icing conditions

The horizontal extent of icing conditions is obviously a factor of considerable importance. Jones and Beimers (17) have deduced some figures of the distance over which an aircraft flying on a constant heading may experience severe icing in convective cloud in E. England, based on ground radar observations of cumulonimbus clouds. They assumed that flight in the echo part of a cloud above the freezing level is associated with severe icing. They estimated that in these conditions, severe icing might at the worst occur for an aggregate of more than 10 miles in 100 miles in 40 per cent of flights; icing for an aggregate of more than 20 miles in 100 miles would only occur on 4 per cent of flights. Continuous icing is likely at the worst on about 40 per cent of flights for more than 8 miles in 100 miles, but on only about 4 per cent of flights for more than 17 miles in 100 miles.

Frequency and cumulative frequency distributions of the horizontal extent of icing encounters in cumuliform and stratiform clouds are presented by Pettit (10); these figures are based on observations made in an aircraft looking for icing conditions. 90% of the encounters in cumuliform cloud had a horizontal extent of less than 5 miles, the corresponding figure for stratiform clouds being 36 miles. The maximum extents were 40 miles and 232 miles in cumuliform and stratiform clouds respectively.

In the summary by Hacker and Dorsch (11), the maximum horizontal extent of icing situations with a given average liquid water content is presented graphically. The data are based on 57 flights. The figures vary from over 300 miles with a liquid water content of 0.1 gm/m^3 to about 1 mile at 1.5 gm/m^3.

4. Recent laboratory investigations

Most recent laboratory work relating directly to aircraft icing seems to have been concentrated on improving the instruments for use on aircraft, which falls outside the scope of the present report. Mention must however be made of an investigation by Fraser, Rush and Baxter (18) of the thermo-dynamic limitations of ice accretion instruments. They calculated the Ludlam limits for rotating cylinders and checked the results experimentally; reasonable agreement was obtained. The limits for the rotating disc instruments and the NAE-Smith detector head were also determined experimentally. They conclude that it is not possible in practice to correct for the limitations and that rotating cylinders are unsuitable for measurements in high speed flights. It is also stated that determinations of droplet size from rotating cylinders may be quite misleading.

A more general laboratory investigation into certain aspects of aircraft icing was carried out by Melcher (19). He measured the rime deposit on a rod 1 cm diameter in a wind tunnel at temperatures between -5 and -17°C and wind speeds between 5 and 10 m/s. Water droplets were introduced into the airstream either by an atomiser or by injecting water vapour from a pressurized container. Samples of the droplet were collected on a glass plate coated with gelatine and their diameters measured with a microscope. Melcher found that the quantity of rime deposited at given temperatures increased almost linearly with the liquid water content (range 0.3 to 1.5 gm/m^3) and that for a given liquid water content the quantity of rime decreased as the temperature decreased. The material of the target had no effect on the quantity of rime but the adhesion depended on the roughness of the surface of the target. One surpising result was that the quantity of rime decreased with increasing wind speed, which is contrary to what would be predicted from Langmuir's theory (4); for the very small droplets used (diameter about 5 μ), the value of the collector efficiency was however rather doubtful.

5. General cloud physics investigations

Considerable effort has in recent years been devoted to investigations into the more general aspects of cloud physics, especially with regard to precipitation. While this work has more bearing on the problems associated with the artificial stimulation of precipitation than with aircraft icing, it may be useful to review some aspects of recent developments. Some of the results have at least to be borne in mind when forecasting icing conditions.

Reviews of the progress made up to 1950 and 1951 have been given by Houghton (20), Mason and Ludlam (21) and Sheppard (22). A very thorough survey of the thermodynamics of the condensation process has been published by Köhler (23).

As pointed out above, the liquid water content of a cloud below 0°C usually decreases rapidly as soon as ice crystals appear. It is therefore relevant to consider the latest ideas about the formation of ice crystals within clouds.

The generally accepted theory is that ice crystals form by the freezing of water droplets; direct sublimation onto suitable nuclei seems to be a rare occurrence, at least above -40°C, although Fournier d'Albe (24) has produced some evidence that it can occur. From the results of various investigations by Findeisen, it seems that the freezing of water droplets depends on the nature of the nucleus of the drop; some nuclei will initiate freezing at a temperature of about - 10°C, while others become effective at about -32°C. Bigg (25) has recently conducted some laboratory experiments from which he concludes that pure water droplets will freeze without having freezing nuclei present, the probability of freezing being a fairly simple function of the temperature and volume of the droplet. The probability function is such that at temperature below -20°C the spontaneous freezing process is sufficiently rapid to account for the rate of ice crystal formation observed by Findeisen and other experimenters.

Bigg applied his formula to the formation of natural clouds in the atmosphere and concluded that without the presence of ice nuclei formation of cirrus clouds is possible below about -35°C, glaciation in stratiform clouds becomes appreciable below about -20°C and freezing of raindrops in strongly convective cloud becomes important below about -13°C.

Similar experiments using a different technique have been made by Lafargue (26). He found that droplets will not freeze above a certain critical temperature (T_c), which depends on both the droplet size and the purity of the water. He concludes that clouds are entirely supercooled between freezing point and T_c, and that below T_c ice crystals and supercooled droplets may exist side by side, the proportion varying during the life of the cloud. Finally he states that below -41°C supercooled droplets cannot exist in clouds.

The effectiveness of a great variety of substances in crystallizing supercooled clouds has been carefull investigated by Hosler (27). He found that the crystalline properties of the substances was not a decisive factor and concluded that the rôle of foreign substances in raising the spontaneous freezing point of water droplets may be in lowering the surface free energy of the droplets due to the presence of polarizable ions. This explanation is based on a theory, due to Weyl, which also explains why small droplets freeze at lower temperatures than larger droplets.

The latest theoretical study of the spontaneous crystallization of water droplet is that of McDonald (28). He calls attention to certain errors in earlier papers on the subject, and on the basis of the best available values of various constants he arrives at -26°C as the theoretical transition temperature, as compared with the experimental value of about -40°C. He stresses the need for an experimental determination of the surface free energy of a water-ice interface and suggests that this might be possible at the triple point.

6. Limitations of available data

It has been pointed out above that much of the existing information about liquid water content and droplet sizes is suspect due to instrumental difficulties. Quite apart from this limitation, however, it must be stressed that little or no information is available about these quantities in tropical clouds. Modern aircraft operate at heights where the temperature is well below 0°C in tropical regions, and in view of the dependence of liquid water content on temperature of cloud base it would be unwise to assume that data from temperate regions apply to the tropics.

Best (29) has shown that the values of liquid water content observed in America in strongly convective clouds are in agreement with the values which would have been expected on theoretical grounds. He therefore argues that equally good agreement can be expected for tropical clouds. He calculated the maximum values of liquid water content for different models of convective clouds with a base temperature of 21°C at 950 mb. From this, and making several reasonable assumptions, he prepared a table showing the value of liquid water content which would be exceeded on a specified percentage number of icing encounters in strongly convective clouds with a base temperature of 21°C for various droplets diameters. For example, for a droplet diameter of 20 μ and temperatures between 0 and -26°C, liquid water contents greater than 0.32 gm/m^3 would be exceeded on 75 per cent of icing encounters and 2.02 gm/m^3 on 5 per cent.

A very thorough statistical analysis of the meteorological icing data obtained in the United States has been made by Lewis and Bergrun (30). Graphs are presented showing (i) the various simultaneous combinations of liquid water content, droplet diameter and temperature which would have equal probability of being exceeded in flight in any random icing encounter and (ii) the probability of exceeding any specified group of values of liquid water content associated simultaneously with temperatures and droplet diameters lying within specified ranges. As the observations on which this analysis is based were obtained during flights in which icing conditions were deliberately sought, there may be some bias towards severe icing conditions. The mathematical basis of the analysis is suitable for application to data which may be obtained in other parts of the world.

Another valuable attempt at producing representative values of the meteorological factors which affect aircraft icing is contained in a recent report by Fraser (31). He developed a basic severity diagram showing the maximum liquid water content to be expected at temperatures down to -40°C, taking 4 gm/m^3 as the value for 0°C and assuming that clouds with high liquid water content start to precipitate when they attain a temperature of -16°C. He also gives a basic distribution diagram showing the proposed maximum average liquid water content for various extents of icing. From these two diagrams he produces a series of graphs showing the severity and distribution requirements in terms of liquid water content, temperature and extent of icing. Fraser finally demonstrates how his graphs can be applied to various icing protective systems.

The only way of obtaining frequency data free from the bias associated with results obtained in special investigating aircraft, is to equip commercial aircraft with suitable instruments. This is now being done in America with aircraft equipped with NACA pressuretype icing-rate meters; the first results have been discussed by Perkins (32). The four aircraft involved had 100 icing encounters over the period January - May 1951, which corresponded to $1\frac{1}{2}$ per cent of the total flying time in icing conditions - in Canada, Trans-Canada Airlines report a figure of 5 per cent (33). Further reports of this investigation should be very valuable.

7. Recommendations

While a considerable volume of data about the characteristics of clouds associated with aircraft icing has now been accumulated for certain regions, it is clearly desirable to obtain further information from other parts of the world, especially the tropics. Observations with special instruments made by commercial aircraft would be of great value.

Anybody who studies the reports of observations made in different places cannot fail to be struck by the different methods of presenting the data. In many cases it is impossible to carry out a useful comparison between different series of investigations without having recourse to the raw data. It is suggested that the possibility of obtaining an internationally agreed procedure for summarizing the observations should be considered.

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