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PREFACE

The Handbook of Weather Forecasting was written mainly for distribution within the Meteorological Office to provide forecasters with a comprehensive and up-to-date reference book on techniques of forecasting and closely related aspects of meteorology. The work, which appeared originally as twenty separate chapters, is now re-issued in three volumes in loose-leaf form to facilitate revision.

Certain amendments of an essential nature have been incorporated in this edition but, in some chapters, temperature values still appear in degrees Fahrenheit. These will be changed to degrees Celsius when the chapters concerned are completely revised.

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ICE ACCRETION ON AIRCRAFT

18.1 INTRODUCTION

Ice accretion on aircraft has long been recognized as a hazard to aviation. Various methods are available to prevent ice accretion or to remove a deposit of ice after it has formed but none provides more than partial protection. When ice forms on an aircraft, either on the airframe or in the engine system, the efficiency of the aircraft may be affected to such an extent that continued safe flight is impossible unless action is taken to remove the accumulation of ice or to fly in atmospheric conditions where ice accretion will cease or will continue at a very much reduced rate. The possibility of ice accretion should therefore be considered by the aviator before and during flight and there is normally a section in each aviation forecast which includes an assessment of the icing likely to be experienced on any particular flight.

Airframe icing affects various parts of the airframe in different ways. Ice formation near the leading edges of the airframe modifies the air flow round the affected part. It normally increases drag and reduces lift. When it occurs near the leading edges of the wings the air flow may be so modified that the aircraft is unable to maintain height. Ice accretion on the fin, rudder and other movable parts may interfere with the air flow to such an extent that control is seriously affected. Ice formation is not confined to leading edges. It may form on other parts of the wing and fuselage and cause a considerable increase in drag. Ice may also form in the gaps which normally exist between the forward edge of a control surface and the fixed surface ahead of it causing the control to jam. The risk of this occurring is normally greater on small than large aircraft. Further, small protrusions on an aircraft tend to ice up more readily than the bluff parts of the aircraft. Thus the efficiency of radio and radar equipment may be adversely affected by ice on the masts, aerials and radomes and the measurement of airspeed may be in error due to icing of the pitot system.

When icing occurs on the extremities of propellor blades there is a loss of efficiency. If parts of the ice on a propellor break away, the resulting lack of balance of the propellor may set up serious vibrations which endanger the aircraft.

Ice may form in the air-intake and induction system of a piston engine thereby causing a loss of engine power due to obstruction of the air passages and to disturbance of the fuel metering. Three types of icing occur: impact icing, throttle icing and fuel-evaporation icing. Impact icing forms when supercooled water drops strike parts of the air-intake and induction system and the manner of its formation is essentially similar to that for airframe icing. Impact ice may form on air-intake mouths, duct walls, carburettor screens, exposed metering elements, throttle butterflies and other protuberances in the induction system. Heating systems are normally fitted so that impact ice may be melted or prevented from forming and ice guards are sometimes fitted at the mouth of the air intake. These guards ice up rapidly in icing conditions and so prevent further obstruction of the intake. The engine then obtains its air from a sheltered intake. As air passes through the carburettor choke and across the throttle butterfly there is a reduction of air pressure associated with an increased air velocity. The reduction of air pressure leads to a lowering of air temperature. Surfaces in contact with the air flow are cooled locally and throttle icing may occur. Throttle icing may form when ambient air temperatures are above 0°C. (up to +5°C.) and free water is present. In general the additional cooling in the throttle intensifies other icing difficulties. Fuel-evaporation icing is caused by the cooling due to evaporation from all surfaces which are wet with fuel. If the surface is cooled below the local frost-point or if free water is present and the local temperature is below 0°C. ice will form and may build up on the surfaces. Fuel-evaporation icing may form with intake air temperatures well above 0°C.

In supercooled water clouds there is little difference between the formation of impact and throttle ice in the induction systems of piston engines, and the icing of gas turbine and jet engines. In many engines the effect of the ice is limited to the air-intake passages and the early stages of the compressor. Thereafter the temperatures are too high for ice formation. In gas turbine and jet engines the fuel is introduced directly into the combustion chamber and there is no risk of evaporative icing. With axial-flow compressors a comparatively light ice formation may spoil the air flow over the blades and reduce the performance. The centrifugal type of compressor is much less sensitive to ice formation.

There is, however, another important type of ice formation peculiar to some forms of turbo-jet and jet engines in which parts of the intake, well before the compressor is reached, may have temperatures well above 0°C. If these parts are not shielded from the impact of ice crystals the first ice crystals to hit the hot spot will melt and, by extraction of the latent heat required for melting, will cool these parts to 0°C. Further ice crystals then adhere to the wet surface and accumulate like a wet snowball which can then slide along the intake wall into the compressor and flame chamber to give a sudden "dowsing" effect. The effect can also be experienced in wet snow and in a climb through the melting level in precipitation when all the surface is wet and subsequent snow-flakes are held by this wet surface.

For ice accretion to occur it is of fundamental importance that water droplets can exist in the atmosphere in the liquid state at temperatures well below 0°C. - the freezing point of water. The degree of supercooling may be considerable before water droplets freeze spontaneously. Laboratory work indicates that the temperature of spontaneous freezing varies with the size of the droplets (being higher for larger droplets) but that at temperatures of about −40°C. even the smallest droplets freeze spontaneously. A supercooled water droplet is in an unstable state, the solid state being the most stable. A supercooled water droplet may be induced to change from the liquid to solid state in three ways: by further supercooling to the spontaneous freezing point, by the introduction of an ice (or similar) nucleus or by shock. The further supercooling of droplets and/or the introduction of ice nucleii into a cloud consisting of supercooled water droplets may transform the droplets from the water to a predominating ice state. This forms a part of the life cycle of many natural clouds and cloud systems, and was considered in Chapter 16. When supercooled droplets impinge on the surface of an aircraft the shock initiates freezing and part of the droplet freezes instantaneously. The water which freezes liberates latent heat of fusion of ice (about 80 calories per gramme) and this raises the temperature of the water/ice droplet after impact. It is readily seen that the whole of the water droplet will freeze on impact only if its temperature is −80°C. or below. The fraction of a water droplet which freezes instantaneously on impact is easily calculated to a sufficient degree of accuracy for our purpose. We assume that the amount of water which freezes is sufficient to raise the temperature of the water/ice droplet to 0°C. immediately after impact. If the supercooled water droplet had mass x grammes at temperature $-T$°C. before impact and y grammes froze, then assuming the specific heat of water is unity and that of ice is 0.5, the heat absorbed in raising the temperature of the water/ice droplet to 0°C. is $(x-y)\ T + 0.5yT$ calories. The heat of fusion released is $80y$ calories. Thus

$$80\,y = (x - y)\,T + 0.5\,y\,T$$

$$\text{or} \quad \frac{y}{x} = \frac{T}{80 + 0.5\,T}$$

Thus to a close degree of approximation one eightieth of the droplet will freeze on impact for each degree Centigrade by which the droplet is supercooled below 0°C.

Thus when a supercooled water droplet impinges on an aircraft, part freezes instantaneously. The rate at which the rest of the droplet freezes depends on the rate at which the heat of fusion of water can be extracted from the droplet by conduction to and through the substance of the aircraft and by conduction and evaporation to the surrounding air. Accordingly if a droplet is strongly supercooled a large fraction will freeze instantaneously and, if it is small, there will be a relatively small amount of heat to extract from the liquid water remaining on impact in order to freeze the whole droplet. The air flow and the fabric usually extract this heat rapidly and the droplet tends to freeze almost instantaneously. For larger droplets with higher temperatures the fraction freezing on impact is smaller. There is both a larger fraction and a larger mass of water left in the liquid state. The air flow causes this water to commence to flow back along the surface of the aircraft before freezing is complete. Although both the size of the droplet and the degree of supercooling are both important factors in determining the manner in which the droplets freeze they do not uniquely determine the form of airframe icing which will now be described.

18.2. FORMS OF ICE ACCRETION ON AIRFRAMES

Ice accretion on aircraft may be classified into four main types, each of which occurs also on the ground, namely: hoar frost, opaque rime, translucent rime (glaze or clear ice) and pack snow. The four types are not altogether distinct since intermediate types occur; furthermore two types of ice may form on different parts of an aircraft at the same time.

18.2.1 *Hoar frost*

Hoar frost is deposited on a surface whose temperature is reduced below the frost-point of the air in contact with it and, of course, below 0°C. The water vapour in excess of that necessary to saturate the air with respect to ice condenses into a white crystalline coating of ice, normally of a feathery nature. Hoar frost may occur if the aircraft, after flying in a region where the temperature is below 0°C., moves rapidly into a warmer and damp layer of air. This may result from descent to a lower level or ascent into an inversion. If flight is continued in the warmer air the hoar frost normally disappears as the aircraft warms up. Hoar frost also forms on parked aircraft in the same circumstances that lead to the deposition of hoar frost on the ground.

18.2.2 *Rime*

Rime occurs when supercooled water drops freeze on contact with a surface at a temperature below 0°C. At ground level it forms in freezing fog or cloud and, characteristically, consists of a white, rough, opaque deposit of ice on the windward side of exposed objects. Rime may be deposited on an aircraft flying through a cloud of supercooled drops. The character of rime deposited on an aircraft in flight varies considerably with the circumstances of its formation. Two extreme forms are described but it should be remembered that an aircraft in flight may encounter conditions which lead to a type of ice intermediate between the two extreme forms.

18.2.2.1 *Opaque rime.* This consists of a white, opaque deposit of ice having a light porous texture. It accumulates on the leading edges of wings, struts, etc., and results from the cloud particles freezing with little or no spreading. A large amount of air is imprisoned between the particles. As the accumulation grows out from the leading edges towards the airstream the mechanical impact of the air tends to consolidate the accumulated ice leading to the familiar white, opaque appearance. Ice of this type usually has no great weight. The danger from this form of rime lies in an alteration to the aerodynamic characteristic of the wings and in the blocking or partial blocking of the orifices of the carburettor and other instruments.

18.2.2.2 *Translucent rime or glaze or clear ice.* This consists of a transparent or translucent coating of ice with a glassy-surface appearance. It results from water flowing over the airframe before freezing. The drops unite while in the liquid state and very little air is enclosed between them, thus leading to the translucent appearance. The deposit is not confined to the leading edges for the water remains in the liquid state for an appreciable time after impact and is spread backwards by the air flow before it freezes. On large surfaces such as the wings the initial deposit of glaze ice may have a flat surface but, with a substantial deposit, the surface is generally uneven although still fairly smooth. Ice formed in this way is tough and sticks closely to the surface of the aircraft; it cannot easily be shaken off and, if it breaks off at all, it comes away in lumps which sometimes reach a dangerous size. The danger from this form of ice is primarily aerodynamic but it is increased by the weight of the accumulation and by vibration set up by unequal loading of wings, struts and propellor blades.

18.2.3 *Rain ice*

This is an extreme form of glaze ice which occurs when the source of water is supercooled rain instead of cloud droplets. It corresponds with the formation of glazed frost at ground level which occurs as a layer of smooth ice when rain falls with the surface temperature below 0°C. In the atmosphere temperature does not always decrease with increasing altitude and it sometimes happens that precipitation may fall from a layer where the temperature is above 0°C. through an underlying colder layer where the temperature is below 0°C. The raindrops do not freeze immediately on reaching the colder air, and an aircraft (also with a temperature below 0°C.) flying through the colder air will encounter these supercooled raindrops. The drops are very large compared with cloud droplets and there is much run-back of water after the initial freezing of part of the droplet on impact and before the rest of the water freezes. In these conditions clear glassy ice will form over an extensive area of the aircraft.

18.2.4 *Pack snow*

Dry ice or snow crystals will not adhere to the airframe of a dry aircraft but ice formation may occur while flying in snow when supercooled water droplets are present. The icing of the aircraft in such conditions is primarily due to the freezing of the supercooled droplets on impact though snow-flakes may be embedded in the ice so formed.

18.3 FACTORS AFFECTING ICE ACCRETION ON AIRFRAMES

A detailed theoretical treatment of ice accretion on aircraft based on existing published work would become rather complicated and is not particularly appropriate to this handbook. The resumé given below is modelled on *Meteorological Report* No. 9[1] and contains sufficient background information for most forecasting purposes. Forecasters who wish to study the theoretical aspects of ice accretion more deeply should consult some of the references listed at the end of this chapter. A reasonably complete summary of some theoretical aspects of ice accretion on aircraft is contained in the form of lecture notes compiled by Tribus.[2]

It is common experience that, at ground level, rime accumulates on the windward side of exposed objects and that, on aircraft in flight, not all parts of the airframe are equally susceptible to ice accretion. To arrive at some understanding of ice accretion on aircraft we shall assume that if a supercooled drop makes contact with the airframe it will contribute to the icing of the aircraft so that the problem reduces to determining how much of the free water in the path of aircraft is caught by the airframe.

18.3.1 *Flow round a cylinder*

Figure 1 represents diagrammatically the flow of air and the trajectory of water drops round a cylinder of circular cross-section held perpendicular to the airstream. Points A, B, C and D are sufficiently far upstream for the air flow to be unaffected by the cylinder. Air starting at A will be swept round the cylinder but a drop at A will strike the cylinder at X. A drop starting at B will strike the cylinder at Y but a drop at D will be swept round and will not reach the cylinder. The deviation of the drops from the stream-lines of the air is due to their momentum and it is clear that there will be some limiting drop-path CZ which is tangential to the cylinder at Z. Thus if we consider all the drops in the Section AD, only those within AC will strike the cylinder, that is, only a fraction of the total drops in the path are intercepted.

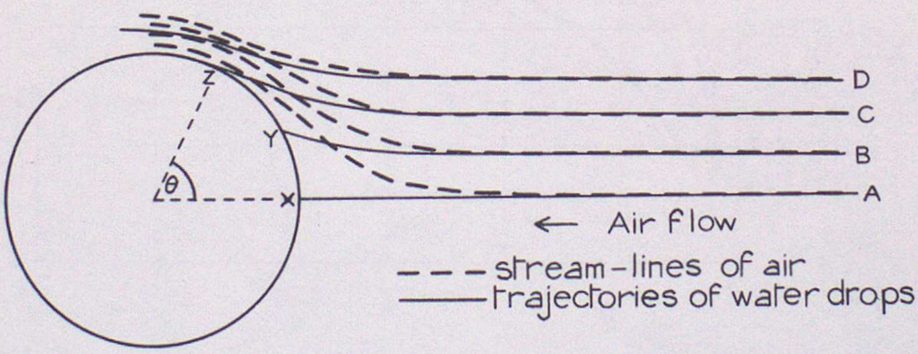

FIGURE 1 *Flow of air and trajectories of water drops round a cylinder*

It can be seen in a general way that the extent of the deviation of the drops from the stream-lines will depend upon the momentum of the drops, that is, upon their size and speed relative to the aircraft, and also that the water-catch will be influenced by the magnitude of the deviation of the stream-lines, that is, by the radius of the cylinder.

18.3.2 *Fraction of water caught*

It is clear that the fraction of water caught must be an important factor in the problem of ice accretion and that a determination of the path of a water drop in an airstream flowing past an object is one of the first requisites to a theoretical treatment. Glauert[3] determined the paths of water drops in an airstream flowing past a circular cylinder and his work was later extended by Langmuir and Blodgett.[4] The dominant factors are the sizes of the drops and the cylinder and the wind speed. Langmuir and Blodgett found that the efficiency of catch, *F*, of a cylinder (that is, the ratio of water caught by the cylinder to the water contained in the swept path) could be related by a series of curves on a plot of *F* against a quantity *k* such that

$$k = 5.87 \times 10^{-4} \frac{a^2 U}{R}, \qquad \ldots . \quad (1)$$

where a is the drop radius in microns (1 mm. = 1,000μ), U is the wind speed in miles per hour and R is the cylinder radius in centimetres. The particular curve to use depends on a quantity Q, defined by

$$Q = 3.93\ RU. \qquad \ldots . \quad (2)$$

The numerical coefficients used in equations (1) and (2) refer to a height of 3 kilometres in the I.C.A.N. atmosphere and have somewhat different values in other conditions. Four curves for variations of Q over a range of three orders of magnitude are shown in Figure 2.

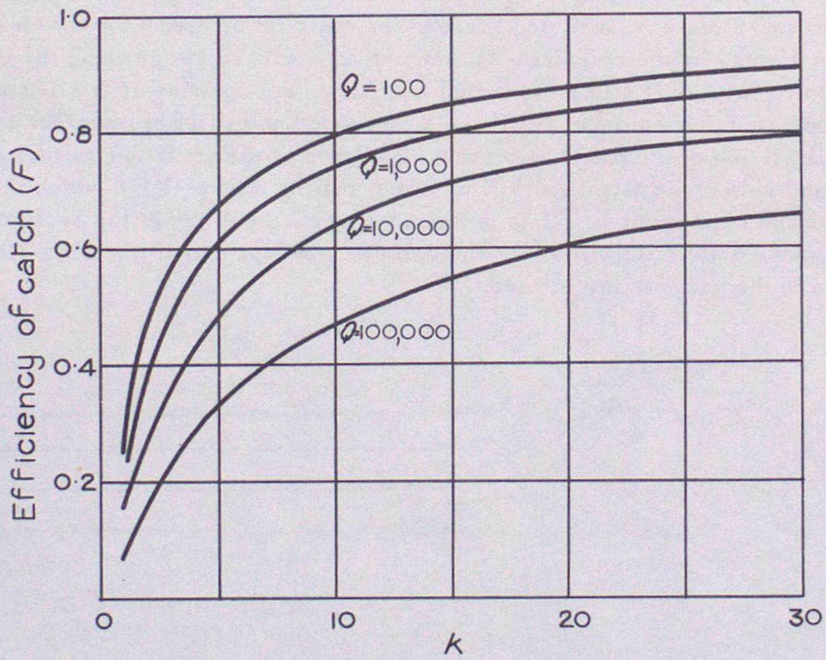

FIGURE 2 *Efficiency of catch (F) of a cylinder as a function of k and Q*

It is seen from Figure 2 that the efficiency of catch is small for small values of k and increases as k increases. The effect of moderate variations in Q is small. A more detailed consideration of the effects of varying drop size, wind speed and radius of cylinder enables the following conclusions to be drawn:

18.3.2.1 *Effect of drop size.* k increases rapidly as the drop radius increases and the efficiency of catch increases accordingly but the effect is greatest when k is small.

18.3.2.2 *Effect of wind speed.* An increase in wind speed increases k proportionately and therefore increases F. As in Section 18.3.2.1 the increase in F is greatest when k is small. Other things being equal, a high-speed aircraft will experience a greater rate of ice accretion (owing to the higher value of F) than a slower aircraft.

18.3.2.3 *Effect of radius of cylinder.* k increases as R decreases so, assuming an aircraft wing is broadly similar to a cylinder, a thin wing catches a greater fraction of the water in the swept path than does a thick wing. It does not follow that a greater total weight of ice is collected by a thin wing, since the swept path has a smaller cross-section than that for a thick wing. On the other hand a small deposit on a thin wing may have a greater effect upon the aerodynamic properties than a similar deposit on a thick wing. The variation of k with R also explains why objects with a small radius of curvature (for example, aerial supports) are more liable to icing than the more bluff parts of the airframe, such as the nose of the fuselage.

18.3.3 *Area of catch*

The angle θ in Figure 1 indicates the part of the cylinder which will intercept water drops. It is found that θ increases as F increases. Detailed consideration shows that when k is small (small drops, low speed or on a bluff part of the aircraft) θ is small and the deposit will consist of a thin line of ice at the stagnation point of the air flow. When k is large (large drops, high speed or a small radius of curvature) θ is large and the deposit will spread further round the affected part. Although high values of k lead to a greater area of catch this does not mean that the thickness of ice is decreased, since the accompanying increase in F ensures that more water droplets are caught.

18.3.4 *Effect of drop size and free water content*

If W denotes the amount of free water per unit volume of air then the amount of free water in the path swept in unit time by unit length of a cylinder of radius R is $2RUW$, where U is the airspeed. Only a fraction F of this water is collected and, if it is assumed that all the caught water leads to ice accretion, the total deposit per unit time on unit length of the cylinder will be $2RUWF$. The cross-sectional area of unit length of the cylinder is $2R$ so that the average deposit per unit time per unit area of cross-section is UWF, if it is assumed that ice collects on the leading edge. If drops of uniform size, the radius of the cylinder and the airspeed are all specified then values of k and Q can be calculated from equations (1) and (2) respectively and the efficiency of catch can be determined from Figure 2. It is then possible to determine the relation between the rate of ice accretion and the liquid water content. Droplet sizes and the free water content are far from uniform in cloud systems and precipitation areas. They vary markedly both in time and space. Lack of knowledge of the constitution of clouds and their variation in time and space at the time of writing precludes any firm numerical estimate on the forecast bench of the rate of ice accretion.

18.3.5 *Effect of kinetic heating*

When an aircraft is in motion the air follows the stream-lines round the component parts of the airframe. The air pressure on the surface of the aircraft varies from place to place, being greatest at stagnation points such as the leading edges where it exceeds the static pressure, and least on the upper surface of the wing where it is less than the static pressure. The local air flow is least where the pressure is greatest, and is greatest where the pressure is least. At the stagnation points the airstream is compressed and heated adiabatically, while there is a fall of temperature where the pressure is less than the static pressure. In addition to this adiabatic heating and cooling, friction between the airframe and the air generates heat at all parts of the airframe except the stagnation points. This frictional heating is greatest where the relative motion is greatest and least where relative motion is least. Thus the frictional heating is greatest where the heating due to compression is least. The compressional and frictional heating together are known as kinetic heating. The amount of heating varies over the surface of the aircraft; it is a minimum on the upper surface of the wing and a maximum at the stagnation point. Conduction of heat through the airframe, particularly if metal, tends to smooth out the temperature differences. The increase of temperature in clear air is small on slow aircraft - about 1°C. on a leading edge moving at 100 knots. This increase varies with the square of the speed of the aircraft and for a true air speed of 500 knots is in the neighbourhood of 25°C. However, in icing conditions parts of the aircraft are wet and, if they are warmed above the ambient air temperature, evaporation takes place so that the latent heat of evaporation (about 600 calories per gramme of water evaporated) must be supplied. This evaporative cooling in icing conditions will partly offset the effect of kinetic heating. Thus although the final effect of kinetic heating may be small it may be important in some critical conditions favourable for ice accretion. It is clear that a rise of temperature from just below to just above 0°C. would prevent ice formation but it should be noted that a rise of temperature to a value below 0°C. may have important effects on the risk or form of ice accretion.

18.3.6 *Summary*

It is seen that several factors enter in a rather complicated way into any assessment of ice accretion on aircraft. These factors may be regarded as falling into two main classes: (*a*) aeronautical/operational and (*b*) meteorological. The aeronautical/operational factors are:

(i) Aerodynamic characteristics of the airframe.
(ii) Airspeeds.
(iii) Aircraft attitude.
(iv) The form of propulsion and the susceptibility of the engine system to icing and its performance in icing conditions.
(v) The effect of kinetic heating and ascent and descent on the temperature of the aircraft.

The meteorological factors are:

(i) Liquid water content.
(ii) Size distribution of water drops.
(iii) Temperatures.
(iv) Humidities.

The rest of this chapter will be confined to further consideration of the meteorological factors and to some rules for forecasting. No attempt is made in this handbook to take any further account of the possible aeronautical/operational factors. Some modification to the suggested forecasting rules may, however, be found appropriate by forecasters when forecasting ice accretion for flights by particular types of aircraft when flown in a uniform and standardized way.

18.4 METEOROLOGICAL FACTORS

18.4.1 *Theoretical and laboratory work*

18.4.1.1 *Temperatures at which supercooled droplets freeze.* Cwilong made a series of expansions in a Wilson cloud chamber to study the deposition of water at low temperatures. His work, which has been summarized by Dobson,[5] showed that with well cleaned air many ice crystals were formed during the expansion if the minimum temperature at the end of the expansion fell below −35°C. If the minimum temperature was above −35°C. only supercooled water droplets were produced. Using ordinary atmospheric air this critical temperature of −35°C. between the formation of ice particles or water droplets is raised to about −27°C. and is much less sharp. Thus Cwilong's results indicate that if clouds form at temperatures below about −27°C. they are likely to consist of ice particles. If the temperature is below −35°C. when clouds form then they are almost certain to consist of ice particles, even if the air be exceptionally clean.

It is also important to know the temperatures at which supercooled water droplets which already exist are likely to freeze spontaneously. Hacker and Dorsch[6] have studied in the laboratory the spontaneous freezing of water droplets supported on surfaces of platinum and of copper foil. They found that there was a range of temperatures within which water droplets froze spontaneously and that even drops of uniform size did not all freeze spontaneously at a unique temperature. No droplet was observed to freeze at a temperature above 20°F. (−6.7°C.) and all had frozen at a temperature not lower than −38°F. (−38.9°C.). All droplets were observed to melt at 32°F. Figure 3 shows the variation of average spontaneous

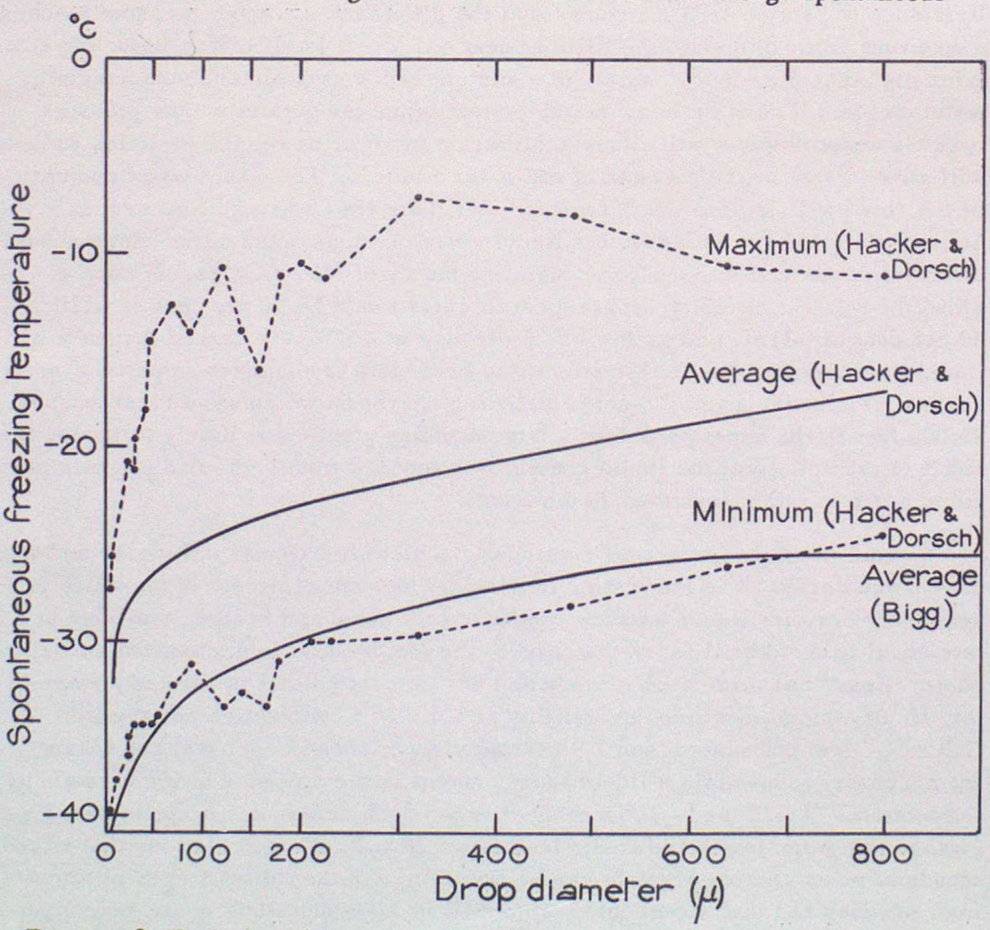

FIGURE 3 *Variation of spontaneous freezing temperatures with droplet size*

freezing temperatures and the maximum and minimum values observed by Hacker and Dorsch. Bigg[7] has also determined the spontaneous freezing temperatures of water droplets which were suspended at the interface of two insoluble liquids, one being heavier and the other lighter than water. Mean freezing temperatures as determined by Bigg are also shown on Figure 3. It will be seen that the results agree in form but differ quantitatively. Both results show that the average spontaneous freezing temperature decreases as the droplet size decreases. Assuming that these results can be applied to cloud droplets this means that the larger droplets will freeze at higher temperatures so that the remaining supercooled water droplets will, other things being equal, tend to be smaller the lower the temperature.

Mason[8] has shown from theoretical considerations that a temperature of –40°C. is a reasonable value for the spontaneous freezing of small supercooled water droplets. McDonald[9] has made a critical survey of the theoretical calculations made by Mason (and other workers) and considers that a number of errors were introduced. In his calculations he attempted to correct the errors but had to make a number of crude approximations and his results indicated that spontaneous freezing of drops of cloud-particle size should occur at a temperature of –26°C. This temperature is somewhat above that observed experimentally and it is clear that theoretical treatment has not yet reached finality.

18.4.1.2 *Significance of the difference between vapour pressure over ice and over supercooled water surfaces.* The vapour pressure over a plane supercooled water surface is greater than over a plane ice surface at the same temperature. Reference to Section 16.2.1.5 shows that the difference in vapour pressure reaches a maximum value of about 0.27 millibar near –12°C. It is clear from basic physical principles that if a cloud consists of a mixture of ice crystals and supercooled water droplets it must be in an unstable state since the greater vapour pressure over the water droplets will cause sublimation to occur on the ice particles which will grow in size at the expense of the water droplets. The liquid water content of the cloud will decrease and, provided that there are no external influences acting on a cloud producing further liquid water, a supercooled mixed cloud should ultimately transform into a cloud consisting solely of ice particles. In such a cloud the relative humidity with respect to water would be 90 per cent at –11°C., 80 per cent at –23°C. and as low as 70 per cent at –37°C. A marked decrease of liquid water content due to this effect may occur in a few minutes in parts of some convective clouds. Lewis[10] quotes a flight observation which shows that at about 16,000 feet in the upper portion of a large cumulus cloud immediately following the onset of precipitation, the liquid content was reduced from 1.9 to 0.2 grammes per cubic metre in rather less than 20 minutes.

Natural clouds are of course continually subject to external influences and to growth and decay. It is interesting to consider the rate of ascent of air which is necessary to cause liquid water to condense in a cloud and become available at a rate equal to the deposition of water on to the ice crystals in a saturated atmosphere. Best[11] has made such a study and has calculated that in the early stage in the life of a cloud, minimum up-draughts of 1.4×10^{-3} centimetres per second (2.8×10^{-3} feet per minute) and 1.9 centimetres per second (3.7 feet per minute) are necessary to maintain a liquid water content in the presence of ice crystals at temperatures of –10° and –30°C. respectively. Such values can occur in association with warm fronts and it can be inferred from Best's calculations that mixed clouds of water and ice crystals can be maintained in the initial stages of warm-front systems and that supercooled drops will be more numerous in the more vigorous systems which show larger up-draughts. A factor in these calculations is the number of ice crystals present per unit volume and in the later stages of a warm-front system this number is particularly difficult to assess as ice crystals which have formed at higher levels will have fallen to lower levels and the number of ice crystals will also have been increased by splintering. For a warm front from which rain is falling at 2.5 millimetres per hour, Best assumes that the number of ice crystals present at a temperature of –10°C. is of the order of 3,000 per cubic metre and deduces that a minimum up-draught of about 4 centimetres per second (8 feet per minute) would maintain supercooled droplets at that temperature.

Best concludes: "There is considerable uncertainty about the present calculations of the critical up-draught but the significance of the values obtained lies not in the precise speeds but in the fact that, in normal conditions, they can be of the same order as the up-draughts associated with warm fronts. Significant variations in n (the number of ice crystals per unit volume) must occur and it must often happen that the actual up-draught is very near the critical value, sometimes smaller and sometimes greater. With variations in n and in the actual up-draught it is easy to visualize the out-of-balance being in opposite directions at places separated by only a few miles or at the same place during comparatively short periods of time. We should thus expect apparently contradictory icing reports from aircraft flying in apparently similar warm-front conditions."

The modest values of critical up-draught to maintain supercooled water droplets co-existent with ice particles makes it clear that convective clouds with their far greater values of up-draught will contain supercooled water droplets and will frequently give icing conditions.

It should however be pointed out that Lewis[12] has deduced a value for the critical up-draught for the co-existence of water drops and ice crystals which is between one and two orders of magnitude greater than Best's figures. Lewis examined observations of snowfall on Mount Washington and used the occurrence or non-occurrence of measurable icing (occurring on an instrument near the ground) as an indication of the existence or absence of supercooled droplets with the snow. From values of the wind velocity and the fact that at the observatory the average inclination of the wind is about 20° from the horizontal Lewis deduced that critical up-draughts of 400 feet per minute or more are required for the co-existence of liquid cloud drops in the presence of moderate snow at a temperature appreciably below 0°C. These values will be biased by orographic effects and the extent of their applicability to clouds in the free atmosphere is not known. Some errors may have been introduced into Best's calculations when numerical values were inserted for the variables in his equation for the speed of the up-draught. The discrepancy between these two values has not yet been resolved. Up-draughts in stable warm-front conditions are certainly less than the larger figure quoted by Lewis. However, a recent examination by Jones[13] of reports of ice accretion indicates that on a number of occasions, which are too numerous to be ignored, supercooled water drops must have existed in warm-front conditions at temperatures well below 0°C. This would lend some indirect support to the possibility of a somewhat lower critical up-draught.

18.4.1.3 *Theoretical computation of liquid water content in cloud.* The maximum liquid water content in clouds can be calculated from thermodynamical considerations. Such calculations have been performed by American workers and, in the United Kingdom, Best[14] has published *Professional Note* No. 106 modelled largely on the American work. The following account is based on *Professional Note* No. 106, which is widely and readily available to forecasters in the United Kingdom.

TABLE 1 *Values of liquid water content in various models of convective cloud*

Pressure	First model					Second model		Third model					
						Ambient relative humidity						Ambient relative humidity	
						70%	100%					70%	100%
	Height above 950 mb.		Temperture		W	W	W	Height above 950 mb.		Temperture		W	W
mb.	ft.	m.	°F.	°C.	$gm.m.^{-3}$	$gm.m.^{-3}$	$gm.m.^{-3}$	ft.	m.	°F.	°C.	$gm.m.^{-3}$	$gm.m.^{-3}$
						Cloud-base temperature 38°F. at 950 mb.							
400	21,068	6,421	−50.0	−45.6	3.01	1.55	1.74	20,996	6,400	−52.8	−47.1	1.55	1.73
500	16,036	4,888	−25.2	−31.8	3.27	1.89	2.15	15,988	4,873	−27.3	−33.0	1.91	2.16
600	11,704	3,567	− 5.3	−20.8	3.18	2.00	2.31	11,676	3,559	− 7.1	−21.7	2.07	2.37
700	7,896	2,406	+10.4	−12.0	2.71	1.82	2.15	7,884	2,403	+ 8.8	−12.9	1.94	2.27
800	4,501	1,372	+22.8	− 5.1	1.89	1.35	1.63	4,496	1,370	+21.9	− 5.6	1.46	1.74
900	1,433	437	+33.3	+ 0.7	0.72	0.54	0.67	1,433	437	+32.9	+ 0.5	0.61	0.74
950	0	0	+38.0	+ 3.3	0.00	0.00	0.00	0	0	+38.0	+ 3.3	0.00	0.00
						Cloud-base temperature 70°F. at 950 mb.							
250	34,212	10,428	−42.0	−41.1	5.99	2.84	3.35	33,909	10,335	−50.1	−45.6	2.88	3.36
300	30,042	9,157	−21.8	−29.9	6.58	3.27	3.89	29,819	9,089	−29.0	−33.9	3.37	3.96
400	23,082	7,035	+ 5.8	−14.5	7.18	3.77	4.63	22,949	6,995	+ 0.7	−17.4	4.05	4.88
500	17,406	5,182	+24.9	− 3.9	6.91	3.70	4.78	17,339	5,163	+20.5	− 6.4	4.19	5.20
600	12,618	3,846	+38.6	+ 3.7	6.14	3.33	4.54	12,583	3,835	+35.4	+ 1.9	3.96	5.12
700	8,473	2,583	+49.5	+ 9.7	4.91	2.72	3.92	8,460	2,579	+47.3	+ 8.5	3.29	4.45
800	4,811	1,466	+58.7	+14.8	3.19	1.78	2.74	4,810	1,466	+57.6	+14.2	2.22	3.15
900	1,526	465	+66.5	+19.2	1.08	0.59	1.00	1,526	465	+66.0	+18.9	0.89	1.30
950	0	0	+70.0	+21.1	0.00	0.00	0.00	0	0	+70.0	+21.1	0.00	0.00
						Cloud-base temperature 82°F. at 950 mb.							
200	40,861	12,454	−30.8	−34.8	6.87	3.26	3.94	40,153	12,339	−49.0	−45.0	3.31	3.90
250	35,611	10,854	− 9.0	−22.8	7.66	3.72	4.59	35,105	10,700	−24.8	−31.6	3.99	4.74
300	31,141	9,492	+ 6.5	−14.1	8.17	4.09	5.06	30,777	9,380	− 6.6	−14.1	4.50	5.43
400	23,811	7,527	+27.6	− 2.4	8.50	4.14	5.59	23,607	7,195	+18.6	− 7.4	5.09	6.36
500	17,911	5,549	+43.2	+ 6.2	7.91	3.72	5.48	17,799	5,425	+36.5	+ 2.3	5.05	6.64
600	12,951	3,947	+54.9	+12.7	6.76	3.05	4.94	12,899	3,932	+50.1	+10.0	4.51	6.27
700	8,683	2,647	+63.8	+16.3	5.43	2.44	4.26	8,659	2,639	+60.7	+15.9	3.87	5.59
800	4,923	1,501	+71.6	+22.0	3.70	1.56	3.16	4,917	1,499	+69.9	+21.1	2.67	4.05
900	1,561	476	+78.6	+25.9	1.44	0.75	1.37	1,560	475	+78.1	+25.6	1.13	1.73
950	0	0	+82.0	+27.8	0.00	0.00	0.00	0	0	+82.0	+27.8	0.00	0.00

Convective cloud

Three models are discussed. The simplest model of a convective cloud consists of a vertical current of air in which water condenses as a result of cooling by ascent, the temperature falls with height at the saturated adiabatic lapse rate and the cloud is isolated from its surroundings so that no air is entrained from outside the cloud. A more elaborate model is obtained by assuming that air is entrained into the cloud from its surroundings and this seems likely to approximate more closely to reality provided a suitable rate of entrainment is postulated. With this second model some assumption must be made about the lapse rate of temperature within a cloud and the simplest assumption is that the temperature follows the wet-adiabatic lapse rate. This is Best's second model. The assumption about the lapse rate is inconsistent with the assumption of unsaturated air being entrained from outside. His third model is a refinement of the second model obtained by adjusting the lapse of temperature within the cloud to some value intermediate between the dry- and wet-adiabatic lapse rates.

In all three models it is assumed that all condensed water is carried up in the rising air current. Formulae were then developed which enabled the liquid water concentration (in grammes per cubic metre) to be calculated. For the second cloud model the rate of entrainment was assumed to be such that the mass of the cloud was doubled as it ascended between two pressure levels 400 millibars apart. For the third cloud model in order to determine the lapse rate of temperature within the cloud it was assumed that entrainment took place only at multiples of 50 millibars and that the temperature of the entrained air was given by dry-adiabatic ascent from the preceding entrainment level. With these assumptions the liquid water content (W) at various heights (above cloud base) for the three models were calculated for three different cloud-base temperatures: 38°F. (+3°C.), 70°F. (+21°C.) and 82°F. (+33°C.), all at 950 millibars. Table 1 shows these values.

It is seen that the maximum liquid water content of all models increases with the cloud-base temperature. For each cloud model there is a temperature and height at which the liquid water content, W, has a maximum value and for a considerable depth of cloud centred at this height of maximum liquid water content the value of W varies but little.

Layer-type cloud

For clouds which are formed by turbulence (such as stratocumulus) an upper limit to the liquid water content is given by assuming that the air is lifted by eddies along the wet-adiabatic curve from the base of the cloud to the top. This value will seldom be attained since the value is appropriate only to the top of the cloud and a layer cloud formed by turbulence is being continuously mixed by that turbulence. Turbulent layer clouds are seldom more than 3,000 feet deep and Table 2 shows the liquid water content of air which has risen along the saturation adiabatic through a height of 3,000 feet above the cloud base to reach the temperature shown in the table at a pressure level of 900 millibars.

TABLE 2 *Liquid water content in layer cloud 3,000 feet deep*

	Temperature at cloud top (900 mb.)				
	32°F.(0°C.)	*14°F.(−10°C.)*	*−4°F.(−20°C.)*	*−22°F.(−30°C.)*	*−40°F.(−40°C.)*
	grammes per cubic metre				
Liquid water content	1.59	1.05	0.65	0.39	0.18

At lower pressures the liquid water content is less. For example an ascent of 3,000 feet above the cloud base to a temperature of 32°F. at 700 millibars yields a liquid water content of 1.47 grammes per cubic metre.

18.4.1.4 *Orographic effects.* When forecasting ice accretion the following three orographic effects should be considered: (i) modification to free air temperatures, (ii) effect on liquid water content, and (iii) effect of any lee waves.

(i) Modification to free air temperatures.

It was shown in Chapter 14 that forced ascent over hills raises or lowers temperatures according to whether the air is unstable or stable with respect to the appropriate adiabatics - dry adiabatics for unsaturated air and wet adiabatics for saturated air. Quantitative assessments can be made from the rules given in Chapter 14. For forecasting ice accretion, changes in the heights of important isotherms should always be assessed. The sign of the change is summarized below:

Condition of the air	*Change in heights of isotherms for air which is forced to ascend*
Stable	Lowered
Neutral	No change
Unstable	Raised

On the lee side of the hills air will descend with consequent adiabatic heating and the temperatures will change again. If some of the condensed water is deposited on the hills, there will be a föhn effect and temperatures to the lee may exceed those in the free air well upwind of the hills.

The effect is clearly complicated but, for forecasting ice accretion in the United Kingdom, the lowering of the height of the 0°C. isotherm in the neighbourhood of hills is probably of most importance.

(ii) Modification to liquid water content.

The liquid water content tends to be greater when air rises over hills for a number of reasons. Firstly there is an absence of entrainment of dry air so that clouds in the vicinity of hills have a higher water content than clouds in the free atmosphere. Secondly the forced ascent of air may lead to further condensation and a corresponding increase in the liquid water content. Thirdly the hills may forcibly lift air from a region of stability to one of instability so that clouds may form over the hills at levels where cloud does not exist in the undisturbed flow. It should also be noted that the vertical velocities in frontal cloud over hills are substantially greater than over level country and the precipitation does not have time to reduce the water content as the air passes over the hills.

(iii) Effect of lee waves.

It is shown in Chapter 20 that a range of hills may cause a train of lee waves in the airstream under suitable distributions of wind speeds and temperatures. When these lee waves occur, the vertical motion will modify temperature distributions and the liquid water content of clouds in a manner rather similar to that caused by high ground. It is important to remember that lee waves can occur at heights several times that of the hills and at distances many miles downwind of the hills. Lee waves may cause modifications to the rate of ice accretion and, when they seem likely, account should be taken of them when assessing and phrasing forecasts of ice accretion.

18.4.1.5. *Use of radar weather echoes.* Radar weather echoes usually exhibit one of a number of characteristic forms which can generally be identified and classified by experienced radar operators. If radar reports are available some useful inferences regarding ice accretion can be drawn from the reports - from levels where the temperature is below 0°C.

A concentration of water drops of adequate size returns a characteristic hard echo. In active cumulus and cumulonimbus clouds high values of liquid water concentration often occur in vertical columns and the radar echo takes this form. If such an echo is received from a cloud where temperatures are below 0°C. the presence of supercooled water drops can almost certainly be inferred and that region is potentially one of severe icing, usually clear or mixed.

Concentrations of large snow-flakes or large ice crystals return an echo which is much less distinct. These conditions are liable to occur in layer-type cloud and degenerate cumulus and cumulonimbus clouds. When associated with layer clouds the echoes show up as horizontal bands. For the forecasting of ice accretion the inferences which can be drawn from these echoes are less certain and helpful, since it is difficult to determine whether or not liquid water drops contribute to the echo. Furthermore, ice particles which have a wet skin, and which therefore adhere to an aircraft if they strike it, give a much stronger echo than when dry. Unless, therefore, the forecaster is reasonably certain that dry snow-flakes only are present it would be prudent to regard these echoes as indicating areas of potential icing.

Radar reports of the level of the "bright band", which is the enhanced echo from melting snow, give a good indication of the 0°C. level and they can be very useful when the 0°C. level is changing rapidly in space or time.

When forecasting ice accretion, the echoes are particularly useful in preparing very short-period or localized forecasts, where some precision is possible. However, radar echoes must be used with considerable discretion. Echoes vary both in space and time and it is important that the radar reports be very recent - particularly in convective conditions in which it would be unwise to extrapolate an existing echo for more than one to two hours and in which new echoes may appear quickly in areas which were previously free from echo. Further it is strongly emphasized that the absence of a radar weather echo does not mean an absence of ice accretion since water droplets may be present in sufficient quantity to cause ice accretion but with diameters too small to give a detectable echo.

18.4.2 *Field observations and statistical data*

For a number of years a series of flights were made in North America to obtain measures of the meteorological parameters of importance to icing on aircraft. The results have been published in several *Technical Notes of the National Advisory Committee for Aeronautics* (N.A.C.A.). The Meteorological Research Flight (M.R.F.) have also made flights to investigate the constitution of clouds - mainly in the vicinity of the United Kingdom. In addition several workers have examined reports of ice accretion encountered by a variety of aircraft engaged on civil or military operations. The following account is a brief summary of some of the available data.

18.4.2.1 *Observed liquid water content of clouds in temperate latitudes.* The data is considered in relation to three cloud types: (i) convective clouds (comprising mainly large cumulus and cumulonimbus clouds), (ii) layer cloud (comprising stratus and stratocumulus clouds) and (iii) medium-type cloud (comprising altocumulus, altocumulus castellatus, altostratus and altocumulus embedded in altostratus cloud).

Data relating to N.A.C.A. reports have been conveniently summarized by Best[14] and Table 3, showing the cumulative percentage frequency distribution of liquid water content (*W*), is reproduced from his paper.

TABLE 3 *Cumulative percentage frequency distribution of W*

Cloud type	*W(gm.m.$^{-3}$)* 0.1	0.2	0.3	0.4	0.5	0.6	0.7	$0.\dot{8}$	0.9	1.0	1.2	1.4	1.63	*No. of obs.*
	Percentage number of measurements <W													
Convective	17.2	34.0	51.1	61.4	72.5	82.8	88.3	90.6	94.5	97.2	99.0	99.5	100.0	215
Layer	19.2	53.8	76.9	91.0	98.1	100.0	..	..	..	..	..	..	..	156
Medium	59.3	91.5	98.6	100.0	..	..	..	..	..	..	..	..	..	140

(i) Convective clouds.

Table 3 shows that about half the convective clouds investigated had values of *W* about 0.3 gm.m.$^{-3}$ or more, about one quarter exceeded 0.5 gm.m.$^{-3}$ and the highest value of *W* observed was 1.63 gm.m.$^{-3}$ The instrument used to measure *W* was of the rotating-cylinder type and the values in Table 3 refer to an exposure of the cylinders of some few minutes. Some rather higher values of *W* were obtained for shorter exposures of about 10 seconds and the highest values recorded were 1.88 and 2.0 gm.m.$^{-3}$ Ludlam[15] has shown that at temperatures not far below 0°C. the rotating-cylinder method will not measure values of *W* in excess of about 2 gm.m.$^{-3}$ due to the run-off of unfrozen water and such a maximum is well below the theoretical limit which could occur in such cumulus clouds. Later investigations by M.R.F. using a refrigerated icing-disc meter have measured appreciably higher values of *W* and Day[16] has quoted a value of 4 gm.m.$^{-3}$ observed over Boscombe Down at a temperature of 20.6°F. (−6.4°C.) in the thick deck of a cold-front cloud which contained embedded cumulonimbus to 30,000 feet. On another occasion values of *W* ranging from 2.61 to 3.75 were observed over the English Channel at heights between 10,900 and 12,800 feet and temperatures between −1.1°F. (−18.4°C.) and 7.9°F. (−13.4°C.) in a cumulus cloud close to maturity and about to glaciate. Thus observational evidence indicates that values of *W* at least as great as 4 gm.m.$^{-3}$ may occur in convective cloud over southern England.

(ii) Layer cloud.

Table 3 shows that rather more than half the layer clouds investigated over North America had values of *W* of 0.2 gm.m.$^{-3}$ or below and that no value exceeded 0.6 gm.m.$^{-3}$ The individual data showed that the frequency of large values of *W* decreased as the temperature decreased. For example, at temperatures from 29°F. to 10°F., 26.1 per cent of the observations indicated a value exceeding 0.3 gm.m.$^{-3}$ (134 measurements) but at temperatures below 10°F. (22 measurements) only 4.5 per cent gave *W* greater than 0.3 gm.m.$^{-3}$

(iii) Medium-type cloud.

The range of *W* is very small and more than half the clouds investigated had values of *W* less than 0.1 gm.m.$^{-3}$

18.4.2.2 *Sizes of water droplets in clouds.* The diameters of water droplets occurring naturally in the atmosphere range approximately from 1μ to 5,000μ (5 millimetres) and appear to cover the entire spectrum between these limits. Any complete account of ice accretion on aircraft must take into consideration the whole range of droplet sizes and the number of droplets of each size. This complicates the problem. Some simplication is obtained by using a mean drop size. There are a number of "means" which have been used but the most common appears to be the median volume diameter, that is, the diameter of a drop such that half the total water present is contained in drops of larger diameters. In the literature this median volume diameter is often called the mean effective diameter.

It is convenient to consider sizes of water droplets for three broad types of cloud: convective, layer and medium-type (as defined in Section 18.4.2.1) and Table 4 (from Best[14]) summarizes much of the American flight investigations.

TABLE 4 *Cumulative percentage frequency distribution of mean effective drop diameter (d)*

Cloud type	*d* (μ)													*No. of obs.*
	6	9	12	15	18	21	24	27	30	35	40	45	50	
	Percentage number of measurements <*d*													
Convective	..	2.4	11.0	25.0	40.4	57.6	76.4	89.9	93.2	95.6	..	97.5	98.1	208
Layer	1.9	20.1	51.0	74.3	85.5	93.1	96.2	97.5	98.8	99.4	100.0	..	..	159
Medium	0.7	5.2	17.0	37.0	54.9	69.6	84.5	88.9	90.4	91.1	..	..	97.1	135

(i) Convective clouds.

The frequency distributions of mean effective drop diameters *(d)* is given in Table 4. The original paper by Lewis and Hoecker[17] shows that large values of *d* occur more frequently in cumulonimbus than in cumulus cloud. For example, the mean effective drop diameter exceeded 24μ in 14.4 per cent of the measurements in cumulus cloud but in 39.4 per cent in cumulonimbus cloud. Durbin[18] has examined observations of cumulus cloud near southern England and finds that in small cumulus (between 1,000 and 2,500 feet thick) about one droplet in a thousand has a diameter larger than 60μ and these large droplets account for about 3.2 per cent of the liquid water. In cumulus clouds between about 4,000 and 7,000 feet thick about one droplet in a hundred has a diameter larger than 60μ and accounts for about 11.4 per cent of the liquid water. Durbin also found that for cumulus clouds (depth not exceeding 7,000 feet) the mean volume diameter tends to increase with height, being about 5-10μ near cloud bases and 20-25μ near cloud tops. Higher values occur locally within the cloud and values of about 45μ have been noted in cloud between 4,000 and 5,000 feet thick which was precipitating.

(ii) Layer clouds.

Little additional comment can be made on Table 4 but the American data suggested that large values of *d* do not occur at very low temperatures.

(iii) Medium-type clouds.

Table 4 shows that large mean effective drop diameters occur more frequently than for layer clouds. Again the American data indicated that very large values of *d* occur more frequently at high temperature than at low temperature.

18.4.2.3 *Temperatures at which icing was reported.* Jones[13] has analysed some 800 reports of ice accretion on aircraft and Figure 4 is a step diagram showing the percentage frequency of icing reports falling within certain temperature ranges. Some comparable figures from the American investigations are also shown but for slightly different temperature ranges.

Figure 4 shows that the preponderance of ice accretion occurred at temperatures above −10°C. to −12°C. and that frequencies diminished rapidly with

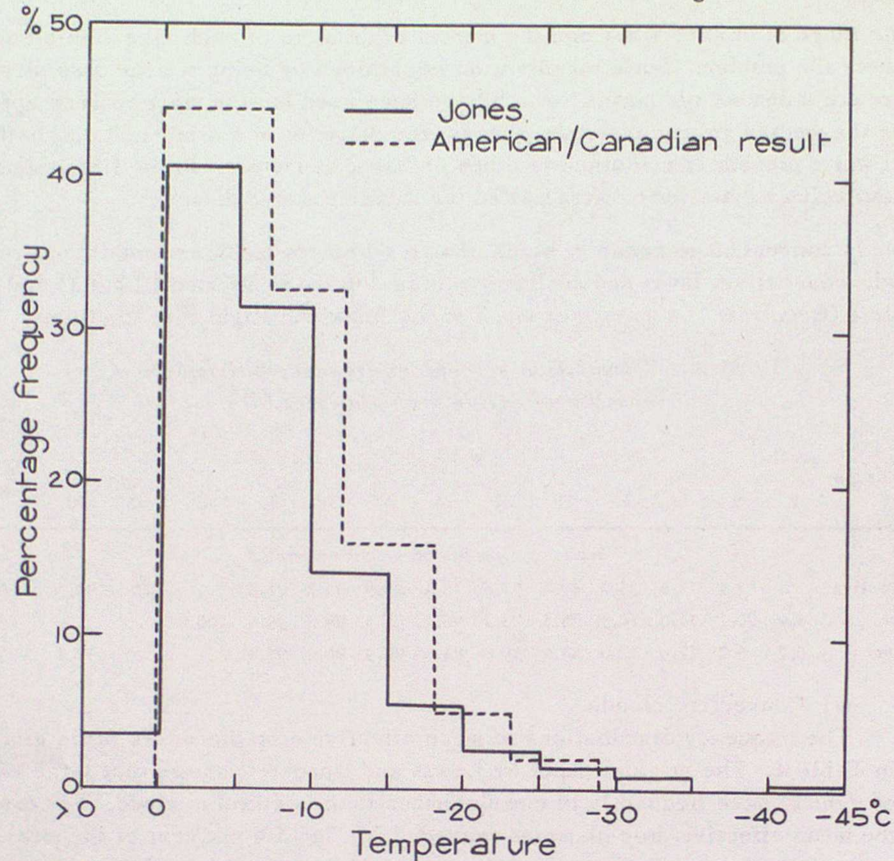

FIGURE 4 *Temperatures at which icing was reported - percentage frequency*

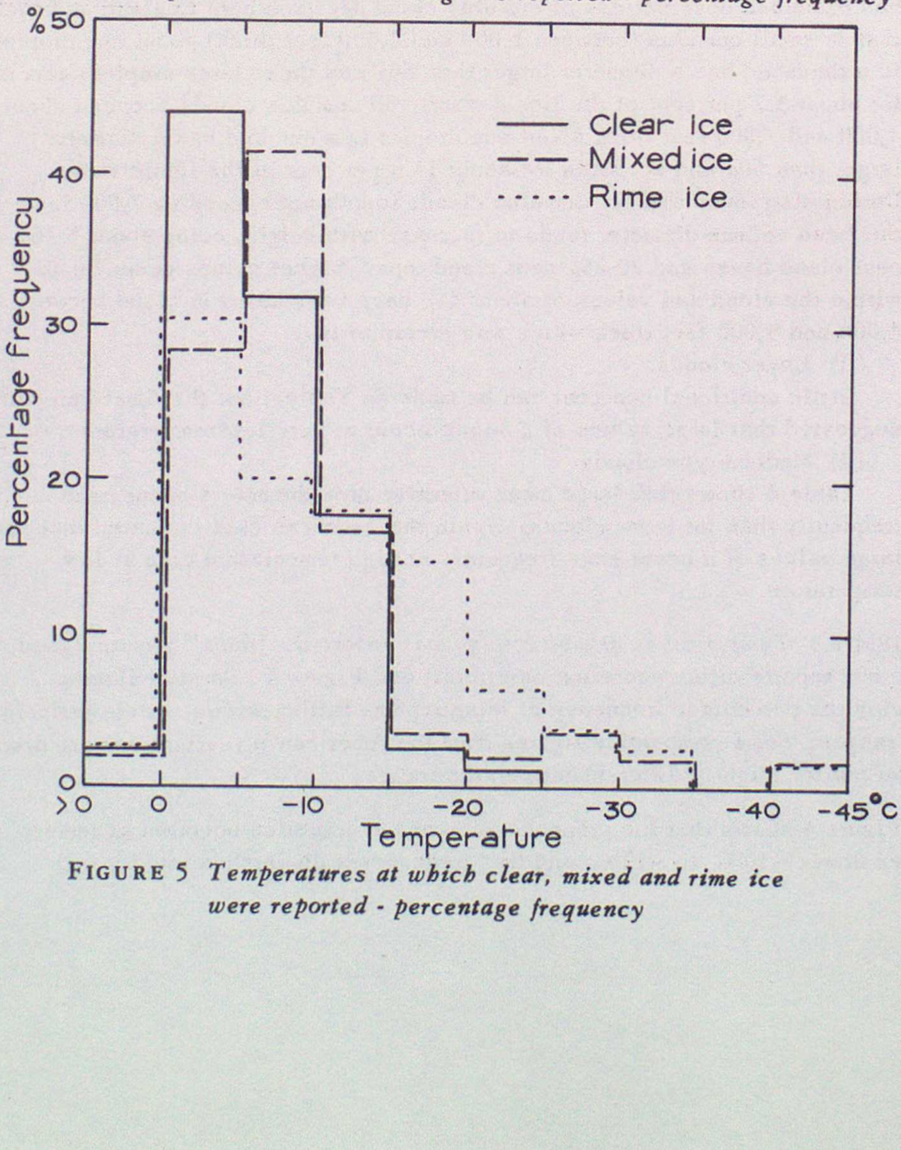

FIGURE 5 *Temperatures at which clear, mixed and rime ice were reported - percentage frequency*

temperatures below about −20°C. Figure 4 was based on positive reports of ice accretion. Since the frequencies with which the various levels were traversed, the frequencies of clouds at those levels and the frequencies of occasions on which ice accretion did not occur in clouds at those levels are all unknown, it follows that Figure 4 does not indicate the risk of ice accretion occurring in the various ranges of ambient air temperatures.

Figure 5 is a similar step diagram (based on data in Jones' paper[13]) showing the frequencies for clear ice, mixed ice and rime ice. Temperatures were most frequently between 0° and −5°C. for rime and clear ice but for mixed ice the maximum had shifted to the range −5° to −10°C. The diagram also indicates that temperatures were between −15° and −25°C. on over 26 per cent of occasions when rime was encountered. In the same temperature range the percentages for clear and mixed ice were very markedly lower.

18.4.2.4 *Ice accretion and cloud type.* The icing reports analysed by Jones[13] were classified (by the aircrew reporting them) as being high, moderate or low in severity and Table 5 (reproduced from Jones' paper) shows their distribution with respect to cloud type.

TABLE 5 *Distribution of classified air masses with respect to cloud type*

Cloud type	*Percentage no. of icing severities in the categories shown*			*Total no. of reports*
	"High"	*"Moderate"*	*"Low"*	
Stratocumulus (Sc)	12	44	44	185
Cumulus (Cu) and cumulonimbus (Cb) sometimes with stratocumulus (Sc)	25	40.5	34.5	182
Nimbostratus (Ns) and stratus (St)	20	33	47	165
Altostratus (As)	13	30	57	107
Altocumulus (Ac)	7	25	68	71
Altocumulus and altostratus mixed (Ac,As)	19	29	52	31
Layer cloud (As,Ns,St) mixed with cumulus	18	45.5	36.5	22
Cirrus (Ci) cirrostratus (Cs) and cirrocumulus (Cc)	(14)	(43)	(43)	7
Out of cloud	(33)	(0)	(67)	12
All reports	17	36	47	782

The values in brackets may be unreliable due to the small number of available reports.

Table 5 shows that icing is most likely to be regarded as severe in cumulus or cumulonimbus types of cloud. There is also a significant percentage of high rates of icing associated with layer types of cloud, which, because of their greater horizontal extent, may constitute a greater total icing hazard than convective cloud. Jones also comments that there was at least one report of high icing rate in every cloud type.

Table 5 must not be regarded as indicating the chance of encountering ice accretion when flying in various types of cloud, since it was compiled only from positive reports of icing. Some indication of the chance of icing can be obtained from Table 6 which was prepared from reports by weather reconnaissance aircraft when flying in cloud at temperatures below 0°C.

TABLE 6 *Number of reports*

Cloud type	Rime ice			Clear ice			Total reports	
	Light	Moderate	Heavy	Light	Moderate	Heavy	Ice	No ice
Stratus	0	0	0	0	0	0	0	88
Stratocumulus	57	30	5	5	0	0	97	114
Cumulus	35	11	8	15	10	3	82	19
Cumulonimbus	0	2	2	1	0	2	7	0
Nimbostratus	11	11	3	0	2	3	30	3
Altostratus	9	4	0	2	1	0	16	85
Altocumulus	49	20	3	5	3	0	80	88
Altocumulus and altostratus	30	5	1	1	0	0	37	47

The following deductions can be made from Table 6:

(i) Cumulus, cumulonimbus and nimbostratus. - The chance of icing is very high and the severity may be heavy.

(ii) Stratocumulus, altocumulus and altocumulus associated with altostratus. - The chance of icing is about 50 per cent and the severity will exceed moderate only occasionally.

(iii) Altostratus and stratus. - The chance of icing is low and is unlikely to be more than moderate in intensity.

18.4.2.5 *Ice accretion and air masses and fronts.* Rohan and Ohaonghusa[19] have analysed aircraft reports from the eastern North Atlantic which were received at Shannon during a year. Some 37,746 aircraft reports were received and only 582 or 1.5 per cent of these reported ice in any form. These reports were classified according to air mass and frontal type as shown in Table 7.

TABLE 7 *Classification of ice reports*

Synoptic characteristics	Intensity of ice			Total
	Light	Moderate	Heavy	
Warm front	140	37	6	183
Cold front	107	26	2	135
Occlusion	44	14	2	60
Warm air mass	33	10	3	46
Cold air mass	116	35	7	158

18.4.2.6 *Probable constitution of clouds.*

(i) Convective clouds.

(*a*) Cumulus clouds. Observations show that cumulus clouds nearly always consist entirely of water drops at temperatures down to −23°C. (−10°F.). There are few observations at lower temperatures but the occurrence of ice accretion in cumulus clouds at much lower temperatures indicates that water droplets must exist at those lower temperatures. As temperatures approach −40°C. spontaneous freezing should occur and all but the smallest droplets should have frozen. Icing has however been reported at ambient temperatures below −40°C. so that some water drops seem to exist at times at these very low ambient temperatures - possibly in the core of the up-current where internal temperatures may differ from ambient air temperatures.

Theoretical and observed values for the liquid water content of convective clouds have been considered in Section 18.4.1.3. Making use of Best's[14] work and assuming a cloud base at 950 millibars, ambient relative humidity 70 per cent and entrainment at a rate so that the mass of the cloud is doubled as it ascends between two pressure levels 400 millibars apart, liquid water contents have been calculated for various levels above cloud base for several temperatures. Best has shown that liquid water contents of 1 and 0.5 grammes per cubic metre are approximately the limiting values separating severe, moderate and light icing. Using these criteria Figure 6 shows the approximate thicknesses within which various degrees of icing may occur in convective cloud.

Variations of about 50 millibars in the cloud base have little effect on the liquid water content and no detailed adjustment seems necessary for other ambient relative humidities.

It is desirable that forecasters should have some knowledge of the probable distribution of liquid water within a cumulus cloud. Figure 7 shows the model proposed by Murgatroyd[20] and Day.[21] Figures 6 and 7 are tentative and subject to exceptions but they should prove useful.

(*b*) Cumulonimbus clouds usually consist of a number of convective cells; some of these cells may be in the growing stage and others in the decaying stage so that the composition of the cloud at the same level may differ markedly in one part of the cloud from another. In general it seems likely that cumulonimbus clouds usually consist of a mixture of liquid drops and ice crystals. Down to about −14°C. (7°F.) liquid water predominates but between about −14°C. (7°F.) and −30°C. (−22°F.) liquid or ice may predominate.

When a cumulus cloud transforms into a cumulonimbus cloud substantial reductions in the liquid water content may occur within about 20 minutes since the ice crystals grow at the expense of the water drops. It is difficult to make any reliable estimates of the liquid water content. For most forecasting purposes it does not seem prudent (with existing knowledge) to attempt to differentiate between icing in cumulus and in cumulonimbus clouds. It is recommended that forecasters use the cumulus model when determining and phrasing forecasts of ice accretion on days of marked convective activity.

Accordingly for convective clouds the following rules are suggested:

(1) At temperatures below −40°C. (−40°F.) the chance of icing is very small.

(2) At heights where the temperature is between −23°C. (10°F.) and −40°C. (−40°F.) the chance of moderate or severe icing is small except in newly developed convective cloud, but light icing is possible.

(3) At heights where the temperature is between −23°C. (10°F.) and 0°C. (32°F.) the rate of ice accretion may be severe over a substantial depth of cloud for a wide range of cloud-base temperatures. Figure 6 should be used to assess the severity of ice accretion.

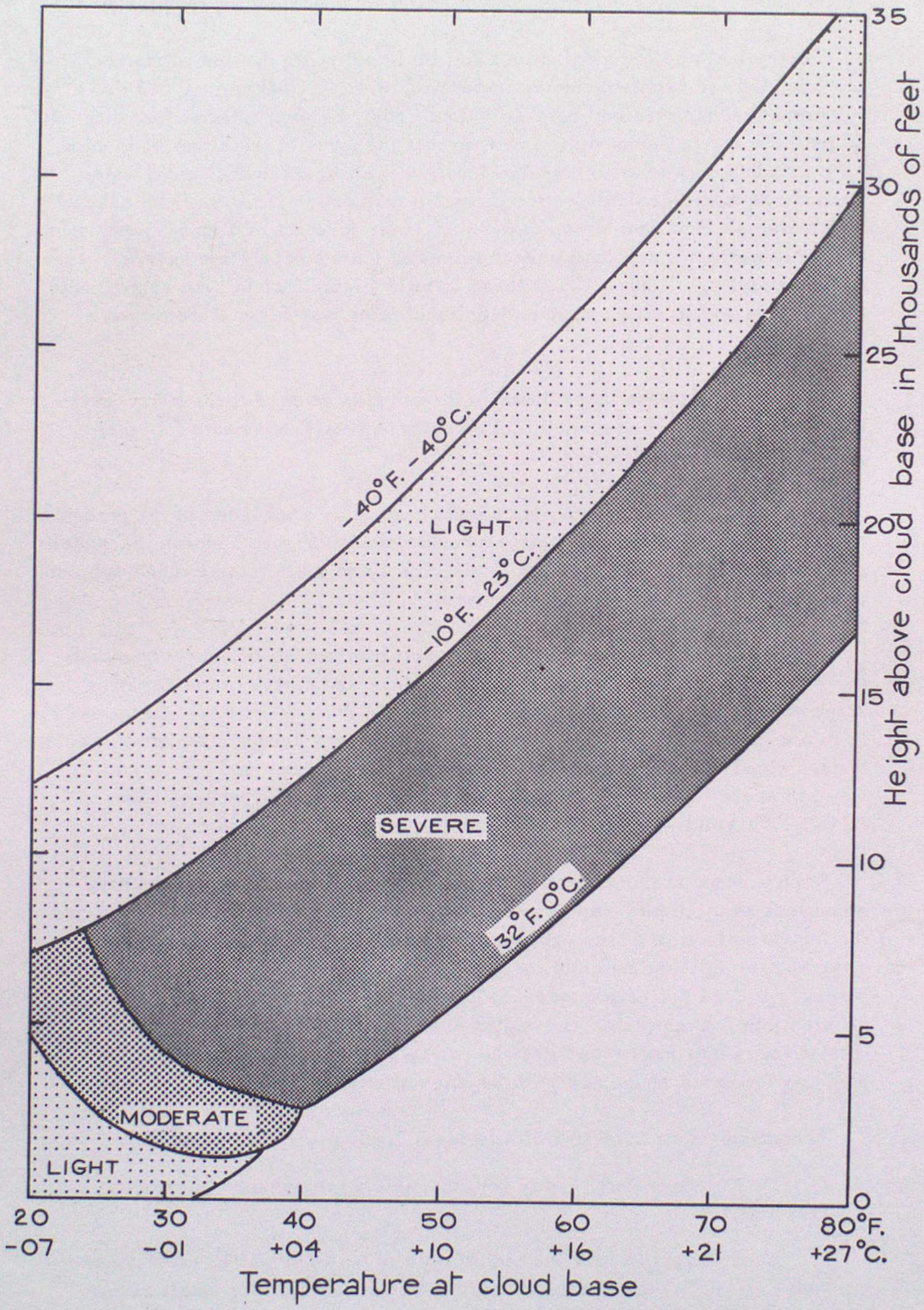

FIGURE 6 *Approximate thicknesses of layers within which various degrees of icing may occur in convective cloud*

Base of cloud at 950 millibars and ambient relative humidity 70 per cent.

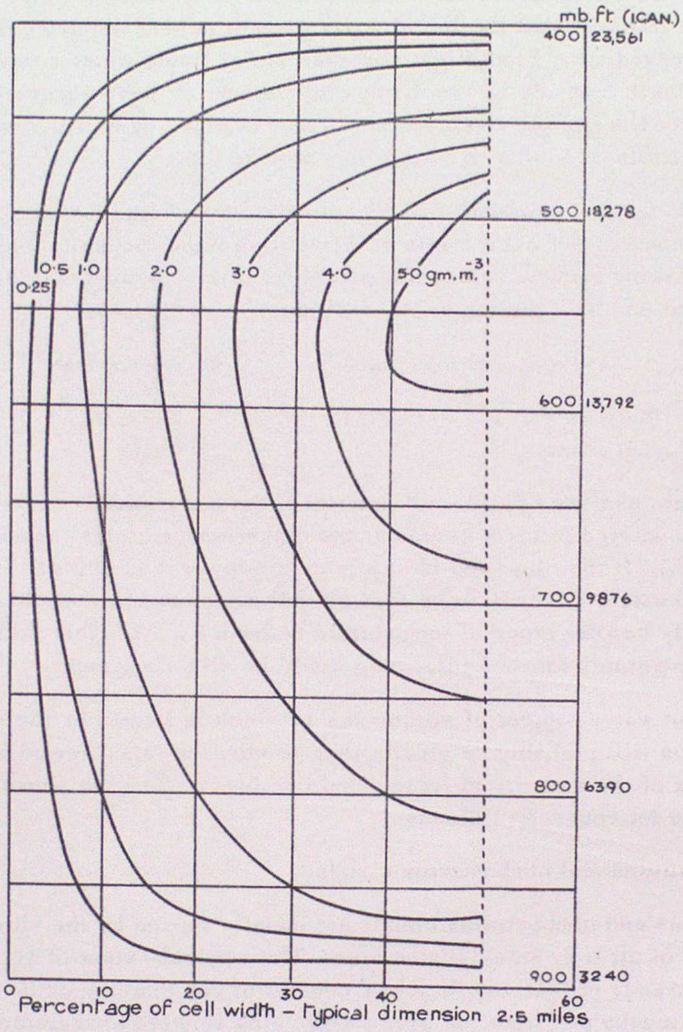

FIGURE 7 ***Distribution of water content to be expected in typical cumulus clouds***

Base of cloud at 900 millibars, temperature 60°F., top at 400 millibars.

(ii) Stratocumulus, altocumulus and stratus clouds. American flight observations indicate that the following generalizations may be made:

(*a*) Stratocumulus cloud usually consists entirely of liquid drops or with liquid drops predominating down to −18°C. (0°F.). No observations were made at lower temperatures.

(*b*) Altocumulus cloud usually consists entirely of liquid drops for temperatures down to about −10°C. (14°F.). At lower temperatures down to about −29°C. (−20°F.) ice crystals may be present but will normally be outnumbered by liquid water drops.

(*c*) Stratus cloud usually contains only liquid water drops.

An upper limit to the liquid water content of those clouds which are formed by turbulence is obtained by assuming that the air is lifted along the wet-adiabatic curve from the base to the top of the cloud. Turbulent mixing within these clouds will normally prevent direct lifting of air from cloud base to cloud top and turbulence at the cloud top will cause some cloud free air to be mixed into the upper

layers of the cloud. As these clouds are usually fairly shallow (often less than 3,000 feet) it is likely that the liquid water content seldom approaches the theoretical upper limit. From flight observations of liquid water content in layer clouds over North America Lewis, Kline and Steinmetz[22] have suggested that a practical upper limit to the liquid water content is given by half the value computed on the basis of adiabatic lifting from base to top.

Using this factor of one-half and regarding values of liquid water content of 0.5 and 1.0 grammes per cubic metre as separating light, moderate and severe icing the following criteria can be suggested for layer clouds 3,000 feet in vertical extent and with the top at 900 millibars.

Temperature at top of cloud	*Severity of icing*
Between 0°C. and –11°C. (12°F.)	Moderate
Less than –11°C.	Light

The reports analysed by Jones[13] indicated that occasionally severe icing might be encountered in layer clouds at the higher temperatures (namely, between 0° and –11°C.). If the cloud top is at a pressure lower than 900 millibars the liquid water content is likely to be less so that moderate icing would be expected over a slightly smaller range of temperature below 0°C. At higher pressure the range of temperatures for moderate icing would be slightly greater.

The liquid water content of stratocumulus which is formed by the spreading out of cumulus will probably be greater than in stratocumulus formed by turbulence, and forecasts of the severity of icing should be biased from the above criteria towards those for convective clouds.

(iii) Altostratus and nimbostratus clouds.

Altostratus and nimbostratus clouds are usually formed by the slow ascent of a large mass of air over an extensive area. The vertical extent of such clouds may be many thousands of feet and they may consist of one continuous layer or several layers. Continuous precipitation over a large area is often associated with these clouds and, according to the Bergeron-Findeisen theory, there will then be an abundance of snow-flakes and ice crystals in the region of, and above, the 0°C. isotherm and a small liquid water content. In these circumstances the chance of severe icing is small and, if icing does occur, it is likely to be light and most probably confined to a shallow layer about 1,000 feet thick immediately above the level of the 0°C. isotherm.

However, if the altostratus and nimbostratus clouds are associated with active fronts or if water continues to be condensed in the ascending air at a rate equal to or greater than that required to supply the water for sublimation on to the ice crystals so that a mixed cloud of ice crystals and water drops can be maintained, then liquid water contents may be substantial and the chance of icing, which may be severe, is high at suitable temperatures. Section 18.4.1.2 discussed the critical up-draught speed required to maintain a mixed cloud and showed two widely different values. Reports of ice accretion examined both by Jones[13] and by Rohan and Ohaonghusa[19] both include a substantial number of occurrences of moderate ice and a few of severe icing in altostratus cloud and warm-front conditions. It is clear that forecasts of ice accretion in altostratus and nimbostratus clouds should not automatically be given as light icing, but the precise synoptic conditions when moderate or severe icing should be forecast have not been formulated. Some suggested rules are given in Section 18.5.

(iv) Cirrus cloud.

Cirrus clouds are normally composed of ice crystals which do not constitute an icing hazard to airframes. However on a few occasions ice accretion on airframes has occurred in cirrus clouds and sometimes at ambient temperatures well below −40°C. Published literature gives no indication of the synoptic conditions under which ice accretion in cirrus clouds may occur over north-west Europe and no guidance can be given.

In Section 18.1 a form of icing in jet or turbo-jet engines was described which can be attributed to the accumulation of ice crystals or snow-flakes in parts of the intake system. If this icing is to build up to serious proportions the concentration of ice crystals would normally require to be dense and such as might occur in a vigorous cumulonimbus cloud in the tropics. High concentrations of ice crystals might occur over north-west Europe in parts of vigorous cumulonimbus or frontal clouds which form in association with warm and moist air masses with high mixing ratios, so that this type of engine icing in certain aircraft might be encountered.

18.4.2.7 *Rain ice.* Little general guidance can be given about the severity of ice accretion to be expected in freezing rain. Rain ice produces striking effects at the surface and may quickly endanger an aircraft whilst in flight at low level and during take-off and landing, either by causing an inability to maintain height, or through modification to the control characteristics, or both. Although the water content of freezing rain may be less than that encountered in some clouds so that rain ice accretion may be slight, working rules for forecasting the occasions of only slight rain ice are not yet available.

18.5 FORECASTING ICE ACCRETION ON AIRFRAMES

Reports of ice accretion encountered by aircraft indicate the very variable nature of icing. One aircraft may report ice when flying through a particular position and a succession of other aircraft flying in the same area may encounter no ice at all. Aircraft making repeated traverses through a particular cloud at various times in the cloud's lifetime may encounter markedly different icing conditions. From experience of these variable icing conditions and the preceding sections of this chapter it is clear that precise forecasting of the severity of icing cannot be achieved at present. Each synoptic situation must be assessed on its merits and the information in this chapter must then be used to compile the forecast of ice accretion.

Ice accretion should normally be one of the last elements of a forecast to be determined. Cloud types, amounts and heights, temperatures, precipitation and upper winds should all be forecast before ice accretion is considered. Even then, forecasts of ice accretion should not be added in a stereotyped manner. The forecaster should consider the general situation and attempt to determine both the chance of icing and the degree of severity from general physical reasoning and the data given in the preceding sections of this chapter. He should then phrase the forecast (within current directives regarding the designation of risks and rates of ice accretion) to convey information on ice accretion in a concise form. The following summary should assist forecasters in preparing both written forecasts and verbal briefings.

18.5.1 *Temperatures and the chance and severity of icing*

(1) At temperatures below −40°C. the chance of icing is very small but not entirely negligible.

(2) At temperatures between −23°C. and −40°C. the chance of moderate or severe icing is small except in newly developed convective clouds which have not begun to glaciate. Light icing may occur.

(3) At temperatures between 0°C. and −23°C. the severity must be estimated according to probable liquid water content.

For convective clouds use Figures 6 and 7 and data in Section 18.4.2.6(i). For stratocumulus, altocumulus and stratus clouds use the data in Section 18.4.2.6(ii). For altostratus cloud use Section 18.4.2.6(iii).

18.5.2 *Temperatures and the type of icing*

(4) At temperatures below −15°C. the most likely type of ice formation is rime ice.

(5) Clear and mixed ice formation may be severe in all types of cloud at temperatures between −1°C. and −15°C. inclusive.

(6) Severe clear and mixed ice are very unlikely at temperatures below −15°C. but heavy rime ice may occur.

(7) If rain is falling from a level where the temperature is $\geq$ 0°C. through a layer with temperatures $<$ 0°C., forecast glaze ice.

(8) If an aircraft is parked in the open and its temperature is expected to fall below the frost-point of the air, forecast the deposition of hoar frost.

18.5.3 *Fronts and ice accretion*

18.5.3.1 *Warm fronts.* The work of Rohan and Ohaonghusa[19] showed that out of every 100 occurrences of ice accretion in warm-front conditions in the eastern North Atlantic about 76 consisted of light ice, some 20 of moderate ice and between 3 and 4 of heavy (severe) ice. It is a matter of some difficulty to decide when to forecast moderate or severe ice but the following suggestions may help.

(9) If widespread and continuous precipitation (other than drizzle) of only light or moderate intensity has been reported from a front which is of slight or moderate activity, the cloud system is likely to contain a preponderance of ice crystals at levels where the temperature is well below 0°C. Well within the cloud system the chance of icing will be small except in a shallow layer about 1,000 feet immediately above the 0°C. isotherm where light or moderate icing may occur. Icing may also occur at the edges of the cloud system. It should be noted that if widespread precipitation of a uniform intensity has not started, both the chance and severity of icing are greater (see (11) and (12) below).

(10) In active warm fronts the possibility of severe icing, usually clear or mixed, should be indicated within 100 miles of the surface position of the front. If the front is particularly active this distance should be increased to 200 miles.

(11) If the presence of upper instability at warm fronts can be inferred from radio-sonde reports, or observations of clouds and precipitation, the possibility of severe icing should be indicated.

(12) Heavy rime may occasionally be experienced in the altostratus sheet as much as 300 miles ahead of the surface position of the warm front and ahead of the associated rain belt.

(13) Temperature distribution may occasionally be favourable near the United Kingdom for the formation of glaze ice (see (7) on previous page).

18.5.3.2 *Cold fronts.* Cloud systems at cold fronts are more scattered than at warm fronts and it is difficult to indicate reliably the general intensity of ice likely to be encountered. Each front should be assessed individually.

(14) If the front is active, if there is a copious supply of moisture in the warm air ahead of the front and if the cloud systems are convective in character, then it would be prudent to forecast severe icing.

(15) If the front is a "kata" cold front, if there is noticeable dryness aloft and if the clouds are pseudo-stratiform a forecast of light icing would seem appropriate.

18.5.3.3 *Occlusions and quasi-stationary fronts.* Forecasts of ice accretion should be assessed according to the predominant warm-front or cold-front characteristics exhibited by the front.

18.5.3.4 *Severity of icing at fronts.* For cold fronts, quasi-stationary fronts and occlusions Jones[13] has suggested that severe icing may occur within 50-100 miles of their surface position. (For warm fronts see Section 18.5.3.1).

18.5.4 *Depressions with ill-defined fronts*

Cloud and precipitation systems in such depressions may be rather ill-defined and variable and, in general, ice accretion must be assessed individually. Jones[13] considers that in the thick cloud associated with the centre of a depression where the fronts are poorly defined, particularly to the north and west of the centre, severe icing may occur within 250 miles of the centre.

18.5.5 *Polar depressions*

These depressions should generally be dealt with as for unstable air masses (see Section 18.5.7 below). It should be noted that clouds in these depressions may consist of extensive cloud layers formed by general convergence in the depressions and that vigorous convective clouds may be embedded in the general cloud system. Such embedded clouds are invisible to aircrew flying in the general cloud systems until the aircraft encounters the convective cell. The rate of ice accretion may increase suddenly and endanger the aircraft.

18.5.6 *Anticyclones*

Ice accretion will generally be slight in clouds in anticyclones. If however there is an extensive sheet of stratocumulus a few thousand feet thick and temperatures are suitable, moderate or severe ice may occur - particularly where the air has had a sea track and an opportunity to pick up additional moisture. A north-north-easterly airstream flowing across the North Sea in winter is a typical situation. In such a case the stratocumulus sheet is best regarded as cumulus and stratocumulus since the air in the lower levels is usually unstable to the sea temperatures.

18.5.7 *Unstable air masses*

Forecasts of ice accretion in convective cloud should be assessed according to the suggestion in Section 18.4.2.6(i). If widespread convective activity is forecast (for example, instability over the sea or a direct polar current traversing high ground) and the temperatures are suitable, severe ice formation, usually clear or mixed, should be forecast.

18.5.8 *Stable air masses*

Ice accretion in layer-type cloud associated with stable air masses can be assessed from the criteria in Sections 18.4.2.6(ii),(iii) and (iv). If the layer cloud is unusually thick (say more than 3,000 feet) the diffusion of cloud-free air into the base and top will be proportionately less important. Consequently the liquid water content may exceed the values quoted in Section 18.4.2.6 which are half the values obtained by adiabatic lifting through 3,000 feet from the cloud base and some allowance for these higher values should be made for thicker layer clouds.

It should be noted that the liquid water content in non-precipitating layer clouds formed by turbulence which are not precipitating is normally a maximum near the cloud top. If general precipitation (other than drizzle) is falling from layer cloud over a wide area, icing is unlikely except in a shallow layer about 1,000 feet deep immediately above the 0°C. isotherm and in the cloud system beyond and near the edges of the area of precipitation.

18.5.9 *Orographic effects*

Due allowance should be made according to Section 18.4.1.4. When the orographic barrier is extensive and the direction of air flow is suitable, there may be extensive regions where, due to the disturbed air flow, the water content of clouds is substantially higher than the average. If the track of the flight is such (for example, parallel to a range of hills) that the aircraft may fly for appreciable periods in regions where these higher water contents may occur, some additional reference to the possibility of prolonged moderate or severe icing should be made. Icing in weak or slow-moving warm fronts may be intensified over high ground.

18.5.10 *Radar weather echoes*

If detailed and up-to-date radar reports are available it may be possible to add some very detailed information about the location of regions where icing may be severe - but only for very short periods ahead of the radar reports.

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