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BY W. H. BIGG, B.Sc.

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ICE FORMATION IN CLOUDS IN GREAT BRITAIN

By W. H. Bigg, B.Sc.

The increase in the amount of cloud and bad weather flying during the past ten years has focussed attention on the subject of ice formation on the wings and other exposed parts of aircraft. Experience has shown that the rate of formation varies considerably. Sometimes aircraft have been forced down in a short space of time and on other occasions, after prolonged flights in conditions apparently favourable for ice formation, only small amounts of ice have been produced. The fact that ice formation constitutes one of the greatest dangers to the regular operation of air routes in certain parts of the world, such as North America and north and north-west Europe, has led to the production in different countries of numerous papers setting out the meteorological conditions favourable for ice formation and the methods by which it may be avoided. The object of this note is to co-ordinate the information given in a number of these papers, to give the results obtained in this country and to formulate rules for the guidance of aircraft pilots and weather forecasters.

Physical Processes.—First it is necessary to remember that in the atmosphere we are concerned with the three states of matter, (1) the gas state—water vapour, which is invisible, (2) the liquid state—water, either in the form of cloud, mist, fog, rain or drizzle and (3) the solid state—ice, first in the form of hail and secondly of ice crystals, frequently constituting a cloud, or in the conglomerate form, snow. With these fundamental facts in mind a list can be made of the possible ways in which ice might form on an aircraft.

(*a*) By direct deposition of ice, either the crystals, snow or hail.

(*b*) By the freezing of any water drops that impinge on the aircraft from rain or in cloud.

(*c*) By sublimation on to the aircraft i.e. condensation from the water vapour state direct to the ice state.

These three processes will now be considered.

(*a*) *Direct deposition of ice.*—No explorations have been made in the clouds cirrus and cirrostratus, which are known to consist of ice crystals, with the object of testing their propensity for ice formation on aircraft. However, from the behaviour of these crystals, which are sometimes seen falling to the ground during spells of very cold weather, it is improbable that they would adhere to an aircraft. The same remark applies to dry hail and dry snow which are swept off the aircraft by the slip stream. Wet snow and sleet or hail mixed with rain are in a different category midway between the first and second processes. The possibility of water drops freezing on to the aircraft and imprisoning the associated snow or hail is definitely present, and there seems little doubt that this does occur. An examination of ice deposits brought down by aircraft sometimes reveals what appears to be small opaque hailstones embedded in the solid layer of clear ice. In the majority of reports of ice formation, however, there is no snow or hail observed during the flight, so that, although this is a process which does give rise to ice formation on aircraft, there must be others.

(*b*) *Freezing of water drops*.—There is general agreement that the most prolific source of ice formation is the freezing of water drops that impinge on the aircraft, and nearly all the cases listed in Table 1A (p. 10) are due to this cause. Visual evidence of the initial water state is afforded, by falling rain in the case of a flight below clouds, and frequently by water streaming over the mainplanes if the flight is being made in clouds. It will be noticed that in the case of the flights in clouds the recorded air temperature, and hence the temperature of the water droplets which constitute the cloud, are at or below the freezing point, i.e., the water drops are supercooled. Such drops are known to exist down to a temperature of at least 0°F. The physics of this state is not at present fully understood, but a partial explanation is given by the fact that the nuclei, on which water vapour condenses to form water drops, are now known to consist of tiny crystals of sodium chloride and certain nitrates and sulphates. These droplets are therefore really salt solutions and so their freezing point is below 32°F. Now from experiments in the laboratory it is known that a supercooled solution will turn into the solid state, either when disturbed by mechanical means or when a small piece of the solid is dropped into it. Further, the temperature of the solution will rise to the freezing point and remain at that figure until the whole of the liquid has turned into the solid state, while at the same time heat (latent heat of fusion) is being liberated.

Consider such a supercooled water drop of mass m at a temperature θ_1, below the freezing point θ_0. Then the heat required to raise the temperature of the drop to θ_0 is $m\ s\ (\theta_0 - \theta_1)$ calories where s is the mean specific heat of water over the range θ_1 to θ_0. Let m_1 be the mass of the drop that freezes on impact with the aircraft. Then the latent heat given out on solidification is $m_1\ L$ calories where L is the latent heat of fusion of ice. Assuming that there is no external source of heat available, i.e., that the material of the plane is at the same temperature θ_1 as the original drop and the air, then the only available source of heat is the latent heat given out by the portion of the drop that freezes.

By equating these quantities

$$m_1 L = m\ s\ (\theta_0 - \theta_1)$$

or $\dfrac{m_1}{m} = \dfrac{S}{L}(\theta_0 - \theta_1)$ and by inserting values for S and L

$$= \frac{\theta_0 - \theta_1}{80} \quad - - - - \quad \text{(i)}$$

If $m_1 = m$ then $\theta_0 - \theta_1 = 80$ or for the whole of the drop to freeze on impact the degree of supercooling must be 80°C. If

$\theta_1 = \theta_0$ i.e. no supercooling $m_1 = 0$ and there is no solidification on impact. The relation also indicates that for a given amount of supercooling ($\theta_0 - \theta_1$ constant) the proportion of the drop which freezes on impact is independent of the size of the drop (m_1/m constant). Also that the amount of freezing on impact is directly proportional to the degree of supercooling.

This analysis as Shaw (1)* has pointed out raises all sorts of possibilities, such as the production of ice with a water-centre or water with an ice-centre. Or again the portion of the drop that has turned to ice may adhere to the aircraft leaving the remaining portion of the drop free to flow over the plane as water. Evidence of ice on the leading edges with water streaming over the rest of the aerofoil has been given by an ascent at Farnborough and also by Noth and Polte (2) and Merit Scott (3). If this view is correct then each drop striking the aircraft would add its quota to the amount of ice on the leading edge, but as McNeal (4) has pointed out, if this was the only process involved there would be little or no danger from ice accretion at moderate degrees of supercooling. To quote a numerical example from his paper, only 10 per cent of the drop is frozen on impact with a supercooling of 8° C. There seems little doubt that it is the solidification of the remaining portion of the water drop that causes the accumulation of ice. McNeal and others have attributed this final freezing to the saturated vapour pressure over the water surfaces at the freezing point being higher than that of the surrounding air and water drops at a temperature below the freezing point, whereby evaporation takes place from the water surface and the resultant loss of heat causes the water to solidify. While this process probably plays a part, especially at temperatures close to the freezing point, it is considered that the fact that the water is at the freezing point and in contact with the air and the aircraft at a temperature below the freezing point is a sufficient reason for final solidification; the latent heat given out being rapidly dissipated in the cold slip stream.

In deriving the above equation it was assumed that no external source of heat was available. Now there probably are occasions, e.g. when an aircraft is ascending, when there is a time lag between the temperature of the air and that taken up by the fabric of the aircraft so that the latter is at a higher temperature than the surrounding air, assuming no inversion of temperature is present. There might then be an external source of heat H available in the fabric and our equation would be modified to

$$H + m_1 L = m\, s\, (\theta_0 - \theta_1)$$

$$\text{or } \frac{m_1}{m} = \frac{\theta_0 - \theta_1}{80} - \frac{H}{80m}$$

*The numbers in brackets refer to the bibliography on p. 35.

The proportion of the drop which froze on impact would therefore be less than before, and if the temperature of the fabric was slightly above the freezing point the final freezing of the remaining portion of the drop would be delayed. This probably explains why more ice usually accumulates on an aircraft when it descends through a cloud of supercooled drops after being at a low temperature above the cloud, than when it ascends directly from the ground (temperature above freezing point) through the cloud.

The size of the supercooled drop is also of importance. Although for a given amount of supercooling in equation (i) the proportion m_1 of the drop which freezes on impact is independent of m the size of the original drop, it is clear that the larger m is, the larger m_1 will be in proportion. Hence large drops will give more ice on impact than small drops. Again, the latent heat liberated by that part of the original water drop, which does not freeze on impact, but which finally solidifies after spreading over the cold surface of the plane, is $(m - m_1)$ L calories. Since m_1 has been shown to be a fixed proportion (say k) of m for a given amount of supercooling, by substituting $m_1 = k\,m$, the above quantity of heat liberated can be written $m\,(1 - k)\,L$. Hence since k and L are both constants the liberated heat is proportional to the size of the original drop. This means that for a large drop, the liberated heat will be greater and will take longer to dissipate, and that complete solidification will be slower as compared with a small drop. Comparing large and small drops we arrive at the conclusions, (1) for large drops there is a greater amount of ice formed on impact but the final complete freezing is slower, and (2) for small drops there is a smaller amount of ice formed on impact but the final complete freezing is quicker. For very small drops it is probable that the time interval between the initial and final solidification is negligible in practice, although, as far as I am aware, there are no data on this point. This leads up to the physical conditions favourable for accumulating ice on aircraft, viz., (1) for large accretions, either a large number of small supercooled water drops which solidify quickly and thus form ice on and close to all leading edges of the aircraft, or large drops which form some ice on the leading edge on impact with the remaining part of the water drop spreading back from the leading edge and freezing relatively slowly; (2) for small accretions, a small number of water drops of any size, the larger drops, of course, giving more ice than the smaller ones. Both the size and number of drops of a given size within a cloud vary within wide limits, and it is unfortunate that in all the experiments on ice formation little or no attempt has been made to measure these quantities. The ideal place would be at one of the mountain top observatories where ice formation in winter is often particularly severe. In ground fogs the droplets of water usually lie between 4×10^{-4} and 3×10^{-3} cm. radius and may number up to 1,500 per c.c. Cloud drops number 250–400 per c.c., and range up to 10^{-2} cm. radius; raindrops from about 10^{-3} cm. to nearly $0{\cdot}2$ cm. radius.

As many motorists are aware, it is possible even at ground level during cold fogs for ice to form on the windscreens of cars, and under the same conditions pedestrians become covered with a white feathery deposit of ice crystals. The rate of deposition varies considerably in the three cases considered, being greatest in the case of aircraft, and a partial explanation is the greater speed of the latter so that many more supercooled water drops are brought into contact during a given time. This and other considerations have led Noth and Polte (2) to the relation :—

$$E_f = \partial w \, v \, t \, c \sin\delta.$$

where E_f = ice formed per unit area.
∂w = water content per unit volume.
v = relative speed of flight.
t = time.
δ = angle of impact of drop.
c = constant depending on the particular qualities of the aircraft.

Undoubtedly the chief difficulty in using this relation is the insertion of a value for ∂w, i.e., the size and relative number of water drops present in the particular cloud, fog or rain in which temperatures are favourable for ice formation.

The above analysis is concerned with the behaviour of supercooled water drops impinging on an aircraft. Now let us consider the case of a water drop at a temperature θ_2 (above the freezing point) impinging on an aircraft whose surfaces are at a temperature below the freezing point. Such cases can occur if raindrops are falling from a warmer upper stratum into a colder one, or if an aircraft, after being at an altitude well below the freezing point, descends rapidly through cloud whose temperature is above the freezing point. Assuming the temperature of the drop is lowered to the freezing point by contact with the cold aircraft then the heat given out by the drop is $m\, s\, (\theta_2 - \theta_0)$ calories, and the latent heat liberated by the portion of the drop that freezes is again $m_1 L$ calories, so that the total heat given out is $m\, s\, (\theta_2 - \theta_0) + m_1 L$ calories. This heat is used to raise the temperature of the surface of the aircraft and the air stream. As the heat gained in this manner is an unknown quantity, it is not possible to equate it to the heat lost by the drop and hence deduce a relation for m_1/m as was done for the supercooled drop. Since the drop has to lose a quantity of heat equal to $m\, s\, (\theta_2 - \theta_0)$ calories before reaching the freezing point it appears as if there might be no solidification on impact but that the whole of the drop freezes soon after, when this and the latent heat is dissipated. This may appear to be of academic interest but it is of importance when the size of the drop is considered. For a very small drop the heat given out is small, is quickly dissipated and the drop solidifies soon after impact. This is the case when a cold aircraft descends through a cloud layer at a temperature above the freezing point.

For a large drop (raindrop) the heat given out is much greater and solidification is slow enough to enable the water to spread over the surface of the plane and form ice well back from the leading edge. This is the case when raindrops fall from a warmer upper stratum. So again we find that small drops freeze quickly and deposit ice on and near the leading edges while large drops freeze more slowly but give a larger layer of ice. If $\theta_2 - \theta_0$ is large, i.e. the water drop is originally well above the freezing point, still more heat will be given out and solidification further delayed. It is therefore probable that cases do occur when the surface of the aircraft is at or not much below the freezing-point temperature, that the latent heat given out is sufficient to raise the temperature of the surface of the aircraft and so prevent solidification. If $\theta_2 = \theta_0$, i.e. the drops are just at the freezing point, the liberated heat is confined to the latent heat and solidification is more rapid especially if the surface of the aircraft is well below the freezing point.

(*c*) *Sublimation.*—Under certain conditions the invisible water vapour in the atmosphere may condense direct into ice crystals without passing through the intermediate stage. The conditions are that the dew point of the air should be below the freezing point and that the air should be cooled down to the dew point. This might occur by contact with the cold parts of the aircraft, particularly on a descent from high altitudes, and lead to a deposition of ice crystals (hoarfrost), and the process would continue as long as the water vapour pressure exceeded the saturation vapour pressure over the ice. Merit Scott (3) has examined this aspect of the problem both theoretically and by wind tunnel experiments, and reaches the conclusion that the maximum rate of deposit, to be expected with a maximum of supersaturation known to occur in the atmosphere, is low, and should not prove dangerous in an hour's flight through such a region.

It is therefore apparent that for ice formation to occur in any quantity the aircraft must be flying through visible moisture and the meteorological conditions may be summarised as :—

1. The freezing at or soon after impact of supercooled water drops in clouds or rain falling into a region where temperatures are below the freezing point.

2. The adhesion of sleet, wet snow and hail mixed with rain, particularly if the latter freezes.

Types of Ice Formation.—From the preceding section it would be expected that different types of ice would result from the different processes involved. Actual flights have led to the following classification :—Clear ice, rime and hoarfrost.

Clear ice.—A layer of transparent ice which usually forms on the leading edges of the aircraft and spreads back along the planes. It is frequently rough with heavy protuberances to windward but can be smooth and of streamline form. The adhesion is firm. It is the same type which gives glazed frost at ground level when rain falls on to a frozen surface. From this analogy and the theory evolved in the preceding section it has come to be recognised that clear ice is formed by the comparatively slow freezing of large water drops either in cloud or rain and that the roughness is due to the simultaneous freezing of drops of different sizes.

Rime.—A layer of opaque crystalline ice which usually forms on the leading edges and does not spread far back along the planes. It is usually smooth and streamline in form but can be rough. Although the adhesion is not so firm as in the case of clear ice, there have been numerous occasions when a rime formation has been brought down to ground level and has withstood the shock of landing. The crystalline structure is not always obvious at first sight but can be seen if a layer of the ice is broken. The formation is considered to be due to the more rapid freezing of small drops mentioned in the preceding section and the opacity to the imprisonment of air as the drops solidify. It is the type which produces small ice crystals on all objects at ground level during a freezing fog.

Hoarfrost.—The deposit is of a white feathery nature and does not build up to any thickness. Except for inconvenience caused by a deposit on windows, the type can be ignored as a possible danger to aircraft.

A number of the deposits examined at ground level appear to consist of mixtures of clear ice and rime ; a result which is not surprising when the different sizes of drops that constitute either cloud or rain are considered, and the fact that hail or snow may get imprisoned when any water drops present freeze.

From the above definitions we are now in a position to postulate the meteorological conditions under which clear ice or rime would be expected to be formed on an aircraft. On the assumption that large water drops in the atmosphere are formed chiefly by condensation on to smaller drops caused by vertical ascent, we should expect clear ice to be formed where there are up-currents, i.e. either at fronts and mountain barriers or by convexion, or a combination of any of them. For example, a mountain barrier over which a front is passing would augment the frontal up-current. The cloud types associated with these up-currents would be altostratus, nimbostratus, cumulus and cumulonimbus. On the other hand rime would be associated with clouds that exhibited little vertical movement of the air such as stratus and stratocumulus. These clouds are frequently surmounted by an inversion of temperature which limits vertical movement, but turbulent motion within the cloud, leading to condensation in the up-currents and evaporation in the down-currents, might result in the formation of comparatively large water drops near the top. So the possibility of clear ice in stratus and stratocumulus cannot be ruled out although rime should predominate.

Again, in the four cloud types previously mentioned there is always the possibility that hail or snow may get imprisoned in the clear ice and give the appearance of rime or that smaller drops may be encountered as well as large drops. It is considered, therefore, that no hard and fast rule can be laid down.

The theories derived in the preceding sections will now be discussed in connexion with the results obtained from actual flights.

Weather conditions favourable to ice formation.—(*a*) *Clouds.*—A large number of cases of ice formation on aircraft have been reported from different stations during the period 1932–7. By far the greatest percentage of these have occurred when the aircraft was in cloud with air temperatures at or below the freezing point. From a total of 217 reports, 81 per cent occurred within the range of temperature 18°–32° F., the highest percentage, 36, being from 23°–27° F. Only 12 reports showed ice formation at temperatures below 8° F., five of which were below -2° F.

A study of extended flights at both Farnborough and Bircham Newton indicated that ice deposits would be classed as slight, moderate and heavy according as the rate of formation was $< 0{\cdot}5$ in./hr., $0{\cdot}5 - 1{\cdot}5$ in./hr. and $> 1{\cdot}5$ in./hr. An analysis of all the cloud flights on this basis indicated that about 20 per cent gave heavy deposits, the frequency distribution as regards temperature being similar to that for all cases, viz. the maximum number falling within the range 18°–32° F. There was only one heavy deposit with a temperature below 8° F.

As the effect of opaque ice on the performance of the aircraft is usually held to be less severe than the clear type it seemed relevant to make a more detailed survey than that given in Table 1A. The actual data have not been reproduced but the general conclusions are as follows :—

(1) Both types of ice were observed with equal frequency.

(2) Both gave a maximum frequency of formation in the range of temperature 23°–27° F., but whereas only 12 per cent of clear ice cases occurred at temperatures below 23° F., the figure in the case of opaque ice was 43 per cent. On the other hand more clear ice cases occurred at temperatures above 27° F. than opaque.

(3) Moderate deposits were equally divided, but clear ice gave three times as many heavy deposits as opaque ice.

(4) The mean time interval, after entering cloud and before ice formation was noticed, was $4\frac{1}{2}$ minutes for clear ice and 7 minutes for opaque, the corresponding amount of supercooling being 6° F. and 10° F.

The last statement appears to indicate that the time interval is proportional to the degree of supercooling but an analysis of the individual records showed no such simple relation. It would also appear to conflict with the theory developed above, that clear ice is formed by the comparatively slow solidification of large water drops, but it is probable that the relatively larger total amount of ice formed on impact is more readily visible. The theory also led to the conclusion that, the portion of each drop freezing on impact is proportional to the degree of supercooling. This partly explains why clear ice tends to form at higher temperatures than opaque ice, because with small amounts of supercooling less ice forms on impact and more water is left to spread back and freeze slowly. Another reason is that any drops that form at low temperatures have less opportunity of increasing to a large size owing to the decrease of saturated vapour pressure with temperature.

The results in Table IA. show that ice is liable to form on an aircraft whilst flying in any type of cloud except perhaps members of the cirrus group which were not explored. The cloud in which it is most frequently encountered is stratocumulus, in fact this type accounts for more than half the total number of observations. This is due to the fact that it is a frequent cloud type in winter,

TABLE I.—FREQUENCY OF ICE FORMATION IN CLOUD WITH RESPECT TO TEMPERATURE

Cloud		Temperature °F.									
		Above 32°	32° to 28°	27° to 23°	22° to 18°	17° to 13°	12° to 8°	7° to 3°	2° to -2°	Below -2°	Total
		A. Aeroplane ascents 1932-7									
Stratocumulus ..	All cases ice ..	..	37	52	21	8	5	1	..	..	124
	Heavy ice ..	..	6	13	2	1	2	..	..	..	24
	No ice	..	10	9	1	1	..	..	1	..	22
Stratus	All cases ice ..	..	5	1	..	..	..	..	..	..	6
	Heavy ice ..	..	..	..	..	..	..	..	..	..	0
	No ice	..	..	..	..	..	..	..	..	..	0
Cumulus	All cases ice ..	..	6	17	6	4	2	1	..	..	36
	Heavy ice ..	..	1	1	1	1	1	1	..	..	6
	No ice	..	1	2	1	1	1	..	..	..	6
Cumulonimbus ..	All cases ice ..	..	5	3	9	..	3	..	3	1	24
	Heavy ice ..	..	2	..	7	..	1	..	..	..	10
	No ice	..	1	..	..	1	..	1	..	..	3
Nimbostratus ..	All cases ice ..	..	2	5	5	1	1	..	..	..	14
	Heavy ice ..	..	..	..	1	1	..	..	..	..	2
	No ice	..	1	1	2	..	2	..	..	1	7
Altostratus ..	All cases ice ..	..	1	..	1	..	1	1	..	1	5
	Heavy ice ..	..	..	..	..	..	..	..	..	..	0
	No ice	..	..	3	..	3	..	..	1	3	10
Altocumulus ..	All cases ice ..	..	..	..	1	..	3	..	1	3	8
	Heavy ice ..	..	..	..	..	..	1	..	..	..	1
	No ice	..	1	1	..	..	1	..	..	..	3
All types	All cases ice ..	..	56	78	43	13	15	3	4	5	217
	Heavy ice ..	..	9	14	11	3	5	1	0	0	43
	No ice	..	14	16	4	6	4	1	2	4	51
		B. Ben Nevis Observations 1884-92									
	All cases ice ..	..	52	54	30	19	2	..	..	..	157
	Clear ice	..	25	8	1	..	..	..	..	..	34
	Opaque, white or brown.	..	22	33	24	18	..	..	..	..	97
	No specification..	..	5	13	5	1	2	..	..	..	26

when upper air temperatures are at their lowest, and as the layer may extend unbroken for hundreds of miles, opportunity for ice formation is favourable if the aircraft remains in the appropriate layer. There have been several days on which ice has been reported from different parts of the country in the same layer of stratocumulus. In spite of this, heavy ice deposits are not very frequent ; about 20 per cent of the total flights in stratocumulus. The frequency distribution of ice formation with respect to temperature is similar to that quoted for all types of cloud, a result which is not surprising owing to the preponderance of stratocumulus exploration. Stratocumulus is generally found at heights of from 1,500 to 5,000 ft. and its thickness does not usually exceed about 2,000 ft.

Ice formation in the lowest type of cloud, stratus, is not very frequent and there were no heavy deposits. The base of stratus cloud is usually below 1,000 ft., and frequently at or near ground level, but this cloud has normally little vertical thickness. Temperatures below freezing point in the first 1,000 ft. above sea level are not very frequent in this country and it is not surprising that nearly all the cases of ice formation in stratus have occurred at temperatures between 28° and 32° F. In Germany (5) this type of cloud gives the largest percentage, 45, of ice formation, with stratocumulus second with 16 per cent. On the other hand in America stratocumulus is outstanding.

Turning to cumulus and cumulonimbus, we leave the layer type of cloud and come to what are termed heap clouds, i.e. isolated clouds with bases at 2,000 to 5,000 ft., and towering up to 8,000 to 12,000 ft. in the case of cumulus and often to 20,000 ft. in the case of cumulonimbus. Up-currents, frequently strong, are known to exist in these clouds, and this is one of the conditions for the production of large supercooled water drops. This probably explains the reports of ice formation when aircraft traverse the tops of these clouds, the total time in cloud being only a few minutes, and also the greater percentage of heavy deposits. The temperature distribution for cumulus is similar to that for stratocumulus but for cumulonimbus the maximum frequency occurs at temperatures between 18° and 22° F. and there are four cases at temperatures below 3° F. This is due to the higher top and hence lower temperature of cumulonimbus cloud. The number of heavy deposits in cumulonimbus is high, about half the total ascents, and is unique among the different cloud types in this respect.

The cloud types nimbostratus and altostratus combine both features of the preceding types in that they usually have considerable horizontal and vertical extent. The base of altostratus is above 8,000 ft. and may extend to 20,000–30,000 ft. Nimbostratus may be regarded as altostratus whose base has been lowered below 8,000 ft. and it is not unusual for the base to fall to 2,000–3,000 ft. There is thus ample opportunity of remaining in these clouds at low temperatures. Ice formation, however, is not very frequent, and, particularly in the case of altostratus, the number of occasions on which no ice was reported is double that on which ice formation occurred, and there were no heavy deposits. The temperature distribution for ice formation in nimbostratus follows that for stratocumulus and cumulus but in altostratus the few cases are evenly distributed over the whole range from 32° F. down to below -2° F. Nimbostratus and altostratus are the cloud types associated with fronts, (discussed below), in particular, the region where advancing warmer air is slowly rising up over colder surface air.

Finally there is an upper layer cloud altocumulus often of large horizontal extent but of little vertical thickness. The base is usually found between 8,000 and 20,000 ft., and for this reason any ice deposits would be found at low temperatures. The figures show most of these occurred below 13° F. and there was only one heavy deposit in eleven explorations.

Details of some of the individual flights are given in Tables II–IV arranged in order of descending temperature. The thickness of the ice deposits is in most cases based on visual estimate but some have been measured after landing. It will be observed that the opaque form of ice predominates in stratocumulus, clear ice in nimbostratus and cumulonimbus while the forms are about equally divided in cumulus. These facts are in accordance with the theories developed in the section on types of ice formation.

An analysis of the air supply, using gradient winds, was made on a large number of days on which ice was reported, and in all cases the air, at least in the lowest levels, was of polar origin. It is a matter of conjecture whether this applies to some of the upper clouds considered, particularly the nimbostratus and altostratus clouds which were probably formed in equatorial air overrunning the colder surface air. There seems little doubt that most of the stratocumulus, cumulus and cumulonimbus cases occurred in polar air. This fact is not surprising when we consider that the lower cloud forms stratus, stratocumulus and cumulus which form in equatorial air would have temperatures above the freezing point in these latitudes up to at least 4,000 ft. Moderate or heavy ice deposits were found in cumulus and cumulonimbus cloud in polar air having a track (a) direct southwards (b) over the Atlantic and (c) over the continent before reaching the British Isles. Similar tracks apply to such deposits in stratocumulus cloud with the addition of cold continental air.

In a number of these ice reports evidence of supercooled water drops is afforded by the streaming of water over the planes prior to visible ice formation, so that there seems little doubt that the theory advanced in the section on physical processes is substantially correct. there are, however, about 20 per cent of the total flights made, in which no ice was reported, although conditions appeared similar to those under which ice did form. Some of these are set out in Table V. In certain cases it is evident that the aircraft was not a sufficient length of time in the cloud, for there is usually an interval of from 1 to 10 minutes before the ice becomes visible during an ascent

Table II.—Stratocumulus and Stratus

Date	Time G.M.T.	Cloud: Base	Cloud: Top	Deposit first observed at: Height	Deposit first observed at: Temp.	Deposit apparently ceased at: Height	Deposit apparently ceased at: Temp.	Lowest Temp. in cloud	Time in cloud	Amount of ice	Type of ice	Change in form or amount of cloud	Place of observation	Remarks
Stratocumulus														
		ft.	ft.	ft.	°F.	ft.	°F.	°F.	min.	in.				
Dec. 18, 1933	1430	3,000	3,800	3,200	28	Above clouds 4,600	32	..	10	$\frac{1}{4}$	Opaque, smooth	None	Bircham Newton	Ice melted on leaving clouds above and below.
Nov. 28, 1933	1030	2,500	4,500	3,000	28	4,000	25	25	60	2–3	Clear, rough	None	Bircham/Newton	Air speed dropped from 105 to 70 m.p.h.
Nov. 27, 1933	1200	2,500	4,000	3,000	27	Continued to form flying level.	..	25	60	1	Clear, smooth	None	Bircham Newton	..
Nov. 30, 1933	1030	2,000	4,500	2,000	27	4,500.	32	21	35	$\frac{3}{4}$	Clear, smooth	None	Bircham Newton	Vibration of flying wires.
Jan. 1, 1934	1100	2,600	3,500	2,500	27	Above clouds 3,600	..	..	25	1	Clear, smooth	None	Bircham Newton	Heavy on controls—climbing power reduced.
Oct. 27, 1933	1500	2,000	4,000	3,500	27	3,500	27	..	30	$\frac{1}{2}$	Opaque,* smooth	None	Bircham Newton	*Clear ice formed on top of opaque—no deposit after first 15 min.
Oct. 18, 1933	1445	6,000	9,000	7,000	25	Melted above clouds 9,100	32	..	8	$\frac{1}{2}$	..	None	Bircham Newton	Vibration of engine.
Oct. 30, 1933	1300	3,000	7,000	5,000	25	..	..	18	20	$\frac{1}{8}$	Opaque, rough	None	Bircham Newton	Impossible to build up much ice.
Nov. 2, 1933	1010	2,000	4,500	3,000	25	4,000	21	21	75	2	Clear, rough	Increasing in amount	Bircham Newton	..
Dec. 11, 1933	1100	3,500	4,300	4,000	25	Continued to form flying level	..	23	75	1	Opaque, rough	None	Bircham Newton	Air speed reading low—aircraft tail, heavy.
Dec. 5, 1933	1000	2,000	2,200	2,000	23	Continued to form flying level	..	23	75	$\frac{3}{4}$	Opaque, rough	Decreasing in amount	Bircham Newton	..
Dec. 7, 1933	1340	2,000	5,000	3,000	23	..	..	..	90	$1\frac{1}{2}$	Opaque, smooth	None	Bircham Newton	..
Dec, 16, 1933	1045	4,000 5,000	4,500 > 6,500	4,500	23	Most ice at 6,000	18	18	40	$\frac{3}{4}$	Clear,* smooth	None	Bircham Newton	*At leading edge, opaque further back—air speed reduced.
Nov. 2, 1933	1335	4,000	8,000	7,000	19	..	..	14	60	$\frac{1}{8}$	Opaque, rough	Decreasing in amount	Bircham Newton	Impossible to build up much ice.
Dec. 14, 1933	1100	4,000	5,200	4,200	14	..	..	..	70	1	Opaque, smooth	None	Bircham Newton	Engine vibration—aircraft tail, heavy.
Dec. 8, 1933	1100	3,500	7,000	6,000	12	7,000	..	..	45	2	Opaque, rough	Decreasing in amount	Bircham Newton	Ice disappeared slowly above clouds at 8,000 ft. 14° F.
Feb. 15, 1933	1100	6,300	7,000	6,500	10	6,800	9	9	40	$\frac{3}{8}$	Opaque, smooth	..	Farnborough	..
Feb. 8, 1935	1030	6,000	7,000	6,800	10	..	..	10	60	$\frac{1}{8}$	Opaque	..	Abingdon	..
Jan, 28, 1935	1020	7,000	8,000	7,000–8,000	7	..	..	7	1-2	thin	..	..	Felixstowe	..
Apr. 25, 1932	1500	8,000	9,200	..	..	..	..	8	over 30	heavy	Opaque, rough	..	Andover	..
Stratus														
Mar. 29, 1935	1000	500	5,500	4,000	32	5,500	27	27	20	$\frac{1}{2}$	Clear, rough	Forming	Bircham Newton	Cold front—considerable vibration.
Apr. 4, 1934	1000	800	4,000	3,000	32	4,000	28	28	20	$\frac{1}{4}$	Clear, rough	None	Bircham Newton	Ice fell off above clouds 4,500 ft. (27° F.).
Jan. 29, 1932	1140	1,200	3,000	2,500	30	Flying level	..	30	5	$\frac{1}{4}$	..	..	Farnborough	..
Nov. 17, 1932	1125	2,500	3,400	3,200	30	..	..	30	10	$\frac{1}{16}$	..	..	Farnborough	..
Apr. 4, 1936	1100	2,000	4,000	2,500	28	Continued to form flying level	..	..	4	$\frac{3}{16}$	Opaque	..	Abingdon	Ice brought down.

Table III.—Cumulus and Cumulonimbus

Date	Time G.M.T.	Cloud: Base	Cloud: Top	Deposit first observed at: Height	Deposit first observed at: Temp.	Deposit apparently ceased at: Height	Deposit apparently ceased at: Temp.	Lowest Temp. in cloud	Time in cloud	Amount of ice	Type of ice	Change in form or amount of cloud	Place of observation	Remarks
Cumulus														
		ft.	ft.	ft.	°F.	ft.	°F.	°F.	min.	in.				
Sept. 26, 1932	1440	4,000	7,000	5,400	32	Flight in layer 5,400–6,000	30–32	30	20	$\frac{1}{4}$	..	..	Farnborough	..
Sept. 27, 1932	1400	4,000	7,000	6,800	27	..	..	27	20	$\frac{5}{8}$	Clear, smooth	..	Farnborough	..
Nov. 21, 1932	1450	4,200	4,900	4,400	27	Flying level	..	27	30	$\frac{1}{16}$	Clear, smooth	..	Farnborough	Not possible to accumulate much ice.
May 11, 1933	1330	3,500	Above 8,000	8,000	27	..	..	27	45	$\frac{1}{2}$	Opaque, smooth	..	Farnborough	Ice formed quickly at 8,000 ft.
Apr. 7, 1934	1000	1,800	3,200	3,000	25	..	..	25	40	$\frac{3}{4}$	Clear, rough	Dissipating	Bircham Newton	Ice disappearing at 9,000 ft. (18° F.) above cloud.
May 26, 1933	1330	2,500	Above 8,000	8,000	23	..	..	23	30	$\frac{3}{8}$	..	..	Farnborough	..
Feb. 24, 1932	1435	1,000	Above 7,000	4,000	30	Straight climb to 7,000	19	19	10	$\frac{1}{2}$	Clear	..	Farnborough	Aircraft unable to climb above 7,000 ft.
Jan. 16, 1933	1450	2,500	6,000	5,000	21	6,000	18	18	30	$\frac{1}{8}$	Opaque, smooth	..	Farnborough	..
Dec. 3, 1935	1400	..	..	6,000	18	7,000	14	14	..	1	Opaque	..	Wales	Ice formed very rapidly.
Apr. 8, 1932	1045	3,000	8,000	..	..	..	..	14	20	..	Opaque	..	Andover	..
May 5, 1932	1100	3,500	8,500	..	..	..	..	3	Over 30	1	Opaque, smooth	..	Andover	Heavy deposit.
Feb. 12, 1932	1120	4,000	7,000	..	..	..	..	−1	35	Heavy	..	..	Andover	..
Cumulonimbus														
Jan. 17, 1935	1500	2,500	..	4,000	29	..	..	..	60	$\frac{3}{4}$	Clear	..	Cranwell	..
Feb. 11, 1936	1100	2,000	..	2,000	28	..	..	..	5	$\frac{3}{16}$	Clear	..	Abingdon	Hail—flight in base cloud.
Apr. 18, 1935	1030	2,400	7,700	5,500	21	..	..	..	40	..	Clear, rough	..	Andover	Ice formed rapidly.
Nov. 16, 1933	1000	2,500	8,500	6,000	23	On descent 4,000	32	15	50	$\frac{3}{8}$	Clear, smooth	None	Bircham Newton	..
July 27, 1932	1100	2,500	15,000	12,000	18	..	..	..	3	$\frac{1}{4}$	..	..	Farnborough	Top of cloud entered at 12,000 ft.
May 22, 1933	1430	5,000	Above 13,000	13,000	18	..	..	..	15	$\frac{3}{4}$	..	..	Farnborough	Ice formed readily at 13,000 ft.
Apr. 11, 1932	1000	1,500	8,000	..	..	..	..	12	5	$\frac{1}{4}$	Opaque	..	Andover	..
Feb. 25, 1935	1530	2,000	Above 8,800	8,800	11	Flying level	11	..	$1\frac{1}{4}$	$\frac{1}{8}$	Clear, rough	None	Worthy Down	Entered cloud at 8,800 ft.
Mar. 3, 1935	1200	2,000	10,000	..	..	..	..	10	10	$\frac{1}{16}$	Opaque	..	Hucknall	..
Apr. 14, 1932	1500	4,400	..	..	..	..	..	1	45	..	Rough	..	Andover	..
Mar. 31, 1932	1500	4,000	..	..	..	..	..	1	Over 30	Very slight	..	..	Andover	..
Mar. 10, 1932	1500	4,000	10,000	..	..	..	..	1	45	..	Opaque	..	Andover	..
Mar. 30, 1932	1430	2,000	15,000	14,000	0	..	..	−6	$\frac{1}{4}$	Thin	..	..	Farnborough	Cloud wet.

TABLE IV.—NIMBOSTRATUS, ALTOSTRATUS AND ALTOCUMULUS

Date	Time G.M.T.	Cloud Base	Cloud Top	Deposit first observed at: Height	Deposit first observed at: Temp.	Deposit apparently ceased at: Height	Deposit apparently ceased at: Temp.	Lowest Temp. in cloud	Time in cloud	Amount of ice	Type of ice	Change in form or amount of cloud	Place of observation	Remarks
Nimbostratus														
		ft.	ft.	ft.	°F.	ft.	°F.	°F.	min.	in.				
Jan. 22, 1936	1400	800	..	600	33	3,300	25	..	2	..	..	..	Abingdon	Snowing—ice in carburettor.
Nov. 22, 1932	1105	1,000	Above 13,000	9,000	30	8,000	32	19	35	1/8	Clear, smooth	None	Farnborough	Ice formed on descent only.
Feb. 25, 1935	1200	1,900	Above 6,400	3,000	30	6,400	19	..	56	1/8	Opaque, smooth	None	Worthy Down	Snow at 2,500 ft. before ice formed—snow imprisoned within ice.
Jan. 6, 1936	1520	1,300	Above 9,000	5,000	30	9,000	15	..	..	1/4	..	..	Sealand	Straight climb.
Apr. 29, 1932	0920	1,000	Above 7,000	..	..	..	..	28	20	Slight	Clear	..	Andover	..
May 30, 1932	1200	4,000	8,000	..	..	..	..	25	20	..	Clear, rough	..	Andover	..
Feb. 18, 1937	1115	4,000	14,000	6,000	26	14,000	14	14	28	..	Clear	..	Grantham	..
Feb. 5, 1936	1530	3,500	..	5,000	22	..	..	..	3	3/8	Clear	..	Abingdon	Ice brought down.
Jan. 24, 1935	1100	5,000	..	7,000	14	..	..	..	4	1/2	Clear	..	Heyford	Heavy rain below cloud.
Mar. 7, 1932	1500	4,800	17,000	..	..	..	..	−8	Over 30	Slight	Clear, smooth	..	Andover	..
Altostratus														
July 19, 1935	1045	8,000	13,000	9,000	28	..	..	..	45	..	Clear, rough	..	Andover	Ice formed slowly, but developed heavy protuberances.
May 18, 1932	0900	11,000	..	12,000	19	..	..	..	40	Slight	Opaque, smooth	..	Andover	Thin cloud, rain falling.
Jan. 24, 1935	1100	17,000	..	17,000	9	..	..	..	..	1/16	Opaque	..	Abingdon	..
Dec. 2, 1932	0925	17,000	18,500	18,000	−4	..	..	−6	2	Thin	..	..	Farnborough	..
Altocumulus														
Jan. 30, 1935	..	11,000	12,000	11,200	18	..	..	..	20	1/4	Clear	..	Farnborough	..
Nov. 9, 1935	1100	11,500	12,300	11,500	12	..	..	10	10	1	Clear	..	Worthy Down	..
Nov. 2, 1934	1435	10,000	11,200	10,000	11	..	..	..	15	1/8	*	None	Worthy Down	*Clear at first, then opaque and rough on top of clear ice.
Nov. 13, 1933	1530	14,500	15,000	14,800	2	..	..	..	..	Very slight.	Opaque	..	Farnborough	..
Nov. 1, 1933	1600	18,000	18,800	18,000	−4	..	..	..	..	Very slight.	Opaque	..	Farnborough	..
Feb. 28, 1934	1530	13,000	14,500	13,000	−10	14,500	−12	−12	..	..	Clear	..	Farnborough	..

TABLE V.—NO ICE IN CLOUDS

Date	Time G.M.T.	Cloud Base	Cloud Top	Time in cloud	Temperatures Height	Temperatures	Temperatures Height	Temperatures	Change in form or amount of cloud	Place of observation	Remarks
Stratocumulus											
		ft.	ft.	min.	ft.	°F.	ft.	°F.			
Nov. 17, 1934 ..	1100	2,000	5,000	10	3,200	33	{ 4,400 5,300	31 39 }	None	Bircham Newton	{ Cloud very wet—water streaming off planes.
Mar. 2, 1935 ..	1100	2,000	3,000	15	3,000	32	4,500	28	None	Bircham Newton	Slight drizzle on ground.
Jan. 10, 1933 ..	1510	3,200	3,400	30	3,200	30	4,000	34	..	Farnborough	Cloud wet and filmy.
Jan. 29, 1935 ..	1100	1,600	2,200	20	{ 1,000 2,200	34 28 }	2,700	28	Dispersing	Worthy Down	..
Mar. 30, 1932 ..	0900	2,000	5,000	45	Lowest	27	..	..	..	Andover	..
Mar. 21 1932 ..	0930	4,500	5,500	Over 15	Lowest	27	6,000	28	..	Andover	..
Nov. 5, 1934 ..	0930	2,000	5,000	7	..	..	5,000	27	Clearing	Bircham Newton	Straight climb.
Nov. 2, 1934 ..	1435	4,200	6,200	12	Lowest	23	..	..	..	Worthy Down	Cloud very wet.
Mar. 4, 1932 ..	1530	3,800	5,000	Over 15	Lowest	23	5,100	28	..	Andover	..
Apr. 1, 1932 ..	1500	4,000	8,500	25	Lowest	14	9,000	23	..	Andover	..
Mar. 11, 1932 ..	0930	9,500	9,800	20	Lowest	−3	..	..	..	Andover	..
Cumulus											
Jan. 21, 1932 ..	1530	2,000	4,250	40	Lowest	32	..	..	..	Andover	..
May 24, 1932 ..	1500	4,000	6,100	Over 15	Lowest	27	6,600	30	..	Andover	..
Apr. 8, 1932 ..	0930	3,500	6,500	30	Lowest	23	6,600	21	Developing	Andover	Cloud developed during morning to 9,000 ft. (14° F.) and ice formed.
Apr. 7, 1932 ..	0930	3,000	7,000	45	Lowest	19	7,100	18	..	Andover	..
Feb. 11, 1932 ..	1130	2,400	4,000	Over 15	Lowest	14	4,500	12	..	Andover	..
Feb. 10, 1932 ..	1030	3,000	7,000	20	Lowest	−4	7,500	−6	..	Andover	Snow at times in cloud.
Cumulonimbus											
Oct. 30, 1934 ..	1430	500	12,000	13	3,000	32	..	..	None	Bircham Newton	Entered cloud flying level 3,000 ft.—heavy snow melted on planes.
Dec. 19, 1934 ..	1030	4,000	15,000	40	4,000	36	12,000	10	Forming	Bircham Newton	Steady climb through cloud—snow met at 11,000 ft. after 30 mins. in cloud.
Mar. 30, 1932 ..	0915	5,000	20,000	40	5,000	27	Lowest	−15	..	Andover	..

TABLE V.—NO ICE IN CLOUDS—*continued*

Date	Time G.M.T.	Cloud Base	Cloud Top	Time in cloud	Temperatures Height		Height		Change in form or amount of cloud	Place of observation	Remarks
Nimbostratus											
		ft.	ft.	min.	ft.	°F.	ft.	°F.			
Nov. 30, 1932 ..	1500	3,500	Above 9,000	15	3,500	36	9,000	25	..	Farnborough	Cloud wet and filmy—rain at 9,000 ft.—slight rain on ground.
Feb. 25, 1935 ..	1500	2,000	Above 6,000	40	2,000	36	6,000	23	None	Bircham Newton	Cloud very filmy.
Feb. 27, 1935 ..	1000	7,400	Above 10,000	20	7,000	25	10,000	16	Becoming thicker	Bircham Newton	Sleet in cloud—none below.
May, 24, 1932 ..	0930	2,000	11,500	30	2,000	37	11,500	10	..	Andover	..
Jan. 5, 1933 ..	1030	6,500	Above 14,000	10	6,500	21	14,000	0	..	Farnborough	Cloud wet and filmy.
May 9, 1932 ..	0915	3,000	Above 20,000	Over 30	..	..	15,000	−10	..	Andover	Rain.
Mar. 7, 1932 ..	1500	4,500	Above 17,000	35	4,500	28	17,000	−13	..	Andover	Dampness felt on face whole time.
Altostratus											
Sept. 3, 1935 ..	1100	9,200	12,000	20	9,000	28	12,000	25	..	Andover	..
Mar. 9, 1933 ..	1030	11,000	Above 15,000	Over 15	11,000	27	15,000	19	..	Andover	Rain at 13,500 ft.
Sept. 9, 1935 ..	1100	8,800	17,200	25	8,000	37	17,000	19	..	Andover	..
May, 20, 1932 ..	0900	13,000	17,000	20	13,000	16	17,000	10	..	Andover	..
Apr. 6, 1932 ..	1000	8,200	Above 14,000	35	8,000	25	14,000	4	..	Andover	..
Sept. 22, 1932 ..	0900	11,000	Above 20,000	30	11,000	32	20,000	3	..	Farnborough	Straight climb—cloud wet and filmy 11,000–12,000 ft., then dry and dense.
Apr. 18, 1932 ..	1030	13,500	Above 19,000	Over 15	13,500	8	19,000	− 8	..	Andover	..
Mar. 21, 1932 ..	0930	21,000	Not reached	Over 15	..	..	21,000	−12	..	Andover	..
Apr. 11, 1932 ..	0930	12,700	Not reached	30	12,600	−5	Lowest	−32	..	Andover	..
Mar. 9, 1933 ..	1130	8,000	Above 27,000	30	7,000	37	27,000	−38	..	Farnborough	Snow shower 9,000 ft.—sun visible throughout—Cloud dry and filmy—Cloud above 15,000 ft. appeared as thin mist.
Altocumulus											
May 23, 1932 ..	0930	5,300	8,000	15	5,000	30	8,000	27	..	Andover	..
Feb. 18, 1935 ..	1430	10,000	11,000	3	10,000	25	..	..	Forming	Bircham Newton	..
Sept. 5, 1935 ..	1430	16,100	17,900	10	16,000	14	17,900	5	..	Andover	..

though much less during a descent. As it is a matter of considerable importance to know whether a given cloud at a temperature below the freezing point will produce little or no ice on an aircraft or a moderate or heavy deposit these cases have been analysed in the light of the theories and facts already set out. An example in stratocumulus cloud on November 2, 1933, will suffice to indicate the anomalies. In the morning ascent a heavy clear deposit was obtained, lowest temperature 21° F. with a 2° F. inversion above. By the afternoon the cloud had become thicker the lowest temperature had fallen to 14° F. with a lapse rate of 4° F. per 1,000 ft. above the cloud, and although the air supply remained the same, only a slight deposit of opaque ice was observed. If our theories are correct then the morning cloud consisted of comparatively large water drops and the afternoon cloud of smaller drops, and there is evidence for this in the description of the cloud, wet and dense in the morning, dry and filmy in the afternoon. In fact these arbitrary descriptions provide in flight the only easy means of assessing the relative size and number of water drops in the cloud, e.g.

wet and dense—relatively large number of large water drops.
wet and filmy—relatively small number of large water drops.
dry and dense—relatively large number of small water drops or ice crystals.
dry and filmy—relatively small number of small water drops or ice crystals.

A description of the cloud was always given in the observations made at Bircham Newton and Farnborough and an analysis of the different rates of ice accretion in stratocumulus bring to light the following facts. In 37 cases of moderate or heavy ice all but eight gave the cloud as wet and dense. In all five cases of slight deposit the cloud was dry and filmy and on three occasions on which a flight exceeded 10 minutes in cloud with no deposit the description was wet and filmy. Remarks by pilots that the part of the cloud was wet and dense where the ice formed and dry and filmy elsewhere are obviously of importance. These peculiarities make the forecasting of ice in stratocumulus clouds one of extreme difficulty. It was thought that the presence or absence of a temperature inversion above the stratocumulus layer might affect the problem but an analysis of 33 cases of deposits ranging from nil to heavy showed the presence of an inversion in all but five. Of these five, three gave a moderate deposit, one slight and the remaining one, no deposit. All layers giving heavy deposits had a temperature inversion above ranging from 2° to 9° F. Also all ascents gave a lapse rate of about 3° F. per 1,000 ft. inside the cloud layers, but there is slight evidence that when the lapse rate below the cloud exceeds this figure the ice deposit is moderate or heavy, and when less, the deposit is slight or non-existent. The state of development of the cloud is also of importance. In a layer that is developing, water drops will be condensing out and might be supposed to be available for freezing on contact, whereas in a layer that is dispersing, the drops will be evaporating, but there are not sufficient data available to postulate a working rule. No assistance is given from surface air supply considerations.

A similar difficulty arises in dealing with nimbostratus and altostratus clouds, and it is surprising that these frontal clouds, which, as the more active part of the front advances, produce rain which may lead to the worst type of icing, viz. : glazed frost, do not in themselves cause heavy deposits in advance of the active part of the front. An examination of the state of the cloud on our arbitrary scale in the six cases in which it was noted, again brings to light some interesting facts. Five of these reported the cloud as wet and filmy and the remaining one as dry and filmy. In the latter (March 9, 1933, Farnborough) a snow shower was encountered at the base of the altostratus and there seems little doubt that the whole of the cloud consisted of ice crystals particularly as the report stated that above 15,000 ft. the cloud appeared as thin mist. No ice was reported in the same cloud layer some 40 miles further west (Andover) on that day although rain was encountered at 13,500 ft. In another ascent at Farnborough on September 22, 1932, the cloud was described as wet and filmy in the first 1,000 ft. then dry and dense above, indicating that water drops were just in the process of formation in the lower part of the cloud at a temperature of 29°–32° F. Another factor is that the aircraft was on a straight climb and would only be a few minutes in that part of the cloud where ice would be likely to form. This may account for the lack of ice in some of the other altostratus cases for although the machines were searching for ice throughout the vertical extent of the layer, they may not have been a sufficient length of time in the optimum region, i.e. where water drops were actually forming, or the clouds may have consisted entirely of ice crystals. As the more active part of the front is approached and the cloud becomes thicker vertically with more water drops available in the lower part of the layer, now termed nimbostratus, it is to be noted that the proportion of " no ice " reports falls considerably. However, there is a residue of cases both in nimbostratus and altostratus, in which rain was definitely reported with temperatures below the freezing point and no ice formation, and our knowledge of cloud and rain formation is not at present sufficiently far advanced to account for these cases.

From the above examples it seems possible that when a cloud is in the initial stages of its development, the water drops are not present in sufficient quantity or size to form visible ice. This also appears to be indicated in cumulus cloud at Andover on April 8, 1932, in which no ice was reported on the 0930 ascent when the cloud extended from 3,500 to 6,500 ft. This cloud developed during the morning to 9,000 ft. and ice formed. Similarly, ice may form in the initial stages of dissipation of a cloud, as in the ascent in cumulus at Bircham Newton on April 7, 1934. It is not perhaps without significance that most of the cases of ice in cumulus occurred after midday when this type of cloud is normally at its maximum development and most of the reports of " no ice " occurred before midday.

The question of salinity of the water drops and its effect on lowering the freezing point, particularly of the smaller drops, is another possible factor which for obvious reasons has not been taken into account. A paragraph in Samuels' paper (6) is relevant in this connexion. " From measurements of the concentration of salts in clear ice and rime deposits and the corresponding sizes of fog and cloud droplets on mountains in Europe, together with certain assumptions, Köhler (reference 7) concludes that the sizes of droplets in clouds, from which no precipitation is falling, and which exist simultaneously at the same elevation, depend on the respective sizes of the salt particles about which condensation has occurred. His calculations show that high concentrations are associated with small droplets and vice versa."

Another aspect has been developed by Minser (8) from considerations of the relative water content of tropical maritime air and polar air. He states that the available water varies from 9 gm. per cubic metre at 50° F. to 17 gm. at 70° F. in the former air supply and leads to the production of large water drops, whereas in clouds forming in air with temperatures below freezing the water vapour available never exceeds 5 gm. per cubic metre. While convection might be strong, this small amount of vapour prevents the formation of large water drops and tends more to the development of snow. These results are probably applicable to air masses in North America but as stated above most of the heavy deposits in cumulus, cumulonimbus and stratocumulus cloud in this country, occur in air which, at least at the surface, is of polar origin. Dight refers to this in an unpublished discussion of some of the Farnborough ascents, and makes the point that if a large mass of relatively damp air with a temperature above the freezing point is involved in the formation, or maintenance of, say cumulus clouds, then it is to be expected that such clouds would carry larger droplets than a similar cloud maintained by air masses with the same relative humidity, but having originally a temperature at or below the freezing point. There does seem to be a certain amount of justification for this in the results given for cumulus in Tables III and V.

The following account, of observations taken at Ben Nevis Observatory (West Scotland, 4,406 ft. above sea level), is composed of extracts taken from an article by Omond (9). " In ordinary weather the top of the hill is enveloped in drifting fog [cloud] and when the temperature of the air and ground is below freezing this fog deposits small crystalline particles of ice on every surface that obstructs its passage. These particles on a wall or large sloping surface . . . . combine to form long feathery crystals ; but on a post or similar small body they take a shape more like fir-cones with the point to windward. . . . . The rate of growth varies with the density of the fog and the speed of the wind . . . . about half an inch per hour may be taken as a rough average. . . . . If there is a damp feeling in the air, if in fact it is mist that is passing rather than fog, the crystals are icy and hard but when the temperature is well below freezing and the fog feels comparatively dry, they are looser in texture, seem when first formed to be attached by a mere point . . . . and are pretty easily knocked off. There is practically no limit to their growth ; last winter during a long continuance of strong south-easterly winds and cold weather, a post four inches square grew into a slab of snow some five feet broad and one feet thick in less than a week; the crystalline mass then fell off by its own weight and a new set began to form." A photograph of such a heavy formation is given in the observations (10).

A considerable amount of data bearing on this formation of ice on terrestrial objects if given in the published volumes of the Ben Nevis Observations. Two of these volumes (10), (11) covering the years 1884–92 were examined in order to ascertain whether they would assist in the elucidation of the ice problem. All cases of ice formation mentioned in the log books together with the corresponding temperatures, relative humidities, rainfall, cloud amounts and wind were abstracted. As readings of these elements were taken hourly the conditions prevailing during ice formation can be clearly traced. Some of these formations reached large proportions and seriously hampered the work of the Observatory and when one, not infrequently, reads of the Observer being let out from the building on a rope to prevent him from being blown off the top of the mountain, and that very few of the hourly readings were missed, one is filled with admiration for these early pioneers.

A summary of the results obtained is given in Table IB. In all cases of ice formation the mountain top was enveloped in cloud, but those cases where rain was reported as falling leading to glazed frost have been excluded from this table as they have been dealt with separately in the following section. It will at once be noticed that the temperature distribution is similar to that given by the aircraft ascents, viz. most of the ice formation occurred between 18° and 32° F. This fact is of importance, for on the one hand we have aircraft exploring different levels and temperatures of the atmosphere, and on the other the variations of temperature at a fixed level in a part of the British Isles not covered by the aircraft ascents, both leading to the same result. This optimum temperature range for ice formation in cloud has also been found in America (6) and Germany (5). No ice was reported at Ben Nevis at temperatures below 8° F.

Descriptions of the various types of formation refer to ice, opaque white or brown fog crystals or snow crystals forming out of fog. In Table IB. it has been assumed that ice refers to clear ice most of which appears to have formed between 28° and 32° F. whereas the opaque crystals are fairly evenly distributed throughout the range 13°–32° F. Smoke pollution appears to have been a problem even in the latter half of last century. The brown crystals had a sooty taste and as they only occurred with a wind from SW. through S. to E. it must be presumed that the pollution came from the industrial areas of the Scottish Lowlands. The above results are not altogether surprising when it is noted that most of the clear ice cases occurred with winds having a westerly component, and hence an air mass presumably warmer and moister than on the days of opaque ice formation when the winds had usually an easterly component. The question of water content is well brought out by the average amount collected in the rain-gauge, during periods of clear ice, 0·382 in., and opaque ice, 0·026 in. Unfortunately, there are no observations of size and number of water drops in clouds but the above figures do indicate that a plentiful supply of relatively large water drops leads to the clear type of ice formation.

Further facts which may be summarised briefly are :—

1. Relative Humidity.—In 89 per cent of the reports a saturated atmosphere was indicated either by the dry- and wet-bulb thermometers reading the same or the wet-bulb reading a few tenths of a degree above the dry-bulb thermometer. This was particularly noticeable with cases of clear ice. On the other hand a few of the opaque ice cases gave humidities of 85 to 99 per cent.

2. Dry, white, feathery, loose crystals.—These occurred at temperatures between 11° and 25° F., humidities of 100 per cent but not sufficient moisture to record in the rain-gauge.

3. Crystals from passing fog.—There are several reports in which ice formation occurred during fleeting passages of clouds across the top of the mountain, temperatures being 20°–30° F. and humidities 100 per cent.

4. White opaque crystals with clear ice on top.—Opaque crystals formed in cloud, temperature 24° F., humidity 100 per cent and rainfall ·001 in./hr., but when the rainfall increased to ·008–·123 in./hr. and temperature rose to 25°–30° F. hard clear ice formed on top of the crystals.

5. Clear ice from very wet mist.—Rainfall ·001–·013 in./hr., temperature 27°–31° F., humidity 100 per cent.

6. Fog became more damp.—Crystals became harder and more icy.

7. Rate of growth.—The largest growth of ice crystals reported was 100 in. in 59 hours or an average of just under 2 in. per hour. This occurred with a rainfall of ·01 in./hr., a temperature of 22°–25° F. and a wind strength of 80–100 m.p.h. It was an exceptional period owing to the high wind which at one period reached an estimated velocity of 100–120 m.p.h. and the crystals were blown off the Observatory tower and chimney as fast as they formed. With lighter winds the growth was more of the order ½–1 in. per hour. This led to an attempt to correlate the amount of ice formation (I) with the wind speed (v), the time (t) and the water content (w) of

the cloud according to the relation $I = k\,w\,v\,t$ where k is a constant. Using the total recorded rainfall as a measure of the water content, k was evaluated for eight different cases (Table VI). In six of these, the value of k is of the same order of magnitude and when arranged in ascending order of magnitude, k is seen to be inversely proportional to the water content w. This result is not surprising when it is realised that the total rainfall is only a very rough measure of the water content of the cloud. However, the results do tend to confirm the theory set out in the section on the freezing of water drops, that ice formation depends on the time in cloud or rain, the speed of the aircraft, and the water content of the cloud or rain.

TABLE VI

w	v	t	I	$k = \frac{I}{wvt}$	Temperature.
in.	m.p.h.	hrs.	in.		°F.
·798	20	20	22	·07	24–30
·16	85	59	100	·12	22–25
·1	21	13	3·5	·13	27–31
·08	96	11	30	·35	22–25
·041	45	48	36	·41	23–26
·091	30	40	48	·44	19–23
·014	61	1	1·5	1·8	24–28
·002	17	5	1	5·9	28–32

(*b*) *Fronts.*—All active fronts* can under favourable conditions give rise to rapid and heavy formations of ice. The conditions are that raindrops (which may or may not be supercooled) fall on to an aircraft flying in air at a temperature below the freezing point. Although the aircraft is usually flying in clear air below the rain-producing cloud, there are occasions in which the aircraft may be in a lower cloud layer. The type is comparatively rare in this country but more frequent in winter on the continent and North America. It usually occurs when the weather is turning milder after a sharp cold spell, i.e. with the advance of a warm front or occlusion of the warm front type. Ice formation is then chiefly confined to certain parts of the rain area, where the temperature is below the freezing point, in advance of the warm front, but the possibility of ice behind a warm occlusion where rain would still be falling cannot be ruled out, although in most cases in this country temperatures would be too high. On the other hand, there have been cases in the rain behind cold fronts or cold occlusions where cold polar or continental air is replacing warmer air. Rain also falls in advance of the cold occlusion and occasionally in advance of cold fronts so that again the possibility of ice in advance of these fronts cannot be ruled out if the temperature is favourable.

* For a description of fronts see Pick (12).

As examples of the two main types of fronts the following have been chosen :—

1. Warm Occlusion on December 21, 1929, moving east up the English Channel. Four aircraft were forced down about midday at Abbeville with $\frac{1}{2}$–1 in. of ice. Drizzle froze on the machines well in advance of the front (Fig. 1), which at 0700 was located running

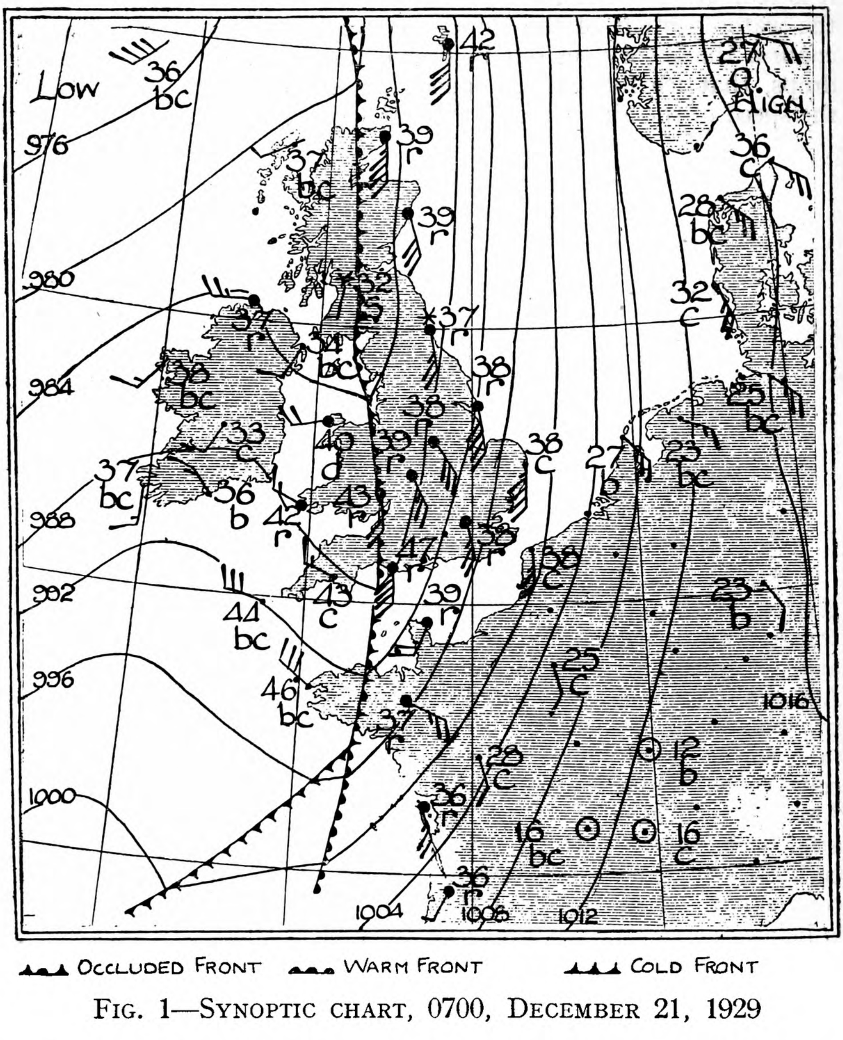

FIG. 1—SYNOPTIC CHART, 0700, DECEMBER 21, 1929

north–south from Liverpool to Bristol and east of Brest. Cold southerly continental air was being replaced by relatively warmer maritime polar air and the upper air ascent at Helder 0800 (Fig. 2) shows two inversions of temperature, one of 9° F. from 1,400 to 2,900 ft. and the other 2° F. from 3,600 to 4,800 ft. The dryness of the air above these inversions indicates that they were formed by subsidence in the cold continental air rather than by the over-running of warmer maritime polar air. Surface temperatures in north France were similar to those at Helder and assuming the same distribution of upper air temperature held, it appears that if the flights had been made at a height of 2,500–5,000 ft., where the temperature was

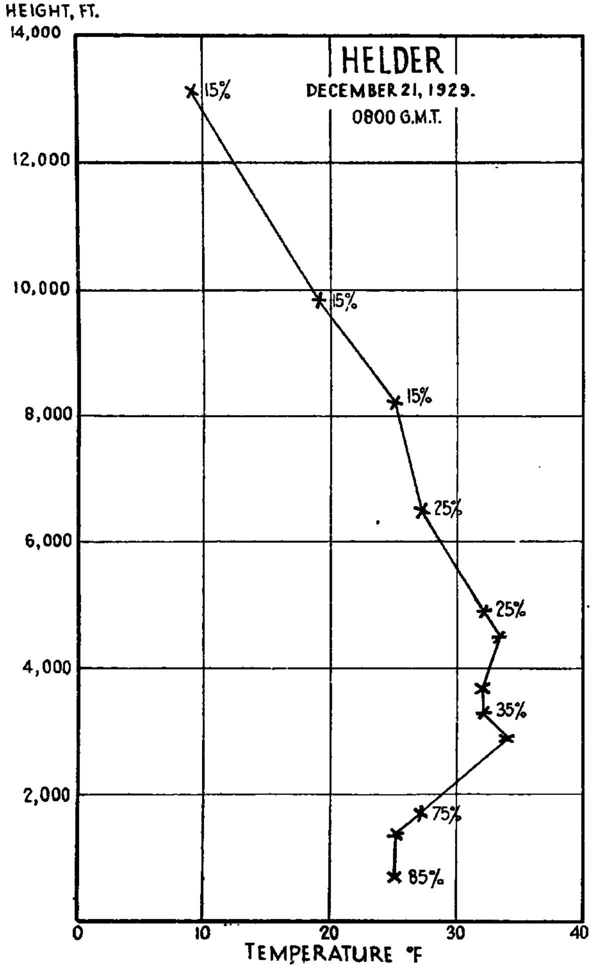

FIG. 2.

32°–34° F. rather than below the clouds which at midday were down to 800 ft. the chance of ice formation would have been far less.

A similar occasion in most respects to the above occurred on February 25, 1933, with the warm occlusion located at 0700 from Bristol to Bournemouth and Guernsey and moving slowly north-east. Ice formed at 900 ft. at 1100 G.M.T. The following readings indicate that warmer air would have been experienced at 1,500–2,000 ft.

Lympne 1200 G.M.T.			Paris 1000 G.M.T.	
Height	Direction.	Speed.	Height	Temperature.
ft.	°	m.p.h.	ft.	°F.
0	135	30	811	30
1,000	145	41	1,791	34
2,000	265	48	3,280	28
3,000	270	46	4,920	25
4,000	275	50		

The above cases were reported from Croydon. A report from another part of the country comes from Barton, Manchester. At 1225 G.M.T. on December 24, 1935, serious ice was experienced at 800 ft. from the Isle of Man to Liverpool and the aircraft had to descend to 200 ft. to keep free from ice. At 1300 G.M.T. two warm

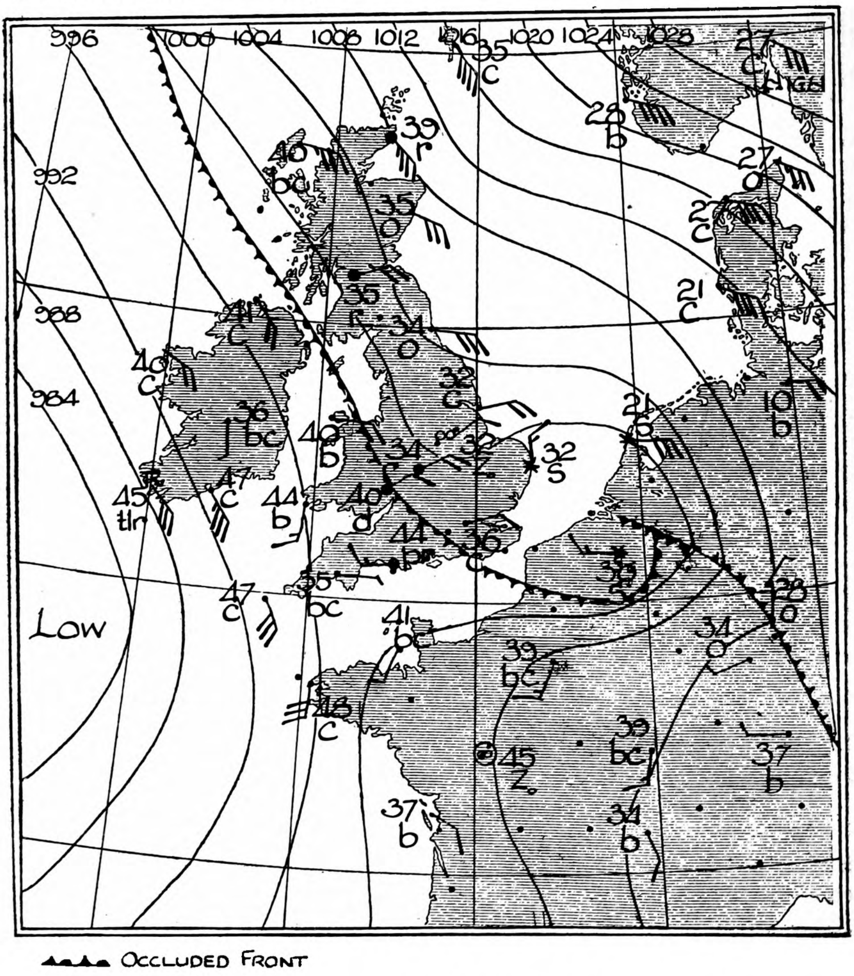

FIG. 3—SYNOPTIC CHART, 0700, JANUARY 26, 1937

occlusions were moving north, the first being located from Holyhead to Felixstowe and the second from Limerick to Aberystwyth, Bristol and Bournemouth. Again cold continental air was being replaced by warmer maritime polar air. Sleet or snow was falling along the route in advance of the first occlusion and surface temperatures were about 35° F. No upper air data are available but it is probable that the temperature at 800 ft. would be round about the freezing point.

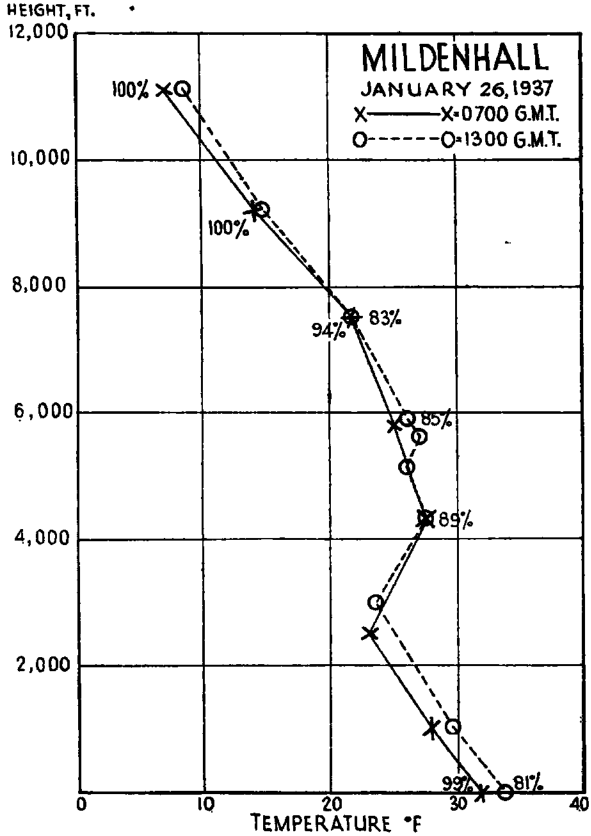

FIG. 4.

2. Cold front or cold occlusion.—R.S. Read gives an account (unpublished) of rapid ice formation on January 26, 1937. An aircraft left Croydon at 0930 G.M.T. for Liverpool and between Croydon and Halton at 1,200 to 1,500 ft. rapid ice formation in 10 minutes resulted in a loss of lift and the aircraft returned to Croydon. The ice was inspected on the ground there, and found to be clear with firm adherence and a rough corrugated surface. The flight took place in polar air of continental origin near and just behind a cold occlusion. At 0700 G.M.T. this extended from Beachy Head to Farnborough, Worcester and the Isle of Man and was moving slowly westwards over the Midlands (Fig. 3). The depth of the continental air at Mildenhall at 0700 G.M.T. was nearly 3,000 ft. (Fig. 4), but between Croydon and Halton, nearer the front, the

depth would be less. Rain and sleet was falling near and a little behind the front with surface temperatures 32° F.–36° F. It is important to note that on this occasion the temperature even in the relatively warmer air above 3,000 ft., did not rise above 27·5° F. Mildenhall reported heavy ice formation above 1,000 ft. with the lowest cloud layer extending from 800 to 2,800 ft., the next layer from 4,000 to 6,000 ft. and the upper layer, altostratus, from 14,000 to 20,000 ft. Although there is no definite information, it is probable that rain, sleet or snow was falling from the upper cloud layer, in which case ice formation would be expected at all heights at least up to 14,000 ft.

Ice formation due to sleet freezing on the aircraft at 400 ft. was also reported on the route Isle of Man to Liverpool at 0800 G.M.T. on February 21, 1936. The aircraft had to return to the Isle of Man. The flight was made just in the rear of a back-bent cold occlusion in which cold polar air with a more direct track from Arctic regions was replacing polar air which had had a long track over the Atlantic, Spain and north-west France. Rain or sleet was falling with surface temperatures about 36° F.

An example in which ice formation was experienced in a front passing over a mountain range occurred on the morning of December 12, 1936. At 0700 G.M.T. the front was located from St. Abbs Head to Sealand and Plymouth, i.e., approximately lying along the Pennines, and moving slowly eastwards. The front was complex, the upper air ascent at Mildenhall showing a rise of temperature up to 6,000 ft. from the 11th to 12th and a fall above this height. Surface phenomena exhibited warm occlusion characteristics with rain or sleet on both sides of the front where warmer maritime polar air was replacing colder continental air. Sleet or snow was prevalent over the high ground of the Pennines where temperatures were at or just below the freezing point. Several aircraft were forced down owing to heavy ice formation on the windward side of the high ground in the rear of the front.

3. Ben Nevis Observations.—The phenomena of glazed frost or silver thaw, i.e. rain falling with the air temperature below the freezing point and solidifying on contact, was of frequent occurrence at the Observatory, as might be expected from its altitude and geographical position, and an excellent summary of the prevailing conditions is given by Mossman (13). The polar front theory had not been developed at that time but there seems little doubt that a large number of the cases described were connected with the passage of both warm and cold fronts.

The lowest temperatures at which the phenomenon occurred was 18° F. It was of rare occurrence below 27° F. as the following table shows. Fully 90 per cent of the cases occurred between 28° F. and 31·9° F. and there are several reports of cessation as the temperature rose above 32° F.

TABLE VII.—NUMBER OF HOURS GLAZED FROST OCCURRED AT VARIOUS TEMPERATURES °F

Below 25°	25°–26°	26°–27°	27°–28°	28°–29°	29°–30°	30°–31°	31°–31·9°
7	8	19	56	86	150	229	298

The mean hourly rainfall during the occurrence was ·02 to ·03 in. and by comparison with the observations at Fort William it was found that the rainfall at the high level station was far in excess of that on the low ground. This shows the part played by the mountain range in producing upward currents, and so augmenting the supply of large water drops produced by the front. There were also reports of hail and sleet giving heavy coats of hard ice at temperatures, 26°–33° F., humidity 100 per cent and rainfall ·002–·133 in./hr.

(*c*) *Other conditions.*—A third condition leading to ice formation is, when an aircraft, flying in clear air at a low temperature, descends and enters a warmer more humid air layer either clear or associated with a cloud layer. Either water vapour (if the air is clear) or small drops of water (if a cloud layer is present) condense on the cold aircraft in the form of ice crystals. The deposit is usually very slight and can be removed by continued flight in air whose temperature is above the freezing point. The deposit may, however, become dangerous if the aircraft has an enclosed cockpit and a landing is being made through a thin layer of stratus cloud near ground level. The windows of the cockpit become covered with a thin layer of ice and it is necessary to open a side window to obtain a view of the aerodrome.

This leads to the question of landing and taking off in a ground fog whose temperature is at or below the freezing point. At Croydon it is of fairly common occurrence in winter for aircraft to get a thin coating of ice from the slipstreams when revving up in thick wet freezing fog and also when taking off. It has also been reported from Speke in dense fog at a temperature of about 25° F. The density of the fog is all important for there have been several cases of ground fog (sky discernible) with visibilities 400–1,000 yds., and temperatures 20°–30° F. at Renfrew when no ice formation was reported. Owing to the smallness of the drops comprising the normal ground fog it is not anticipated that any serious icing will occur. On the other hand, if the fog has a large vertical extent, usually caused by the mixing of different air currents, then the supercooled water drops might be larger and lead to heavier ice formation. Such a case occurred at Mildenhall on March 23, 1937, at 0730 G.M.T. when rapid ice formation was reported from the surface up to 1,600 ft.

There were no cases in the reports from aircraft of ice formation at temperatures just above the freezing point. Such reports have appeared from time to time in different publications and the usual explanation has been evaporative cooling of the water drops impinging on the aircraft. Experiments have shown, however, that at speeds exceeding 100 m.p.h. the thermometer tends to read up to 4° F. too high owing to dynamical heating due to the pressure of air on the thermometer. So this aspect must not be left out of account in considering these and other reports.

Frequency of ice deposits.—From the foregoing theories and practical results it would be expected that the formation of ice on aircraft would have a well-marked seasonal variation both as regards frequency and the heights at which it was experienced. As the level in the atmosphere at which the temperature falls to the freezing point is of supreme importance in this connexion it is relevant to reproduce the average monthly heights (12) for the British Isles (Table VIII) although it is well known that there may be large variations from this figure on any one day. It is only in recent months that all stations have co-operated in the preparation of statistics of ice formation so that it will be some time before a complete frequency table can be constructed which differentiates between heavy and slight ice formation. The only complete series available are those for glazed frost on Ben Nevis (13) and the average number of days during each month of the years 1885–90 are given in the fourth line of the table. These figures give the frequency of glazed frost formation at a height of 4,000 ft. in west Scotland and it is undoubtedly true that these frequencies would have been augmented had the occasions of ice formation in cloud (without visible rainfall) been included. However the seasonal variation is well marked, ice formation being at its maximum from November to March, when the freezing point level is on the average below 6,000 ft., and at its minimum from June to September when the level is above 8,000 ft.

TABLE VIII

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Average Height (ft.) of freezing point.	1,800	1,800	3,300	4,900	6,600	8,400	9,800	10,400	9,800	8,000	5,500	2,600
Average height (ft.) of ice formation.	3,200	3,800	4,100	4,300	6,900	6,400	10,500	—	6,100	5,900	4,600	4,300
Total Reports of ice formation 1932–6.	34	46	20	20	6	1	2	0	3	7	29	27
Glazed frost Frequency Ben Nevis.	6	5	5	2	2	1	0	0	1	2	5	5
Frequency Germany.*	16	15	7	13	9	3	6	7	5	11	18	23
Frequency America.*	26	25	22	15	11	2	0	0	0	12	12	25

* Frequency of ice formation of all kinds.

It is useful at this stage to give the seasonal distribution of all the reports of ice formation on aircraft reported during the years 1932–6 and to derive from them the average height at which ice was first noticed. These are reproduced in lines 2 and 3 of Table VIII. The reports refer only to ice formation in low clouds, i.e. a small number of medium cloud flights have been excluded, but frontal cases have been included. The seasonal variation is again well marked in both the average height of ice formation and in the frequency of reports received.

Similar distributions have been found in Germany (5) and America. The former figures (Table VIII) refer to the percentage number of occasions on which ice was reported out of 4,155 flights at four stations during the period 1930–3, and the latter to 150 observed cases of ice formation from four stations from July, 1931 to June, 1932.

Effects of ice formation.—These vary with the type of ice that forms. In ice-forming clouds the general effect is an accumulation on the forward edges of all exposed parts, e.g. on the boss of the propeller, on the leading edges of the propeller blades and of the wings, struts, bracing wires, etc. The smooth type of ice does not materially alter the aerodynamic shapes, but the added load may become a serious factor. The chief danger from this type is when the ice begins to break away from the aircraft in large pieces. These are liable to damage other parts of the machine, and when the propeller blades are affected the balance of the engine may be seriously altered. Alarming vibrations are also set up in the bracing wires. Pressure head orifices and venturis frequently become blocked causing either misleading, or a complete lack of, readings of the instruments connected to them. Also external controls may become jammed and aerials rendered useless.

In addition to the above, the rough type of ice, (usually clear) leads to a decrease of lift because of the altered wing curvature, and an increase of drag on account of the enlarged area of the wings, leading to dangerous stresses caused by the ill-distributed drag and unfaired surfaces.

Prevention and dispersion of ice deposits.—This subject falls under three main headings—(*a*) mechanical or chemical aids to prevent or disperse the ice whilst the aircraft maintains a level course through the ice forming zone, (*b*) alteration of altitude to avoid the ice zone or to clear deposits already formed, and (*c*) use of forecasts.

(*a*) *Thermal, mechanical or chemical aids.*—The following is a summary from Lockspeiser's (14) paper to which reference should be made for further details. In the thermal method the jacket or exhaust heat is used either directly or indirectly to maintain the temperature of the leading edges above 32° F., but the solution of the problem on these lines has not yet been found.

A mechanical method of dislodging ice appears to have given satisfactory results in America. A pulsatory movement is induced in a rubber overshoe, fitted over the leading edge along the whole length requiring protection, by the inflation of one or more rubber inner tubes. The rubber overshoe is treated with an oil mixture which, it is claimed, reduces the adhesion of ice. The regular pulsation of the overshoe by compressed air enables the ice to be broken up and blown away in the wind.

There is one certain way of reducing the adhesion of ice to a small value, i.e. by ensuring that the supercooled water mixes at the surface of contact with a substance which depresses the freezing point of water sufficiently to maintain a liquid boundary layer. Much work has been done on this aspect of the subject by the application of chemical dopes to leading edges. This forms the basis of Lockspeiser's work in which specially tanned leather along the leading edges forms an outer porous covering to which liquid (ethylene glycol) is fed continuously from the inside through a perforated rubber tube. Ice is either thawed quickly as it forms, or adheres in places and after a few minutes its adhesion is destroyed and the ice blown away. The method has passed service trials and appears so satisfactory that further developments are proceeding.

(*b*) *Navigational aids.*—From the observations given in the section on weather conditions favourable to ice formation it is clear that the technique of the prevention and dispersion of ice deposits (assuming no mechanical or chemical aids available) necessarily depends on the type of cloud in which ice is or is likely to be encountered. In the layer type of clouds stratus, stratocumulus or altocumulus which are not normally more than 3,000 ft. in vertical thickness, ice can be avoided by flying below or above the layer. The latter alternative would usually be taken in the case of stratus which has a low cloud base and in all cases where high ground in cloud lies along the route. In particular, stratocumulus is nearly always surmounted by an inversion of temperature which frequently causes air temperatures to be above the freezing point, so that any ice collected in traversing the layer is rapidly dissipated above the cloud. In those cases where the temperature does not rise above the freezing point but the relative humidity is low, the ice gradually evaporates. There have been cases where the ice has remained on the aircraft for 30–60 minutes above the stratocumulus, but the important point is that the accretion stops soon after the aircraft emerges above the cloud layer. Ice can also be dispersed by flying at a level below the cloud where the temperature is above the freezing point, but if temperatures are everywhere below the freezing point down to ground level there is less likelihood of the ice evaporating below the cloud, where the relative humidity would normally be higher, than in the clear air above the cloud.

In the case of the clouds nimbostratus and altostratus the pilot is confronted with a layer usually several thousands of feet in thickness. These clouds are associated with the passage of fronts (see the section on fronts) and the avoiding of the ice zone will depend on the movement of the front relative to the track of the aircraft and also to the activity of the front. In an active front the ice zone may be said to extend from the region below the clouds where rain or sleet is falling at a temperature of 32° F. up into the cloud until the temperature has fallen to about 10° F. Statistics (Table IA) indicate that in this country there is little chance of serious ice above the 10° F. level. So there are again two alternatives, either an ascent in the cloud to the 10° F. level or a descent through the rain region to a level where the temperature is above the freezing point. In practice, however, it may be impossible owing to the accumulation of ice to reach the former level and if in addition the lower level extends below the level of any high ground that has to be traversed, or extends down to sea level as it frequently does on the continent in winter, there appears no alternative but to land at the nearest aerodrome, or return to the point of departure if this has not in the meantime been similarly affected. On some occasions the relatively warmer air, in which these clouds are forming, has a layer with a temperature just above the freezing point and the flight can then be continued in this layer with no further ice formation. A good example of this is given by Noth and Polte (2) and another in the section on fronts of this paper. If the front is not active, and no rain is falling, the flight can be made below the altostratus or nimbostratus provided the nimbostratus which frequently lowers to 2,000 ft. does not envelope any high ground along the route. The production of rain due to forced convection on the windward side of any high ground being traversed by a front must also be kept in mind if temperatures are low enough to lead to ice formation. Fortunately, altostratus cloud does not usually give rise to ice formation in this country so that if the flight is being made at some distance from the active part of the front it can usually be continued, if need be, in this type of cloud.

The towering clouds cumulus and cumulonimbus can usually be avoided by slight deviations of track when the clouds are isolated. There are, however, occasions particularly in fresh polar air during the afternoon and early evening in which the individual clouds amalgamate to form a fairly solid mass both horizontally and vertically. This also occurs at the cold front, as explained in the section on fronts, and in thunderstorms. Avoidance of the ice-forming region then consists in either a flight below the cloud or in the cloud base if the temperature is above the freezing point. The available statistics indicate that owing to the upward diffusion of water drops by strong vertical currents, no part of these clouds where the temperature is below the freezing point can be considered to give immunity from ice formation. It is, however, probable that above

8,000 ft. the cloud would not be solid horizontally but would consist of numerous but isolated cloud peaks. The possibility of glazed frost formation in rain or sleet beneath the shower clouds cumulonimbus must also be kept in mind if a flight is being made in clear air at a temperature below the freezing point. In this case, it is usually possible in the British Isles to descend to a level where the temperature is above the freezing point. The worst case is where a line of cumulus or cumulonimbus either convectional, or associated with a cold front with temperatures everywhere below 32° F., lies along an extensive mountain range which has to be crossed. Here, the only possibility of avoiding ice formation, if the flight is to be continued, is to climb to an altitude where only the cloud peaks have to be encountered. This would mean an altitude of at least 7,000 ft. in this country but with a range like the Alps might well entail an altitude of 20,000 ft. or higher.

From the above considerations it appears essential that every pilot should have a good working knowledge of clouds and fronts and their characteristics so that they can use that knowledge to avoid the ice forming regions.

(*c*) *Use of forecasts.*—The weather forecaster is usually in a position to give considerable assistance to the pilot in determining the probable ice-forming zones. In this connexion two situations arise (*a*) upper-air temperatures available from one or more localities (*b*) no upper-air temperatures available. In the former case, the heights at which the temperature reads 32° and 10° F. respectively can be directly read from the upper air temperature curve and if the general forecast predicts clouds between these levels then the possibility of ice formation is also present. In the second case, an estimate will have to be made of the above-mentioned heights commencing with surface level temperatures which have not been lowered by night radiation and assuming a lapse rate of 1° F. per 300 ft. If there has been no change of air mass a judicial use can be made of the previous day's upper air temperatures. Or again, in a change to a new air mass a previous ascent in the new air mass will be of assistance. In utilising the above levels it must be remembered that the frequency of ice formation in altostratus cloud is small, but on the other hand ice may be expected in the tops of cumulus and particularly cumulonimbus at temperatures below 10° F. if the clouds are expected to extend beyond that level.

The above methods can also be applied to the passage of fronts (rain belts). In particular the region where rain is falling at temperatures below the freezing point can usually be specified, and, if upper air temperatures are available, a statement made if there is any part of the frontal zone above the ice-forming region where the temperature rises above the freezing point.

For correct forecasts of heavy ice deposits the forecaster requires to know the number and relative size of supercooled drops in the particular cloud formations expected on any day. Under the appropriate frontal conditions and in the case of cumulonimbus cloud a forecast of heavy ice can be given, but with the other cloud types all that can be done in the present state of our knowledge is to indicate the regions (defined above) where ice formation is expected, without a specification of its intensity.

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