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ICE ACCRETION ON AIRCRAFT

Notes for Pilots

[Revised 1942]

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ICE ACCRETION ON AIRCRAFT

Notes for Pilots

By G. C. Simpson, K.C.B., F.R.S.

The Physics of Ice Accretion.—Clouds consist of particles of water in either the solid or liquid state. In the solid state they are small crystals of ice in the form of flat hexagonal plates, like stars, or of long thin hexagonal rods. The size of these crystals varies greatly, and they are generally so small that they cannot be seen individually by the naked eye ; but under favourable conditions they may grow until the plates are as much as an eighth of an inch in diameter, and the rods of a similar length.

Generally speaking, the size depends on the temperature in which they are formed, the larger sizes being found only when the temperature is just below the freezing point. At low temperatures the crystals occur singly and there is little in a cloud of small ice crystals by which a pilot can distinguish it from an ordinary cloud of water drops. At higher temperatures when the crystals are larger their branches become entangled and snow flakes are formed. Each snow flake consists of a number of ice crystals, and with care a dry snow flake can be separated into its constituent crystals.

Cloud particles in the liquid state are always spheres, and they vary in size from nuclei of ultra-microscopic dimensions to raindrops having a diameter of a fifth of an inch, which is the largest drop of water which can hold itself together as it falls through the air.

On first thoughts one would expect that clouds would consist of ice particles when the temperature is below the freezing point and of water when it is above the freezing point. Unfortunately no such simple rule holds good. Water in the form of liquid drops can exist for an indefinite time in an atmosphere many degrees below the freezing point. As the drops must have the same temperature as the air surrounding them we have the apparent paradox of a liquid at a temperature far below its freezing point. This, however, is a condition often met with in nature and such a liquid is said to be supercooled. A supercooled liquid is, however, in an unstable state and it needs little inducement to cause it to take up the solid state appropriate to its temperature. No supercooled drop of water could survive being broken up without the formation of ice, and it is only necessary for supercooled water to be touched with a particle of ice to induce freezing. There again we meet with an unexpected fact. If a supercooled drop is induced to freeze it does not usually turn completely into ice ; only a fraction of the water goes into the solid state, the remainder retaining the liquid state. This is due to the fact that when water turns into ice it releases a relatively large amount of heat which becomes available for raising its temperature. Laboratory experiments have shown that when a drop of water freezes, it releases sufficient heat to raise its temperature through 144° F. Suppose that we have a supercooled water drop at a temperature of —112° F. and induce it to change into ice. Sufficient heat is released to raise its temperature by 144° F. ; thus, after turning into ice the whole drop is at a temperature of 32° F., that is at its freezing point. Now take another supercooled drop at a temperature of —40° F. and induce it to change into ice. When half the drop has frozen sufficient heat will have been released to raise the temperature of the whole drop by 72° F. ; that is, the temperature of the drop at that stage will be $-40 + 72 = 32°$ F., again the freezing point. It is clear that at this stage the freezing must cease for any further freezing would release heat which would only melt the ice already formed. In other words, only 1/144th part of a supercooled water drop will freeze for each degree Fahrenheit its temperature is below the freezing point.

This solidification of a portion of a supercooled drop, with the raising of the temperature of the whole to the freezing point, takes place every time an aeroplane strikes a cloud particle when flying through a water cloud at a temperature below the freezing point ; but this is not the whole story.

To fix our ideas let us imagine an aeroplane flying through a cloud when the temperature is 28° F., that is 4° F. below the freezing point. A drop strikes the leading edge of the wing, it is disrupted, freezing starts and 4/144th part immediately turns into ice and the remaining 140/144th part becomes water at the freezing point. This water, however, cannot remain liquid long, because it is in contact with the cold material of the wing which is at the temperature of the air, and also it is in a stream of air four degrees below the freezing point ; hence, unless it is blown off it soon freezes and ice equivalent to the mass of the drop is attached to the wing.

Here we have an explanation of the different forms in which ice accretion appears on an aircraft. If the temperature is very low and the drops are small the amount of liquid from each drop is so small that it cannot spread, but immediately freezes just where it strikes. In other words, each cloud particle becomes an ice particle attached to the wing. These ice particles remain individuals and a large amount of air is imprisoned between them. The ice accumulation is, therefore, of a light texture and grows out towards the air stream. The mechanical impact of the air, however, tends to consolidate the accumulated ice, and the result is an ice accretion confined to the leading edge of wings and struts which has a white opaque appearance and can easily be shaken off. It is really rime (which is formed in exactly the same way) but compressed by the impact of the air.

If the temperature is relatively high and the drops are large, the amount of water which remains unfrozen on impact is large and tends to spread over the wing ; if at the same time the drops are abundant the water from neighbouring drops unites and the leading part of the wing becomes wet. The air stream causes this water to flow back over the wing, freezing as it flows. Cases are on record in which, during ice accretion in dense clouds, water has been observed to stream off the wing. The ice in this case is formed on the wing from a sheet of liquid water and therefore has the transparent glassy appearance of ordinary ice. Clearly ice formed in this way is tough and sticks closely to the fabric of the aircraft ; it cannot easily be shaken off, and if it breaks off at all it comes away in lumps of an appreciable and sometimes dangerous size.

A form of ice accretion, similar to that just described but much more heavy and dangerous, occurs when the source of the water is rain instead of supercooled cloud particles. Temperature does not always decrease as one ascends in the atmosphere, but on occasions there is a layer of warm air with temperatures above the freezing point overlying a layer in which the temperature is well below the freezing point. Precipitation which falls from the warm layer will be in the form of rain and when this enters the cold layer it will not freeze immediately. An aircraft flying through the cold lower layer will become wet from the rain and the water will freeze owing to the low temperature of the air. Great masses of clear glassy ice will form on all parts of the aircraft, the weight of which may force it down in a very short time. This form of ice accretion is called "glazed frost" in this country and "glaze" in America.

The three forms of ice accretion which we have just considered have all required the presence of water already precipitated into either cloud particles or raindrops. There is a fourth form of ice accretion which may occur in clear air due to the formation of ice on the aircraft directly from the water vapour in the atmosphere. This occurs only when the aircraft, after remaining sufficiently long in a cold region of the atmosphere to take up the low temperature, rapidly moves into a warm damp layer. In this case the temperature of the surface of the aircraft may well be below the dew point of the damp air and also below the freezing point. In consequence, water vapour is condensed directly as ice on to the surface of the aircraft. The method of formation is similar to the formation of hoar frost on grass and shrubs during a clear frosty night, and the ice accretion on the aircraft has the white semicrystalline appearance of hoar frost. Usually this form of ice accretion is not serious, but cases are on record in which aircraft, descending from great heights where the temperature was very low into a layer of damp air or even altostratus clouds, have encountered fairly rapid accretion where none was experienced during the ascent. This has been sufficient to cover the R/T aerial and thereby cause it to alter its capacity with consequent loss of communication and D/F facilities.

The four main types of ice accretion may be summarised as follows in order of increasing danger :—

(*a*) A white semicrystalline coating of ice which covers the surface of the aircraft. It may form in clear air when a cold aircraft enters warmer and damper air during a rapid descent. It has little effect on the flying of the aircraft, but may obscure vision if it forms on the wind screen and interfere with radio communication by coating the aerial with ice.

Surface equivalent : hoar frost.

(*b*) A light white opaque deposit of ice which accumulates on the leading edges of wings, struts and wires of an aircraft. It forms when flying in filmy clouds consisting of small supercooled cloud particles and generally at low temperatures. The deposit has not great weight ; but its danger lies in an alteration of the aerodynamic characteristic of the wings and in the choking of the orifices of the carburettor and flying instruments.

Surface equivalent : rime.

(*c*) A transparent or translucent coating of ice which has a glassy surface appearance. It forms within dense cloud consisting of large cloud particles and generally at temperatures near the freezing point. Its danger is due to the weight of the accumulation and to vibration set up by the unequal loading of wings, struts and especially the blades of the propellers. When appreciable blocks of ice break off the vibration may become so intense that there is danger of fracture of the aeroplane structure.

Surface equivalent : intermediate between rime and glazed frost.

(*d*) A heavy coating of clear ice which forms all over an aircraft when rain falls on it from a warm upper layer while it is flying in a layer with temperature below the freezing point. The danger is great owing to the weight of the large mass of ice which may accumulate in a short time.

Surface equivalent : glazed frost.

The Meteorology of Ice Accretion.—The physics of ice accretion show that for ice accumulation to become dangerous it is necessary that there should be an abundance of water in the liquid state at air temperatures below the freezing point. These conditions are met with only in clouds or in rain, and the meteorology of ice accretion is mainly concerned with the formation of clouds, the formation of precipitation and the temperature.

The Formation of Clouds.—Cloud is always formed by the cooling of air below the dew point, that is below the temperature at which the air is saturated. At higher temperatures the water is present in the form of invisible vapour. Atmospheric air contains a large number of " condensation nuclei ". When the temperature of the air approaches the saturation point these nuclei attract water molecules and commence to grow in size. After saturation has been reached all the water condensed out of the air in consequence of further lowering of the temperature goes to increase the size of the drops formed around the nuclei. The cooling of the air which leads to condensation is normally due to ascending currents, for air cools by expansion as it rises. As soon as the air rises to the height where it reaches its saturation point cloud particles are formed on the nuclei as already described. In still air these would fall; but in general the air is rising at a greater rate than that at which the particles would fall in still air; they would therefore be carried upwards, growing in size all the time. An ascending current is therefore of considerable importance for ice accretion; it supplies the vapour which is condensed into water and carries the water particles thus formed upwards into cold regions where they become supercooled. The greater the velocity of the upward current, whether formed by warm air ascending or by the forcing upwards of air streams where they impinge on rising ground, the greater the accumulation of water in the cloud, and the greater the probability that the cloud particles will consist of supercooled water drops.

Precipitation.—A cloud of any great thickness may be divided into three parts. In the upper part where the temperature is well below 0° F. (−18° C.), the cloud will be entirely ice, the cloud particles themselves consisting of minute ice crystals; in the middle part with temperature between 0° F. (−18° C.) and 32° F. (0° C.), the cloud may consist of either ice crystals or water particles or a mixture of both; in the lower part where the temperature is above 32° F., the cloud particles are water.

Precipitation, i.e. snow, sleet or rain, normally starts in the middle layers as snow, the individual ice crystals becoming interlocked into snow flakes which fall more rapidly than the ascending current of air can drive them up. When the snow descends into regions where the temperature is above the freezing point the snow flakes first partially melt, giving rise to sleet, and finally melt completely into raindrops. There is reason to believe that all appreciable rain, other than drizzle, is formed in this way.

In the upper part of the cloud ice accretion cannot occur for the ice crystals are dry, and if they strike the aircraft they fall away again; like any other kind of dry dust. If there is only dry snow in the middle part of the cloud, there will be little or no ice accretion for the snow which strikes the aircraft is quickly shaken off. It is, however, in this part of the cloud that supercooled cloud particles occur, and all the typical forms of ice accretion which have been described above may be encountered. In the lower part of the cloud ice accretion can only occur if there is sleet; for sleet, being of a sticky nature, adheres to aircraft and quite appreciable accumulation may be collected.

Temperature.—The part played by temperature in the process of ice accretion is primarily that of determining whether or not ice will form. If there are water drops present ice will be formed when they strike the aircraft whatever the temperature may be so long as it is below the freezing point. The temperature, however, plays an indirect rôle because generally speaking the temperature determines the amount of water present.

The total amount of water vapour which air can contain is strictly limited by the temperature, and, when condensation takes place in a mass of air, the amount of water deposited as cloud particles for a given fall of temperature is the greater the higher the temperature. Thus clouds formed in the cold air of the upper atmosphere are less dense than the clouds formed in the warmer air of the lower strata. We should therefore expect for this reason alone that ice accretion would be less the lower the temperature. This is borne out by actual experience, for 217 records of ice formation on aircraft in England during 1932–7 were distributed as regards temperature as shown in the following table* :—

Temperature	Above 32° F. (0°C.)	32° to 28° F. (0° to −2°C.)	27° to 23° F. (−3° to −5°C.)	22° to 18° F. (−6° to −7°C.)	17° to 13° F. (−8° to −10° C.)	12° to 8° F. (−11° to −13° C.)	7° to 3° F. (−14° to −16° C.)	2° to −2° F. (−17° to (−19° C.)	Below −2° F. (−19° C.)	Total
Occurrence of ice formation	0	56	78	43	13	15	3	4	5	217

The numbers in this table have no very strict meaning, for the number of flights within each group of temperatures was not the same ; but it does show clearly that ice formation is more frequently met with in this country at temperatures just below the freezing point than at temperatures much lower. Temperatures between 32° F. (0° C.) and 23° F. (−5° C.) account for more than half the occasions of ice accretion in this country, and a similar result is found in other countries also. At lower temperatures the frequency falls off rapidly and practically ceases at 0° F. (−18° C.). In other investigations occasional occurrences of icing at temperatures one or two degrees above the freezing point have been reported and generally ascribed to the lowering of the temperature of the deposited water due to rapid evaporation (wet-bulb effect). Ice accretion can also take place at temperatures slightly above the freezing point when sleet is encountered. Thus while, generally speaking, the freezing point is the temperature at which ice accretion ceases, one must be prepared to meet it occasionally at temperatures one or two degrees higher.

Annual Variation of Ice Accretion.—In order to exhibit the variations of the frequency of ice accretion from month to month the following table has been prepared based on the reports referred to above :—

Table I.—Annual Variation of Ice Accretion

	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

The bottom line of this table shows that in this country in 1932–6 there was very little ice accretion reported during the summer months—June to September—while the months of greatest accretion were January and February.

* Ice formation in clouds in Great Britain. By W. H. Bigg, B.Sc., *Prof. Notes, met. Off., London, No.* 81, 1937.

The reason for this is clearly seen when one examines the first line which gives the average height at which the freezing point occurs in the different months. The greater part of the flying in this country was carried out at heights between 2,000 and 5,000 ft.; hence during the summer relatively few planes flew at a height where the temperature was below the freezing point, thus accounting for the absence of reports during the period June to September. In December, January and February the height at which freezing occurs is well below the height at which aeroplanes normally flew, hence the reports during that season were relatively numerous. In the second line is given the average height at which ice formation was first noticed; this line of figures, however, is misleading if one uses it to find the height at which ice accretion is most likely to be met with. In January and February the average height of the freezing point is 1,800 ft.; but the average height at which ice accretion was observed was between 3,200 and 3,800 ft. This is not because ice accretion is most likely to be met with at that height, but chiefly because the majority of the aircraft were flying at that height. If there had been an equal number of aircraft at all heights the most frequent layer of ice accretion would have been lower than that actually recorded. For practical purposes the first line gives the most valuable idea of the height at which ice accretion is likely to be met with at different seasons, as ice accretion is predominatingly confined to the 5,000 ft. or so above the height at which the freezing point occurs.

The result of this investigation is just what one would expect, both on theoretical grounds and on the results of experience. Ice accretion was most frequently met with in the winter, first because there is then more cloud and bad weather, and secondly because the temperature, at the height at which flying took place, is round about the freezing point, which is the temperature at which ice accretion is the most frequent and the most dangerous. During the summer there is less cloud, and the freezing point is not reached much below 8,000 or 9,000 ft.; for both these reasons aircraft seldom became involved in ice accretion during the summer months. (Wartime flying has greatly altered the situation with regard to ice accretion in summer. At heights between 10,000 and 15,000 ft. and occasionally even higher, the temperatures in summer are favourable for ice accretion, whereas in winter they are generally too low. Some of the meteorological situations likely to produce heavy icing high up are referred to on p. 10.)

General Rules for Avoiding the Dangers of Ice Accretion.—When ice accretion is observed in flight there is one and only one method of escaping its dangers, and that is to get out of the ice-forming layer at the first possible moment.

For all practical purposes, except in cumulonimbus cloud, the ice-forming layer is limited to the temperatures between 32° F. (0° C.) and 8° F. (−13° C.). Unfortunately these temperatures represent normally a height difference of 7,000 ft., and it is not always possible for an aircraft to climb this distance, especially if its climbing qualities have already been affected by ice accumulation. Still it is not always necessary to climb the full amount for the ice accretion ends with the cloud, so that, if the upper surface of the cloud is known to be within reach, one way of escape is to ascend into the clear air above the cloud where further ice accretion will cease and the ice already formed will evaporate or shake off.

The alternative is to descend to where the temperature is above the freezing point, and this is the most usual procedure in this country, for during periods of heavy cloud and precipitation even in winter the temperature at the ground is usually well above the freezing point, and there is on most occasions sufficient room for flight below the clouds.

If, however, the cloud is down on the hill tops, or the visibility is bad beneath the cloud owing to mist or precipitation, there is no alternative to rising upwards in the hope that the ice accretion will decrease with lower temperatures or the top of the cloud will soon be reached.

In the winter another dangerous condition may arise in which it is rarely safe to descend. This occurs when glazed frost is observed to be forming, caused by raindrops falling on to the plane and freezing there. Luckily this form of ice accretion does not often occur in this country; but when it does, it is always due to a warm air current, in which the rain forms, mounting upwards over a layer of cold air, the temperature of which is below the freezing point. In these circumstances there are three courses open to the pilot: (*a*) Immediately to turn back, (*b*) to climb quickly into the warmer air from which the rain is falling, (*c*) to fly at a lower level if it is certain that there is a region from general ground level to at least 1,000 ft. above the highest ground in the area in which the air temperature is above 32° F. (0° C.).

One of the greatest difficulties which face a pilot when he meets with ice accumulation is to decide what to do. Ice accretion varies greatly in intensity, from a light deposit which can do no damage to a heavy deposit which makes the aircraft unmanageable in a very few minutes. Ice accretion may be met with in a climb and quickly left behind; on the other hand, if the aircraft is in level flight quite a small rate of ice accretion may produce in course of time dangerous accumulations. Experience and common sense are the best guides as to what action should be taken; but the following points might be made:—

(*a*) The lower the temperature and the thinner the cloud the less the danger of large accumulation of ice, and the more time required for the accumulation to build up.

(*b*) If the cloud is dense and clear ice is observed to be forming the danger is great, and no time should be lost in seeking security. The danger is greatest when ice is observed to be forming at the same time that rain, sleet or snow is falling.

(*c*) If the reserve power of the aircraft is great escape is best attempted upwards, unless it is definitely known that good conditions exist below.

(*d*) If the aircraft is heavily loaded and has little reserve power, an ice-free region should be sought at lower altitudes as soon as ice accretion, no matter how small, is observed, except when the icing is of the glazed frost type (see above).

(*e*) If action is taken quickly the reciprocal course is often the wisest.

If it is known or suspected that ice accretion may be encountered on a flight—and its possibility should always be borne in mind during the winter months—a meteorologist should be consulted and if possible a synoptic chart examined. From the synoptic chart the regions of activity along a front can be seen and their motion determined. Regions where the wind impinges on high land, so causing increased danger, can be marked out. The meteorologist will be able to calculate the height of the layer in which the freezing point occurs, and compare it with the height of the cloud base and the height of the hills. Unfortunately a meteorologist can seldom estimate the top of the cloud layer; but on some occasions even this may be possible. With this information the pilot will be in a position to choose the route to take, to consider alternative routes if the one he has chosen proves impracticable, and he will be prepared to decide quickly whether to ascend or descend when ice-forming conditions are experienced. If before starting the pilot decides to rise above the clouds if he meets ice accretion, it would be best to lay the course above the clouds from the start.

The thermometer should be watched when flying in, or about to fly in, clouds or rain. The most dangerous temperatures for icing are between 32° F. (0° C.) and 19° F. (−7° C.), but it may occur at temperatures as low as 0° F. (−18° C.) in cumulonimbus clouds. If the reading is in the danger zone, look for signs of ice on the windscreen, or falling airspeed. If these signs occur look at the leading edge of the wing, using a torch at night.

Situations in which Ice Accretion may be Encountered.—*High Flights.*—If flights are made at heights where the temperature is below about 12° F. (−11° C.), the clouds will be cirrus, altocumulus, altostratus or cumulonimbus. We know that cirrus clouds consist of ice crystals and therefore ice accretion cannot occur in them. Altocumulus and altostratus clouds are known, from the colours they show in the neighbourhood of the sun and moon, often to consist of supercooled water particles and there are records of ice accretion occurring in them. These clouds are, however, thin and cannot contain much water, therefore the ice accretion is not likely to be heavy. Prolonged stay in the clouds might produce appreciable accretions, but there are no records of heavy accumulation in either altostratus or altocumulus clouds.

The case of high flights in cumulonimbus clouds will be considered later.

Flight across a Warm Front.—A warm front is associated with a very extensive, almost horizontal layer of cloud. The base of the cloud is low near the front where there is usually steady rain in summer and snow or sleet in winter. Ahead of the front the base of the cloud becomes higher, and the whole cloud sheet thins out slowly into a layer of altostratus or cirrostratus cloud as one recedes from the front.

The main cloud sheet near the front is very thick, extending from a few hundred feet above the surface to a height of at least five or six thousand feet, and often to a height well above ten thousand feet. The cloud sheet near the front, as seen from the ground, has apparently a level base and is dark in appearance owing to the great thickness of the cloud; it is called nimbostratus. At all times of the year the top of this prefrontal cloud layer is in the region of the atmosphere where the temperature is below the freezing point. Hence there is a layer in the cloud in which ice accretion may, but does not always, occur.

The circumstances in which ice accretion occurs at fronts are not known; but experience has shown that ice accretion is most likely where the front is "active," i.e. where precipitation is falling.

As it is at warm fronts that warm air mounts over cold air the conditions are particularly favourable there for the formation of glazed frost. An aircraft flying through the precipitation at a warm front in the winter with surface temperatures at or near the freezing point may encounter very dangerous conditions.

High land near to a front is particularly dangerous for two reasons. In the first place, the base of the cloud may be lower than the hills, and secondly, the air is forced to rise and so the accumulation of liquid precipitation is increased, thus making ice accretion, if it occurs, much more rapid and heavy. Some of the worst disasters due to ice accretion have occurred in the cloud system accompanying a front where it passes over high ground.

In the summer there is little danger in crossing a warm front because the layer with temperatures below the freezing point is sufficiently high to leave plenty of room below it for navigation.

In the winter also there is usually room to navigate an aircraft under the cloud at a warm front, or to keep within the region where the temperature is higher than the freezing point if the cloud has to be entered. But if the temperature at the surface is below 40° F. (4° C.), the possibility of being forced to fly in a cloud in which ice accretion will occur and the especial danger of high ground must always be borne in mind.

The conditions at an occluded front are so similar to those at a warm front that it is not necessary to treat them separately. On the whole the main cloud layer at an occluded front is higher than near a warm front ; but the weather there is frequently very " dirty " and rapid ice accretion may occur.

Flight across a Cold Front.—At a cold front there is not usually an extensive unbroken layer of clouds. The clouds are generally of a broken nature and if they have to be entered they are soon left again. The clouds are, however, of the convection type with strong ascending currents which will carry cloud particles in the liquid state far into regions where the temperature is below the freezing point. Also the clouds originating in polar air behind the cold front are on the average at a lower temperature, so that the ice accretion layer is nearer the surface than at the warm front.

Flight through Cumulus and Cumulonimbus Clouds.—Owing to the frequency with which cumulus clouds occur in this country, ice accretion is more frequently met with in these clouds than in the nimbostratus clouds associated with warm fronts and occlusions. When cumulus clouds develop into cumulonimbus clouds (the thunder cloud), the ice accretion becomes much more serious, extends through a greater thickness of cloud and occurs at the lowest temperatures.

The reason for this is not difficult to understand. A cumulus cloud makes visible an ascending current of warm air which is pushing its way upwards through the surrounding cooler air. The air enters the cloud at its base, then rises almost vertically with a velocity which may be only small when the cloud first forms but becomes very large as the cumulus cloud develops into a cumulonimbus cloud. When the ascending currents become very violent, as in a thunderstorm, vast quantities of liquid cloud particles are carried far up in the atmosphere to very low temperatures, thus providing the most favourable conditions for heavy ice accretion.

The reports of ice accretion experienced by aircraft in these clouds bear out this conclusion. Out of 36 cases of ice accretion in cumulus clouds six of them were " heavy," while of 24 cases in cumulonimbus clouds as many as 10 were " heavy " and four occurred at temperatures below 3° F. (−16° C.).

Normally cumulus clouds are of limited extent, and there should be little difficulty for an aircraft flying through cumulus clouds and noting ice accumulation to get out of the cloud. Also ice accumulation seldom occurs in a cumulus cloud below 5,000 ft., so that there is plenty of room to get below the ice-forming layer. In cumulonimbus clouds ice accretion occurs still higher. A pilot does not readily enter a cumulonimbus cloud because of the danger from lightning and violent ascending currents. Ice accretion adds one more to these dangers so that aviators are well advised to keep clear of cumulonimbus clouds if possible.

Frontal Cumulonimbus and high-level Cumulonimbus.—Cumulonimbus clouds sometimes amalgamate along fronts to form a belt possibly hundreds of miles long and in extreme cases some scores of miles wide. Generally speaking an increase of the width of the belt is accompanied by a decrease in the intensity of the convection, but icing may remain rather heavy for a considerable period.

In some cases the instability develops above 10,000 ft. and the cumulonimbus towers up from a continuous layer of clouds. In some part of the layer there may be unbroken clouds with strong rising currents in the middle of them, causing heavy icing. This condition is more dangerous than that associated with isolated cumulonimbus clouds, which can be seen either in daylight or in bright moonlight. The instability above 10,000 ft. may cause actual thunder and lightning, but more frequently there are merely local intensifications of the rising currents and increased icing. In summer and autumn, and to a less extent at other seasons, upper instability can occur in the warm-front cloud systems, and though as a rule the rising currents are less violent than at cold fronts, the clouds are much more extensive. Upper instability is a frequent cause of heavy icing in summer at levels between 10,000 and 15,000 ft., and occasionally even up to 20,000 ft. The heaviness of the rain at ground level generally gives a good indication of the degree of icing to be expected, but it must be remembered that if the precipitation is produced entirely at a high level, and if there is dry air below, a considerable amount of the precipitation may evaporate before reaching the ground.

In very strong upward currents it is possible to experience heavy icing even at temperatures below 0° F. (−18° C.).

Flight through a layer of Stratocumulus Cloud.—Ice accretion in this country is met with more frequently in stratocumulus clouds than in all other types of cloud put together. Of the 217 cases reported during 1932–7, 124 of them occurred in stratocumulus clouds. One reason for this is that during the winter this type of cloud is very frequent and often extends in an unbroken layer over the greater part of the country. It is also a low cloud, and therefore in the winter it very frequently occupies that part of the atmosphere where the temperature is just below the freezing point.

Stratocumulus cloud is not formed in an ascending current of air, as is the case with cumulus clouds, nor in the forced continuous rise of warm air over cold air as at a warm front. Stratocumulus is essentially a layer cloud and is formed in suitable conditions, when innumerable small eddies diffuse moisture upwards into the layer, and the moisture is unable to escape upwards owing to the stability of the layer above. The air is "bumpy" below and in the clouds, while above them there is smooth flying. When closely examined stratocumulus clouds are found to have a cellular or wave-like pattern due to the air rising in some places and falling in others. There are frequent "holes" in a layer of stratocumulus clouds. As there is no continuous rise the cloud particles cannot be carried up and accumulate, the cloud particles are, therefore, of no great size and precipitation seldom falls from this type of cloud. Hence it is relatively seldom that aircraft experience heavy ice accretion within stratocumulus clouds unless they remain a long time within them. The base of the clouds is usually above 2,000 ft. and the tops below 5,000 ft., so that aircraft need seldom fly for any length of time within the cloud layer itself. Frequently cumulus clouds develop below a layer of stratocumulus and penetrate into it, causing an intensification of icing.

Forecasts of Ice Accretion.—The following are the existing instructions for forecasts of ice accretion :—

(*a*) The approximate height above mean sea level of the freezing level is given in all forecasts for aviation. When there are two levels both are given. The heights are given to the nearest 500 ft. for levels up to 5,000 ft. and to the nearest 1,000 ft. for higher levels.

(*b*) When no cloud is expected or only cloud below the freezing level this is indicated in the forecast.

(*c*) When cloud is anticipated at the levels at which the temperature is favourable for icing, the estimated icing conditions are indicated by one of the following terms :—

Icing index high.
Icing index moderate.
Icing index low.

These terms indicate broadly the relative amount of water which it is anticipated will be in the cloud available for deposition as ice on aircraft. The amount actually deposited on aircraft will be dependent on the period during which the aircraft is flying in the levels concerned.

(*d*) If a stratified (or layer) cloud is anticipated in the layers favourable for ice formation, i.e. the layers between temperatures of 32° F. (0° C.) and 15° F. (—9°C.), normally about 4,000 ft. in vertical extent, the forecast will include a statement in the form " Layer cloud ; base at X extending above Y, icing index I in cloud between P and Q ", X being the probable height of the base of the layer, Y the freezing level, I the icing index, P and Q the heights between which icing is expected. If X is above Y the statement will be in the form " Layer cloud ; base at X, icing index I, in cloud between X and Q ". When it is possible to do so, both the upper and lower limits of the cloud will be indicated.

(*e*) If clouds of the cumulonimbus type are expected to extend above the freezing level, the conditions favourable for ice formation may extend to levels of temperature down to 0° F. (—18° C.), i.e. through about 8,000 ft. of vertical extent. The likelihood of such clouds will be indicated in the forecasts by a statement in the form " Cumulus or cumulonimbus cloud ; base at X extending above Y, icing index I, in cloud between P and Q."

(*f*) If icing caused by supercooled rain falling from a warmer upper layer is anticipated, specific reference to it is given in the forecast.

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