TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 885

METEOROLOGICAL-PHYSICAL LIMITATIONS OF ICING IN THE ATMOSPHERE

By W. Findeisen

Hauptversammlung der Lilienthal-Gesellschaft für Luftfahrtforschung, Berlin, October 12-15, 1938

Washington
January 1939

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Icing, i.e., the accumulation of ice on parts of an airplane, is caused by air containing drops of supercooled water. On striking the front edges of an aircraft, these supercooled droplets are stimulated to freezing and form an ice deposit. The deposition of slushy snow is, strictly speaking, not ice accretion, although it may become, on occasion, fraught with meaning, since it particularly restricts the pilot's vision when coating the windows of his cabin.

Supercooled water exists in supercooled water clouds and in supercooled rain.. In the majority of cases, icing occurs in supercooled water clouds, very rarely in supercooled rain. Ice clouds, that is, clouds containing only ice crystals, present no icing hazard. The small particles do not stick to the surfaces of an airplane.

The weather-reporting service can meet its task of forecasting the zones of icing hazards, if it can ascertain at any time the distribution of water clouds and ice clouds above the zero-degree boundary.

In this respect, the most recent cloud research has achieved significant results as will be briefly described in the following**. Water clouds are the result of condensation of water vapor contained in the air at the condensation nuclei, which are very minute particles of hygroscopic substances of several hundred-thousandths of a millimeter diameter, normally fluid. Water clouds can form

*"Meteorologisch-physikalische Begingtheiten der Vereisung in der Atmosphäre." Reprint of paper presented at meeting of Lilienthal-Gesellschaft für Luftfahrtforschung, October 12-15, 1938, Berlin.

**Published in detail in Meteorologische Zeitschrift, 1938, pp. 121-133.

at temperatures above zero as well as at much lower temperatures, certainly at any height range of present-day aviation. However, the creation of water clouds at lower temperatures becomes always more improbable, because the formation of ice clouds is promoted. Ice clouds are formed by sublimation of water vapor at the sublimation nuclei, which, in contrast to the condensation nuclei, are solid and insoluble in water. Below a certain temperature, usually at around -15° to -20°, ice clouds form instead of water clouds, provided sublimation nuclei are present.

The stratification of ice and water clouds in the formative stages of a cumulo-nimbus cloud is shown in figure 1. The small cumulus formed first consists of water droplets only, hence presents a supercooled water cloud in the range above the zero-degree boundary. On further growth the ascending air current reaches the critical temperature (dashed line in fig. 1), where the sublimation at the sublimation nuclei begins. From then on only ice crystals are formed. The supercooled water droplets carried by the rising air current into the uppermost part of the cloud, evaporate quickly in favor of the ice crystals, because the water vapor absorption capacity of ice crystals at low temperatures is considerably greater than that of the water droplets. In the zone where supercooled water droplets occur along with ice crystals especially, the ice crystals grow fast as a result, and increase by freezing with supercooled water droplets. Thus freezing sleet begins, which finally cannot be carried any longer by the rising air current and, so, drops. On dropping through the broad layer containing the supercooled water droplets, the ice particles grow still more, in the same fashion, as the leading edges of an airplane are coated with an ice layer by such a supercooled water cloud. So, hailstones are formed. Through the continuous descent of ice crystals the supercooled water droplets are gradually eliminated. The supercooled water cloud disappears, but the ice cloud pushes down from above to take its place. Soon the dropping ice particles cannot grow again as fast as before. Remaining smaller, they melt on dropping below the zero-degree boundary and form raindrops. With the progressive shrinkage of the water cloud, the rain intensity gradually abates. From the course of the precipitation, the formative stages of the cumulo-nimbus can at any time be recognized and hence the stratification of ice and water clouds and the position of the zone of ice formation can be assessed.

Such inferences can also be drawn for stratus clouds, as illustrated in figure 2. No normal rain falls from water clouds, or at the most a drizzling rain, which, however, does not fall on the ground unless the clouds are low and the atmospheric humidity is high. For that reason, the strato-cumuli (right-hand side of fig. 2) do not bring rain. From the absence of rain it can be concluded, from the ground, that the cloudiness pertains to pure water clouds in which, therefore, icing must be present, because they lie above the zero-degree boundary. Ice clouds have a much greater precipitation tendency than water clouds. Still, even the alto-stratus gives no precipitation, so long as its lower edge is very high and the falling ice crystals vaporize as a result in a dry interlayer. But through the continued falling of ice crystals, the air below the alto-stratus becomes more and more humid and the lower boundary of the ice cloud sinks (from right to left in fig. 2). Ultimately the ice crystals reach the supercooled water clouds, where they quickly form frozen sleet, as in the previous example (fig. 1), fall rapidly, and finally turn to raindrops. The start of a moderate or very heavy rain on the ground is typical of the cloud stratification shown in figure 2. At the same time, it indicates the dissolution of the supercooled water clouds.

After that, the rain stops again temporarily or else slackens at any rate. The ice-crystal cloud continues to sink on account of the falling motion of the crystals and finally reaches the zero-degree boundary. Then the alto-stratus becomes a nimbo-stratus; fundamentally both types of clouds are identical. Near the zero boundary the ice crystals combine into bigger snowflakes. which during further fall melt into raindrops and result in a light to moderate rain. Under wintry atmospheric conditions, i.e., low zero-degree boundary, the snow flakes do not melt, hence there is snow on the ground. The lower level of the nimbo-stratus, the true rain cloud, lies fundamentally near to the zero-degree boundary, for there all small ice crystals must melt. Below the nimbo-stratus, new water clouds are almost always formed on the strength of convection movements in the air, which, by the high humidity underneath the rain cloud, leads very easily to cloud formation again. These lower tattered clouds (fracto-stratus or fracto-cumulus) themselves produce no precipitation, but become suggestive of the intensity of the rain if, on occasion, they extend beyond the zero degree boundary. Then the ice crystals dropping through these clouds become much larger. The rain on the ground then becomes heavier for a while, and therewith indicates the formation of supercooled water clouds and the existence of a fresh icing hazard in the layer a little above the zero degree boundary.

At the upper level of the ice crystal cloud water clouds (alto-cumuli) are formed very regularly, because there the air is poor in sublimation nuclei, and newly starting vertical movements can produce only rain clouds. On account of this there is practically always a danger of icing in the uppermost layer of the rain cloud. Although the alto-cumulus layer is usually of from about 200 to 300 meters thickness, it still may occasionally extend for 1,000 meters or more. Such is the case in considerably aged rain clouds whose upper level is low and give only little rain any more.

From these two illustrative examples (figs. 1 and 2), it is apparent that dependable precipitation records of themselves give a very satisfactory indication of the ice- and rain-cloud layers. Observation of the clouds themselves also offers a substantial aid. Ice and rain clouds disclose characteristic differences in their appearance. With some experience in ground observation, or better yet, from an airplane, it can be reliably ascertained whether a cloud contains ice crystals or water or both, i.e., (knowledge of level of zero degree boundary presumed) whether a cloud presents an icing hazard or not.

The well-known old and subsequently improved method of classifying the clouds according to form and height affords no safe possibility of distinction between ice and water clouds. When new viewpoints are applied to the known classification, the following should be fundamentally classed as ice clouds: cirrus, ciro-stratus, alto-stratus, nimbo-stratus; further, as ice-and-water cloud: cumulo-nimbus (fig. 1) and alto-cumulus with cirrus stripes (cirro-filum). In very cold weather, winterly strato-cumuli or cumuli may occasionally consist wholly of ice crystals. But generally all other clouds are water clouds throughout; of course, ice particles from some other source may, on occasion, drop through these clouds.

The ice clouds contain fewer but larger particles than the water clouds. Hence, they are optically thinner and appear sometimes merely like heavy mist. Their borders are hazy because the large particles drop rapidly and evaporate more slowly outside of the clouds than the much smaller water drops. But the water clouds are sharply outlined. At times the ice clouds are recognizable on optical phenomena; from an airplane on the well-known parhelion created by reflection on the ice crystals.

Figures 3 to 8 portray the typical differences in the appearance of ice and water clouds. Figure 3 shows the upper level of a stratus cloud, figure 4, that of an ice cloud (nimbo-stratus) from above, topped by loose water clouds (alto-cumuli) as in figure 2. The ice cloud is visible through the parhelion formed in a rift between the upper water clouds. Figure 5 shows an ice cloud (nimbo-stratus) from below, with cloud tatters (fracto-cumuli) containing water only (as in fig. 2) appearing beneath it as a gray veil.

The cumuli and alto-cumuli of figure 6 contain nothing but water. Figure 7 shows next to water clouds (cumuli, left, back) a cumulo-nimbus, in the advance stages of change into an ice cloud (as in fig. 1). A smaller winter cumulo-nimbus consisting almost exclusively of ice particles is shown in figure 8, and a cumulus containing water only, to the left of it.

To estimate whether icing is imminent or not in a cloud makes, of course, the knowledge of the temperature imperative, aside from the determination of the particle type. As far as the pilot is concerned, the height of the zero-degree boundary is sufficient. And this can be given fairly accurately on the basis of the daily measurements in Germany. But in the forecast of the zero-degree boundary from the ground, it is absolutely essential to bear in mind that every airplane speed has its own zero-degree level. On account of the impact and friction phenomena of the air on the airplane, the temperature of the airplane is always higher than the air temperature, and so much more as the airplane speed is higher; even the density of the clouds flown through plays its part. Owing to these temperature rises, the zero-degree level decisive for the icing of an airplane is always higher than the meteorological zero-degree level.

In cloud-flying between 1,000- and 2,000-meters height, the following figures are applicable:

Flying speed	200	250	300	350	400 km/h
Elevation of 0° boundary	170	270	390	530	700 m

The conventional types of airplanes today therefore reach 0° temperature and hence the beginning of ice formation at heights which are at least 200 meters above the meteorological 0°. High-speed aircraft is especially favored. For instance, it happens that a slow airplane cannot cross the German secondary mountain chain without icing hazard, while a fast airplane at 1,200 to 1,300 meters is at the same time without danger. This is important also for the appraisal of the lower limit of the icing hazard. During flight, the pilot will keep a close watch on his thermometer while noting that it does not indicate the meteorological but rather the increased temperature. Since the temperature rise in flight through a cloud is about 40 percent lower than outside of it, he must, before flying into dangerous ice clouds, seek an altitude where the thermometer, depending on flying speed, reads at least 0.5° to 2° above zero.

The establishing of icing zones on the basis of the available station reports and on the basis of the weather map must rely, above all, on the precipitation and cloud observations of the individual stations. Just as precipitation and clouds in different places are usually different, so also the icing zones change. Uniform location and range of icing zones over extended regions are rare. Moreover, the icing zones are not tied in simple fashion to fronts or air masses. Quite often the icing hazard in extended precipitation zones is exactly the lowest. Of course, supercooled rain occurs occasionally in precipitation zones by well defined temperature stratification. But the icing hazard in supercooled rain is not very great, so long as the flight through it is not protracted. The amount of water contained in air in supercooled rain is substantially less than in the supercooled clouds. Even the extent in height of the icing hazard is usually quite restricted in supercooled rain and can be readily predicted.

According to the foregoing, the icing hazard can, in most cases, be avoided by correct execution of the flights according to meteorological viewpoints and by meteorologically correct navigation (horizontal and, above all, vertical). The zones of icing hazard are usually narrowly confined. Their location can be ascertained with, in most cases, sufficient accuracy, before take-off.

The cloud research will be able to deepen and improve our previous knowledge of the characteristics and the existence of supercooled water clouds, and so become an additional aid in icing forecasts.

Translation by J. Vanier,
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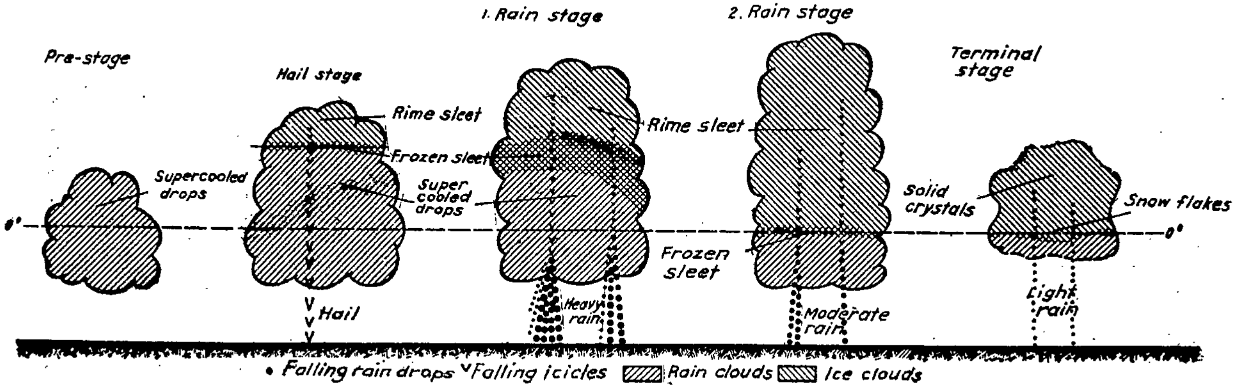

Figure 1.- Distribution of ice and water clouds in swelling cloud formation(formative stages of cumulo-nimbus)

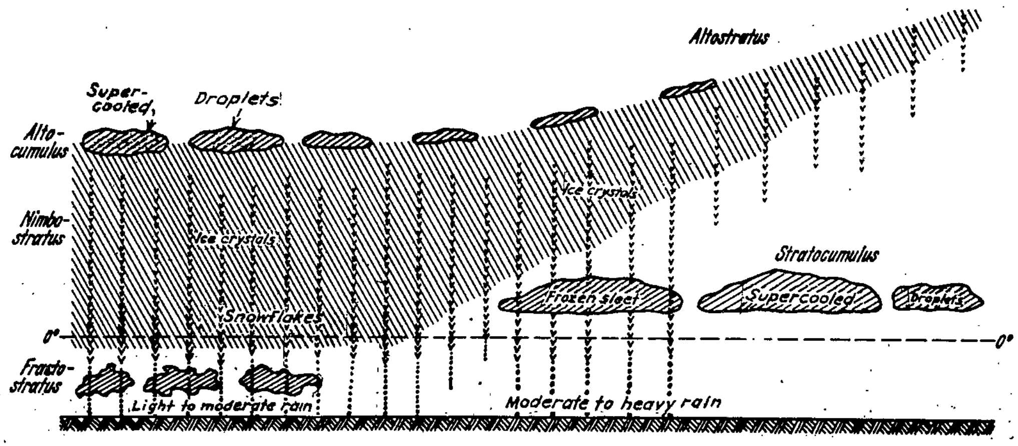

Figure 2.- Ice-and-water-clouds in stratified clouds(formative stages of nimbo-stratus)

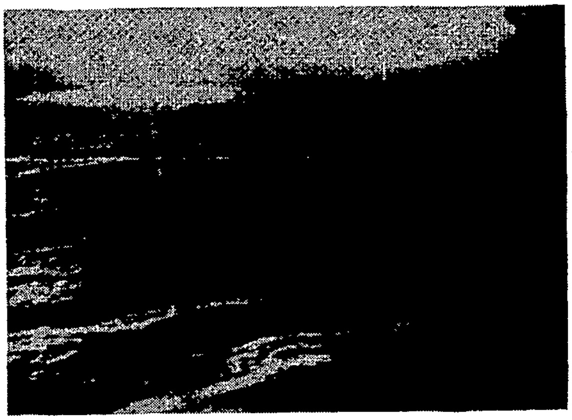

Figure 3.- Upper level of a stratified water cloud(stratus)

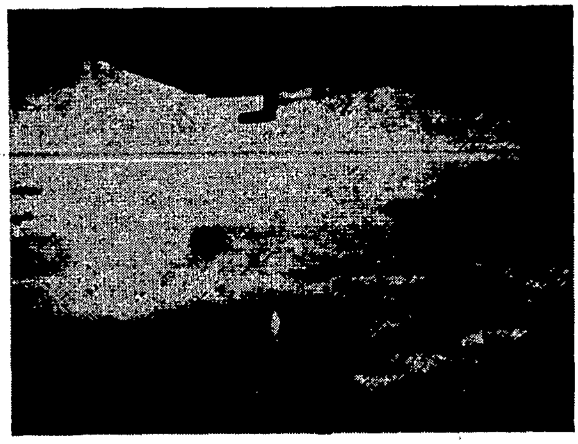

Figure 4.- Upper level of a stratified ice cloud, topped by loose water clouds(alto-stratus with alto-cumulus)

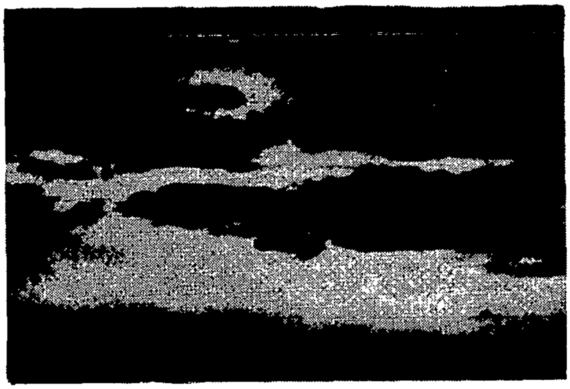

Figure 5.- Lower edge of a stratified ice cloud with water clouds beneath(nimbo-stratus with fracto- cumulus.

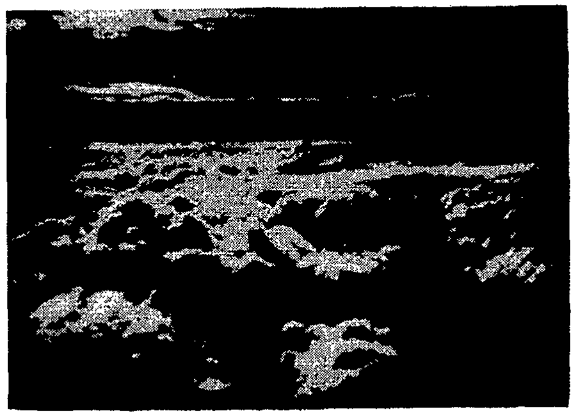

Figure 6.- Cumulous water clouds(cumulus, alto-cumulus)

Figure 7.- Cumulous cloud containing both water-and-ice-particles(cumulo-nimbus)

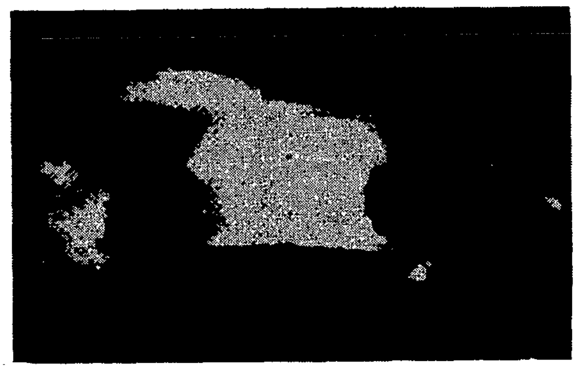

Figure 8.- Cumulous ice cloud(wintry cumulo-nimbus)