Hailstones and their effects on aircraft*

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ABSTRACT. To explain formation of large hailstones which cause serious damages to aircraft, current theories regarding the formation and growth of hailstones are reviewed in the light of observed structure of hailstones and physical conditions inside large convective clouds. The role played by updraft is discussed in detail. Following Schumann (1938) an equation is given for the ultimate diameter of a hailstone in terms of updraft velocity, concentration of condensed water at temperatures below 0°C, average density of the hailstone and the depth of fall above the freezing level. Substitution of mean as well as extreme values of the different parameters involved in the equation seem to show that hailstones of sizes 10–12 cm in diameter would not be infrequent in the tropics although an extreme size of 18 cm in diameter would certainly be a rare occurrence. Observed damages to aircraft by hailstones suggest impact at low angles of elevation and this is explained by a consideration of relative fall velocity (terminal velocity—updraft velocity) and the speed of aircraft. The meteorological problem of forecasting hailstorms is discussed and it is concluded that in the present state of our knowledge safety considerations would demand a more reliable guide to aviators, *viz.*, an airborne radar which can provide early warning of severe hailstorm cells while in flight.

1. Introduction

Almost every year inspite of utmost care and vigilance exercised by aircrew to avoid flying through hailstorms a few reports are received of considerable damage to aircraft caused by hailstones. A few recent instances may be cited here. On 27 May 1959, a Viscount aircraft of the I.A.C. flying on Karachi-Delhi route at 5700 metres a.s.l. encountered a severe hailstorm which damaged the aircraft to such an extent that it had to be sent back to its manufacturers in U. K. for major repair. Almost all the leading edges of exposed surfaces were perforated with holes some of which were as large as 12—15 cm in diameter. One opening on the starboard side of the nose of the aircraft was perhaps, even larger in size and another hailstone pierced directly through the wind screen, completely smashing it and seriously injuring the pilot. Fig. 1 shows a series of four photographs of the aircraft after it landed at its destination. Radar observations on this day revealed clouds over the area which extended to heights of 12-14 km a.s.l., while the freezing level was 4·5 km. On 9 May 1959, a Packet aircraft flying between Dijon and Northolt in Europe at 2550 metres flew through a hailstorm and as a result the leading edges of the mainplane of the aircraft were dented by hail. On 28 January 1959 while flying near Jaipur at 6 km, a jet aircraft got into a severe hailstorm. The damages recorded in this case were : Engine swirlvanes dented, tailplane leading edges dented, and fabric on the leading edges of the rudder fin damaged. The experience of the pilot of the aircraft is thus described in his own words—"At 6 km I entered cloud at 250 kts. Two violent bumps from turbulence caused the aircraft to roll past 90° and enter a steep spiral dive. In the course of the dive I heard very severe rattling noises and felt a great deal of turbulence. I recovered below clouds at high speed. I noticed that at the same time in the recovery an acceleration of $+6\frac{1}{2}$ g had been recorded."

The three instances of encounter with hailstones just related are, perhaps, typical of conditions inside hailstorms in so far as they bring to light some of the more important characteristics of these storms and the effect of hailstones in general on aircraft in flight. Some of these characteristics and observed effects would appear to be as follows—
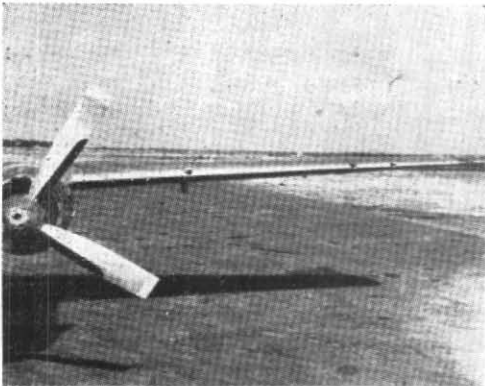
FIG. 1. PHOTOGRAPHS OF VISCOUNT AIRCRAFT
DAMAGED BY HAILSTONES

(a) A hailstorm is characterised by severe vertical currents and extreme bumpiness,

(b) Hailstorm clouds extend much above the freezing level and to great heights in the troposphere,

(c) Hailstones can grow up to very large sizes; usually, a size distribution would appear to exist,

(d) The parts of aircraft that are usually affected by hailstones are the leading edges of exposed surfaces,

(e) In jet aircraft particularly in those of the turbo-jet type the engine swirlvanes would appear to be particularly susceptible to hailstone damage, and

(f) Hailstorm of tropical latitude would appear to be much more severe in intensity than those of the temperate latitude.

In the present paper physical processes leading to the formation of large hailstones in clouds and the aerodynamics of hailstones in relation to still air as well as the vertical air currents are examined in detail. The effect of hailstones on moving aircraft is then examined and it is shown that a consideration of relative fall velocity of a hailstone in relation to speed of aircraft would apear to explain the observed effects.

Meteorological factors involved in hailstorm formation are indicated and difficulties of forecasting stressed. The advantages of carrying airborne radar to detect and avoid active hailstorm cells in flight are pointed out.

2. The genesis of the nucleus of a hailstone

Hailstones invariably form in convective type of clouds. Observations made from aircraft and by radar show that the tops of cumulonimbus clouds in the tropics quite often reach heights of 14-15 km a.s.l. where the ambient air temperature may drop to —60

to —70° C. The average summer freezing level over the tropics is at a height of 4-5 km a.s.l. Experiments performed in the laboratory show that when water drops are supercooled, potential centres of crystallisation develop within them and that an increasingly large number of drops freeze as the degree of supercooling increases (Brunt 1941). Below a temperature of —41° C, however, all drops will freeze. In the open atmosphere also there is enough evidence to show that the number of drops that freeze inside a cloud progressively increase with height above the freezing level until at a height where the temperature is reduced to near about—41°C, practically all the cloud drops would freeze into ice or snow crystals. Above this height the cloud is said to be glaciated. In a tropical cumulonimbus cloud, glaciation occurs above a height of about 10·5 km and is usually revealed in the form of false cirrus in the anvil part of the top.

With this distribution of particles in liquid and solid phases inside a vertically-developed cloud the questions that naturally arise in regard to formation of hailstones are: At what height inside the cloud does the nucleus of a hailstone originate and how does it form initially and grow later into a large hailstone that we observe to fall ? These are fundamental questions, not all of which have been satisfactorily answered yet. We, however, visualise from the observed structure of a hailstone as consisting of successive shells of white and clear ice round a core of white ice that the nucleus of a potential hailstone probably forms as a result of coalescence between an ice or snow crystal and a supercooled water drop or between two supercooled drops in the layer of the cloud in which there is co-existence of supercooled drops and ice crystals. Perhaps, this process of coalescence is particularly effective in that part of the cloud where ascending ice or snow crystals after meeting a stable atmosphere above are reflected back into the layer of supercooled drops and snow flakes producing ample opportunities for collisions. Following

Gaviola and Fuertes (1947), we may enquire what really happens (a) when two snowflakes collide, (b) when a snowflake and a super-cooled water drop collide, and (c) when two supercooled water drops collide. Of course, when two snowflakes collide we may say that nothing of consequence happens. If two or more supercooled water drops at a temperature of say—30°C collide, they may form a wet ice kernel at 0°C, 5/8th of its water content remaining liquid owing to release of latent heat of 80 cal. per gm due to freezing. If a snowflake at —30°C collide with supercooled water drops or with wet ice kernels formed by them, we may have the following complex processes taking place : (a) The liquid water will wet the ice crystals due to capillary and freeze upon them, their temperature rising on account of released latent heat of fusion. The snowflake thus becomes more compact; (b) if more liquid water is available by collisions with further supercooled water drops or wet ice kernels the temperature will rise to 0°C and part of the system will remain liquid. We have then a wet large crystal of snow at 0°C. Owing to surface tension of the liquid phase and to solution and re-crystallisation the wet crystals will assume more or less a spherical form. With air bubbles trapped and liquid water in the surface layer the nucleus of a hailstone has thus been formed. The further process of development of this nucleus into hailstone will depend upon a number of factors, particularly the concentration of ice or snow crystals and supercooled water drops with which it will collide and its velocity of fall in relation to updraft velocity inside the cloud at different heights.

Recently, Ludlam (1958) has given a theory of hailstone growth in which he holds the view that the embroys are the rare large cloud drops which are found in the lower parts of the clouds and which freeze in the supercooled parts of the clouds on being lifted by up-draughts. Appleman (1958), however, has stated that for the embroys to become effective the depth of the cloud layer below the level of freezing of the cloud drops must not be large, otherwise the drops will prematurely fall out as rain and not lead to formation of hail nuclei.

3. The aerodynamics of hailstone

Terminal velocity—The fall of a hailstone through the atmosphere is resisted by aerodynamic drag and its momentum is shared by the cloud particles which accumulate on its surface due to capture. The terminal velocity V of a particle of diameter d is given by the expression

$$V = \left\{ (\pi/6) d \, \sigma \, g \left/ \left(\frac{m\pi}{4} + k \, \rho \right) \right. \right\}^{\frac{1}{2}} \quad (1)$$

where m is the concentration of liquid water in the atmosphere, gm/c.c., k the drag coefficient, ρ the density of air, gm/c.c., σ the average density of the hailstone (0·7 gm/c.c.), and g the acceleration due to gravity (=980 cm/sec²).

In equation (1), $m\pi/4 << k \, \rho$, hence as a first approximation we may write

$$V = A \, (d/k)^{1/2} \quad (2)$$

where $A^2 = \pi \sigma g / 6 \rho$

If we assume a mean density 0·7 gm/c.c. for a hailstone, A varies inversely as the square root of atmospheric density provided we make the further assumption that g varies little with height. As k is known to vary with flow characteristics, equation (2) by itself cannot give us value of V or d or the desired relation between V and d unless we make use of a supplementary relation

$$R = V d / \nu \quad (3)$$

where R is the Reynolds number of fluid motion, and ν the coefficient of kinematic viscosity.

TABLE 1

Physical characteristics of the atmosphere at different altitudes during May-June (India)
(Mean conditions)

Height a.s.l. (km)	Pressure (approx.) (mb)	Temperature (°C)	Density (gm/c.c.) $\times 10^3$	Kinematic viscosity (cm^2 sec^{-1})	A	B
0	1000	40	1·11	·17	572	·00445
3	700	12	0·86	·20	646	·00457
6	500	—10	0·67	·24	732	·00475
9	300	—30	0·43	·35	914	·00527

TABLE 2

Values of k at different Reynolds Numbers R

$R \times 10^{-5}$	0·3	0·5	1	2	3	4	5	6	7
k	·50	·41	·22	·14	·09	·08	·07	·07	·07

Substituting the value of V from eqn. (3) in eqn. (2) we obtain

$$d = B\,(R^2 k)^{1/3} \qquad (4)$$

where $\quad B = (\nu/A)^{2/3}$

Since both A and B vary with height, their values along with the properties of the atmosphere at levels 0, 3, 6 and 9 km above m.s.l. in the tropics are given in Table 1. Equations (2) and (4) enable us to compute values of V and d at different levels of the atmosphere provided we know how k varies with R. For this purpose we make use of an experimental result determined in respect of a near-spherical body such as a tethered balloon (Saha 1956), as shown in Fig. 2.

The procedure for determining the terminal velocity for different diameters of hailstones at any given height of the atmosphere consists in finding k for a given value of R. These values of k and R are substituted in eqn. (4) and d is determined. Eqn. (2) then gives the corresponding value of V. Table 2 gives the values of the Reynolds number and the drag coefficient used in the present computation.

The variation of terminal velocity with the diameter of a hailstone is presented graphically in Fig. 3. The general trend of variation appears to be the same at all levels, the terminal velocity increasing with the size of the hailstone but the rate of increase is steeper at the higher levels. For the same size of a hailstone its fall velocity is much greater at higher levels than at the lower levels. For example, a hailstone of diameter 10 cm will move with a terminal velocity of 70 metres/sec at 3 km and 90 metres/sec at 9 km and the difference widens as the hailsize increases.

The general nature of the V—d curve presented in Fig. 3 is markedly different
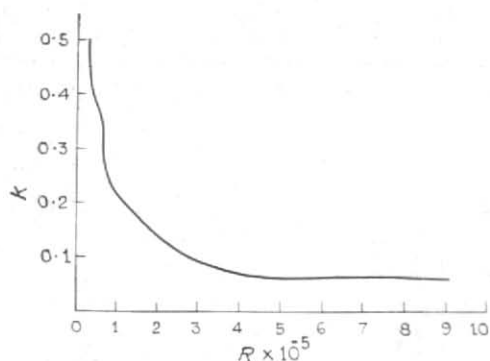
FIG. 2. VARIATION OF DRAG COEFFI-
CIENT k WITH REYNOLDS NUMBER
R IN RESPECT OF A NEAR-SPHERI-
CAL BODY

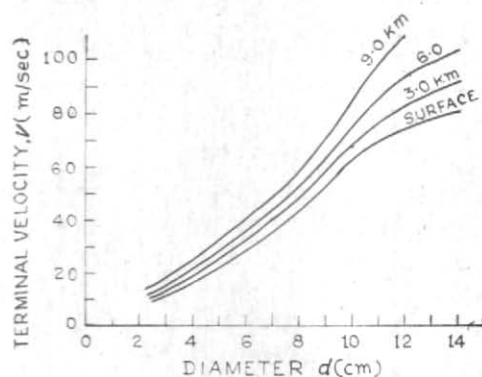FIG. 3. TERMINAL VELOCITY vs DIAM-
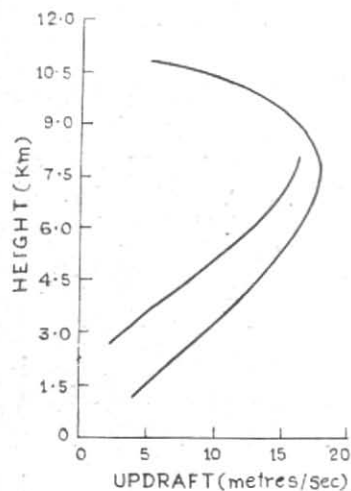ETER CURVES FOR HAILSTONES AT
0, 3, 6.9 km a.s.l.

FIG. 4. DISTRIBUTION OF
UPDRAFT WITH HEIGHT IN
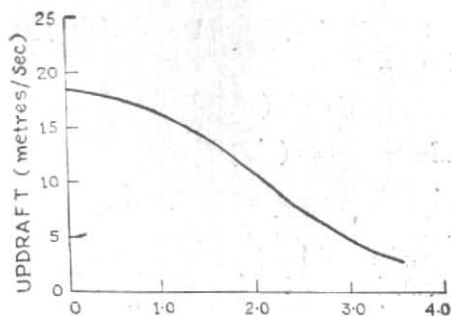THE CENTRE OF Cu AND
Cb CLOUDS

FIG. 5. RADIAL DISTRIBUTION OF
UPDRAFT AT THE HEIGHT OF
MAX. UPDRAFT AT 9 km a.s.l.

from that found by Bilham and Relf (1937) by using a $k-R$ relation in respect of a spherical body towed by an aircraft. An S-shaped curve found for $V-d$ is interpreted by these authors to mean that there is an upper limit to the size of a hailstone and that this limit is about 13 cm in diameter. In accordance with the present study, there is no theoretical limit to the size of a hailstone. The only limit would seem to be placed by the density of the hailstone, the strength of the ascending air currents, the concentration of condensed water in the part of the cloud in which the temperature is below 0°C and the height above the freezing level at which the nucleus forms.

Vertical air currents—Direct observation or measurement of vertical velocities of air inside a growing cumulus or cumulonimbus cloud is rather scanty. The United States Thunderstorm Project (Byers and Braham 1948) which studied the structure and circulation pattern of thunderclouds in various stages of development found by direct aerial measurements that there is only updraft in these clouds till the precipitation stage is reached when updraft is replaced by downdraft in the portion of the cloud through which rain or snow falls. The general distribution of updraft with height in the central region of a growing cumulus cloud and a mature thundercloud are shown in Fig. 4. It will be seen that below a level of about 1·5 km above the ground, the updraft is very feeble. It increases uniformly with height above this level till a maximum strength is reached at height of about 9·0 km beyond which the updraft becomes feeble again. In the tropics where the top of a mature cumulonimbus cloud may often extend to 15 km a.s.l., the magnitude of updraft at any height may be somewhat different but it is believed that the general pattern of distribution with height will remain the same as shown in Fig. 4. The horizontal variation in the magnitude of updraft from the centre to the periphery of a cloud of horizontal extent 8 km at the level where the maximum updraft is experienced, is shown in Fig. 5.

It will be seen that the updraft is feeble at the periphery but increases towards the centre. In fact, the presence of feeble updraft at the periphery is due to diverging motion superimposed on vertical velocity in the upper parts of the clouds. The mean distribution of updraft as presented in Figs. 4 and 5, indicates that the maximum updraft of magnitude 18—20 metres/sec is reached in the central parts of a cloud at a height of about 9·0 km a.s.l. Stronger updraft of the order of 30 metres/sec or even more may be experienced in individual clouds, especially in the tropics. The distribution of updraft described herein is generally supported by a theory of cumulonimbus evolution, proposed by Ludlam (1958).

Relative velocity—In studying the rate of fall of a hailstone through an ascending air mass, it is the relative velocity which is to be taken into consideration. A study of the distribution of terminal velocity and of updraft as presented in Figs. 3 and 4 enables us to draw some interesting conclusions regarding the distribution of relative velocity. The maximum updraft of about 20 metres/sec prevails in a cloud at a height of about 9·0 km and at this height we find that the terminal velocity of a hailstone 5 cm in diameter is about 40 metres/sec, *i.e.*, double the strength of updraft. A hailstone of 5 cm in diameter should, therefore, fall with a relative velocity of 20 metres/sec at this level. For hailstones of larger sizes the relative velocity of fall is still greater at this level and many times greater at lower levels where the updraft progressively weakens.

It seems clear, therefore, from the diagrams that the largest size of a hailstone that can be supported by the strongest of updraft is about 3·0 cm in diameter at a height of about 9·0 km. This means that if a hailstone of this size were to find itself at any other level either above or below 9·0 km a.s.l., it would have a relative velocity of fall of magnitude equal to the difference between the terminal velocity and the updraft velocity at that level.

4. Formation of large hailstones

A plausible theory of the formation of large hailstones must, *inter alia*, take into account the vertical distribution of updraft and fall velocities as discussed in Section 3 of the paper as well as the concentration of condensed water in the supercooled region of the cloud and the height from which the nucleus falls. Perhaps it might be worthwhile to review here briefly two current theories on the subject which would seem to have been widely accepted. One of these, due principally to Humphreys (1940), proceeds on the assumption that the nucleus of a potential hailstone is formed in the layer of freezing temperatures when a large raindrop is moved up to this layer by strong vertical currents. Its subsequent growth leading to formation of concentric shells of clear and white ice takes place by multiple incursions between the realm of raindrops and the region of snow across the freezing level. A second theory (Gaviola and Fuertes 1947) seeks to explain the growth of a hailstone during a single fall through a deep layer of freezing temperatures in which supercooled water droplets and ice crystals or snowflakes are known to co-exist. The formation of the nucleus of a hailstone in accordance with this theory was explained in Section 2. The theory explains the formation of concentric layers of white and clear ice by assuming that while the surface is wet, a transparent layer forms and when it dries, an opaque white layer appears. The theory discards the necessity of strong vertical currents for the formation of large hailstones.

We may examine these prevalent theories to find out to what extent they conform to observations. The multiple incursion theory which rests on the assumption that the growth of a hailstone is due to its up and down movements across the freezing level ignores the important fact that the largest hailstone that can be supported by the strongest of updraft in the cloud is about 3·0 cm in diameter and that this updraft also occurs in a region of the atmosphere which is much higher than the freezing level. Hence we conclude that the formation of large hailstones say 10 to 12 cm in diameter cannot be explained by this theory. The single fall theory, however, envisages fall of a nucleus of a hailstone from a height of about 8 km which is the base of the snow layer to a height of about 4 km and the authors of the theory estimate that as a result of this fall a nucleus of 0·1 cm in diameter will grow to a size of 5 cm in diameter. They remark that hailstones larger than 5 cm in diameter are rare and that fast ascending currents are superfluous in the formation of hailstones.

Perhaps it may not be difficult to visualise the process by which concentric shells of clear and white ice form in a hailstone but conditions differ widely in the tropics regarding the height from which a nucleus falls and the strength of updraft inside the cloud. As already stated in Section 2, glaciation occurs in a tropical cumulonimbus cloud immediately above a height of about 10·5 km and it is plausible to hold that it is at about this height that simultaneously a large number of hailstone nuclei will be generated. After formation, the nuclei being relatively heavier than surrounding particles will commence descent and they will have a depth of about 6 km to fall through to reach the freezing level. They will, however, have to fall through an ascending airmass and the strength of the updraft varies from level to level. The general distribution of updraft as presented in Fig. 4 indicates that the maximum time is allowed for the growth of the hailstone in the layer 8-10 km in which the updraft is the strongest. As the hailstone falls out of this layer, the relative velocity increases rapidly both due to feebleness of updraft as well as large increase in the size of hailstone. On descending through the freezing level, the hailstone does not produce any more solid layer because of the warmth of the region and aerodynamic heating, both of which may, in fact, lead to small amount of melting of the outermost layer of the hailstone. Ludlam (1958) has shown that in the case of hailstones larger than 4·0 cm in

diameter, this melting is practically negligible.

It seems fairly clear, therefore, that a plausible theory of formation of large hailstones in the tropics, as perhaps elsewhere, should be able to relate the ultimate size of a hailstone with the strength of updraft and the concentration of condensed water in a region of the atmosphere in which the temperature is below 0°C and the height above the freezing level at which the hailstone initially forms. Such a theory was first advanced by Schumann (1938) who worked out the strength of updraft and concentration of condensed water in the atmosphere needed for formation of a hailstone, of a required size, assuming the hailstone to fall in turn from two given heights, viz., 7 km and 9 km to the freezing level at 4 km. The ultimate size considered by Schumann was 8 cm in diameter. Perhaps we may proceed on similar lines and deduce for the ultimate diameter D of a hailstone an expression

$$L = \frac{\sigma}{m}\left(2\,D{-}6\right) - \frac{4u}{m}\left(3\,k\rho\sigma/\pi g\right)^{\frac{1}{2}} \times \left[\left(2\,D\right)^{\frac{1}{2}} - 2\cdot45\right] \qquad (5)$$

where L is the depth of the atmosphere (above the freezing level) through which the hailstone falls, u the updraft velocity, and other parameters have meanings given under eqn. (1).

In deriving eqn. (5) the initial diameter of the nucleus of the hailstone was assumed to be $3\cdot0$ cm at 9-km level. This assumption would appear to be justifiable in view of the fact that the hailstone commences its real long descent through the cloudmass only after this initial size has been built up by vertical air currents. If we wish to find the diameter of the hailstone as it falls to the freezing level, we take $L = 4\cdot5$ km and other

parameters of equation (5) are assumed to have the following average values in respect of the layer involved : $m = 20$ gm/cubic metre, $u = 20$ metres/sec, $k = 0\cdot1$, $g = 980$ cm/sec^2, $\rho = 5 \times 10^{-4}$ gm/c.c., $\sigma = 0\cdot7$ gm/c.c. With the substitution of these values in eqn. (5), we get a value of $12\cdot1$ cm for D. If the hailstones were intercepted at a height of $5\cdot7$ km which was approximately the flight altitude of the aircraft which was severely damaged by hailstones in India, the diameter would have been found to be about $10\cdot0$ cm. Unless we are prepared to believe that conditions inside the hailcloud as regards vertical velocity and concentration of condensed water were substantially different from those assumed here, this would perhaps give an idea of the size of the hailstones that damaged the aircraft. If we use an extreme value of m and u known to exist in severe cumulonimbus clouds in the tropics, we might arrive at an extreme value of D. The Thunderstorm Project measured updraft of the order of 30 m/s in some of the severe thunderclouds and Schumann (1938) quoted a value of $m = 38$ gm/cub. metre deduced from a case of heavy rainfall in Panama. If we, therefore, substitute $u = 30$ m/s and $m = 30$ gm/cub. metre in eqn. (5), we arrive at a value of about 18 cm for D. We must admit that there has seldom been a report of a hailstone of such giant magnitude falling to the surface of the earth but hailstones of diameter 10 to 12 cm are certainly not rare in the tropics. Before concluding this section we may briefly remark on the heat exchange that are assumed to occur between the falling hailstone and its environment. Owing to release of large quantity of latent heat of fusion when supercooled drops freeze on the surface of the hailstone and certain amount of aerodynamic heating, it is likely that the temperature of the surface of the hailstone is higher than that of the environmental atmosphere above the freezing level. The hailstone, however, loses heat by conduction as well as by evaporation through the thin film of air which forms the boundary layer of the

TABLE 3

Relative fall velocities of hailstones and angles of impact on aircraft flying level at
6 km a.s.l., aircraft speed 200 kt

Diameter (cm)	2	3	4	6	8	10	12
Relative fall velocity, Q(m/s) ($u = 16$ m/s)	—2	0	5	20	36	60	78
Angles of impact, α (degrees)	—1	0	2	11	20	31	38
Relative fall velocity, Q(m/s) ($u = 30$ m/s)	—16	—14	—9	6	22	46	64
Angles of impact, α (degrees)	—9	—8	—5	2	12	26	37

TABLE 4

Relative fall velocities of hailstones and angles of impact on aircraft flying level at
9 km a.s.l., aircraft speed 300 kt

Diameter (cm)	2	3	4	6	8	10	12
Relative fall velocity, Q (m/s) ($u = 16$ m/s)	0	4	9	24	43	71	94
Angles of impact, α (degrees)	0	1	3	9	16	25	32
Relative fall velocity, Q (m/s) ($u = 30$ m/s)	—14	—10	—5	10	29	57	80
Angles of impact, α (degrees)	—5	—4	—2	4	11	21	27

hailstone as it falls. It is assumed that this process of cooling is efficient and practically all the water released on the surface of the hailstone freezes and contributes to the rapid growth of the hailstone.

5. The effect of hailstones on aircraft in flight

We may calculate the angle at which large hailstones would impinge on an approaching aircraft by considering the relative velocity of fall and the speed of the aircraft at a given height. The relative fall velocity of a hailstone is its terminal velocity, diminished by the speed of updraft. Figs. 3 and 4 help us to determine the relative fall velocities of hailstones of different diameters at various heights of the atmosphere. If Q be the relative fall velocity of a hailstone impinging on an aircraft of speed I, the angle of impact (angle above horizon) is given by $\tan^{-1}(Q/I)$. In Tables 3 and 4 are presented the angles of impact of hailstones of different diameters on two aircrafts, one flying at 6 km a.s.l. at airspeed 200 kt and the other at 9 km a.s.l. at airspeed 300 kt assuming average updraft of 16 m/s and an extremely strong updraft of 30 m/s at both heights.

In Tables 3 and 4, negative values of relative fall velocity are indicative of upward movement of small-size hailstones under strong updraft. Likewise, negative angles of impact would mean that hailstones impinge on aircraft at angles slightly below the horizon. It would seem to follow clearly from Tables 3 and 4 that the angles of impact of hailstones on aircraft in general decrease with speed of aircraft and the speed of updraft inside the cloud.

Jet aircraft flying at high speeds through cumulonimbus clouds are, therefore, liable

to be hit at low angles of elevation and it is mostly the leading edges of exposed surfaces like the nose, windscreen, leading edges of wings, rudder fins and engine swirlvanes which are likely to be effected.

From theory presented in this paper we may draw the following interesting conclusions regarding sizes of hailstones likely to be encountered by aircraft at different heights. The region above 10·5 km will be free from hailstones. Aircraft flying in the layer 10·5—9·0 km will stand the risk of being hit by hailstones of size up to 3 cm in diameter. But the real danger will probably lie in the layer 9·0—4·5 km where giant size hailstones of diameter ranging from 3 to 15 cm may hit the aircraft. The danger continues even below the freezing level right down to the ground.

6. The problem of forecasting hailstones by meteorological staff

We are not sure as to how reliably a meteorologist can forecast the occurrence of a hailstorm in the present state of our knowledge of meteorology and cloud physics. Reliable estimates are required of a large number of physical variables and although we know that hailstones invariably fall from large cumulonimbus clouds, all such clouds do not give hailstones. Further, it is well known (Appleman 1958) that there is a marked seasonal and geographical variation in the distribution of hailstorms. The basis of analysis and prognosis of hailstorms would, perhaps, follow the same lines as in forecasting of thunderstorms. We have seen that strong updraft and large concentration of condensed water in a great thickness of cloudmass above the freezing level are essential requirements for the formation of large hailstones. Appleman (loc. cit.) has pointed out that a great thickness of cloudmass below the freezing level prevents formation of hailstones. It is well-known that updraft in a cloud results from the transformation of potential energy due to latent instability of the atmosphere into kinetic energy. Hence if from a thermodynamic diagram on which air-sounding data are normally plotted we are able to assess the total amount of realisable energy, we may relate it to the vertical velocity and thence to the diameter of largest hailstones that may be expected. It was on these lines that a technique for forecasting the maximum size of hailstones in clouds was suggested by Fawbush and Miller (1953) and Foster and Bates (1956).

We have seen in the present paper that the ultimate diameter of hailstones is dependent not only upon updraft velocity but also upon other important cloud characteristics. Perhaps in certain types of clouds like Nor'-westers in India, these other characteristics may be assumed to be present when strong updraft prevails. But this cannot be generalised and detailed information on important parameters involved would be required. To the extent this information is lacking, the situation would appear to be unsatisfactory.

7. Early warning by aircraft radar

The present position is that meteorologists even with their best of data can indicate in only a rough way when to expect a hailstorm or encounter large hailstones in clouds. Considering the extent of damages that have been caused to aircraft by some of the worst encounters and the potentiality for greater damages at any time, one may say that this position is not satisfactory. We have instances when flying in smooth altostratus cloud, pilots have occasionally been taken completely by surprise by hideous and treacherous Cb clouds with large hail inside. Safety consideration would demand some kind of radar arrangement to be carried permanently in the aircraft to provide early warning of the presence of precipitation elements including hailstones in clouds. Radar response from an active Cb cloud which holds large-size water drops and hailstones in suspension is pronounced and cannot but be a clear indication of the dangers of flying through such a cloud. The warning is adequate in that the response is received from a great distance and the pilot has

sufficient time at his disposal to take evasive action.

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