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POSSIBLE EFFECTS OF HEAVY RAIN ON AIRCRAFT

By J. S. SAWYER, M.A.

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POSSIBLE EFFECTS OF HEAVY RAIN ON AIRCRAFT

By J. S. Sawyer, M.A.

A number of reports from pilots who have flown in tropical rain have mentioned downward currents associated with it. In particular Wexler[1*] reported that, in a flight beneath the cloud of a hurricane off the east coast of America, a continuous downward force was observed on the aircraft and it only ceased when the clear centre of the storm was reached.

The following brief investigation was made to assess the importance of the various factors which might contribute to the downward motion of an aircraft during rain.

Rain may produce downward motion of the air through which it falls by the following methods :—

(i) by frictional drag of the falling raindrops,

(ii) by cooling the air by conduction on account of its lower temperature and thus producing air denser than its environment which consequently descends, and

(iii) by cooling the air by evaporation, thus producing down currents as indicated in (ii), or modifying the lapse rate so that vertical instability and convection currents result.

In addition to causing downward motion of the air heavy rain might directly produce downward motion of an aircraft by :—

(iv) the impact of the raindrops upon it, and

(v) the weight of the rain-water on the aircraft during the short period before it was blown off.

The magnitude of these effects are considered in turn. It is found that the latter two (iv) and (v), which are considered first, have no appreciable effect on modern aircraft. Frictional drag (i), is usually less than cooling by conduction and evaporation except when the rain is very heavy.

Effect of impact of the rain on an aircraft.†—In order to assess the magnitude of the downward thrust exerted on an aircraft by the impact of rain, it will be sufficient to assume that, if the horizontal area of the aircraft is A, the total downward momentum of all the rain falling through an area A in an interval of time, t, will be destroyed (or transferred to the aircraft) by impact during this period. This implies that the same amount of rain strikes a moving aircraft as would a stationary one, and that it leaves the aircraft with zero vertical velocity.

It is uncertain how far this can be justified, but it probably over-estimates the downward thrust on the aircraft, because part of the rain which would strike a stationary aircraft will be carried clear of an aircraft in flight by the air moving over its wing surfaces. This however is unimportant for the present purpose which is to derive an upper limit to the thrust produced by rain.

The following notation is used :—

A = horizonal area of aircraft.
r = radius of raindrops.
σ = density of water.
v_r = downward velocity of raindrops of radius r.
n_r = number of drops of radius r per unit volume.
n = total number of drops per unit volume.
R = rate of rainfall.

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*These numbers refer to the Bibliography on p. 7.

†The effect of the impact of rain is to produce both a downward thrust and a horizontal drag. Only the former is considered in the present note.

C.G.S. units are used and, thus, R is expressed as centimetres of rain per second.

With this notation the downward momentum of a drop of radius r is

$$\tfrac{4}{3}\pi\sigma r^3 v_r$$

and the number of drops of radius r striking the aircraft in time t is $An_r v_r t$. Thus the momentum destroyed in time t is

$$\tfrac{4}{3}\pi\sigma At\sum_r r^3 n_r v_r^2,$$

where the summation is made over all possible radii of raindrops.

Thus the downward force acting on the aircraft due to the impact of the rain is

$$\tfrac{4}{3}\pi A\sigma\sum_r r^3 n_r v_r^2,$$

and if F is written for the force per unit area of the aircraft

$$F = \tfrac{4}{3}\pi\sigma\sum_r n_r v_r^2 r^3.$$

To obtain the magnitude of F we assume the raindrops are all of one radius r and have one velocity v. Then

$$F = \tfrac{4}{3}\pi\sigma n v^2 r^3,$$

$$\text{but } R = \tfrac{4}{3}\pi n v r^3,$$

$$\text{thus } F = R\sigma v.$$

Neglecting the possible downward motion of the air itself, the maximum velocity of falling raindrops[2] cannot exceed 800 cm./sec. and thus, since $\sigma = 1$ in C.G.S. units, F cannot exceed $800R$. F and R are both expressed in C.G.S. units, *viz.* dynes per square centimetre and centimetres per second.

The highest recorded rate of rainfall in England is 32 mm. (1·25 in.) in 5 min. at Preston[2]; this gives a value of $R = \cdot 01$ cm./sec. and a maximum value of the downward thrust $F = 8$ dynes/cm.^{2} or $1\cdot 7 \times 10^{-2}$ lb./sq. ft.

Even the highest recorded rate of rainfall in the world, 26 mm. (1·02 in.) in 1 minute in California[3] gives a value for F of only $6\cdot 8 \times 10^{-2}$ lb./sq. ft.

Both these values of the downward thrust from impact of rain are insignificant compared with the wing loading of a modern aircraft which is usually from 30 to 50 lb./sq. ft.

Effect of the weight of rain on an aircraft.—If we assume that on the average the rain-water remains on the surface of the aircraft for a short period, t sec., the mass of water on the aircraft at any one time is equal to the mass of water striking the aircraft during such a period of t sec., namely $Rt\sigma$ per unit area. This exerts a downward force on the aircraft equal to its weight, that is $Rt\sigma g$ per unit area.

If the water remains on the aircraft for only one second this downward force is $981R$ dynes/cm.^{2} compared with a maximum of $800R$ dynes/cm.^{2} due to the impact of the rain.

Thus the downward force on the aircraft due to the weight of the rain exceeds the force due to its impact, if the rain-water remains on the aircraft for only one second. However, the two effects together can, even in extreme cases, produce a downward force no more than one hundredth of the normal lift of a modern aircraft, and are thus insignificant.

Effect of rain in producing downward air currents.—The effect of rain in cooling the air through which it falls has been discussed by Gold[4], and he indicated how, under suitable conditions of lapse rate of wet-bulb potential temperature below the cloud, this cooling may result in vertical instability and convection currents below the cloud.

In the problem of estimating the downward velocities of air currents likely to be produced by rain many factors are involved, and therefore later sections of this note will be confined to a consideration of the relative importance of the frictional drag and cooling effects of rain. However, it is first desirable to consider briefly the manner in which downward air currents can be produced during rain.

If we consider first rain falling uniformly over a wide area, so large that it may be treated as infinite, the effect of the frictional drag of rain will be to apply a downward force uniformly to the air throughout the rain area. This will result, after a slight compression of the air, in an increase in the downward gradient of pressure in the air, but as this will be uniform throughout the rain area there will be no horizontal pressure gradient, no horizontal air motion and consequently no vertical air motion.

Under similar conditions, the cooling of air by rain will cause a slight increase in density and therefore of the downward force per unit volume of air. As when produced by frictional drag this will result in no downward motion if the rain falls uniformly over a wide area, unless the lapse rate of temperature is so altered as to give rise to instability, when both upward and downward currents will occur in the rain area.

In the second place we consider rain falling over a limited area outside which there is no rain, or the rain falls at a different rate, then the additional downward force due to the frictional drag or cooling is applied to the air over a limited area only, a horizontal pressure gradient arises and air in the region of heavier rain will be displaced downwards and outwards at the base while that in the region of lighter rain will be displaced upward. If the lapse rate of temperature in the region outside the rain is less than the saturated adiabatic, the displacement of the air will be limited, because during its downward motion in the rain area its temperature will follow the saturated adiabatic, and ultimately reach a level at which it will be sufficiently warmer and lighter than the air outside the rain area to balance the downward force on it due to the rain. If, however, as is more likely, the temperature lapse outside the rain area equals or exceeds the saturated adiabatic the rain will produce a continuous air circulation descending in the rain area and ascending outside.

Although we cannot arrive at any reliable estimate of the downward velocity of such an air current we can compare the magnitude of the downward force produced by the frictional drag of the rain and by its cooling effect. This is done later.

We can also see that rain of the same intensity is likely to produce stronger down currents when it is restricted to a small area (*e.g.* a small shower) than when it occurs in a larger storm. It is also worthy of note that the temperature differences which can be expected to be caused by the evaporation of rain falling from shower clouds are of several degrees Centigrade and similar in magnitude to those observed in upward convection due to surface heating and condensation. It may thus be expected that the downward currents caused by cooling of air by rain beneath shower clouds will be of similar velocities to the up currents observed in convection cloud.

In a recent paper Buell[5] attempts to estimate the velocity of downward air currents due to the frictional drag of rain. This he does—ignoring any changes in temperature in the descending air and the difference between the temperature of the descending air and its environment, ignoring the sharp increase in surface pressure observed during heavy rain[6], and ignoring turbulent friction between the descending air and the surrounding air unaffected by rain. Assuming that the air is accelerated from rest at a height S in the atmosphere from which the rain falls, he derives an equation for the downward air speed V which may be written in the notation of the present paper as

$$\left(\frac{V}{v}\right)^2 + \frac{2}{3}\left(\frac{V}{v}\right)^3 = 2g\frac{\sigma}{\rho}\frac{RS}{v^3}$$

where ρ is the density.

A typical value obtained from the graphs given in Buell's paper for very heavy rain at 25 mm./hr. falling through 5,000 ft. is a down current of 800 ft./min., and Buell also shows that on the basis of his estimates, recently observed rain of 10 mm. (0·4 in.) in 4 min. at New York could, by falling through a layer of 15,000 ft., account for a down current of 2,500 ft./min.

Ignoring, as he does, the momentum acquired by air outside the rain area at least equal to that within it, it is fairly certain that Buell's figures are a considerable over-estimate of the normal down currents in rain. On account of this alone we might expect his results to be too large by a factor of two, whereas friction will undoubtedly cause a further reduction in the speed of the air currents.

One special case perhaps deserves mention in which very large down currents might be produced by rain, theoretically even exceeding Buell's estimates: this occurs when a small closed circulation is set up, as in the roll cloud of a line squall, and it is possible for rain continuously to accelerate the air within a closed circulation by falling through the descending portion.

Relative importance of frictional drag and cooling by rain in producing downward air currents.—Although it would be difficult to assess the velocities of the vertical currents set up by rain we can quite easily compare the relative importance of frictional drag and cooling by rain as agencies in causing vertical motion. If we assume that the falling rain has reached its terminal velocity, the downward force exerted by the weight of each drop must be exactly balanced by the upward frictional force exerted on it by the air. This latter force represents the downward force exerted by the rain on the air and is equal to the weight of the rain.

Using the notation as before and assuming the rain consists of drops of uniform size and velocity v, the mass of rain per unit volume of air is $R\sigma/v$ and its weight $R\sigma g/v$. Thus the downward force acting on unit volume of air is increased from its weight ρg to $\rho g + R\sigma g/v$.

We are thus led to inquire what change in temperature of the air would lead to an equal increase in the downward force per unit volume by reason of the change in the air density.

Suppose the temperature of the air is T °A, and that a decrease in temperature to T_1 and corresponding increase of density to ρ_1 give an increase in weight per unit volume equal to the frictional drag of the falling rain, then

$$\rho_1 g = \rho g + \frac{R\sigma}{v} g.$$

But, from the gas laws, $$\frac{\rho_1}{\rho} = \frac{T}{T_1},$$

$$\text{thus } \rho\,\frac{T - T_1}{T_1} = \frac{R\sigma}{v}$$

$$\text{or} \quad T - T_1 = \frac{R\sigma T_1}{v\rho}$$

For the present purpose we may approximate by taking $T_1 = T$ on the right-hand side of the equation ; thus

$$T - T_1 = \frac{R\sigma T}{v\rho}$$

If we substitute values $T = 280°$A., $\sigma = 1$ gm./cm.^{3}, and $\rho = 1{\cdot}26 \times 10^{-3}$ gm./cm.^{3},

$$T - T_1 = 2{\cdot}2 \times 10^5 \times \frac{R}{v}.$$

For convenience we consider the same examples of rain as considered by Gold[4] :—

(i) Very heavy rain at the rate of 50 mm./hr. ($R = 1{\cdot}4 \times 10^{-3}$ cm./sec.) with drops 2 mm. diameter (rate of fall $v = 600$ cm./sec.)* gives

$$T - T_1 = 0{\cdot}05°\text{C.}$$

(ii) Heavy rain at the rate of 5 mm./hr. ($R = 1{\cdot}4 \times 10^{-4}$ cm./sec. with drops 1 mm. diameter (rate of fall $v = 450$ cm./sec.)* gives

$$T - T_1 = 0{\cdot}07°\text{C.}$$

(iii) Rain at the rate of 1 mm./hr. ($R = 2{\cdot}8 \times 10^{-5}$ cm./sec.) with drops 0·2 mm. diameter (rate of fall $v = 100$ cm./sec.)* gives

$$T - T_1 = 0{\cdot}06°\text{C.}$$

(iv) The absolute maximum observed rainfall of 1,550 mm./hr. (1·02 in./min.) quoted above ($R = 4{\cdot}3 \times 10^{-2}$ cm./sec.) assuming the rain has the limiting velocity of 800 cm./sec.* gives

$$T - T_1 = 12°\text{C.}$$

The above results show that in light or moderate rain, and even in heavy rain up to about 25 mm./hr. the effect of the downward drag of the rain will be no greater than the effect of the cooling of the air a small fraction of a degree Centigrade.

The effect of rain is to cool the air to its wet-bulb temperature. Thus since a wet-bulb depression of 0·2°C. corresponds to a relative humidity of over 90 per cent. and, under conditions of complete mixing is exceeded at all levels more than 120 ft. below the cloud base, evaporative cooling of air by this amount may be expected on most occasions. Consequently the effect of the downward drag of the rain can be neglected in comparison with the circulation set up by the cooling, unless the rain is very heavy, exceeding 25 mm./hr. In extreme cases of exceptionally heavy rain the frictional effect may considerably exceed that due to cooling.

*The downward velocity of the air itself is ignored—its inclusion would decrease $T - T_1$ and mean that a greater rainfall would be needed to produce the same downward force.

Frequency of heavy rain.—The frequency of rain of various intensities is given below for Tiree, Scotland; Batavia, Java; and Ocean Island, Pacific.[7]

FREQUENCY PER YEAR OF RAIN EXCEEDING GIVEN INTENSITIES

	Intensity, mm./hr.					
	⩾2	⩾5	⩾10	⩾25	⩾50	⩾100
Tiree	287	42	7	0·6	0·2	—
Batavia	153	80	38	6·2	0·3	0·1
Ocean Island ..	693	433	268	100	28	2·6

Rain exceeding 25 mm./hr., and thus effective in producing downward air currents by frictional drag, is rare in tempeiate latitudes, but becomes frequent at some places in the equatorial regions (100 occasions per year at Ocean Island, 6 at Batavia).

However, the area in which rain falls with such intensity is usually small, the average diameter of such areas of intense rain being about 5 miles.

Conclusion.—The results obtained above can be summarised as follows:—

(1) The most important factor in producing downward air currents in rain is the cooling of the air by the evaporation of the rain.

(2) The effect of the frictional drag of the falling rain can only exceed the effect of the cooling with exceptionally heavy rain. In light or moderate rain it is negligible.

(3) The direct effect of the impact or weight of rain on an aircraft is negligible.

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