CONVECTIONAL VORTEX RINGS - HAIL

Robert E. Horton

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Abstract—Vortex-ring clouds and cloud systems sometimes occur, especially in early stages of violent convective storms. The vortex rings are usually enveloped in cloud in later stages of the storm and are either invisible or not distinguishable from convolutions of cloud. Conditions favorable for the formation of vortex-ring cloud systems are also favorable for severe hailstorms.

It is difficult to account for the uniformity of size and layering of hailstones in many storms on the basis of suspension by varying gustiness in a continually ascending air current. Also it is difficult to account for an ascent velocity sufficient to sustain large hailstones and lasting long enough to permit their formation.

These and other characteristics of hailstones are met if, in some hailstorms, ring-vortex ascent of moist air occurs and hailstones are formed within the vortex ring or rings. This provides requisite ascent velocity for suspension of large hailstones and a much longer period of suspension than direct ascent in the core of the vortex.

It is concluded that hailstorms are of two kinds: (1) Those occurring in conjunction with continuous convective upflow of a column of air without formation of vortex rings, which may be designated as 'tubular convective' storms; and (2) those occurring in conjunction with ring-vortex storms and producing much more uniform hail and permitting larger hail to form.

The treatment of the subject is hydrodynamic rather than thermodynamic and details are given of the rheologic or flow conditions involved.

Part 1--Vortex rings in cumulus clouds

Examples—Vortex motion in the atmosphere occurs in well developed cyclonic circulation and with increasing intensity in tropical hurricanes, typhoons, tornadoes, and waterspouts; also, on a smaller scale, in dust whirls. In all these cases the vortex motion is about a vertical axis, one terminal of the vortex filament being at the ground surface. Little consideration seems to have been given to another type of vortex motion, where the filament is closed, forming a vortex ring.

The ordinary, vertically convective system comprising most thunderstorms may be considered hydrodynamically as a rheologic or flow system, resembling the flow through a vertical pipe connecting two reservoirs, with lower pressure in the upper reservoir. This may be called the tubular type of vertical convection.

The first published illustration of a storm of this type the author has found, is that shown on Figure 1, reproduced from a drawing by MEARS [1931]. This storm occurred in Westmorland, England, in the Pennine Range, about 16000 ft, August 28, 1930. Mears described what he saw as follows: "...A huge column of cloud, steadily increasing in height, perhaps half a mile or more in diameter and capped by an immense mushroom top... .The column below was not smooth or spiral as in pictures of tornadoes and waterspouts; it was composed of vast 'vortex rings,' which increased in number as the whole edifice grew, until there were at least five. We estimated the height of these rings at about 500 ft each, they were closely touching and rotating visibly at a high speed. The rotation was outwards from the top and downwards, and we thought that the surface velocity might certainly be not less than 60 mph."

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Mears described the formation of this cloud as a result of a warm moist air layer which developed on a flat platform forming the Crossfell sector of the Pennine plateau. The platform is about two sq mi in area, at elevation 2500 ft, and was covered with heather. There was no rain at the location of the observer but heavy thunderstorms occurred nearby that afternoon and evening. Apparently Mears observed a violent vertically convective storm early in its formation. Mears estimated the height of the cloud at about 10,000 ft and the diameter of the torus ring sections as about 500 ft.

Another example of vortex ring cloud is described by Crichton [1928]. This cloud was observed over London at 15h30m GMT, September 18, 1928 (see Fig. 2). Crichton states that the sky was about 30 per cent covered with cloud, which was neither true strato-cumulus nor cumulus. Crichton states: "The main clouds were not really isolated in the sense that each was entirely independent of the other; they appeared to be intimately connected as their pattern and texture were very similar and although I observed only one complete vortex, other clouds showed signs of having recently been of a vertical type."

Additional examples of vortex ring clouds are given by Shipley [1941], who also gives a sketch of his conception of the cross-section of a thunderstorm. This comprises a small convection tube surrounded by a series of thick horizontal vortex rings or a tubular sheet vortex. He also gives qualitative evidence that somewhat similar conditions result in the production of hailstones and lightning. His model differs in several important respects from either the author's model of a hailstorm (subsequently described) or that of a thunderstorm. Shipley suggests that initially there is a small vortex ring between each pair of larger rings but rotating in the opposite direction and which is broken up at an early stage. The two rings constitute a vortex pair. A vortex pair is often observed behind a moving solid in water.

It may, however, be considered as a truncated vortex ring. A single vortex ring is stable and there is no reason for Shipley's assumption.

After reading these accounts the author began to watch for the same phenomenon and on one occasion observed, in the mid-afternoon, an example of a succession of vortex rings forming a cumulus cloud and quite as perfect as that described by Mears. The rings appeared to be thicker, relative to their diameter, perhaps 2000 ft. The cloud probably extended to 20,000 ft and there were at least five or six rings wholly unobscured by cloud. There was an evident outward and downward motion of the visible surface of the rings as described by Mears. The cloud system moved rapidly eastward and the rings apparently became enveloped in cloud and there was abundant lightning visible, so that rain was apparently forming. The author was much too fascinated by the magnificent spectacle of this hydrodynamic system, projected, as it was initially, against blue sky, to think of making a sketch. On a few other occasions, in conjunction with active thunderstorms, the author has observed portions of what were obviously vortex rings protruding from one side of a mass of cumulus cloud accompanying a thunderstorm. It is conceivable that this phenomenon may be of quite frequent occurrence but has passed unobserved. In one instance parts of several vortex rings were visible but apparently not forming a uniform chain with a common vertical axis but appearing more like one side of a small pile of doughnuts.

Characteristics of vortex rings--It seems probable that this phenomenon occurs in conjunction with the initiation of vertically convective storms of a certain type, where, as described by Showalter [1944] "Pronounced rain activity is generally associated with air masses possessing a marked degree of convective instability, which in turn is generally associated with a lower layer of initially high moisture content separated from a much drier layer above by a stable layer or temperature inversion."
If an aperture is broken through the stable-cover layer described by Showalter, the conditions will be those required for generation of a vortex ring or rings as a result of the underlying air gushing up through the opening.

Whether tubular convection or a vortex-ring system develops will depend on the combination of conditions. If the uprush of moist air is gradual and steady, tubular convection only will result. If the uprush is abrupt, strong, and discontinuous, vortex rings will form above the stable layer. As many will form as there are successive impulses.

These statements are easily verified by any one, using the smoke-box apparatus devised by P. G. Tait [DALHEAR, 1894; and RISTEEN, 1898]. The inside of the smoke-box is sprinkled with ammonia and a saucer containing a little hydrochloric acid is set in the box. The top cover of the box must be flexible, as, for example, cardboard. Each successive tap on the cover will eject a quantum of white ammonium chloride smoke, which on ejection will form a perfect vortex ring. What is generated is really a vortex-ring system but in the smoke-box experiment the only visible component of the system is the torus or ring.

![Diagram of vortex ring system](image)

**VORTEX RADIUS** \( r \)

**TORUS** \( R \)

**CORE** \( R - r \)

**OUTER** \( R + r \)

**CORE VELOCITY** \( V_c \)

**FIELD** \( V_f \)

**RING** \( V \)

**AREA VORTEX SECTION** \( A \)

**VELOCITY RELATIONS, RING-VORTEX SYSTEM**

<table>
<thead>
<tr>
<th>POSITION</th>
<th>DISTANCE ( r' )</th>
<th>TRANSITIONAL VELOCITY ( V' )</th>
<th>ANGULAR VELOCITY ( \omega' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>WITHIN VORTEX SECTION</td>
<td>( r &lt; r' )</td>
<td>( \omega r' )</td>
<td>( \omega )</td>
</tr>
<tr>
<td>SURFACE</td>
<td>( r = r' )</td>
<td>( \omega r = V_c )</td>
<td>( \omega )</td>
</tr>
<tr>
<td>FIELD CIRCULATION</td>
<td>( r &gt; r' )</td>
<td>( V_c r / r' )</td>
<td>( \omega r^2 / r' )</td>
</tr>
</tbody>
</table>

**STRENGTH OF VORTEX = CIRCULATION** \( = 2 \pi r^2 \omega = \Delta V \)

**TORUS VOLUME** \( V = 2 \pi r^2 \)

**MASS** \( M = \rho V / g \)

**RADIUS OF GYRATION, VORTEX SECTION** \( = k = V / 2 \sqrt{2} r = 0.707 r \)

**ANGULAR MOMENTUM** \( = MKr \)

Referring to Figure 3, a vortex-ring system comprises (1) the torus or ring, (2) the core, which travels upward through the ring, and (3) the surrounding field. The ring travels upward as if its section were being rolled forward by the core. The relative motions of the ring, field, and core can easily be illustrated by laying a pencil across the palm of the left hand, held horizontally.
Then if the palm of the right hand slides forward over the pencil with a velocity $v_c$, corresponding to the velocity of the core of the vortex ring, the velocity $v_T$ of the pencil, which corresponds to the translational velocity of the ring, will be $v_c/2$ if the left hand is held stationary. If the left hand is moved backward with a smaller velocity $v_f$, corresponding to the field velocity of the vortex-ring system, then the pencil or torus will travel in the same direction as the core, with a velocity $v_T = (v_c - v_f)/2$. In general, the ring will travel upward with a velocity which may range in value between zero and $v_c/2$, this velocity depending, among other things, on the ratio of the radius $R$ of the ring or torus to the radius $r$ of the ring section. The outer ring radius $R + r$ is greater than the core radius $R - r$, and the volume of the return or field current must, for steady conditions, equal the volume of the upward current in the core. The downward speed of the outer part of the ring will bear more or less the same ratio to the upward velocity $v_c$ at the surface of the core as the reciprocals of the ring and core radii, or

$$v_T = v_c \left[1 - \frac{(R - r)}{(R + r)}\right]/2$$

Using this assumption in conjunction with the equation

$$v_T = \frac{(v_c - v_f)}{2}$$

gives

$$v_f = v_c \left(\frac{R - r}{R + r}\right)$$

Such a vortex-ring system possesses certain definite properties:

1. The torus is composed wholly of the ejected fluid.
2. The torus retains its individuality during the life of the ring. In this respect a vortex ring differs from a traveling wave, in which the system of motion persists but the fluid comprising the wave continually changes.
3. Within the ring section, or shaded section, as shown on Figure 3, the law of vortex motion prevails. The angular velocity of the ring section is constant, as in a rotating solid.
4. The ring system is subject to relatively little frictional resistance, behaves like a single mass, and, as may be observed in case of a ring from a smoke-box, it can travel a distance many times its outer diameter on its initial energy before it is broken up by viscous resistance.

If a vortex-ring system is produced by an uprush of air through a cover layer it will possess some properties different from those of an ordinary vortex ring, that is, the torus is composed of moist air and travels into drier air. The ejection of the ring mass through the aperture in the cover layer and the formation of the ring sets some of this drier air in motion as field circulation forming the core and return current. This air may be carried above its condensation level, becoming cloud, and then travel around the outside of the torus as part of the surrounding field. In this way the torus proper is enveloped in cloud and wholly or partially obscured from view. What is seen is a cumulus cloud.

If a ring vortex of constant density expands or contracts, the relations of the torus radius $R$ and the vortex radius $r$ must be such as to provide (1) constancy of volume and (2) conservation of angular momentum. These results will follow if $r$ varies as $1/R$, and conversely. If a ring vortex expands during ascent, or contracts during descent, as the result of changes of pressure and temperature, the volume of the vortex ring is changed in proportion to the expansion ratio, while the angular momentum remains constant. These conditions are met if the vortex radius $r$ remains constant while the torus radius $R$ varies in proportion to the expansion ratio.

The expansion of vortex rings in ascent is well illustrated by Mear's sketch (see Fig. 1). If there are several successive impulses, producing a chain of vortex rings, as in Mears' sketch, the diameter of the opening of the cover layer may increase with each successive ejection of a ring. Under these conditions the rings later formed will be of larger diameters and the whole column of rings may appear of nearly the same diameter as in the instance observed by the author.

The preceding considerations suggest:

1. Atmospheric vortex-rings systems are not likely to reveal themselves except in the early stages of formation of a vertically convective storm before the ring or rings have become obscured by vapor condensed by uplift of drier air through the core. If the upper air is abnormally dry a ring or system of rings may be projected to a considerable height before it becomes enveloped in cloud.
In case of a succession of rings, when one ring is formed, it apparently brings about differential inertia effects between the air remaining beneath and above the cover layer, so that the cover layer vibrates up and down, producing a succession of surges and rings. This phenomenon is easily produced with a smoke-box by attaching a weight to the flexible cover so that when once disturbed, it vibrates back and forth for a time. When the vibrations become sufficiently slight, rings are not formed although there may still be an upward flow of moist air through the break in the cover layer.

If it were possible to dissect flat-bottomed, fair weather, cumulus clouds, some might be found to contain vortex rings but many would not because of either (a) the lack of an appropriate cover layer and aperture, or (b) lack of a sufficiently strong, rapid impulse to develop a ring system.

CONVECTIONAL VORTEX RINGS

Air circulation in thunderstorms and hailstorms

As early as 1875, John Wise [BLASIUS, 1875; SHAW, 1932] wrote a classical account of his experience trapped inside of a violent thunder and hailstorm during a balloon ascension. Wise tells how his balloon was carried toward and into a huge black cloud, apparently of circular form and four to six mi in diameter, how he found himself "whirling upward with a fearful rapidity, the balloon gyrating and the car describing a large circle in the cloud." Pelted by hail and snow, he was hurled rapidly upward, then violently surged downward, apparently some hundred feet. This happened eight or ten times, covering an interval of 20 min, until, finally, he was disgorge from the cloud and landed in a field in drenching rain. He noted the "violent convolutorial motion or action of the vapor cloud." Hardly could a more perfect description be given of the motion within a large vortex ring surrounding the core of a hailstorm.

An example of the formation of a tubular sheet vortex is easily observed but not always recognized in the case of dense smoke and steam ejected from the funnel of a locomotive when laboring heavily. In this case there is a series of successive impulses, each producing the ejection of a quantum of vapor and smoke and a vortex ring. This is not greatly unlike the more or less uniform gustiness of wind in a thunderstorm.

It can readily be shown that if ordinary turbulent flow of a fluid is considered as primarily laminar flow, on which is superposed resistance resulting from turbulence generated in the boundary layer in the form of vortex-ring systems transmitted into the interior of the flow, then 99.50 to 99.99 per cent of the energy available to produce translatory motion will be converted into vortex-ring energy and so will become latent in so far as producing motion of translation is concerned. Because of the relatively small resistance of laminar as compared with turbulent flow, the small remaining translatory energy suffices to produce the observed velocity of translation. In the case described, the energy entrained in the vortex rings is slowly dissipated as heat by viscous resistance within the fluid. This affects the velocity distribution but does not affect the mean velocity, which is determined by the amount of remaining translatory energy available. This is determined by conditions at the boundary and hence the rate or manner of dissipation of the latent energy of the vortex rings does not affect the mean velocity.

Experiments carried out by the author with a smoke-box having a round orifice at one end showed that the character of the vortex ring produced by a single impulse differed with the duration and sharpness of the impulse. A gentle pressure on the lid of the box lasting perhaps half a second produced a small vortex ring with outside diameter little greater than that of the orifice and a very small central opening or core diameter and a low velocity. A somewhat shorter, less prolonged impulse produced a larger ring with smaller torus section, larger core diameter and higher velocity. A sharp, short impulse produced a vortex ring with an extremely small torus and a core diameter about equal to the diameter of the orifice.

With a slow gentle impulse all the ejected fluid was entrained in the vortex ring. With stronger impulses, increasingly larger amounts of the ejected fluid remained separated from the ring as a part of the core, until finally, for a sharp, quick impulse, a large portion of the ejected fluid shot forward as a jet and only a small portion was entrained in the ring. These results are summarized in Table 1. In each case the ring traveled forward a certain distance at nearly a constant velocity and with a slight increase in diameter, then suddenly expanded to several times its original diameter, its forward motion stopped and the ring dissipated.

In each case similar experiments were carried out where, instead of a single ring, impulses of equal intensity and duration were produced as nearly as possible at uniform intervals, forming a chain of successive rings which approached each other as they traveled forward, and finally all came to rest at the same distance from the orifice. For slow, gradual impulses all of the
ejected fluid was contained in the rings, as shown on Figure 4A. For a succession of short, sharp impulses, the rings were so small and moved so rapidly as to be barely discernible but in view of the fact that most of the ejected smoke from the box remained in the core, there was formed virtually a steady stream or jet of fluid, as shown on Figure 4B. Except for extremely slow-moving rings the core diameter appeared to be nearly identical with the diameter of the rings. Assuming this to be the case and that the conditions are such that nearly the entire volume of ejected fluid is entrained in the ring, then a simple relation between the dimensions of the ring and its velocity as it leaves the orifice can be obtained as follows:

Let \( V_j \) = volume of ejection or volume of ring; \( v_j \) = velocity of ejection through the orifice; \( t \) = duration of the impulse; \( r \) = core radius of the ring; and \( R \) = outer radius or torus. Then

\[
V_j = \pi r^2 v_j t
\]

Also

\[
V_j = \pi (R + r) \cdot \pi [(R - r)/4]^2
\]

### Table 1—Effect of impulse on vortex ring

<table>
<thead>
<tr>
<th>Impulse</th>
<th>Cross section</th>
<th>Core radius</th>
<th>Torus radius</th>
<th>Ejected fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradual</td>
<td></td>
<td>Small</td>
<td>Large</td>
<td>Goes into ring</td>
</tr>
<tr>
<td>Moderate</td>
<td></td>
<td>Medium</td>
<td>Medium</td>
<td>Mostly in ring</td>
</tr>
<tr>
<td>Quick</td>
<td></td>
<td>About same as aperture</td>
<td>Small</td>
<td>Mostly in core</td>
</tr>
</tbody>
</table>

Figs. 4A and 4B—Vortex-ring chains
Let \( \rho = R/r \). Equating (2) and (3) and solving for \( v_j \) gives

\[
v_j = \pi r \left( \rho^3 - \rho^2 - \rho + 1 \right)^{1/4}
\]

It can readily be shown that this equation has one real and two conjugate imaginary roots. Only the first of these roots need be considered. The value of this root can be expressed algebraically but for practical purposes it is more satisfactory to use a graphical solution.

Figure 5 shows values of \( \rho = R/r \) in terms of \( z = v_j t/r \). For a given orifice radius \( r \), and for the assumed conditions, the outer ring radius \( R \) can be obtained from the strength and duration \( v_j t \) of the impulse. This curve gives results in accordance with the experimental results above described.

If a series of impulses or gusts occurs in a current of moist air flowing through a break in the cover layer, then the experiments described indicate that a varying range of conditions may result, as shown on Figure 6. For slow, prolonged impulses a tubular sheet vortex would be formed around an ascending core of air, as shown on Figure 6A, most of the moist air being contained in the vortex rings, which would gradually ascend and spread out at a certain height above the cover layer or orifice, at which height their energy is exhausted. For a series of short, sharp impulses, as shown on Figure 6B, most of the moist air would be contained in the ascending core and the surrounding chain of vortex rings or tubular sheet vortex would form a thin sheet or boundary of the ascending core. An infinite number of conditions can apparently exist. The conditions shown on Figure 6B are apparently those of most intense thunderstorms. Those occurring as shown on Figure 6A are much less usual and are probably those accompanying many hailstorms.

Figure 6A represents a type of flow of one fluid through another which has not, so far as the author knows, been considered in hydraulic literature, and the laws and theory of its occurrence have not been fully determined. It can and apparently does occur under at least two natural conditions (1) in some thunderstorms, and (2) in some cases of density currents in lakes and reservoirs.
In case of turbulent flow in a pipe the resistance to flow occurs almost wholly in the boundary layer and results from the conversion of translatory energy into non-translatory or rotational energy of vortex rings. In this way most of the energy available to produce flow becomes in effect latent at the boundary. In case of a pipe the vortex rings are projected into the interior of the fluid current. For the conditions shown on Figure 2, the resistance to flow is again the result of translatory energy becoming latent in vortex rings formed at the boundary of the current. In this case there is no solid boundary and the vortex rings form a tubular sheet vortex surrounding the current and so remain outside of the region of flow. The translatory current in the core is composed wholly or chiefly of fluid drawn into the core between the successive rings as a part of the field circulation of the vortex system. Under these conditions the generation of vortex rings at the boundary has no effect on the velocity distribution in the core and the flow in the core is of a type in which the resistance and the mean velocity are the same as for ordinary turbulent flow but the velocity distribution within the core resembles closely that for laminar flow.

The mean velocity in a pipe represents the mean ordinate of a solid of revolution having as its base the cross-section of the pipe and as its ordinates the point velocities throughout this cross-section. So-called hydraulic slope formulas give the mean velocity in terms of slope S, hydraulic radius r/2, and roughness factor n. The formula now mostly used is that of Manning, which may be expressed in a form which is dimensionally sound,

\[ v_m = \frac{(1.486/n)(r/2)^{2/3}}{S} \]

Also, the mean velocity is given by the equation

\[ v_m = \frac{(1/\pi r^2)}{\int_0^r v_r \pi dr} \]

Equating the two values of \( v_m \) and solving the resulting integral equation, an expression for velocity distribution or for \( v_r \) in terms of \( r \) can be obtained. Using the Manning formula this procedure leads to a law of velocity distribution closely resembling that for laminar flow, the velocity at the boundary being zero in both cases and the velocity increasing from the boundary to the center of the pipe in accordance with a parabolic law but with a different value at the central point from that for laminar flow.

The result obtained in this way is not the only possible velocity distribution. In this case it is a velocity distribution conforming to the required mean velocity for turbulent flow but with the velocity distribution in the pipe essentially the same as for laminar flow.

In the author’s model of a thunderstorm (see Fig. 6B) the ascending air in the core is considered to be almost wholly moist surface air. A small fraction of the total volume of surface air is incorporated in the thin tubular sheet vortex surrounding the core. In the model of a hailstorm (see Fig. 6A), the ascending moist air is all or nearly all included in the large vortex rings comprising the tubular sheet vortex, and the ascending air in the core is either dry country air or this mixed with more or less moist surface air detached from and not incorporated in the vortex rings. The fluid comprising the field circulation need not be and generally is not the same as that comprising the vortex ring. Two vortex rings close together, with parallel axes, will always remain a little apart, even when one passes through another, as is easily shown by experiment. The source of air in the core in the hailstorm model is a part of the field circulation surrounding the vortex rings. This passes into the core between successive rings, and a mass of air equal to that entering below a given ring passes out of the core above the same ring. In the meantime it becomes more or less mixed with moist air carried upward, with the result that the tubular sheet vortex is usually enveloped in cloud and is invisible.

Part 2--Hail

Characteristics of hail—Hail is economically important, chiefly because of the damage it produces. While high rates of precipitation can and do occur in the form of hail, the author has not found an instance in which hail produced a serious flood, even on the small area over which it occurs. The time required for melting the hail reduces the rate of contribution of surface runoff to streams to less than the maximum for runoff from rain.

Hailstones have the following characteristics:
(1) Hail occurs in unusually violent, vertically convective storms.
(2) It usually occurs at or near the onset of the storm and in the early stages of its development.
The precipitation of hail is usually of short duration, seldom more than a few minutes; there may be two hail periods, separated by a short interval of rain.

(4) Hailstones of various sizes occur in a given storm but there is often a particular size (sometimes two sizes) of hailstone which strongly predominate.

(5) Alternating layers of soft and hard ice comprising stones of a particular size have about the same diameters, forms, densities, sequence, and thickness.

Thus far atmospheric vortex-ring systems have been considered as a possible and probably not infrequent rheologic system accompanying convective storms. Whether such phenomena are of practical importance in dynamic meteorology remains to be determined.

The formation of hailstones is commonly attributed to water particles being carried upward through the hail and snow stages by a violent ascending air gust, then dropped out, caught at a lower level by another gust, and so on [HUMPHREYS, 1914]. Air currents accompanying vertically convective storms are subject to extreme gustiness. Aviators who have passed through such storms sometimes report losing and gaining height of more than a thousand feet at a time [ANONYMOUS, 1934]. Such examples of extreme bumpiness are commonly attributed to gustiness in an ascending air current. They are, however, equally well or better accounted for if the aviator happened to be caught in a ring vortex.

The ascending gusts in the tube-like core of a convective storm are neither uniform in intensity nor duration. Judged by gustiness at the ground level, they must be extremely irregular. Since the hail produced in a given storm is often mostly of uniform size, structure, and layering, it seems difficult if not impossible to explain the formation of such hailstones if they are the result of ordinary gustiness in an ascending air current. The height and velocity of ascent and descent would then be largely fortuitous, and hailstones of all sizes and with wide variations in character of layering would apparently result. References giving examples of hailstones of predominantly uniform size and structure follow.

ARENBERG [1938] describes a hailstorm at Washington, D. C., April 27, 1938, which the author also witnessed. This storm had the following features: Rain began 12h30m; small hail, hard ice 1/8 inch diameter, 12h32m to 12h34m; fragmental hail, one inch size predominating, 12h37m to 12h54m. These hailstones were unmistakably fragments of much larger hailstones and contained at least 12 thin concentric layers. The stones were mostly of conoidal shape and were evidently sectors of spheres two inches to three inches in diameter. The apex angles of the conoids (measured from photos) were about 60° and remarkably uniform. Arenberg gives calculations indicating that a large hailstone may be exploded by expansion of supercooled water on freezing. J. Schremp [ARENBERG, 1938, p. 277] suggests that fractures of the large hailstones may have resulted from atmospheric pressure waves generated by a nearby bolt of lightning. The form of the fragments is nearly that which would result from explosion by a central point charge in blasting homogeneous material. From the theory of blasting, this would produce conical fragments with a 45° slope or 90° central angle. If the material was less dense near the surface, the central angle would be smaller, as here observed.

ELLISON [1928] gives the following description of a hailstorm at Armagh, Northern Ireland, August 29, 1928: "But just before 15h, the storm broke without any warning. It did not approach, but seemed to develop right overhead out of nothing at all. A few very large drops of rain, making splashes as big as pennies, then a flash, and a crash of thunder following instantaneously, and not rain but hail, in stones as big as nuts and marbles, fell in sheets."

"The storm lasted altogether less than an hour, but the greatest intensity lasted about 20 min. The rainfall, as recorded at the Observatory, was 1.59 inches in 50 min, of which one inch fell in the first 20 min. The trace of the Beckley recording rain-gage was so close that it was difficult to say whether it had emptied itself four or five times during that time. The amount collected in the Snowdon gage close beside it, however, agreed with the larger amount. The greater part of the precipitation being hail, the rate of fall must have been considerably greater than the gages indicated, as the funnels were nearly full of hail, which took some time to melt. There were two distinct forms of hailstones; small cones with hemispherical base, and spheres of clear ice. These were mixed in about equal proportions." The description is accompanied by a photograph showing "hail lying a foot deep in the roadway, The Mall, Armagh, August 29, 1928."

Large hail with a uniform layer structure occurred at Bagdad, April 24, 1930 [ANONYMOUS, 1930]. "At 14h15m, GMT, slight rain commenced, and at 14h30m the wind began to drop to calm and a heavy fall of hail occurred, continuing for seven minutes...An average specimen was cut open and found to consist of five layers of alternating hard transparent ice and soft white ice,
Behavior of a heavy particle in a ring vortex—The uniformity of successive concentric rings in hailstones in a given storm suggests strongly that they are not the result of mere haphazard circulation due to ordinary turbulence but rather are the result of some definite system of motion generally occurring somewhere in conjunction with uprushes of air which produce hailstorms. The requisite conditions are apparently provided by vortex rings surrounding the ascending core of air. An ordinary smoke ring comprises two components with a common system of motion (1) the invisible air molecules, (2) enormously larger smoke particles. Both types of particles are, however, of colloidal or sub-colloidal size, so they are held in suspension by the Brownian movement and are little subject to gravitational motion. An ordinary smoke ring does not differ greatly from a hydrodynamic scale-model of an atmospheric vortex ring, perhaps several miles in outer diameter, with a vortex diameter of the order of several hundred feet, the two components in this case being (1) air, as before, (2) snowflakes and hailstone nuclei, replacing the smoke particles.

Snow and minute solid ice particles are of course acted on by gravity and if they are in vertical rotation they are acted on by centrifugal force. The centrifugal force effect for small, light particles is, however, generally small compared with gravitation because of the large vortex radius r relative to the rotational velocity v. Centrifugal force is given by the equation \( F = \omega^2 r/2g \). Hailstones of ordinary sizes are so strongly acted on by gravity that it is doubtful if they partake of the circular rotation within the vortex ring.

Some idea of the behavior of a hailstone within a ring vortex may be obtained by considering what would happen if a very small, heavy, solid particle, such as a pebble, were dropped into an ordinary experimental smoke ring. If it is dropped into the ring on the outer side, its velocity will be increased by the downward velocity in the ring and it will fall through the ring with some acceleration. If it is dropped into the ring on the core side, its velocity will be decreased and it may either fall through the ring or, with a suitably high ascent velocity in the ring, it may be brought to rest and carried back upward. As illustrated by Figure 7, the pebble will be acted on by two forces (1) gravitation, (2) the impact of the gas forming the ring vortex and flowing against the pebble. The direction of this impact varies with the position of the pebble in the ring. If the pebble is near the bottom of the ring, on the core side, the impact velocity tends to deflect the pebble away from the center of the ring section. If the pebble is near the top of the ring section the force tends to deflect the pebble to the left (see Fig. 7) and it may be carried over the top and then dropped out. Apparently a solid object with a constant terminal velocity can make only a single circuit or loop in passing through the section of a ring vortex.

An alternative condition, where there is a series of successive vortex rings, one above another, is that a solid object, such as the pebble here considered, with a constant terminal velocity, could drop from one ring to another, passing through a loop-like orbit within each successive ring, thus providing a series of alternate uplifts and descents, in each of which, in case of a hailstone, a pair of layers of hard and soft ice could be formed. This, however, is not believed to be the usual condition of formation of hailstones. It is a condition which can and probably does occur...
if the ring sections are of equal diameter and one below another. The distance the stone would
fall in passing through different rings would not vary greatly and the result might be a series of
alternate layers of soft and hard ice, the number of such layers being equal to the number of suc­
cessive rings surrounding the vertically ascending core of air.

The distance the stone would fall in passing through different rings would not vary greatly and the result might be a series of alternate layers of soft and hard ice, the number of such layers being equal to the number of suc­cessive rings surrounding the vertically ascending core of air.

**Terminal velocities of hailstones**—Using drag coefficients derived by towing spheres behind an airplane and equating the force with the resistance, Bilham and Relf [1937] determined the terminal velocities for spherical hailstones of different diameters and densities by use of the equation

\[ v_t = \sqrt{\frac{2 agd}{3 k_d}} \]  

(7)

- \( d \) = diameter, in ft; \( a \) = density of hailstone, lb/ft\(^3\); \( p \) = density of air, lb/ft\(^3\); \( k_d \) = drag coefficient; \( R \) = Reynolds number = \( \frac{v_t}{\gamma} \); \( v_t \) = terminal velocity, ft/sec, relative to air stream;
- \( \gamma \) = kinematic viscosity of air. Since the terminal velocity \( v_t \) is also the velocity of the ascending air current required to hold the hailstone in suspension, it may also be referred to as the suspension velocity. The terminal velocity \( v_t \) depends on the drag coefficient \( k_d \) and this depends on Reynolds number \( R \) and on the velocity. Consequently (7) must be solved by trial except for diameters less than 1.5 inches, for which \( k_d \) is sensibly constant and equal to 0.25. Bilham and Relf give terminal velocities for different densities, using, for air, \( \gamma = 0.000159; \) \( p = \text{density of air} = 0.0758 \text{ lb/ft}^3 \), and with values of \( k_d \) as shown in Table 2. For Reynolds number \( R \) between \( 3 \times 10^5 \) and \( 4 \times 10^5 \) the drag coefficient \( k_d \) drops off abruptly with change of regime of flow from laminar to turbulent. The terminal velocity increases abruptly for the critical diameter of hailstone to more than double its value for slightly smaller diameters.

Because of this change of flow regime, a hailstone which has grown to 4.8 inches in diameter will always fall, since to sustain it would require an ascending air current with a velocity of nearly 400 ft/sec. Bilham and Relf's calculated terminal velocities for different densities are accurately represented by the lines on Figure 8 and by the simple empirical formula there given. These are for surface conditions. For conditions at 10,000 ft elevation the terminal velocities are increased 15 per cent.

**Alternating terminal velocities**—As a hailstone grows, taking on alternate layers of high and low density ice, its terminal velocity will alternately increase and decrease for suitable conditions of density and layering. If the initial diameter and density of a hailstone are \( d_1 \) and \( \rho_1 \), and its density \( \rho_2 \) after the addition of a layer of ice of density \( \rho' \), increasing its diameter to \( d_2 \), then

\[ \rho_2 = \left[ \frac{d_1^3 \rho_1 + (d_2^3 - d_1^3) \rho' / d_2^3}{d_2^3} \right] \]

(8)

Diameters are in inches and densities are relative to water.

Assuming a hailstone with layering as in the example given above, the densities after addition of successive layers, using \( \rho' = 0.9 \) for hard ice and \( \rho' = 0.25 \) for snow ice, layers, the corresponding terminal velocities are as shown in Table 3. After the first soft layer is added, the terminal veloc­ity decreases with the addition of each successive low density layer. This suggests the possibility of the necessary alternations of hailstone velocity relative to that of the air current taking place in a steadily ascending air current without invoking gustiness as shown by the last column of Table 3. In this case the hailstone would continually ascend but at alternating higher and lower velocities relative to the air stream. If the accretion rate were proportional to the relative velocity, then the thicknesses of layers of either type of ice would be relatively constant and a large number of hailstones having the same or nearly the same structure and diameters would result. The steady flow conditions favoring this result certainly do not ordinarily exist in the core of a vertically convective storm.
Fig. 8—Terminal velocity in ft/sec of spherical hailstones; Bilham’s data, Q. J. R. Met. Soc., April 1937, p. 153, surface conditions

Table 3—Variation of density and terminal velocities

<table>
<thead>
<tr>
<th>Layer</th>
<th>$\rho'$</th>
<th>$d_1$</th>
<th>$d_2$</th>
<th>$\rho_2$</th>
<th>$v_t$</th>
<th>Ascent velocity$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.90</td>
<td>0</td>
<td>0.125</td>
<td>0.90</td>
<td>25.5</td>
<td>44.5</td>
</tr>
<tr>
<td>2</td>
<td>0.25</td>
<td>0.125</td>
<td>0.625</td>
<td>0.255</td>
<td>30.3</td>
<td>39.7</td>
</tr>
<tr>
<td>3</td>
<td>0.90</td>
<td>0.625</td>
<td>0.875</td>
<td>0.668</td>
<td>58.1</td>
<td>11.9</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
<td>0.875</td>
<td>1.375</td>
<td>0.357</td>
<td>53.4</td>
<td>16.6</td>
</tr>
<tr>
<td>5</td>
<td>0.90</td>
<td>1.375</td>
<td>1.625</td>
<td>0.529</td>
<td>70.3</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

$^a$In a uniformly ascending air current with a velocity of 70 ft/sec.

Gustiness, in the ordinary sense, is unquestionably much less pronounced in a ring vortex surrounding an ascending core of air than within the core. This results from various causes and can be proven experimentally by projecting a smoke ring through turbulent, smoky air. The ring may pass through the turbulence with apparently little effect. It appears that the combination of alternating terminal velocities, in conjunction with the air circulation in a vortex ring, provides the requisite conditions for the formation of large numbers of hailstones of similar sizes and characteristics.

A hailstone nucleus may originate at any point within the section of a ring vortex, as at $p'$, in Figure 9. Initially, it is so small that it may be carried around with the vortex in a nearly circular path but as it grows in size its terminal velocity increases until, when it reaches the point marked 1 on Figure 10, the vertical component of air velocity is insufficient to sustain it and it falls to point 2, taking on a layer of low-density ice as it falls, with a resulting decrease in its terminal velocity, so that at the point 2 the vertical component of rotational vortex velocity is again sufficient to sustain it and it starts a second upward course. Successive loops in the path of a hailstone may be somewhat as illustrated schematically by Figure 9. Finally, when the hailstone reaches sufficient size so that its terminal velocity exceeds the vertical component of vortex velocity at the lower point of its descent, it falls out of the vortex to the ground.

The determination of the equation of the looped spiral orbit of a growing hailstone enveloped by a vortex ring presents an interesting problem in mathematical physics, involving physics, physical chemistry, fluid and solid dynamics, thermodynamics, and some as yet unsolved problems concerning...
the laws of condensation, particularly the effect of wind on rate of condensation. At a given position in the vortex section a hailstone which has fallen far enough to attain its terminal velocity will have the following velocities; where $r'$ is the distance from the center of the vortex filament to the center of the hailstone.

\[
\text{Falling velocity} = v_t + v_ar'/r \\
\text{Ascent velocity} = v_t - v_ar'/r
\]

\[
\text{Time of ascent/Time of fall} = \frac{(v_t + v_ar'/r)}{(v_t - v_ar'/r)}
\]

The last equation shows that the time of ascent will be greater, often much greater, than the time of fall, in executing a given cycle.

No assumption has been made as to the manner in which accretion occurs and hailstones grow in size. Authors are not in agreement either as to this [SCHUMANN, 1938] nor are they in agreement as to the temperature of a hailstone relative to that of the surrounding air. A hailstone is not cooled or heated in rising or falling, as much as the air, and it seems clear that at the top of a cycle a hailstone is warmer relative to the surrounding air than when at the bottom of a cycle. Its temperature may be and probably is below freezing in both locations. VON HANN [1926] states that the temperature of hailstones, measured immediately after their fall, is often much below 0°C and can reach from -5 to -15°C.

It is assumed that a hailstone forms a hard ice layer in ascent and a softer ice or snow-ice layer in descent.

It will be seen that small hailstone nuclei are quite certain to be carried over the top in their first circuit within a ring vortex and will then fall to the ground either as graupel (soft hail) or, after melting, as rain, while larger nuclei will in general form hailstones, whatever may be their point of origin within the ring vortex.

Calculations above given are based on an assumed density of 0.25 for soft ice accretion during descent. Probably the newly added material if in the form of ordinary snowflakes will have initially a density 0.1 instead of 0.25, as assumed in Table 3. The terminal velocity during descent may then drop off rapidly and only a relatively small vertical velocity component will be required to start the hailstone on another upward course. Each soft layer therefore will become consolidated more and more as new layers are added.

It is to be remembered that when thick rings are formed, nearly all of the ejected moist air goes into and remains in the rings. The core and surrounding field are constituted of drier air. Apparently hail is not likely to form in both the core and the vortex in the same storm.
With respect to an observer in the path of the core of a ring-vortex hailstorm, hail should occur in two periods, separated by a short interval, as happened in the hailstorm of April 27, 1934 at Washington. As a result of storm travel these two periods may overlap, affording continuous hail. With respect to an observer so located that a portion of the ring vortex, but not the core, passes over him, there would be only one hail period.

Number of cycles and time of ascent of a hailstone—If the hailstone fell at a velocity equal to its terminal velocity, the latter remaining constant, then since its velocity in rising is $v_t - v_a$ and in falling, $v_t + v_a$, relative to the earth, its mean velocity of ascent and descent relative to the surrounding country air would be zero. If the major axis of its orbit were equal to the diameter of the vortex it would make approximately one cycle for each revolution of the vortex. Variations of these conditions as to height and form of orbit and terminal velocity will alter this result and it appears that a hailstone will execute a cycle in less rather than in more time than is required for a revolution of the vortex.

If the gross time required per cycle is assumed equal to $t_r$, the time of revolution of the vortex, then the least number of cycles executed by the hailstone while the vortex is rising through a height $h$ will be

$$N = \frac{h}{4\pi r} \quad (12)$$

and the least time of suspension will be

$$T = \frac{h}{v_a} \quad (13)$$

For example, taking $h = 31,480$ ft, which is about the maximum, and $r = 500$ ft, a hailstone will pass through at least five cycles in rising, and if $v_a = 50$ fps, the time of suspension $T = 10.4$ min. The core of the vortex will rise through the same height in one-half of this time or 5.2 min. Actually the time of ring ascent will always be greater than these figures indicate, for two reasons: (1) The ring velocity $r$ is governed by the velocity at the outer surface of the core. This will always be smaller than (usually about two-thirds) the mean velocity $v_a$ of the core. (2) The ring velocity will be reduced by the effect of the downward velocity of the field and so will be less than one-half of the peripheral velocity of the ring.

It will be seen that the ascent velocity of the vortex ring is always less than one-half the ascent velocity at the periphery of the core and still smaller relative to the mean ascent velocity of the core. A ring vortex provides both the high velocity of ascent at the position of the hailstone, required for suspension of large hail, and the considerable duration of the process of hail formation which seems necessary in case of large hailstones.

Whatever may be the manner of growth of a hailstone, whether by condensation of vapor, absorption of cloud particles or by accretion of supercooled raindrops or snowflakes, some idea of the travel distance and time required for the growth of a hailstone may be obtained by a simple method used by Schumann [1938].

If $m$ is the water concentration in the air, grams/cc, including vapor, liquid, and frozen water, and $z$ is the fraction of the total water encountered by the hailstone in its path which is absorbed or condensed on the hailstone, then Schumann’s analysis shows that the distance $S$ which the hailstone must travel relative to the air to sweep up sufficient water to give it a radius $R$, in cm, is given by the formula

$$S = \frac{\rho (4R - 1)}{zm} \quad (14)$$

where $\rho$ is the density of the hailstone, grams/cc. Assuming that the hailstone grew by condensation of vapor and that all the vapor in its path was taken up, and with $m = 5 \times 10^{-6}$ and $\rho = 0.6$, starting with a stone $1/4$ cm in diameter, $S = 16$ km. Schumann states that the maximum value of $m$ for vapor is $5$ to $7 \times 10^{-6}$, grams/cc, but believes the high-rain intensities indicate that raindrops in suspension may increase this to as much as $38 \times 10^{-6}$.

Schumann also studied the time required for the growth of a hailstone and concludes: “that there must either be extraordinarily high concentrations of condensed water or that there must be extremely violent up-currents to maintain the hailstone for a sufficient length of time in the environment favorable to its growth.”
Limiting conditions of hailstone formation—BILHAM and RELF'S [1937] analysis leads to the result that hailstones over 4.8 inches in diameter cannot form, but only for the reason that when this size is attained, their suspension velocity is quite suddenly increased, so that it would require an ascending air current of over 200 ft/sec to sustain them. Authentic hailstones of over four inches diameter are on record, also fragmentary stones with radii indicating that the parent stone was over four inches in diameter.

The peripheral velocity of a vortex filament or the surface velocity of the core must at least equal the suspension velocity of the hailstone in order to permit a stone of a given diameter to form. BUELL [1943] has given an equation for the maximum ascent velocity in the cumulus-congestus in a convective storm in terms of the height J in millibars of the barometric jump at the onset of the storm. Buell's equation can be reduced to the form

\[ v_g = 43\sqrt{J} \]  

(15)  

in ft/sec. From Figure 8

\[ v_t = 76 \sqrt{\rho d} \]  

(16)  

Equating \( v_g \) and \( v_t \) gives

\[ J = 3.13 \rho d \]  

(17)  

for \( J \) in millibars, \( d \) in inches, and \( \rho = \) unity for water.

Table 4 shows the calculated terminal velocities \( v_t \) and \( J \) for hailstones of a density of 0.6 and of different diameters.

<table>
<thead>
<tr>
<th>Diameter (in)</th>
<th>( v_t ) (ft/sec)</th>
<th>( J ) (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>41.3</td>
<td>0.94</td>
</tr>
<tr>
<td>1.0</td>
<td>58.4</td>
<td>1.88</td>
</tr>
<tr>
<td>1.5</td>
<td>71.2</td>
<td>2.82</td>
</tr>
<tr>
<td>2.0</td>
<td>82.3</td>
<td>3.76</td>
</tr>
<tr>
<td>2.5</td>
<td>92.3</td>
<td>4.70</td>
</tr>
<tr>
<td>3.0</td>
<td>101.0</td>
<td>5.64</td>
</tr>
<tr>
<td>3.5</td>
<td>109.2</td>
<td>6.58</td>
</tr>
<tr>
<td>4.0</td>
<td>116.8</td>
<td>7.52</td>
</tr>
<tr>
<td>4.5</td>
<td>123.8</td>
<td>8.48</td>
</tr>
</tbody>
</table>

For the conditions shown in the table it would require an ascent velocity of 82 ft/sec and a barometric jump of 3.76 mb to produce a hailstone two inches in diameter, and an ascent velocity of 124 ft/sec and a barometric jump of 8.46 mb to produce a hailstone of approximately the limiting diameter. These results while approximate are apparently of the right order, and the simple relation given by this equation indicates that the maximum diameter of a hailstone which can be produced in a given storm is in direct proportion to the height of the barometric jump. The equation gives an indication of the size of hail which can be formed in a given storm in terms of the quantity \( J \), which can be directly measured at the ground surface. Comparison of these results with observed sizes of hailstones and values of \( J \) have not been made.

The observed fact that hailstones are often fragments of initially much larger hailstones indicates that when hail forms, many of the hailstones grow to the maximum possible size for the given conditions. This is in accordance with the expected result if hailstones are formed in ring vortices but not if they are the result of accidental or fortuitous gustiness. Apparently most but not all hailstones which grow nearly to the maximum possible size explode but some do not. In the Washington storm, for example, hailstones over two inches in diameter were observed in the outskirts of the city [ARENBERG, 1938].

BROOKS [1944] has analyzed data on hailstone sizes from Hallstoms in India [ELLIOTT, 1899]. Brooks gives an equation for the number of stones in all storms having diameters equal to or exceeding \( d \) inches. Brooks' equation in terms of relative frequency is

\[ F_r = (0.295)^d \]  

(18)  

Let 0.295 = a and \( a^d = e^{-kd} \). Then \( d \log_e a = -kd \) and \( k = -\log_e a = 1.22 \).

As an inverse exponential function

\[ F_r = e^{-1.22d} \]  

(19)  

where \( F_r \) is the fraction of the total (taken as unity) or exceeding a given time.
The integral frequency below size \( d \) is \( 1 - F_r \). The relative frequency for a given size is obtained by the differentiation of \( (1 - F_r) \) or

\[
f = 1.22e^{-1.22d} \tag{20}
\]

Solving (20) for \( f = 1.0 \) gives \( d = 0.0164 \text{ mm} \) as the smallest size of hailstone included in the data. The data used were from 507 samples in hailstorms which occurred in India from 1833 to 1899 and the frequency distribution is the relative frequency of hailstones of different sizes in different storms but not in the same storm. Agreement between observed and computed frequencies is nearly perfect for hailstone diameters less than 1.5 inches. For larger diameters the observed number of hailstones is greater than the computed number, as would be expected if many of the hailstones were initially of large diameters and a large fraction of the smaller stones, which chiefly determine the form of the frequency curve, were produced by fragmentation.

**Maximum precipitation intensity as hail**—As already noted, all of the moist air ejected through the cover layer in the formation of an atmospheric ring vortex goes into the vortex ring. A ring or succession of rings is therefore capable of producing as much precipitation as could be produced under otherwise similar conditions in a vertically convective storm of the tubular type.

One cubic meter of saturated air at 32°F contains 4.8 gm of water vapor, of which perhaps 4.5 gm is precipitable. A ring vortex with torus radius of 2000 m and vortex radius of 200 m contains a volume of approximately \( 1.6 \times 10^9 \text{ m}^3 \), which, when saturated at 32°F contains about \( 7.2 \times 10^9 \text{ gms of precipitable water vapor} \). This would produce a precipitation depth of \( 0.047 \text{ cm} \) over \( 152 \times 10^9 \text{ sq cm} \) an area equal to a circle having a diameter equal to the outer diameter of the ring. A m n of successive rings would produce \( n \) times this amount.

The maximum recorded rainfall for short intervals is given by the equation [U. S. WEATHER BUREAU, 1941] \( P = Vt^3 \), where \( t \) is time in minutes and \( P \) is rainfall in inches. This equation applies only for time intervals of one to 15 min and tropical or subtropical locations near sea lev

\[
N_1 = 275/\rho d^3 \tag{21}
\]

The number of hailstones per sq ft of diameter \( d \), in inches, required to produce one inch of water, is given by the equation

\[
N = N_1/3600 = 0.0764/\rho d^3 \tag{22}
\]

For density \( \rho = 0.6 \) these formulas give the values shown in Table 5. Since it requires only one hailstone one-half inch in diameter per sec per sq ft to produce a precipitation intensity of one inch per hour, a comparison of these figures with observed maximum rain intensities indicates that hail may be capable of producing higher precipitation intensities than are ever observed from the fall of rain.

The funnels of non-recording and tipping bucket recording rain gages are usually completely blocked by hail and no record of true intensity of precipitation is obtained. The question is therefore open whether hail or rain produces greater intensities. Hail is, of course, always precipitation from suspension storage. The question is of some interest in relation to derivation of equations for maximum rain intensity, which are much used by engineers in the design of storm-sewers, airport drainage, and other works.

**Conclusions**

(1) Atmospheric vortex-ring systems occur in conjunction with violent convective storms. When they occur the ascending moist air is concentrated in the vortex rings.

(2) The conditions favorable for the occurrence of convective vortex-ring systems are also favorable for the production of hailstorms.
Hailstorms are apparently of two types: (a) Where the hail is formed in an ascending current of moist air and results from gustiness. Such storms are likely to produce hailstones of various forms, sizes, and different internal structures but not generally of maximum sizes. (b) Storms where the hail is formed in ring vortices. Such storms are likely to produce hailstones of maximum sizes, and fragmental hailstones and frequently a large proportion of the hailstones will be relatively uniform in size and internal structure.

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