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On the Growth of Large Hail

GRIFFITH M. MORGAN, JR.—*Illinois State Water Survey, Urbana, Ill.*

ABSTRACT—Calculation of the trajectories of precipitation particles growing in a simplified thunderstorm updraft model shows some effects that have a bearing on understanding the mechanism of water storage in thunderstorms, the growth of large hailstones, and the techniques to be used in hail prevention.

The updraft model is characterized by a region of inflow overlain by one of outflow, with the vertical component of air velocity increasing along inflowing streamlines and decreasing along outflowing streamlines. For simplicity, streamlines are assumed to be arcs of circles in the vertical plane, and the velocity distribution in this plane is equivalent to solid rotation. Air density is assumed constant everywhere, and particles are assumed to move horizontally at the same speed as the air and vertically at a speed equal to the vertical component of air velocity minus their terminal velocity. In such a flow regime, the motion of particles is along families of concentric circles centered on the intersection between the locus of points of zero horizontal air velocity and the vertical air speed isotach corresponding to the terminal fall speed of the particle (called the "balance point" of the particle). Particles of different sizes move along different families of circular trajectories, and consideration of the way in which these families intersect illustrates the large dispersion in the directions of motion of the different components of the precipitation size spectrum at each point in the cloud. Growth of particles is specified as a linear increase of fall speed with time, sawtooth fashion for liquid drops (to simulate the spontaneous breakup responsible for the Langmuir chain reaction), and continuous for hail particles.

The results of trajectory calculations show: (1) that in the region of the balance points of large raindrops (diameter ≈ 3–5 mm) the drop trajectories are of an indefinitely (timewise) recirculating character, indicating a tendency to store water in that region (identified with the "accumulation zone" introduced by Russian hail researchers); (2) that in the higher speed regions of the updraft, drop trajectories lead to ejection of the drop from the storm and little or no storage of water (identified with the "echo-free vault" introduced by English cloud dynamicists); (3) that hail embryos, in the form of frozen large raindrops, start their growth in the region of liquid water storage and move along looping trajectories that carry them across the updraft to the region of highest velocities at a rate such that they achieve fall speeds (size) about equal to the maximum updraft speed; and (4) that introducing cloud seeding material into the high speed updraft core should be ineffective for hail prevention due to rapid ejection from the storm. Seeding material should be introduced directly into the accumulation zone (Russian method) or at points below the cloud where the airflow will carry it through the accumulation zone.

1. INTRODUCTION

Hailstones grow in vertical currents of thunderstorms by the collection of supercooled water droplets and ice crystals on embryos or "seeds." The embryos are either snow crystals that develop into graupel, or frozen water drops. The embryos' number, nature, and height (temperature) of origin are in some way determined by the type and number of ice nuclei present in the cloud.

Any hail growth theory consists of explaining the retention of hailstones in the storm for time periods long enough for them to grow to sufficient size (about 1 cm) to survive melting while falling to the surface. Few, if any, of the existing models and theories are general enough to explain the occasional occurrences of giant hailstones weighing up to 766 g, which have been reliably reported (Anonymous 1971). Such stones require a mechanism that involves rapid growth, long residence time in the storm cloud, or both, to explain their growth.

The well-known Russian hailstorm model (Sulakvelidze et al. 1966) seeks to explain hail growth in the first way by invoking large water content in the cloud, in small regions called "accumulation zones." Browning and Ludlam (1962) stressed the second approach by suggesting that hailstones that are thrown out aloft are swept back into the storm updraft at lower levels and "recycled" through the storm.

Ludlam (1958) observed that, "It would, of course, be possible to produce a stone of any desired size by postulating a persistent updraft which steadily increased in speed, always being just that required to support the stone in the supercooled region of the cloud. . . ." It would be possible to achieve such a result with a time dependent, one-dimensional approach such as that of Musil (1970) by carefully controlling the time increase of the updraft velocity profile to just match the growth of the hail particle. It will be shown here that if the airflow is steady and of a very general two-dimensional type and if hail embryos are introduced in the proper region, the growing hailstone will move within the updraft in a manner dictated by its growth such that it tends to maintain itself in regions where the updraft speed is nearly matched by the stone's fall speed.

Interestingly, both the accumulation of large amounts of liquid water in a storm and the prolonged retention of stones must be explained in terms of the trajectories followed by large drops and by growing hailstones in the three-dimensional airflow pattern of the thunderstorm. The manner in which accumulation and recycling are determined by the airflow is discussed in this paper.

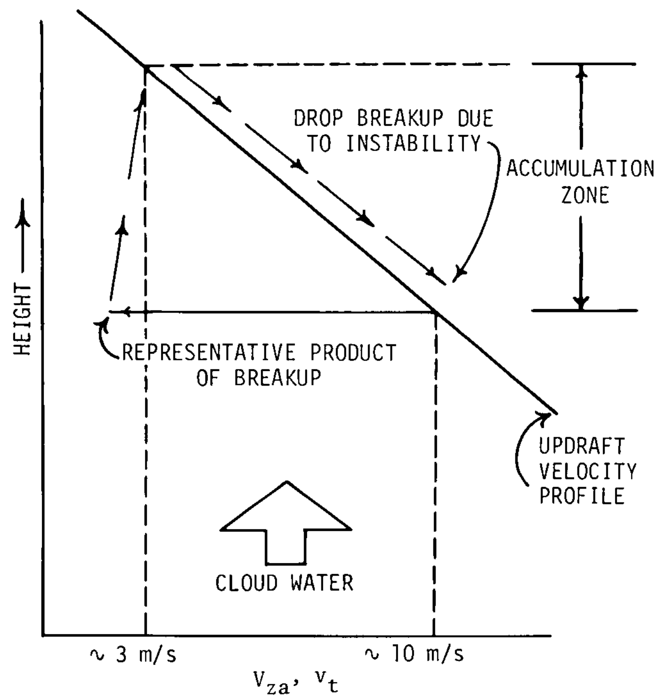

FIGURE 1.—The one-dimensional model of the circulation in the large-drop accumulation zone. V_{za} and v_t are the vertical air speed and terminal fall velocity of the particle, respectively.

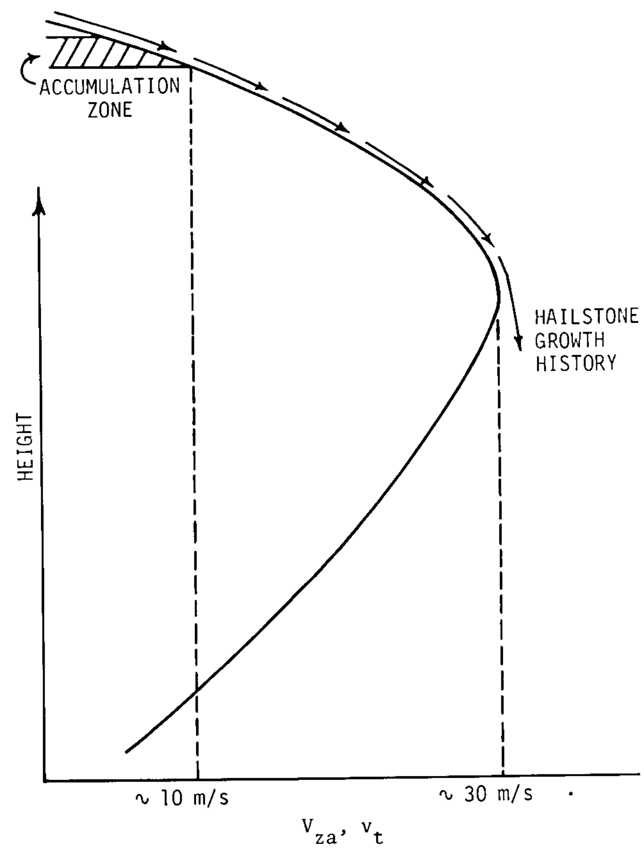

FIGURE 2.—The one-dimensional accumulation zone model for the case of an intense updraft capable of producing large hail.

The discussion centers around a two-dimensional steady updraft because the importance of the spatial structure of the updraft to the motion and development of precipitation is to be emphasized. It should be clear, however, that introducing time variations in the updraft structure will probably yield similar results having greater generality.

2. THE ACCUMULATION ZONE (AZ) CONCEPT

The Russian model featuring the accumulation of large amounts of liquid water is based on the Langmuir chain reaction mechanism occurring in a "trapping" region of the airflow. The chain reaction is a mechanism for rapidly increasing the number of large water drops in the storm. When large drops reach a critical size (diameter ≈ 5 mm), they spontaneously break up into a few (2–10) large (≈ 1 mm) drops and a larger number of small drops. These new relatively large drops (precipitation size) continue to grow at the expense of the cloud liquid water and after some minutes again reach critical size and break. The cycle repeats as long as there is cloud water to feed the drop growth.

If this process takes place in the upper part of a storm, or above the level of greatest updraft velocity where the vertical air speed decreases with height (fig. 1), the large drops cannot escape. Particles tend to settle to the point where the updraft speed equals their terminal fall speed. When they break up, the breakup products are swept upward to their new point of equilibrium and move downward as they grow. The number of drops so trapped increases repidly, and the amount of water in the zone increases because of the capture of the cloud water that streams in from below. Hail also may be able to grow very rapidly in the high concentration of liquid water that results.

Although this concept of water accumulation and hail growth seems very elegant, there are several important weaknesses in it. First, the region in which the updraft strength decreases with height is also one of horizontal divergence that will limit the residence time of drops in the region. Second, it has been shown by Haman (1968) and Iribarne (1968) that accumulation of water as described above causes a deceleration of the updraft, due to the weight of the water. As a result, the vertical extent of the accumulation zone (fig. 1) becomes very thin and the horizontal divergence increases. Both of these effects work against significant accumulation. Third, even if the above factors were not important and an accumulation zone did form, it could at most account for the growth of small hail. The base of the accumulation zone lies where the updraft speed equals the terminal fall speed of the largest drops, and hailstones falling out of the accumulation zone would have fall speeds of about this value. Any further growth of the stones would occur outside of the accumulation zone at slow rates, as shown in figure 2, which points up the inconsistency in the Russian model. The frozen particles emerging from the accumulation zone would be better described as embryos than as hailstones. In fact, the main role of the accumulation phenomenon in thunderstorms may be as a source of embryos in the form of large frozen drops.

Haman (1967, 1968) and Iribarne (1968) have considered more realistic models of accumulation showing that accumulation takes place in several regions of the cloud if rain can fall back into the updraft at low levels after being thrown out aloft. Such feedback of precipitation can be examined best by determining the trajectories followed by growing particles in updraft airflow models.

3. SIMULATION OF PRECIPITATION TRAJECTORIES

To describe completely the trajectories of growing hailstones requires specification of (1) the airflow field in which growth occurs, (2) the initial position and fall speed of the embryos, and (3) the fall speed of the growing stones for all subsequent places and times.

Normally, derivation of the fall speed of the stone is accomplished from the established relations giving fall speed and rate of growth in terms of liquid water content, ice crystal content, temperature, stone shape, stone size, stone roughness, etc. Besides being very difficult, dealing with the computation of particle trajectories in all its complexity may tend to obscure some simple and important effects that a less complete treatment can reveal.

Trajectories of large drops and hailstones growing in a greatly simplified model of the airflow are here examined with the fall speed histories of the particles specified as linear functions of time, totally independent of any physical conditions or laws. No account is taken of the effects of water concentrations on buoyancy and airflow nor of the variations of air density with height. This could as well enhance the effects shown as hinder them. I believe that the effects to be shown as important here are not dependent on the exact height, width, and time relationships employed, but represent a general qualitative property of particle growth and motion in the general type of flow employed. This flow is characterized by inflow overlain by outflow, with the vertical component of velocity increasing along inflowing streamlines and decreasing along outflowing streamlines.

The equations governing particle motion merely express the fact that particles follow horizontal air motions exactly and move vertically with respect to the air at their terminal fall velocity:

$$V_{zp}=V_{za}-v_t$$

and (1)

$$V_{xp}=V_{xa}$$

where

V_{zp} is vertical velocity of the particle with respect to the ground,

V_{za} is vertical air speed,

V_{xp},V_{xa} are horizontal velocities of particle and air, and

v_t is terminal fall velocity of particle (a positive quantity).

Trajectories of particles may be determined from the equations

$$dx=V_{xp}dt=V_{xa}dt$$

and (2)

$$dz=V_{zp}dt=(V_{za}-v_t)dt.$$

As a preliminary approach to studying hailstone growth trajectories, the following simplifying assumptions were made:

1. Particles grow in such a way that their terminal fall velocity increases at a constant rate; that is,

$$v_t=v_{t0}+K_3t. \tag{3}$$

2. Updraft streamlines are circular in shape in the x-z (vertical) cross section, which allows specifying the entire updraft with simple mathematical forms involving very few parameters.

The choice of a constant rate of increase of fall speed, K_3 (assumption No. 1), is made primarily for convenience but is quite reasonable. If variations in air density are ignored, the fall speed as a function of drop diameter is given by

$$v_t=C_1D^{1/2}, \tag{4}$$

so that (C_1 is a constant)

$$\frac{dv_t}{dt}=\frac{C_1}{2}D^{-1/2}\frac{dD}{dt}. \tag{5}$$

The rate of increase in mass M of a drop of diameter D and collection efficiency E growing by accretion in a cloud of water content m (g·m^{-3}) is

$$\frac{dM}{dt}=\frac{\pi\rho D^2}{2}\frac{dD}{dt}=\frac{\pi}{4}mED^2v_t \tag{6}$$

where ρ is the density of water. Use of eq (4) gives

$$\frac{dD}{dt}=\frac{mEC_1D^{1/2}}{2\rho} \tag{7}$$

and combining eq (5) and (7) gives

$$\frac{dv_t}{dt}=K_3=\frac{mEC_1^2}{4\rho}=C_2m \tag{8}$$

where C_2 is a constant. From this, it is clear that a constant value of K_3 simply implies a constant value of cloud water content, which, for the present purpose, adequately justifies such a choice.

With the second assumption (circular streamlines in the x-z cross section) it is convenient to superimpose a polar coordinate system on the x-z plane. The radial coordinate is R. The (x,z) and (θ,R) coordinate frames are related by

$$x=R\sin\theta;\quad dx=R\cos\theta\,d\theta+\sin\theta dR$$

and (9)

$$z=-R\cos\theta;\quad dz=R\sin\theta\,d\theta-\cos\theta dR.$$

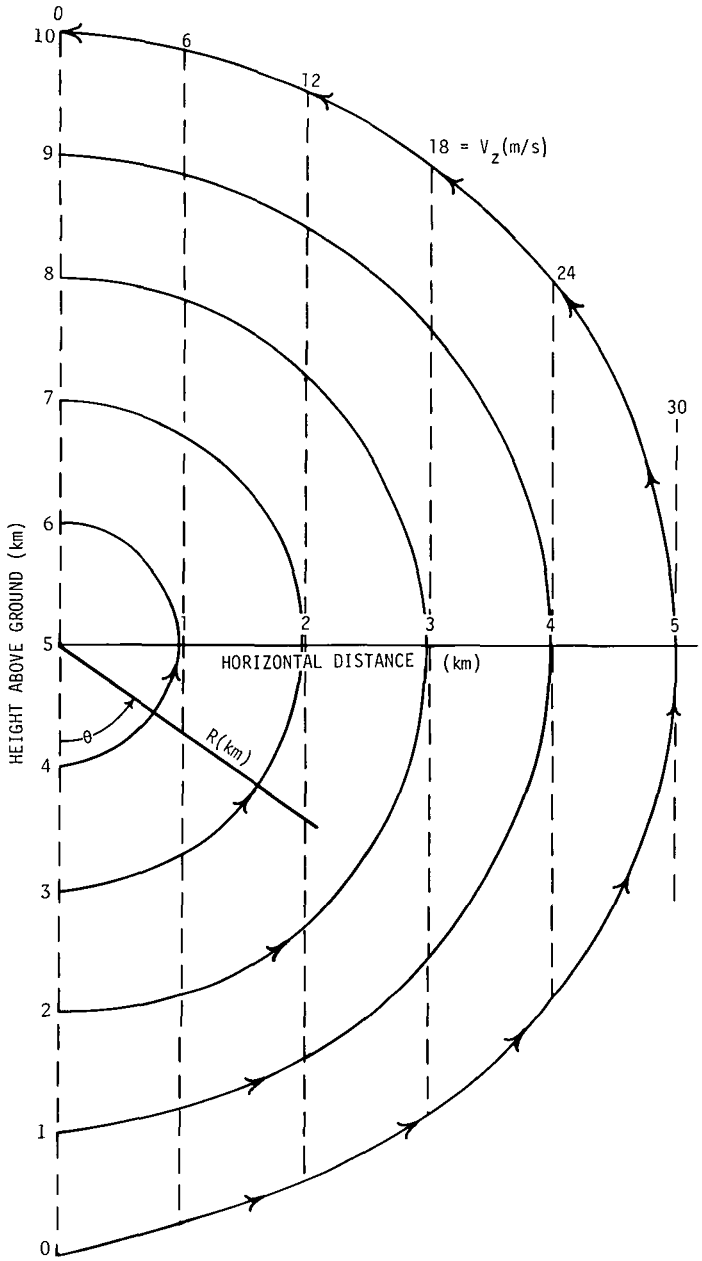

FIGURE 3.—Streamlines and isotachs of vertical velocity for the model updraft employed in the trajectory computations.

The following form has been adopted for the updraft velocity distribution:

$$V_{ta}\ (R,\ \theta) = \text{tangential air velocity} = V_{ta}\ (R) = K_1 R;$$

that is, the tangential velocity is constant along any streamline and is a linear function of radius. The vertical and horizontal components are then:

$$V_{za} = K_1 R \sin \theta$$

and $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ (10)

$$V_{xa} = K_1 R \cos \theta.$$

This updraft with its isotachs of vertical velocity (dashed vertical lines) is shown in figure 3. The vertical coordinate is shown in terms of height above ground, so that the origin used in the equations is found at a height of 5 km in the drawing. The constant K_1 has been chosen as 6×10^{-3} s^{-1} which gives a maximum velocity of 30 m/s at a radius of 5 km. Thus, the maximum vertical velocity is also 30 m/s. The updraft described here is 10 km in vertical extent and 5 km in width. This could be considered as somewhat analogous, (1) to the forward portion of the steady-state supercell analyzed by Browning and Ludlam (1962) and Browning (1963), (2) to the flanks of a vertical, still-air storm, or (3) to the rear side of a back-feeding storm (Weickmann 1969).

In this simple updraft, a particle of constant terminal velocity will follow a perfectly circular trajectory centered on the point of intersection between the line along which the streamlines are tangent to the vertical (shown here as a horizontal line at z=5 km but in a real storm not necessarily so) and the vertical air speed isotach whose value corresponds to the terminal velocity of the drops. This intersection is the place in the updraft where the drop in question would remain perfectly stationary. Each drop size has a "balance point" in the updraft, as defined by such an intersection. The updraft considered here is steady, so that the circular drop trajectories are also the instantaneous streamlines of the flow of all drops of a given size. This fact, that droplets of different sizes are moving along different families of concentric circles, helps one to visualize the great dispersion in the directions of motion of the various sizes of particles that occurs at each point in the cloud. This important complexity of the flow of water substance in a storm cloud is masked or oversimplified in one-dimensional approximations or in approximations that have all the precipitation at a point falling at the same speed (Kessler 1969) or that divide the precipitation into two or three fall speed groups (Takeda 1971). It should be emphasized that one cannot equate the terms "accumulation zone" and "high reflectivity region". The accumulation of large drops in a region of the storm does not necessarily imply unusually high liquid water contents (LWC). The LWC will be determined by the overall pattern of convergence and divergence of the large drop motion. High reflectivity may denote high liquid water content, the presence of hail, or a mixture of water and hail, so that great circumspection is required in the interpretation of the radar echo.

4. RESULTS OF TRAJECTORY CALCULATIONS

Large Drops

Trajectories have been determined by computer calculation of the incremental equations [eq(2)] using a 15-s time step. The growth of drops has been treated so as to approximate the breaking and growing of drops that constitutes the Langmuir chain reaction. Initial drop fall speed was chosen as 3 m/s, corresponding to the fall speed of the drops which result from instability breakup. Growth rate, expressed as a linear increase of fall speed

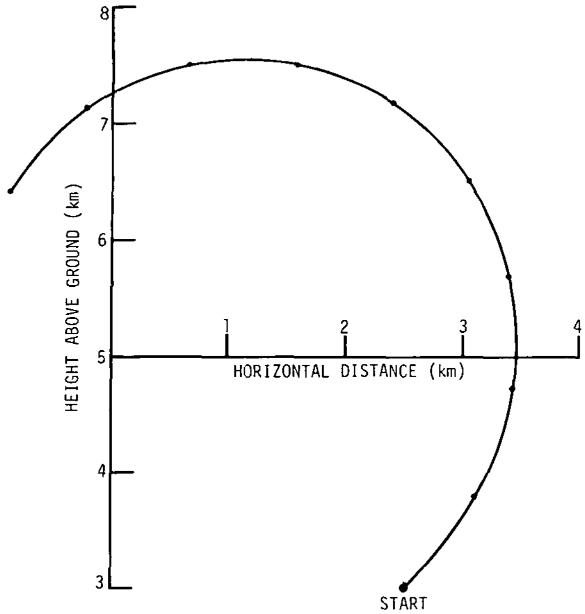

Figure 4.—Large-drop trajectory characteristic of the high-speed regions of the model updraft.

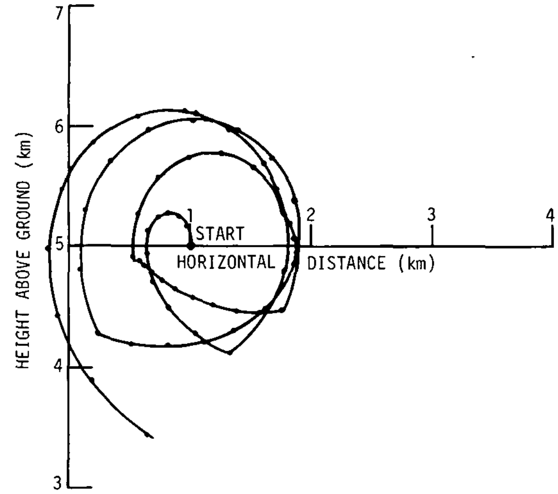

Figure 6.—A trapped trajectory showing continued recirculation. Total time elapsed is 1 hr.

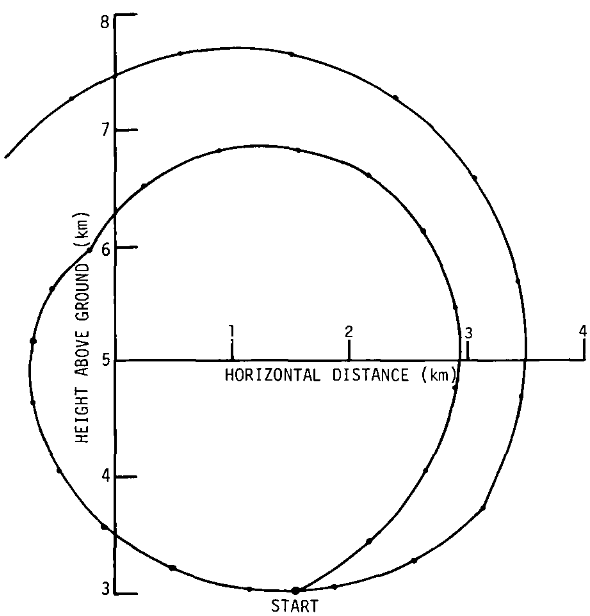

Figure 5.—Large-drop trajectory exhibiting limited recirculation. The trajectory has left the updraft after 27 min, having shown two instability breakups (visible as kinks in the trajectory).

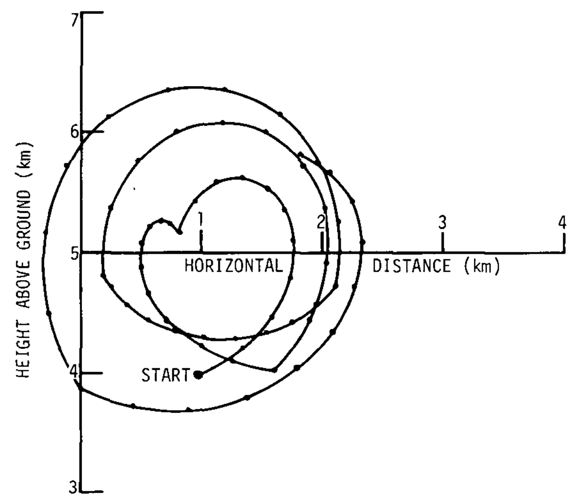

Figure 7.—Same as figure 6, for a different starting point.

with time, was chosen so that the drops would reach a fall speed of 10 m/s in 600 s. At this point, drop breakup was simulated by setting the fall speed back to the initial value of 3 m/s. This is the same as following the trajectory of *one* of the breakup products after each breakup. Trajectories were determined for an array of starting points covering the entire updraft cross section. Examples of these are shown in figures 4, 5, 6, and 7 with time intervals of 1 min marked on each trajectory. The trajectory of figure 4 is "typical" of those found at most points within the updraft, especially in its high-speed region; the particles rapidly pass through the updraft and enter the downstream flow (anvil). Figure 5 is an example of an "intermediate" type of trajectory showing a sufficient residence (or recirculation) time to accomplish several cycles of growth and breaking. The trajectories of figures 6 and 7 can be called "trapped" trajectories and are typical of those which originate in the neighborhood of the balance points of drops with fall speeds between 3 and 10 m/s. Computation and plotting of these trajectories were arbitrarily terminated at a total elapsed time of 1 hr, and it can be assumed that these particles would continue indefinitely to recirculate in the manner shown.

All sets of computed trajectories have been summarized in figure 8. Here the updraft has been subdivided into regions according to the type of trajectories occurring

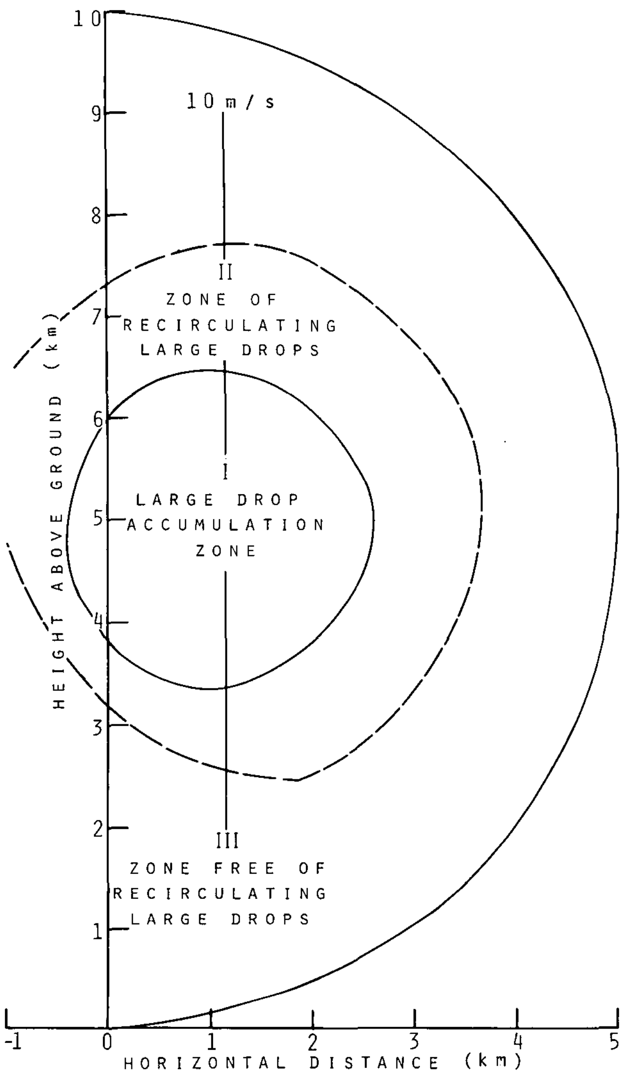

FIGURE 8.—The three principal regions of the model updraft as defined by the type of trajectories occurring in each.

in each. Zone III is the zone of no recirculation. Zone II is the zone of recirculation of large drops. The lower part of the boundary between zones II and III is very important and is determined by the deepest observed penetrations of large drops coming from above. This could be interpreted as illustrating the formation of the boundary between an echo-free vault and its forward overhang within which storage and concentration of liquid water begin to take place.[1] Zone I encompasses all the trajectories exemplified by figures 6 and 7, and could be considered as an accumulation zone (AZ) in its fullest sense (the Russian AZ, though different from this in storm location and trapping mechanism, is a trapping zone in which large drops proliferate in number by means of the chain reaction). It would appear from figure 8 that the echo-free region would not be very well developed for an updraft whose maximum speed did not exceed about 20 m/s.

Although large-drop trajectories have been computed for Zone III, it is clear that in reality, there is no means of introducing large drops into this zone. If a few were introduced, say in the lower part, the trajectories show that they would not proliferate there, and Zone III would remain a large-drop deficient region. This, along with the character of the trajectories, suggests that cloud seeding in the updraft core for hail prevention may be of questionable value. The resulting frozen drops and ice crystals may be destined to simply become part of the anvil plume.

Hail Trajectories

Hailstone embryos have been taken as the largest drops (fall speed=10 m/s). Trajectories were then determined for four different growth rates, and, as with large drops, in terms of a linear rate of increase of fall speed over the complete array of starting points. Four growth rates were chosen so as to have the fall speeds increase from 10 to 30 m/s in 10, 20, 40, and 60 min. The first is a very fast growth, probably unreasonably fast and about twice that deduced by Browning (1963), and the last is probably unrealistically slow. The 20-min growth comes closest to that of Browning.

Examples of the resulting computed growth trajectories are given in figures 9A–9E, and these depend strongly on starting point. All plots were terminated when hailstones crossed the $R=5$ km streamline or the $x=-1$ km vertical. The basic time interval was 15 s, and the marks on the trajectories are at 1-min intervals. The most interesting of these trajectory sets is figure 9E. Here, the trajectories start very near to the balance point of the embryo. The growing stones move in a general cross-stream direction and exit from the updraft near its maximum velocity, having attained nearly the maximum possible size. It is important to observe that, the slower the growth rate of hailstones originating at or near their balance points, the more closely the growth trajectories will approach the line of no relative horizontal motion ($z=5$ km). Again, this does not depend on the line being horizontal. The trajectory for the fastest growth rate in figure 9D is also noteworthy as an example of the type of motion that is possible when the growth rate and updraft speed distribution are properly related.

To summarize the results of hail trajectory computations, the time of residence of hailstones in the updraft has been determined for each growth rate as a function of starting position (figs. 10–13). A particle was considered as leaving the updraft whenever it crossed the $R=5$ km streamline, the $x=-1$-km vertical, or fell below 2.5 km. Figures 10–13 show that, for the three slower growth rates, a starting point near the natural balance point of the embryo results in growth to about the largest possible

[1] The echo-free vault, introduced under that name by Browning and Ludlam (1962) but probably to be identified with the various "notches" and holes in echoes reported as being associated with hail and severe weather during the 1950s (e.g., Stout and Hiser 1955), is generally recognized as evidence of the presence of a strong, persistent updraft that does not allow the descent of precipitation from above through its stronger parts.

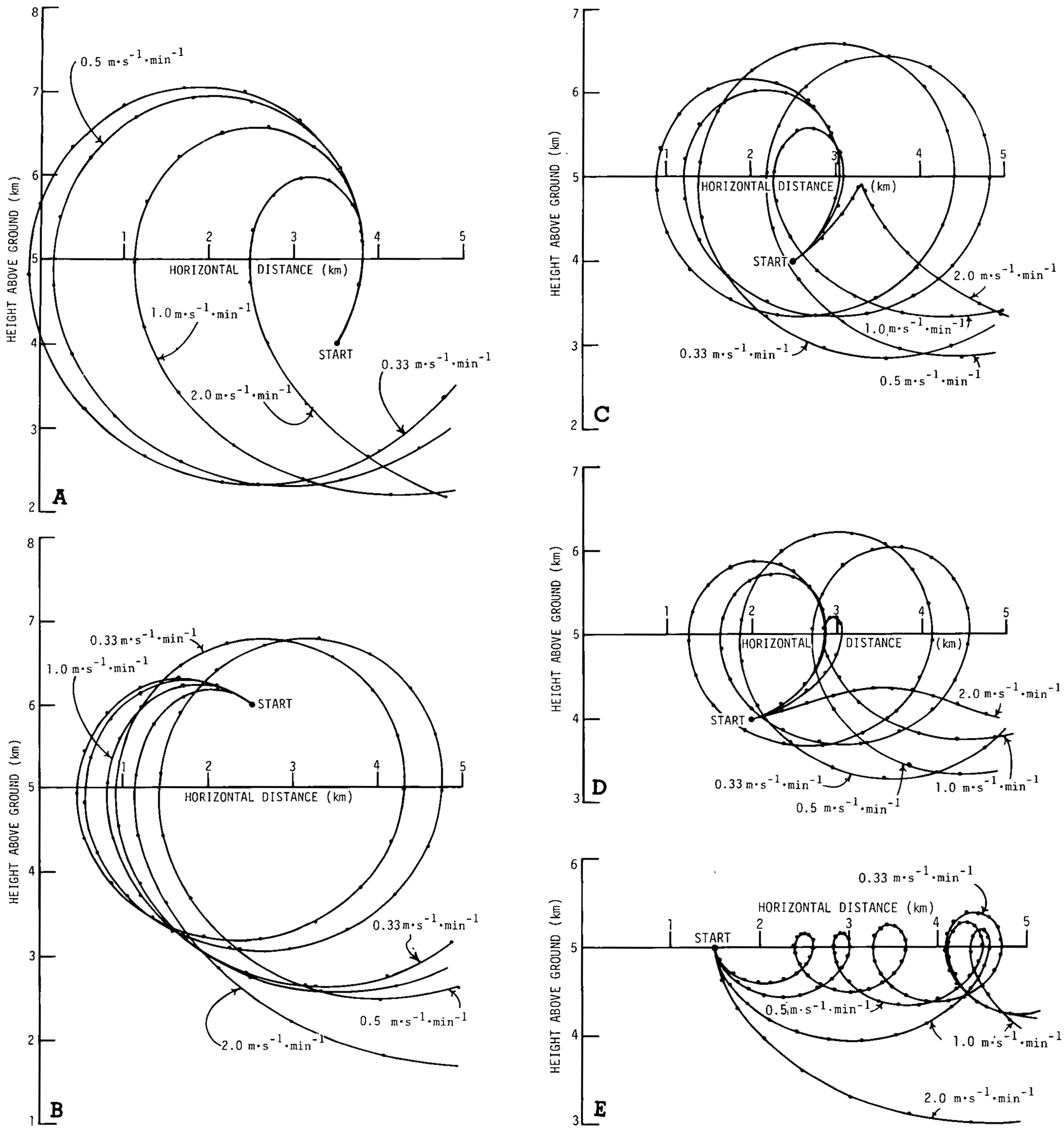

FIGURE 9.—Example of hailstone growth trajectories. Coordinates are the same as in figures 3 and 8. Growth rates are indicated as increases of fall speed with time.

size. This maximum possible size is limited only by the maximum vertical velocity of the updraft. In the assumed updraft, where the maximum velocity is 30 m/s, the hailstones produced have fall speeds of about that value. For the production of the giant stones sometimes observed, all that is required is a larger value of maximum velocity.

The trajectories derived here of hailstones growing at moderate to slow rates, starting from near their balance points in the updraft, are such that the stones experience an updraft that oscillates in time about the perfect condition described by Ludlam (1958). For the fastest growth rate (fig. 13), the maximum growth occurs when the

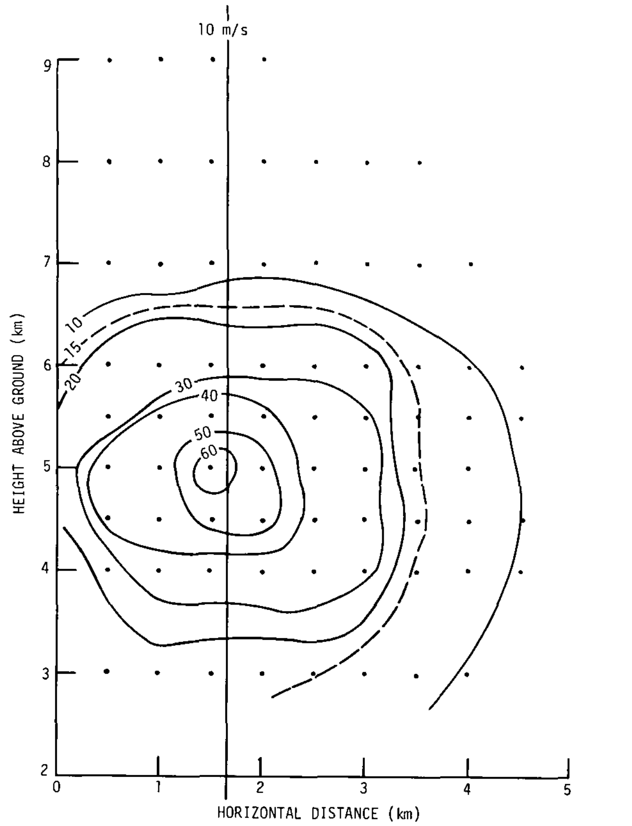

FIGURE 10.—Residence time of hailstones in the updraft model as a function of starting position. Growth rate is 0.33 m·s⁻¹·min⁻¹. Isopleths of elapsed time are labeled in min. Coordinates are as in figures 3 and 8.

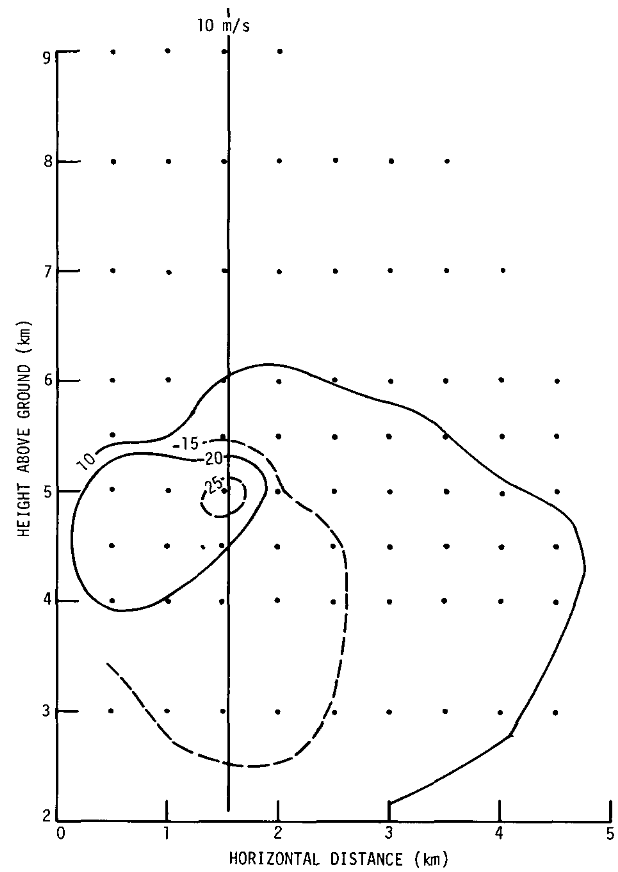

FIGURE 12.—Same as figure 10, except growth rate is 1.0 m·s⁻¹·min⁻¹.

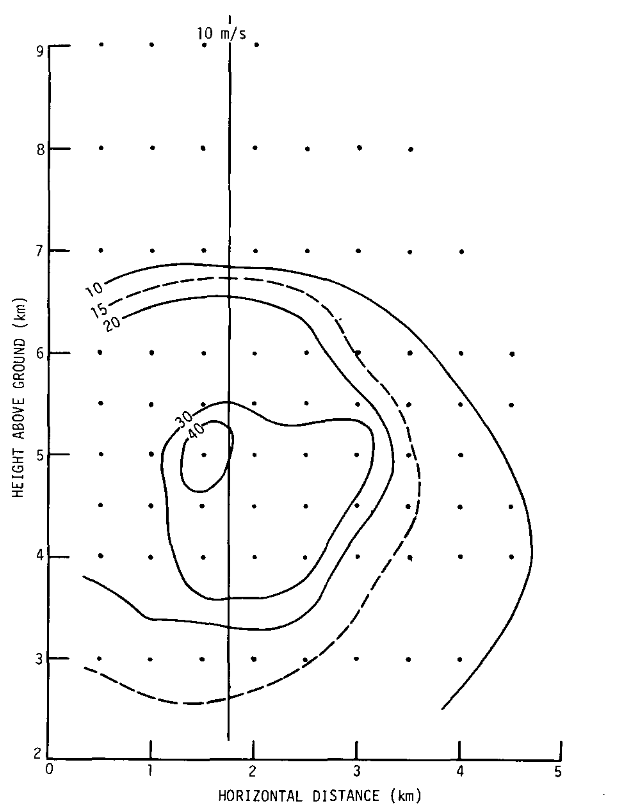

FIGURE 11.—Same as figure 10, except growth rate is 0.5 m·s⁻¹·min⁻¹.

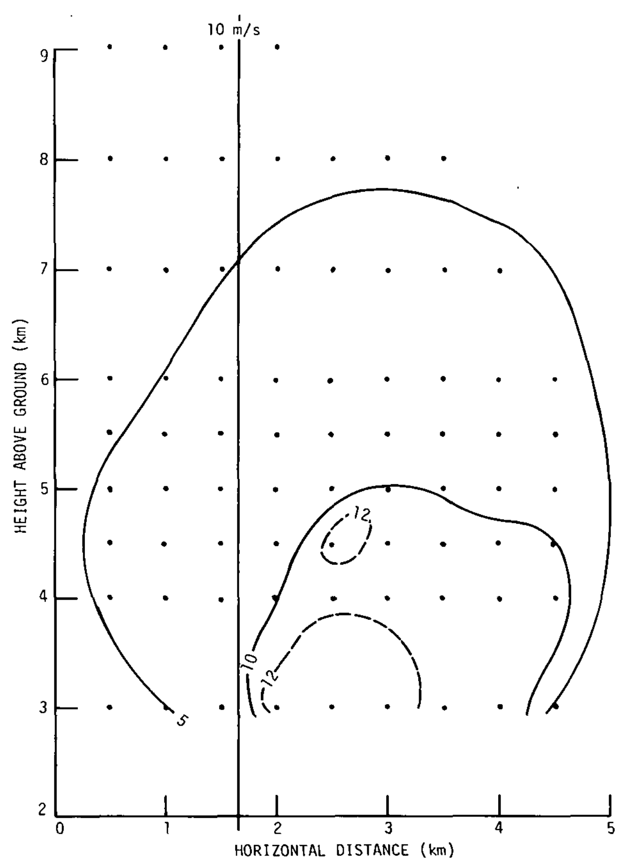

FIGURE 13.—Same as figure 10, except growth rate is 2.0 m·s⁻¹·min⁻¹.

embryo is introduced in the lower part of the high speed portion of the updraft. This is because the rapidly growing stone moves rapidly into the region of high vertical air speed from such starting positions. However, this is a region where large drops, the hail embryos, are not to be expected. Those hail embryos that start their growth near their balance position leave the updraft in the immediate vicinity of the region of maximum vertical air speed, which will produce a narrow swath of hail at the ground. This is a significant characteristic of many hailstorms, particularly those containing large hail, as has been shown by Changnon (1970) on the basis of detailed surface hail observations.

The region of near balance for the embryos is also the center of the large drop storage region, or accumulation zone, which is thus not the region of hail growth but the source region of hail embryos. This is reasonable because the accumulation zone is the region of highest concentration of large drops.

5. SUMMARY AND SPECULATIONS

The airflow model and the simplifying assumptions employed here have been chosen with little attempt at realistically modeling actual thunderstorms. Emphasis has been, instead, on pointing out possible modes of motion of particles of various classes growing in a general type of airflow. Nevertheless, on the basis of these results, the following ideas may be advanced:

1. Storage of water should occur on the flanks of thunderstorms in a region roughly identified with the intersection of the isotach of vertical air speed corresponding to the fall speed of large drops and the surface of no horizontal motion. This type of storage was described in a more qualitative way by Haman (1968; note his fig. 5) and this storage region might be identified with the "forward overhang" of Browning and Ludlam.

2. The liquid water storage region is not precisely the region of hailstone growth, but might be considered the source region of hailstone embryos in the form of large frozen drops. Embryos that start their growth in this region of the cloud are more favored to remain in the cloud long enough to attain large size than are those starting elsewhere. This would suggest that artificial freezing of the water in the accumulation zone could prevent hail, at least for a time, by creating an overabundance of hail embryos leaving the preferred starting region. It might also bring about a loading of the updraft as the newly frozen particles leave the accumulation zone (because of their growth beyond the critical size for drops) and move into the higher speed region of the flow. Should the updraft maintain its integrity following the induced freezing and release of heat, the considerations shown here would predict the danger of increased hailfall somewhere downstream when the competing embryos have grown, however slowly, to fallout size or when the storm enters its dissipation phase. These various possibilities are linked solely by speculation and should not be emphasized.

3. Seeding in the updraft maximum may not be a very efficient way of suppressing hailstorms because of the rapid transport through the storm and because of the streamlines bypassing most of the liquid water.

4. The inner limit of the liquid water zone should be the boundary of the echo-free vault of Browning and Ludlam (1962), though hail particles could penetrate deeper into the updraft and, if sufficient in concentration, form its boundary.

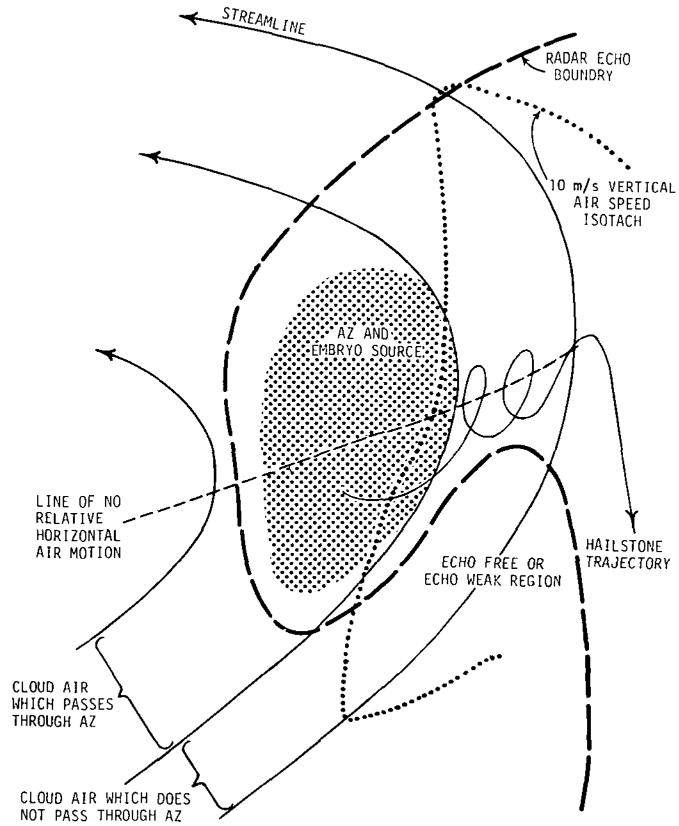

FIGURE 14.—Water accumulation, hail growth, and radar echo for a steady-state updraft.

5. If the flow of air into the storm is as smooth and layered as most believe, the inflowing air that flows through the accumulation zone may originate at a considerable height above ground. It is the ice or freezing nucleus content of this air that, along with the range of temperatures encountered in the accumulation zone, will determine the natural rate of production of embryos. Nucleus counts performed at ground level would be irrelevant to this process.

6. The dependence of all these factors on the exact morphology of the storm may be the principal cause of the difficulty of hail forecasting. Many storms have strong updrafts, but few produce large hail.

The various processes discussed are shown in figure 14, superimposed on an airflow pattern similar to that derived by Browning (1963) for a quasi-steady state hailstorm. The radar echo boundary has been placed purely by intuition. This drawing is presented solely as an illustration of the way the processes of accumulation and hail growth might interact.

ACKNOWLEDGMENTS

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