The Observed and Computed Microstructure of Hail-Producing Clouds in Northeastern Colorado

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ABSTRACT

The modification of thunderstorms to suppress hail requires a knowledge of where, when and how much to seed. We show that growth by accretion by precipitating particles (hail, rain and graupel) in a summer convective storm depends on the path that the particles take with respect to the cloud air circulation in which the cloud droplets are embedded, as well as on the ambient atmospheric parameters of temperature, moisture, stability and larger scale circulations. For this purpose we used a two-dimensional simulation of the circulation in which the most important features of one-dimensional time-dependent microphysics simulation can be incorporated into the calculations at each time step.

The effect of changes in the altitude of ice particle initiation is calculated using simulations of the clouds and their environment on two days during this period when the total amount of hail differed by more than an order of magnitude. The simulated hail size and amount varied in the same sense as the observed.

The simulation is applied to the case used by Browning and Foote (1976) to develop a conceptual model of a severe hailstorm. The results show that in order to obtain the tilt of the updraft shown by Browning and Foote, the presence of a squall line or gust front would be required—a situation that they say is possible from their observed meteorological data.

1. Introduction

The modification of thunderstorms to suppress hail requires a knowledge of where, when, and how much to seed. The complexities of these storms, the many orders of magnitude over which the physical parameters range, and the large number of physical processes involved demand serious simplifications in order that the calculations in a numerical simulation can be made rapidly and repeatedly.

A synthesis of surface and airborne motion observations and a theoretically determined two-dimensional convective cell circulation is used as the framework on which to base calculations of the time varying microphysical and microdynamic interactions of cloud and precipitation elements. This approach allows us to start with observations taken as close as possible to the time of the output of hail.

The observations and supporting meteorological and operational information reported here were obtained during the June 1972 hail suppression operations of the National Hail Research Experiment (NHRE), a division of the National Center for Atmospheric Research. The observational results from sailplane flights into the updrafts of developing cumulus clouds in northeastern Colorado show some important variations in the microstructure of the cloud droplet and ice particle distributions. Some of these variations are apparently caused by the combined interactions of cloud droplets and precipitation particles within the updraft and its horizontal and vertical structure. The observed circulation in and around these single-cell storms is simulated kinematically in steady state to reproduce roughly the vertical motion profiles observed in the updraft while the microphysics measurements were being taken. In the simulation, the microphysics is introduced in a time-dependent way and repeated runs made in an attempt to determine in what manner the observations could be reproduced. We found that these calculations of the microphysics and the circulation interactions could explain the order-of-magnitude increases or decreases in precipitation particle and cloud droplet number density anomalies exhibited by the observations. Something very similar to this was accomplished in one dimension by Kessler (1963). Our situation requires at least two dimensions because of environmental shear and the cross-streamline motion of hail and hail embryos due to their high fall velocity.

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2. Analytical synthesis

a. Assumptions

The convective field of air motion is an axisymmetric two-dimensional vortex pair circulation producing a central updraft with an initially vertical axis. The observations of the updraft structure and simultaneous microphysical properties of these clouds led us to make some useful conjectures and assume the following:

1) Precipitation growth proceeds rapidly through the accretion of the supercooled cloud droplets by much larger ice particles.

2) The circulation is steady state with respect to the microphysical growth.

3) In dynamic interactions between the cloud air and environmental air, the density of the air at any altitude is assumed the same inside the cloud and outside.

4) Cloud droplets exist from cloud base to cloud top everywhere there is an upward component to the air motion and no cloud anywhere else.

b. Analytical specification of cloud air circulation

The analytical description of the convective cell circulation results from calculations of a two-dimensional dynamic simulation of convection typically produced by randomly distributed thermals near the surface (Drake *et al.*, 1975). The horizontal and vertical components of velocity in this circulation are given by Sartor and Cannon (1977) as

$$U_x(x,y)=C_1\left(\frac{x}{a}\right)\left[2\left(\frac{y+C}{a}\right)^2+\lambda a\left(\frac{y+C}{a}\right)-1\right]\times\exp\left[-\frac{1}{2}\left(\frac{x}{x_0}\right)^2-\left(\frac{y+C}{a}\right)^2\right]+U_{xe}(y), \quad (1a)$$

$$U_y(x,y)=C_1\left(\frac{y+C}{a}\right)\left[1-\left(\frac{x}{x_0}\right)^2\right]\times\exp\left[-\frac{1}{2}\left(\frac{x}{x_0}\right)^2-\left(\frac{y+C}{a}\right)^2\right]. \quad (1b)$$

Here $C=H_O-H_G$, where H_O is the altitude of the maximum updraft and H_G the altitude of the ground, x_0 is the half-width of the updraft, $a=2^{\frac{1}{2}}C$, and $C_1=2^{\frac{1}{2}}U_y(0,0)/\exp(-\frac{1}{2})$, where $U_y(0,0)$ is the maximum updraft velocity. $U_{xe}(y)$ is the horizontal component of the environmental wind in the x direction as a function of height. A variety of observed updraft profiles can be duplicated by adjusting the height of the maximum updraft, strength of the maximum updraft, the spacing $2x_0$ of the circulation poles and the lower (H_G) boundary. This circulation is modified for the change in height of the density of the air, $\rho=\rho_0 e^{-\lambda y}$, where λ is the coefficient of y required to produce a standard atmosphere, ρ_0 being the air density at sea level. The horizontal translational wind velocity and the vertical shear of the horizontal wind can be added when required. Any nonzero wind shear will result in a circulation with a tilted updraft. The updrafts of multicell clouds may be simulated by superimposing the streamfunctions for any number of single cells to obtain the composite circulation.

c. Microphysics

The liquid water content (LWC) of the cloud droplets is specified as a function of altitude, but remains constant with time and the cloud droplets are assumed to move with the cloud air. Water and ice loading of the cloud air are not present. Ice particles with 100 μm diameter can be introduced into the updraft throughout its entire width at a single level or in increasing numbers at successively higher levels as the observed temperature decreases with altitude and progressively more ice nuclei become active. The ice particles grow continuously by accreting the supercooled cloud droplets (Sartor and Cannon, 1977). As the mass and size of the ice particles increase, their collection probabilities and velocities change based on calculations for equivalent volume spheres according to a scheme used by Sartor (1970).

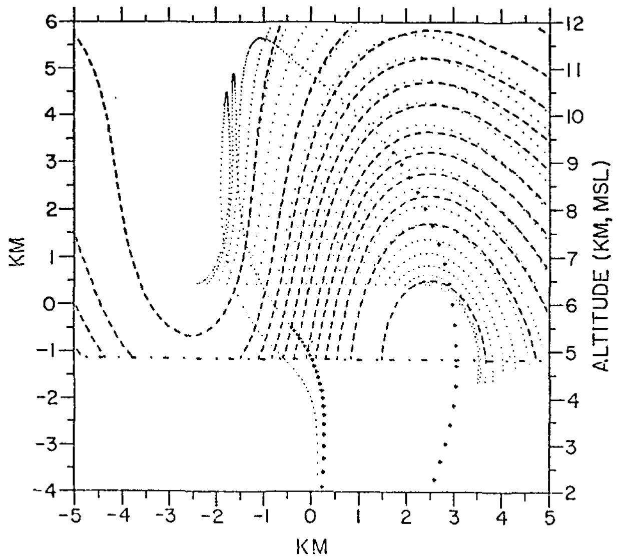

FIG. 1. Particle trajectories for 15 June 1972. Cloud base is 4.9 km, cloud top 12 km, maximum updraft 10 m s^{-1}, mean vector wind shear 0.5 m s^{-1} km^{-1} and liquid water content is $0.16y-0.72$, where y is altitude (km MSL). Particles with initial radii of 50 μm are introduced at 6.5 km. Streamlines are indicated as dashed lines, ice particle trajectories as dotted lines and hail particles (diameter $\geqslant$5 mm) as plus signs.

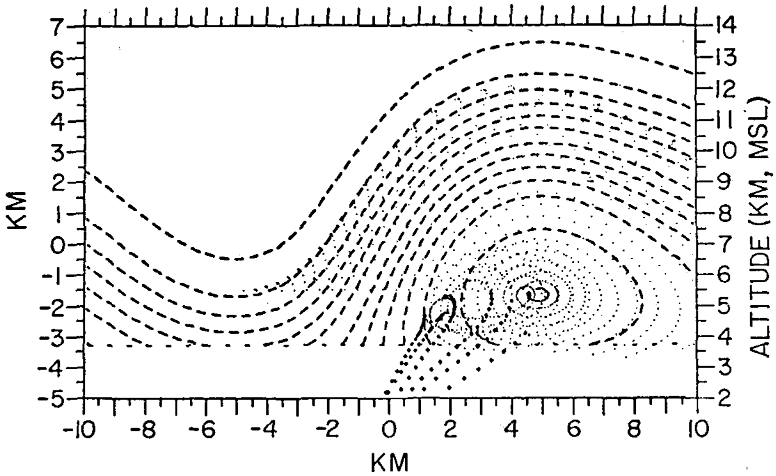

FIG. 2. Particle trajectories for 23 June 1972. Cloud base is 3.7 km, cloud top 14 km, maximum updraft 20 m s^{-1} at 7 km, mean vertical wind shear 5 m s^{-1} km^{-1} and liquid water content is $0.41y-0.96$, where y is altitude (km MSL). Particles with initial diameters of 100 μm are introduced at 5.5 km MSL. Streamlines are indicated as dashed lines, ice particle trajectories as dotted lines and hail particles (diameter $\geqslant$ 5 mm) as plus signs (in this and similar figures to follow, the plus signs are more or less diamond-shaped).

3. Calculations

a. *Concentration and dispersion of precipitation particles*

The precipitation particle distributions in two and three dimensions can be altered by their interactions with the horizontal convergence and divergence in the cloud air circulation. Near the core of an updraft below the updraft maximum, growing precipitation particles move with a sufficiently strong component downward that they cross the streamlines of the velocity field where it is increasingly horizontally convergent, becoming concentrated into a much smaller volume. Concentrations of particles can be diminished when introduced higher up in the same updraft. Having less time to grow before encountering regions of strong horizontal divergence, they are dispersed in the upper portion of the cloud. This phenomenon is described by Cannon and Sartor (1974) and illustrated with the convective cell circulation kinematic simulations used in this paper. In Figs. 1 and 2, dots represent the successive positions of the ice particles each 30 s. The packing of these dots is directly related to the concentrations of the particles. The highest concentrations depicted in Fig. 1 (a simulation for 15 June 1972) appear in the upper left-hand border of the updraft and in Fig. 2 in the lower right-hand corner of the updraft (23 June 1972). Streamlines in the illustrations are indicated by the dashed lines.

b. *Simulation of hail growth using sailplane and surface observations*

A two-dimensional simulation of the convective circulation in and around the clouds observed on 15 and 23 June 1972 requires all the terms in Eq. (1a), except the last, and Eq. (1b). By adding the last term in (1a), we incorporate the average observed environmental wind and apply the microphysical thermodynamic and rawinsonde measurements to calculate the resulting precipitation distributions. Observational and input data and calculated results are given in Table 1 for these two days.

The convective circulation was simulated in part by using the updraft characteristics obtained from sailplane observations between the times of 2212 and 2232 GMT on 15 June 1972 and between 2318 and 2333 GMT on 23 June 1972. The NHRE rawinsonde data for the environmental winds and other meteorological information were taken from observations made nearest these periods.

Fig. 1 illustrates for 15 June 1972 the trajectories of the ice particles (dotted lines) as they grow from the initiation altitude of 6.5 km MSL[2] by accretion of supercooled cloud droplets. At each altitude where the ice particles are initiated, they are spread uniformly across the entire updraft. At the initiation altitude of 6 km and below none of the embryonic ice particles reaches the minimum dimensions of hail ($D \geqslant 5.0$ mm, denoted by plus marks). Starting from 6.5 km (Fig. 1) two small hailstones are formed: one from 7.0 km, one from 7.5 km and none from 8.0 km. These hailstones represent 8, 4 and 4%, respectively, of the 25 precipitation trajectories calculated at each level. The next to the last row of Table 1 gives the observed and calculated, average hail diameter plus or minus one standard deviation

[2] All altitudes are in km MSL.

TABLE 1. Data input to or calculated from numerical simulations and observations for the 15 and 23 June 1972 cases.

	15 June 1972		23 June 1972	
	Observed	Calculated or input data	Observed	Calculated or input data
Seeding rate (g min^{-1})	43		57	
Sailplane max altitude (km)	7.4		6.7	
Temperature at max altitude (°C)	−18.4		−9	
Ambient temperature at max altitude (0°C)	−21			
Estimated surface height (km)	1.5	(2.0)	1.5	(2.0)
Cloud base (km) CB	4.4	(4.9)	3.2	(3.7)
Estimated cloud top (km) CT	11.5	(12)	14	(14)
Max updraft (m s^{-1})	>10	(10)	>20	(15–35)
Mean vector wind shear (m s^{-1} km^{-1})	0.5	(0.5)	5.0	(5.0)
Max LWC (g m^{-3})	<0.6	$0.16Y-0.72$** LWC CB=0.06 LWC CT=1.2	>1.5	$0.41Y-0.96$** LWC CB=0.56 LWC CT=4.78
Total hail (cm^3)	1.5×10^2		2.8×10^3	
Number [%] of hailpads	4 [2%)		61 [30.5%]	
Hail per pad (cm^3)	37.5		45.9	
Average hail diameter±σ* (cm)	0.851±0.226	0.543±0.04	1.05±0.95	0.83±0.18
Max hail diameter (cm)	1.08	~0.57	~2.95	1.70

* σ refers to one standard deviation from the mean.
** Y is altitude (km MSL).

and the last row, the observed and calculated maximum (max) hail diameters. The calculated hail diameters on 15 June 1972 are smaller than observed but do fall within two standard deviations of the observed mean. These calculations were made with an environmental vertical wind shear of 0.5 m s^{-1} km^{-1}. When the shear is increased to 0.625 m s^{-1} km^{-1}, no hail falls in any of the computed cases. These results are consistent with the observations of only small hail hitting four pads on this day (0.9% of the total number of hailpad stations). Note the trajectories in Fig. 1 starting second and third from the left (west) as they move across the main updraft and grow into hail. In this situation our assumption of no cloud droplet depletion would be realistic and seeding in the region where these trajectories originate could result in more hail. Massive seeding of the central and right-hand (eastern) side of the updraft where ice particles grow to hail could turn the supercooled droplets to ice preventing hail growth higher up in the updraft. Seeding with an agent that "poisons" the natural nuclei, delaying their activation altitude until they reach 8 km or above would, according to the trajectories in Fig. 1, not produce hail. This might be a more effective way to suppress hail.

On 23 June 1972 the vector mean shear of the horizontal wind from the NHRE rawinsondes was 5 m s^{-1} km^{-1} and the average maximum updraft obtained with the NOAA-NCAR cloud physics sailplane in a developing cumulonimbus cloud was 20 m s^{-1} or greater. Cloud base was more than a kilometer lower, the cloud base temperature 12°C warmer, and the LWC at least four times greater than on 15 June. Greater than an order-of-magnitude more total hail mass fell on the 23rd hitting 61 pads, 30.5% of the total hailpad stations in the network. The calculated average hail size is within one standard deviation of the observed. Again, as for 15 June, the standard deviation of the calculated hail diameters was much less than observed (see Table 1). Because of the strongly tilted updrafts, depletion is less significant in this case. Using the value of the average maximum updraft of 20 m s^{-1} observed with the sailplane in the earlier stages of the convective development on the 23rd, the streamlines of the circulation and the particle trajectories for ice nucleation altitudes of 5.0 km (the minimum altitude at which nucleation is possible), 5.5 km (Fig. 2), 6.0 km, 6.5 km and 7.0 km were computed; nucleation at the three lower altitudes results in hail in 16, 24 and 12%, respectively, of the trajectory calculations. None of the trajectories beginning at 6.5 km and above results in hail at the ground. In the meteorological situation on 23 June 1972 cloud seeding with silver iodide to suppress hail would be effective only by converting to ice all the supercooled droplets in the layer below 5.5 km and in the right-hand (easternmost) one-quarter of the updraft where the streamlines of the cloud air originate that contain a naturally undepleted supply of supercooled droplets to feed the hail growth region where the plotted dots change to plotted plus signs.

Other calculations were made with the 23 June data in which ice particle initiation takes place at 5.5 km, the wind shear is 5 m s^{-1} km^{-1}, and the average updraft velocity takes on values from 10 to 35 m s^{-1}, separated by 5 m s^{-1} increments. All of these updrafts except 10 m s^{-1} produce hail increasing in average size with increasing updraft. The percentage of the trajectories resulting in hail at the ground is 4% in an updraft of 15 m s^{-1}, 24% at 20 m s^{-1}, 12% at 25 m s^{-1}, 28% at 30 m s^{-1} and 16% at 35 m s^{-1}. Those updrafts in these calculations that exceed 20 m s^{-1} are greater than observed with the sailplane in the clouds of the 23rd. However, updrafts in thunderstorms occurring later in the afternoon following the sailplane flights could easily have reached 35 m s^{-1}.

c. The Browning and Foote conceptual model for 21 June 1972

We use meteorological and cloud physics data in the NHRE area supplied by Browning and Foote (1976) for a severe storm producing giant hailstones first near Fleming, Colo., on 21 June 1972 in simulations of the growth of hail and the trajectories of precipitation particles. The two-dimensional circulation cell simulation is computed in the vertical plane that is parallel to the horizontal direction of the updraft (340°). This minimizes the influence of the third space component and corresponds to the Browning-Foote depiction in Fig. 3.

We have approached the quantitative simulation of the meteorological and cloud physics situation of 21 June 1972 in two ways that differ only in the manner in which the updraft of the cloud air motion is tilted. In the first instance we use only the meteorological data given by Browning and Foote including the wind shear and wind relative to the storm for simulating a circulation in which we introduce the microphysics and compute the hail and precipitation growth and trajectories. Data details appear in Fig. 3. The result of numerically combining of the streamline field of the convective circulation with the environmental streamfunction of the observed wind relative to the motion of the storm gives a tilt of the updraft axis to the right. Browning and Foote depict a circulation in which the axis of the updraft tilts to the left, upwind with respect to the environmental winds, much as Newton (1966) finds in the circulation of a large, sheared squall line cumulonimbus passing over Oklahoma City on 21 May 1961 (Fig. 4). Browning and Foote note that the radar and meteorological data permit either interpretation. It seems to us that the difference in tilt in this case hinges on the strength and speed of the forward propagation of the gust front, air mass front or squall line moving from the west or northwest. The U.S. Daily Weather Maps of 0600 MDT for both 21 and 22 June 1972 show an oscillating frontal pattern to the west of the area. Newton attributes the backward tilt of the main updraft of the Oklahoma storm to a squall line moving forward (left to right or northwest to southeast) with a speed exceeding that of the storm. With a frontal system upwind from the Fleming storm, this seems a plausible explanation in the Browning-Foote model also.

Fig. 5 is the computer printout of our numerical simulation of the Fleming storm using only the total of the flow fields of the convective and environmental circulations. The initial ice particles are introduced across the updraft at 6.0 km altitude. The calculations

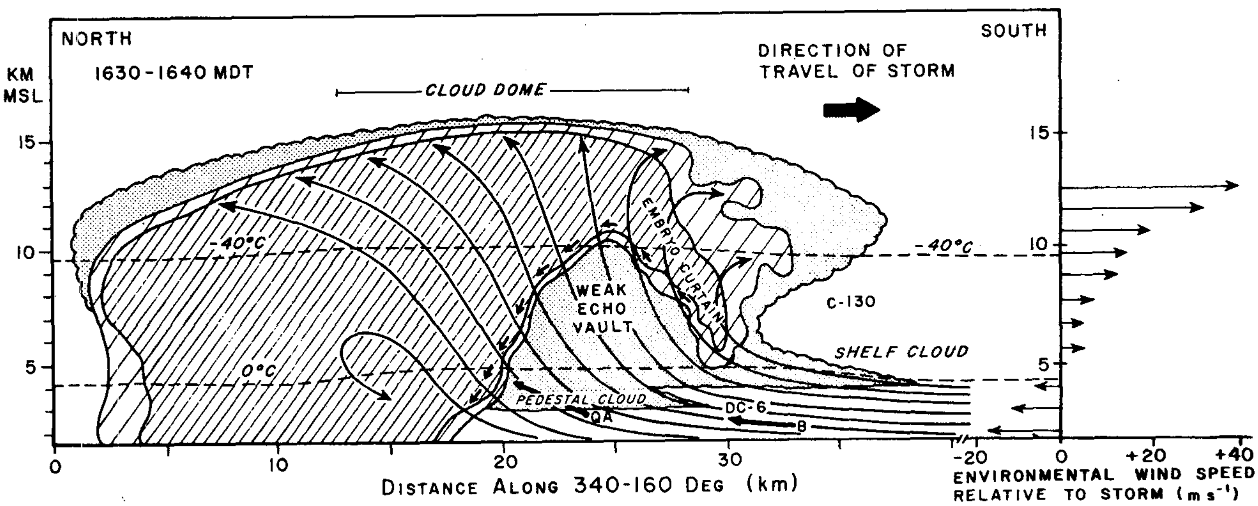

FIG. 3. Vertical section showing features of the visual cloud boundaries of the Fleming storm at 1630–1640 MDT superimposed on the pattern of radar echo (from Browning and Foote, 1976). The section is oriented in the direction of travel of the storm, along the straight line drawn in the 340°–160° direction through a pronounced weak echo vault. Two levels of radar reflectivity are represented by different densities of hatched shading. Areas of cloud devoid of detectable echo are shown stippled. Bold arrows denote wind vectors in the plane of the diagram as measured by two of the aircraft (scale is only half that of winds plotted on right side of diagram). Short, thick arrows skirting the boundary of the vault represent a hailstone's trajectory. To the right of the diagram is a profile of the relative wind component along the storm's direction of travel, derived from a Sterling sounding 50 km south of the storm.

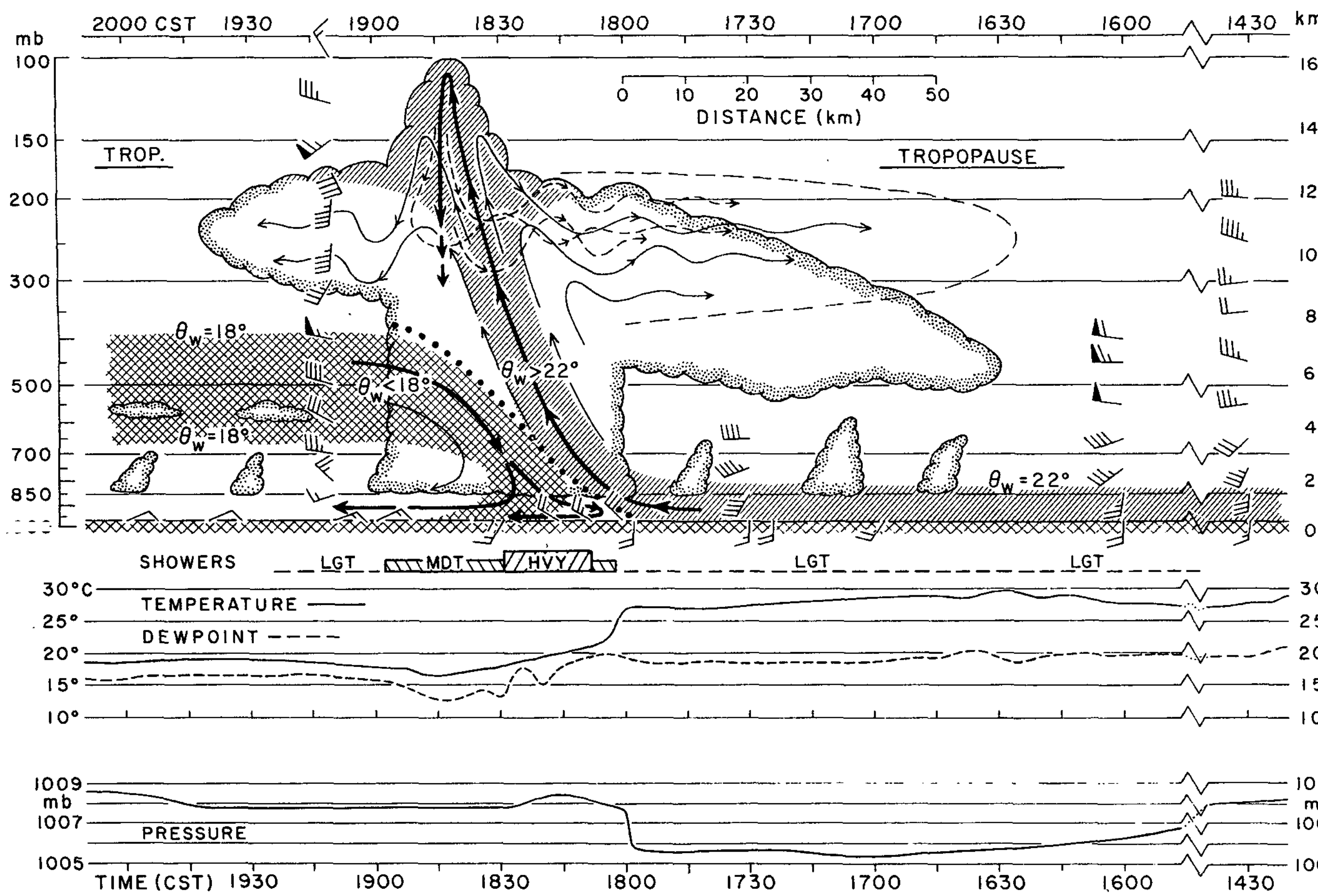

Fig. 4. Partly schematic cross section (from Newton, 1966) through squall line of 21 May 1961, as it passed Oklahoma City (fivefold vertical exaggeration).

result in hail (⩾5 mm diameter) from all the test particles initiated at 6 km. Some grow so large (~10 cm in diameter) that they exceed the drag coefficient of our table and are prematurely truncated while still in the cloud and still growing. Note that there is a weak echo region (indicated by WER in Fig. 5), where only cloud droplets and embryonic ice particles are found. Fig. 6 is a computer printout obtained by tilting the axis of the updraft to agree in angle and direction with that of the Browning-Foote conceptual model (Fig. 3) and the graupel embryos are introduced across the updraft and the downdraft (on the right) at 0.5 km increments of altitude between 6 and 10 km. Half of the precipitation embryos introduced into the

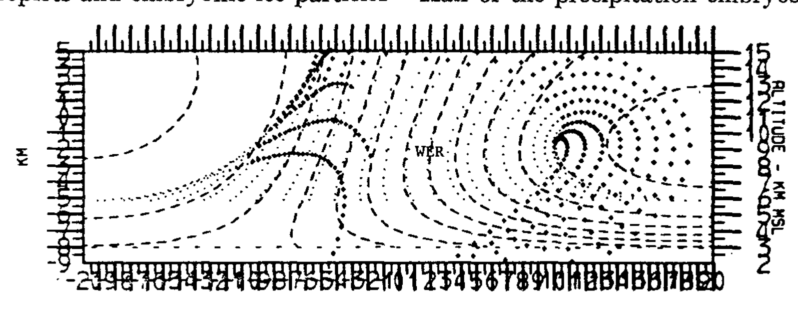

Fig. 5. Numerical simulation of Fleming storm of 21 June 1972. Ice particles are initiated at 6.0 km. Frame indicates cloud and ground boundaries. Streamlines depicted by dashed lines are obtained by combining the streamfunctions of a convective circulation and the relative environmental winds. Note regions of absence of larger precipitation particles (particles ⩾5 mm diameter are indicated by plus signs).

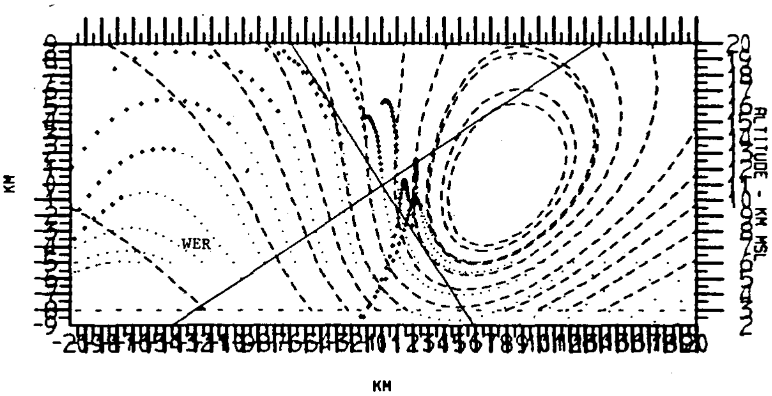

Fig. 6. As in Fig. 5 except the convective component is rotated to the left to obtain an updraft that is tilted to agree with the Browning-Foote conceptual model (see Fig. 3). Ice particles are initiated at 6.0 km.

downdraft at 7.5 km and one-quarter of those introduced at 4.5 km reenter the updraft of the main cell. In each case where this happens, the hail grows large sooner and falls out earlier adding to the total hail produced. The particles appearing in the right-hand downdraft could have come from a "daughter" storm further to the right in Fig. 6. If so, then these calculations suggest that seeding of the "daughter" storm to produce more embryos could also produce more and larger hail.

4. Discussion and conclusions

It seems safe to conclude that the real atmosphere is not less complex nor subject to smaller perturbations than incorporated into these calculations. The natural variability is at least as great as we have considered here. Even with these considerably simplified two-dimensional simulations, we can see that relatively small changes in the input parameters can produce important changes in the hail distributions. But there are certain useful conjectures that we can make from this work about seeding techniques in general. It would appear that the only completely safe way to seed to ensure smaller hail is the massive seeding of the updraft to convert most of the supercooled *cloud droplets* to ice. Adding more embryonic ice particles into the base of the updraft continuously could cause depletion of the subsequently formed supercooled cloud droplets starving those ice particles already moving above this nucleation altitude. Seeding in the wrong portion of the updraft could result in even greater amounts of hail even if hail size is not increased or decreased. Any appreciable degree of efficiency obtained by seeding in this manner requires prior computations and predictions using known meteorological and physical parameters.

Seeding with an agent that destroys the nucleating abilities of natural nuclei until they enter the region of horizontal divergence could be a safer, more effective way of modifying convective clouds to suppress hail.

The results do indicate that prior to seeding, we must know a great deal about the synoptic- and subsynoptic-scale meteorology and air mass properties before we can seriously hope to efficiently act to modify hail and precipitation or even to determine whether hail formation will be increased or decreased by one method of seeding or another.

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