Wind structure and its impact on hail production: a VORTEX ‘95 case study using airborne Doppler radar

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ABSTRACT

Dual-Doppler analysis of the 17 April 1995 data collected by the National Center for Atmospheric Research airborne Electra Doppler Radar during the Verification of the Origins of Rotation in Tornadoes Experiment was used to resolve the kinematic structure of the storm, which was used to perform a hail trajectory analysis. Hailstone embryos introduced into the right flank of the storm followed the cyclonic branch of the horizontal flow which was found to favor the largest hail growth. A placement of the axis of maximum vertical vorticity upstream of the updraft both directs particles into the updraft, and redirects particles into the updraft after initial descent. This configuration was found to allow for two passes over the updraft or recirculation, as described in past studies. These findings agree with the current understanding of hail growth within thunderstorms.

It was found in this study that the placement of a deep, relatively weak updraft around the maximum cloud liquid water content level played a key role in supporting large hail growth in both size and quantity, as well as concentrating the hail fallout into a small area. A stronger maximum updraft that lifted the particles above the level of maximum liquid water content was found to provide a smaller concentration of large hail growth, as well as spreading the particle fallout over a larger area due to stronger advection in the midlevels of the storm. These findings seem at odds with the notion that the strength of the updraft alone determines final hail sizes.

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INTRODUCTION

Hail, one of the most damaging forms of severe weather in the United States, caused between $400 million and $2 billion in property and crop damage in the United States between 1996 and 2002 (NWS Office of Services, 1995-2002). Improved data collection and analysis techniques have led to increased understanding of storm wind structure and how it influences hail formation. In the 1960’s and 70’s, many studies investigated hail formation in an attempt to better predict their occurrence and find methodologies for hail suppression. Marwitz (1972a, b, c) proposed three categories of hailstorms and highlighted their different structures based on data from conventional radar, in situ aircraft, and surface instruments as well as visual observations.

Browning and Foote (1976) later proposed a conceptual model of the wind structure that leads to hail formation. One important aspect of this model involved the particle trajectory a hailstone would take through the storm in order to provide the conditions necessary for ice accumulation (Browning and Foote, 1976). Browning and Foote relied solely on conventional radars without Doppler capability, so the internal wind structure could only be inferred. With the advent of Doppler radar capability, ground-based multiple-radar networks have been used in projects such as the 1976 National Hail Research Experiment (NHRE) and the 1981 Cooperative Convective Precipitation Experiment (CCOPE). Radial winds from these multiple-Doppler measurements have been combined to resolve three-dimensional winds within the storms. Studies such as Knight and Knupp (1986) and Miller et al (1988, 1990) used the Doppler-derived winds to calculate hail growth from smaller particles known as hail embryos.

Because ground-based radar networks are not movable, measurements are not possible until a storm enters the network. However, this issue can be addressed by the mobility of airborne Doppler radars, providing an opportunity to collect detailed observations wherever a hailstorm is located. Airborne radar systems have an additional advantage in that they can collect high-resolution data in close proximity to the storm.

This study uses measurements taken during the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX) with the National Center for Atmospheric Research (NCAR) Electra Doppler Radar (ELDORA). The details of ELDORA’s mobile capabilities and unique dual-antenna, dual-PRF (pulse repetition frequency) radar system are discussed in Wakimoto et al (1996). These dual-Doppler measurements are used to synthesize three-dimensional wind fields along with a simple particle trajectory model (Knight and Knupp 1986) to determine the nature of hail growth in this storm. These results are used to determine consistencies between this case study and our current understanding of hail formation within thunderstorms.

BACKGROUND

Basic Radar

As detailed in Rinehart (1997, Chapters 2 and 5), a basic radar system consists of six components: an antenna, a receiver, a transmitter, a modulator that controls the transmitter, a master clock and/or computer, and the display. The radar transmitter sends out pulses of electromagnetic energy at some wavelength $\lambda$, spaced apart at a rate known as the pulse repetition frequency (PRF). The pulses then scatter back from targets within the beam and return to the antenna to be detected by the receiver. The strength of the returned signal is proportional to the sum of individual backscattering cross-sections of meteorological targets. This so-called
reflectivity varies due to sizes and numbers of particles, as well as with other non-meteorological factors (Rinehart 1997, Chapters 2 and 5). A Doppler radar detects a particle’s motion directly toward or away from the radar, in this case driven by the wind (Rinehart 1997, Chapter 6). The motion creates a Doppler shift in the frequency of the transmitted pulse during its travel between the radar and the target, which can be converted into a radial velocity. This velocity information is very useful in the study of atmospheric phenomena such as gust fronts, mesocyclones, tornadoes, and microbursts (Rinehart 1997, Chapter 6).

There exist several non-meteorological returns or artifacts that must be removed from the radar dataset before it can be used in a wind synthesis. These include signals scattered from the ground as well as other surface obstacles such as buildings and towers. These artifacts are collectively referred to as ground clutter. The radar also detects moving objects such as birds, airplanes, and insects (Rinehart 1997, Chapter 4). Additionally, there can be signals from meteorological targets that can be mistaken for desired data. Rinehart (1997, Chapter 6) describes how a radar can detect a storm at distance R that is beyond its maximum unambiguous range ($R_{max}$), but places the storm’s echo at a distance $R - R_{max}$ instead of at R. This phenomenon, known as second-trip echoes, is identifiable by the wedge-like shape pointing towards the radar. Another phenomenon occurs due to the scattering pattern of a radar beam. If a target located some angular distance to the side of the centerline of the radar beam has a particularly strong return signal, it will contaminate the desired return within the main lobe. This sidelobe return is recognizable in the data by a reflectivity signal in close proximity to a strong signal that looks identical in shape and size, yet has a weaker reflectivity (Rinehart, 1997). If these artifacts are not removed from the individual radar datasets, they will almost certainly negatively impact the Doppler wind calculations.

**Doppler Analysis**

According to Armijo (1969), data from three Doppler radars are necessary to perform a Doppler analysis; however, data from two radars are sufficient given that certain assumptions are made (Armijo 1969). The horizontal winds in the X and Y directions (U and V, respectively), the mass continuity equation, and the terminal fallspeed of the particles ($V_t$) are necessary for this calculation. With three radars, the total vertical motion of particles ($w + V_t$) can be directly calculated, but for two radars this term must be inferred by integrating the mass continuity equation and using the reflectivity data to compute $V_t$. The radial velocities are combined in vector calculations to obtain the U and V wind components (Armijo 1969).

**Hail Formation**

Hail results from an initially small particle collecting supercooled cloud liquid water to form a larger ice particle, usually somewhat of a spherical shape. This initial particle, or hail embryo, can form from numerous different sources, but mainly consists of a small ice particle (such as graupel) or a larger water droplet. These particles provide the surface for ice to freeze on at temperatures near or somewhat colder than 0°C, since the spontaneous freezing of water occurs only at much lower temperatures. Typical hail sizes range from marble- to golf ball-sizes, although hail can grow to the diameter of a grapefruit or more.

Few storms have been studied in detail, especially when the frequency at which hailstorms occur is considered, but there is mounting evidence as to how hail generally forms
within thunderstorms. One such case study by Miller et al (1990) found that hail grew along three main paths, as depicted in Figure 1. Of the three, the cyclonic and straight-line paths were found to be the most conducive to large hail growth. Also noted were the sources of embryos within this particular storm and the kinematic structure of the storm at different levels (Miller et al 1990).

![Figure 1](image.png)

Figure 1, from Miller et al (1990). These three-dimensional ribbons display the three main paths that they found to dominant hail production: cyclonic (C), straight-line (SL), and anticyclonic (A). The hatched areas are the reflectivity above 52 dBZ. The streamlines are the mid-level winds ventilating the storm, and the broad arrow represents the main low-level inflow into the storm.

**METHODS**

**Data Collection**

The radar data for this study were collected during the April 17th, 1995 mission of VORTEX using the NCAR Electra aircraft. A strong line of thunderstorms developed across northern Texas and southern Oklahoma, which included an intense isolated thunderstorm in front of the line. The Electra took off at 19:00:00UTC (all times are Universal Time, local Central Standard Time is UTC-6) on a practice mission, but joined the National Oceanic and Atmospheric Administration (NOAA) P-3 aircraft at 23:30:00UTC when the storm formed a tornado near Temple, Oklahoma. The Electra began to sample the front of the squall line.

Beginning at 00:00UTC, April 18th (18:00 Central Standard Time, April 17th), the NCAR Electra aircraft intercepted the storm near Elmore City, Oklahoma. Figure 2 is the 00:10UTC National Weather Service (NWS) WSR-88D reflectivity image. The large isolated supercell that is within the ELDORA sampling area is the storm of interest, and the red line indicates the path of the storm through its lifetime of six hours. The storm turned right of the mean winds and entered its severe stage as it passed KFDR, the NWS Frederick radar.
storm ended its severe stage shortly after ELDORA began sampling it. Figure 3 shows the flight track of the mission, with the highlighted area being the interception of the storm. The aircraft made five passes within close proximity of the storm over a 30-minute period. The data of interest are from legs one through four of this interception, which lasted a total of about 25 minutes. ELDORA exited the sampling of this storm during leg five, so this leg will not be used for analysis. At the beginning of leg one (00:00UTC), an F1 tornado was reported near Velma, OK. During leg two (at 00:05UTC), 1.75 inch diameter hail was reported near Elmore City, OK. Because hail formation usually takes at least 10-15 minutes, this hail began its growth before the beginning of ELDORA’s collection period.

Figure 2. WSR-88D reflectivity data from KTLX at 00:05UTC April 18th, 1995. The red line is the total path of the storm, and the small area labeled is ELDORA’s sampling of the storm. The bend to the right at KFDR marks the place where the storm enters its severe stage, and the bend back with the mean wind (SW-NE) at the end of ELDORA’s sample is where the storm exits its severe stage. The colored scale is in dBZ.
Figure 3, flight track of the Electra aircraft. The interception of the storm is from 00:00:00UTC to 00:30:00UTC, outlined in the circle above. The colored bar is the altitude of the plane in meters. The axes are in latitude and longitude, with the color code showing the altitude of the aircraft.

Figure 4 displays the processed radar data from the NCAR SoloII software package (Oye et al. 1995), at 00:01:36 from the aft-looking radar. The top image is the reflectivity data and the bottom image is the radial velocity data. For the reflectivity image, the scale goes from –20 to 60 dBZ (on a logarithmic scale). For the velocity image, the scale is in m/s with the white being 0m/s. The greens and blues are negative velocities, representing winds blowing towards the radar. The oranges and reds are positive velocities, representing winds blowing away from the radar. The radar’s position is marked in the bottom right corners of each image. The curled reflectivity structure and WER greatly resemble the “hail embryo curtain” that has been noted in many studies such as Browning and Foote (1976). Also noted is the velocity data with the strong winds blowing away from the radar and into the storm. This is suggestive of a strong updraft that also resembles Browning and Foote’s conceptual model. However, it is difficult to infer the 3-D wind structure from this image since the data are the radial velocities from only one antenna direction.
Radar position

Figure 4. SoloII image of the reflectivity (top) and radial velocity (bottom) data at 00:01:36, where the reflectivity curl shows most prominently in the aft radar display. The radar’s position is indicated, with the reflectivity curl reaching to about 5km away from the radar at 30-45° angle upwards from the radar. The reflectivity is in dBZ, which is a logarithmic scale. The radial velocity data are in m/s, with 0 being indicated by white. The greens are negative (towards the radar) velocity values, while the yellows are positive (away from the radar) values.

Instrument Specifications

ELDORA’s observations and specifications for the VORTEX project are detailed in Wakimoto et al (1996). Briefly, ELDORA uses two rotating antennas that are mounted to the tail of the NCAR Electra aircraft, one that points ~16° fore, the other ~16° aft with respect to the aircraft, which is illustrated in Figure 5. As the antennas rotate in the tail cone of the plane, they scan in approximate vertical cross sections of the surrounding atmosphere on both sides of the aircraft.

Figure 5. Schematic of ELDORA’s antennas. The fore and aft radars point 16° to the front and to the rear of the aircraft respectively from a horizontal plane perpendicular to the aircraft’s direction of travel. This results in a conical scanning pattern with the radar being the center of the cone.
Figure 6 illustrates ELDORA’s scanning technique as the aircraft flies near a thunderstorm. An advantage of ELDORA is that it is capable of transmitting at four different frequencies, which increases the number of independent samples (Wakimoto et al. 1996) and allows for a fast scanning rate of up to 144° per second, which is more than twice as fast as the NOAA P-3 airborne radar that scans at about 60° per second. This faster scan rate reduces the distance the plane travels between antenna revolutions, which improves the along-track spatial sampling resolution (Wakimoto et al. 1996).

Wakimoto et al. (1996) also noted that since anticipated wind speeds can exceed 50 m/s, ELDORA uses two PRFs to increase the maximum unambiguous velocity $V_{\text{max}}$ to 100 m/s, which is five times the $V_{\text{max}}$ of single-PRF airborne Doppler radars. $V_{\text{max}}$ is the maximum velocity the radar can detect without resulting in an ambiguity that makes the computed velocity unrepresentative of the actual velocity, which is known as velocity aliasing or folding. The maximum unambiguous range $R_{\text{max}}$ is the maximum distance the radar can detect particle motion without aliasing. Exceeding $V_{\text{max}}$ or $R_{\text{max}}$ results in ambiguities known as velocity or range aliasing or folding, since $V_{\text{max}} = (\text{PRF} \lambda) / 4$, while $R_{\text{max}} = c / (2\text{PRF})$, where $\lambda$ is the radar pulse’s wavelength and $c$ is the speed of light. Many ground-based radar systems must compromise between $V_{\text{max}}$ and $R_{\text{max}}$ since a change in PRF to achieve a higher $V_{\text{max}}$ results in a lower $R_{\text{max}}$. ELDORA resolves this problem by traveling within close proximity to a storm and by using the dual-PRF system, making ELDORA capable of reliably detecting high wind velocities (Wakimoto et al. 1996).

Software

The Doppler radar data were edited with SoloII to remove any noise or other radar artifacts described earlier. SoloII is an interactive data editing software package that allows for quality control within the individual radar sweep files (a sweep being one full revolution of the radar rotodome). Figure 7 is from SoloII at 00:00:00 (the beginning of the first flight leg) from the aft radar, displaying the radial velocity data. The top image is the unedited version while the bottom image is the edited version. Figure 7 shows examples of sidelobes and background.
noise. For this study, the unedited reflectivity data were used; however, the edited radial velocities are used for the Doppler analysis since noise contamination can greatly effect the winds that are synthesized.

![Figure 7] Velocity data at 00:00:00UTC showing unedited and edited data. The wind velocity units are in meters per second (m/s), with the positive values being winds blowing away from the radar on the radial velocity scan. The white regions indicated are side lobes, most likely receiving a return from the storm’s core although the beam is pointing above the storm. The multi-colored flecks are background noise.

The wind fields have been resolved using the Custom Editing and Display of Reduced Information in Cartesian Space (CEDRIC) software (Mohr et al. 1986). CEDRIC has a variety of methods of resolving wind fields, but which method is used is dependent particular case. Outputs that display the geometric properties of the data and synthesis, as well as the ability to output the variables involved in the synthesis, enables the user to test the sensitivity of the synthesis to different errors. For this analysis, the variational synthesis technique is used due to the high beam-elevation angles involved in the data collection for this storm. CEDRIC was also used to calculate the vertical vorticity (the strength of the rotations within the wind structure of the storm), the vertical velocities, and the convergence. A positive horizontal vorticity of 10^{-2} \text{s}^{-1} (10 \times 10^{-3} \text{s}^{-1}) is the threshold for a mesocyclone within a storm (Moller et al. 1994). The vertical velocity display helps to overlay the vertical winds with the horizontal winds to get a better three-dimensional picture. The convergence (or divergence) is used to determine the interaction of the storm’s wind structure and the environment. To test the accuracy of the analysis, other calculations within the software were performed to display the geometry of the Doppler analysis.

CEDRIC was also used to generate plots of the synthesized wind fields overlaid upon other parameters. All of the data were rotated so that the x-axis is along the direction of the mean wind, which is out of the southwest in this case. The y-axis is perpendicular to the direction of the mean wind. All heights are at mean sea level (MSL), and the surface is at 500m. The horizontal grid is 40km by 50km, with the small tic marks being every 1km, and the large tic
marks being every 10km. The vertical plots in this paper are on a y-z plane, with the horizontal mean wind coming out of the plane.

The hailstone growth was calculated using the simple precipitation growth trajectory model created by Knight and Knupp (1986). This program uses the CEDRIC wind field data as well as the vertical thermodynamic profile data that was from an environmental sounding taken about 5 minutes before the beginning of the first flight leg. The growth model uses a simple microphysical scheme where all particles are assumed to be spherical objects that evenly sweep out cloud water every 10s time step, which is then converted to particle mass. The amount the particle collects is dependent upon the prescribed liquid water content and collection efficiency. Several assumptions were made for the particle trajectory calculation. First, all of the wind vectors were advected to a single time, so the calculation is made with storm-relative velocities as if the storm is not moving or evolving. Any melting or particle breakage is not taken into account, and the program assumes hail growth can occur anywhere between the cloud base and -40°C (although hail growth does not occur at temperatures warmer than 0°C). The liquid water is assumed to be in the updraft core, with lesser amounts in the updraft’s fringes. No liquid water is assumed to be in the downdraft region. The particle must reach above 5mm within its trajectory, which ends when the particle either leaves the data field or reaches the ground level (Knight and Knupp, 1986). Knight and Knupp found that the modeled final particle size’s greatest sensitivity has been due to the prescribed liquid water content and the realized wind fields.

SYNTHESIZED WIND FIELDS AND TRAJECTORY MODEL RESULTS

General Structure

Figure 8 depicts the storm relative winds overlaid upon reflectivity at a height of 2km. The cyclonic (counterclockwise) winds that are rotating about the point indicated are what create the low-level mesocyclone. The two extensions shown on the right flank of the mesocyclone are the flanking line of smaller cells that are merging with the main storms, which provided a source of hailstone embryos.
Figure 8, the 00:00UTC storm-relative wind field overlaid upon reflectivity data at 2km. The low-level mesocyclone and a merging flanking line of cells are indicated.

Embryo Source Region

Figure 9 is a vertical projection of the several backward growing trajectories, where cm-sized hailstones are started near the ground and are allowed to “ungrow” to micron sizes. Two passes over an updraft are evident by the looping structure within the trajectory. However, keeping in mind that the particle is also moving quickly horizontally out of the plane, then the loop in the first part of the trajectory is more of a helical structure whereas the second part of the trajectory is a simple up-down pass over the main updraft. All particles at all diameters and heights follow similar full or partial paths, but the length of time the particle spends within the embryo curtain and how evident the helical structure is varies with size.
Figure 9, vertical projection of a backward growth trajectory onto the reflectivity data at $x = 35 \text{km}$, with the circles indicating where the particle ended the backward trajectory at 100 microns. This shows that the particles began in the embryo curtain region on the right flank of the storm. Also, the recirculating structure evident along the particle path actually makes a helical trajectory out of the plane toward the reader and along the mean winds.

Figure 10 is a horizontal projection of the trajectories in Figure 9 overlaid upon the reflectivities at 1km. The vertical dashed line at $x=35 \text{km}$ marks the location of the section slice that is shown in Figure 9 was taken from. This horizontal projection shows the particles’ paths around the right flank and back into the main updraft. The larger reflectivity values seen along the trajectories shown in Figure 9 are actually above the height of the horizontal section shown in Figure 10. This depiction (Figure 10) is representative of backward trajectories for several diameters and heights, with larger-sized particles following along paths closer to the main updraft than those of the small-sized particles. No evidence of either a straight-line or anticyclonic growth trajectory (Miller et al. 1990) was found within this particular case.
Figure 10, horizontal projection at a height of 1 km of the backward growth trajectory shown in Figure 9. This shows the particles mostly following the mean wind towards the right side of the image. This also shows the particles originating along the right flank of the storm, near where the flanking cells are merging with the storm. The lack of high reflectivities along the particles’ paths is a result of this projection’s location below the higher reflectivities shown along their paths in Figure 9.

These two Figures combined show that the reflectivity curl shown in Figure 11 is actually a two-dimensional slice of the three-dimensional helical trajectories of growing hail. As slices are made through the storm at different x-locations, this reflectivity structure curls around on itself until it reconnects and finally joins the main storm structure. The embryo does not grow significantly in this part of the trajectory, but mostly grows to about 1mm size. Most of the growth is gained as the particle makes its second pass over the main updraft, since by that point the particle is large enough to begin sweeping out large quantities of cloud liquid water.
Figure 11, yz projection of the storm-relative winds overlaid the reflectivity at x=35km. This shows the southwestern-most terminus of the embryo curtain, along with the circulation of the vertical vector winds in this vertical plane. These winds along with those in the plane perpendicular to this plane lead to the helical trajectory shown in Figure 9.

Vertical Vorticity and Updraft Placement

Figure 12 displays the 3km storm-relative winds overlaid upon the vertical velocities during leg one. The main vorticity axis, which is a measure of the rotation of the storm-relative winds about the vertical axis, is located slightly upstream and towards the right flank of the main updraft. This configuration allows embryos in the right flank of the storm to be advected into the main updraft, allowing for optimal growth potential. In contrast, the 3km storm-relative winds during leg 3 (Figure 13) shows that the main vorticity axis has now shifted to a location perpendicular to the mean wind from the main updraft, and is much closer in proximity. This configuration also brings the vorticity axis farther away from the right flank then the updraft. This was found not to be as efficient at introducing hail embryos into the main updraft, since the horizontal winds turn inward more toward the downstream side of the main updraft.
Figure 12, the 00:00UTC storm relative winds overlaid upon the vertical velocity data at 3km. The main updraft axis is indicated, as well as the main vorticity axis located slightly upstream and towards the right flank. This configuration was found to be the most conducive to hail formation in this case study.

Figure 13, the 00:10UTC storm relative winds overlaid upon the vertical velocity data at 3km. The main updraft is indicated, but now the main vorticity axis is not located upstream, and is farther away from the right flank. This configuration was found not to be as conducive to hail formation as the configuration in leg one.

Vertical Updraft Configuration

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Figure 14 shows the vertical profile of the maximum updrafts for legs one and three. The adiabatic cloud liquid water content (clwc), shown in Figure 15, was obtained from the environmental sounding taken five minutes prior to ELDORA’s sampling of the storm. The updraft in leg one is relatively weak at 18 m/s, yet is centered around the peak of the clwc for roughly 5 km. During leg 3, the updraft maximum is almost 10 m/s faster, but accelerates sharply to a level that is mostly above the peak of the clwc. The resulting particle trajectories attended to be much flatter, reaching lower heights trajectory than those shown for during leg one and, remaining mostly within the maximum clwc layer. For leg three, the particles follow a more vertically-spiked trajectory where they remained above the maximum clwc for quite some time.

Figure 14, vertical profile of the maximum updraft within legs one and three. The blue lines represent the cloud base, 0°C, and -40°C. The maximum adiabatic cloud liquid water content is at z=7km. The updraft maximum for leg one is at 18 m/s, but over a 5 km layer centered on the maximum CLWC. Leg three’s maximum updraft is at 27 m/s over a 2 km layer that is above the maximum CLWC.
Final Sizes and Fallout

The three-dimensional kinematic structure during leg one resulted in larger hail diameters and a larger concentration of large hailstones, despite the weaker updraft and vorticity values. Figure 16 is a bar graph showing the final diameters of all particles introduced into the model at all levels for legs one and three. Although both were capable of producing large hail, the average diameters and concentrations of large particles were greater in leg one. Also affected were the final fallout positions of the hailstones, which are illustrated in Figure 17. The much more concentrated fallout positions during leg one combined with the increased concentration of larger particles would certainly increase this storm’s chance of producing more crop and property damage than during leg three. Leg three’s fallout pattern is spread out over a much wider area, decreasing the likelihood of producing more damage.

The final results of this case are a bit surprising, because despite the relative weakness of the updraft in leg one, the combination of other factors and proper configuration allowed this storm to produce large hail. Based on conventional wisdom that a larger updraft would support larger hail, leg three should have been the producer of the larger hailstone sizes. However, the updraft maximum location above the peak of the clwc in leg three would not only suspend the particles at a level where they wouldn’t be able to grow, but would also put the particles into the much faster horizontal mid-level flow, which would spread them over a much larger area at the ground. The combination of a deep updraft centered around the maximum clwc, a vorticity axis located upstream and towards the right flank of the main updraft, and a primary embryo source region located on the right flank allowed for large hail growth despite the relatively weaker values of the individual parameters when compared to those during leg three.
Figure 16, graph of the final diameter distribution of all embryos at all levels. Leg one's concentration of larger final sizes is greater than leg three's, and the average size overall is larger as well.

Figure 17, final positions of hail particles for legs one and three overlaid upon the reflectivity at 1km. The fallout for leg one is concentrated over a much smaller area than in leg three, which results in the storm being much more damaging during leg one than leg three when combined with the larger concentrations of big hailstones.
CONCLUSIONS

This case study had several aspects in common with the current knowledge of how hail grows within thunderstorms. The right flank of the storm, along with the flanking line of smaller cells merging with the main line, were found to be sources of hailstone embryos. The cyclonic branch was found to be the dominant hail-producing path within this particular storm, although no evidence of a prominent straight-line or anti-cyclonic growth trajectory (Miller et al. 1990) was discovered. The overall kinematic structure was found to allow a general recirculation of embryos within the storm, although only two passes through the main updraft were involved. The travel within the embryo curtain is not a primary growth period. However, the finding that the configuration of a cyclonic vorticity slightly upstream and toward the right flank of a deep, relatively weak main updraft produced the largest and most concentrated hail distribution is something that might warrant further investigation, since this finding is unique to this case at the present time.

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