A CASE STUDY OF CLOUD SEEDING TO REDUCE HAIL DAMAGE

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ABSTRACT: A large tornadic, hail-producing, supercellular thunderstorm developed in northwest Kansas on the afternoon of 29 June 2000. This storm was observed by a network of polarimetric radars that were being used for research by the Severe Thunderstorm Electrification and Precipitation Study (STEPS). The storm of interest was seeded by the Western Kansas Weather Modification Program (WKWMP) for more than two hours as it transitioned from multicellular to supercellular mode, produced an EF-2 tornado and copious amounts of hail (with diameters up to 4.5 cm) for over one and one-half hours. Published studies based on the research radars' observations provide a time history of this storm's hail production in terms of volume containing hail, graupel, and other precipitation types, as well as volume containing significant updraft. Using these analyses, it is shown that the storm invigorated, and the volume of the storm containing hail increased dramatically shortly after seeding began. It is not known how the storm would have developed, or the size and quantity of the hail that would have been produced, had it not been seeded. It is suggested that a large sample of similar supercellular storms, both seeded and unseeded, be analyzed by polarimetric radar-based techniques in order to better understand the impact of seeding on hail development. Such analysis could be done inexpensively using National Weather Service (NWS) radar data.

1. INTRODUCTION

Beginning in the late 1940's, among the earliest applications of cloud seeding with glaciogenic agents was seeding to mitigate hail damage (Byers, 1974). Conceptual models for hail damage mitigation by cloud seeding, and the cloud seeding techniques themselves, have evolved over the last half-century, but still basically involve dispersing glaciogenic materials into either the bases or tops of feeder clouds in newly developing portions of a storm complex with hopes of modifying storm evolution in such a way that less damaging hail develops. In the northern High Plains region of the United States, statistical studies have compared hail damage in areas in which aircraft seeding was conducted, to hail damage in neighboring areas that were not seeded (Miller et al. 1975, Smith et al. 1997). These studies suggest that on a seasonal basis there can be roughly 45% lower monetary losses due to hail damage to crops in seeded areas, compared to unseeded areas, using seeding strategies implemented in the 1970's and later in these regions.

Hail production by storms is highly variable. Some of this variability and complexity is reviewed in Foote (1985). He classifies a broad spectrum of storm types according to both dynamic and microphysical processes thought to be critical to hail production. One storm may produce copious amounts of hail damage while another storm in the same region, similar in character according to available visual and radar observations, may produce much less hail damage. The heaviest hail fall is typically restricted to narrow swaths less than a mile wide and perhaps several miles long. Some swaths may cross populated areas and cause highly visible damage, while similar ones may cross areas where there are fewer ob-

servers, structures, or vegetation susceptible to damage. Observations sufficient to quantify hail production by a large population of storms are not routinely available. Crop insurance records are very difficult to obtain for use in studies like those conducted by Miller et al. (1975) and Smith et al. (1997) as insurance companies regard them as proprietary information.

The addition of polarimetric capability to the National Weather Service (NWS) WSR 88-D weather radar network in the United States, along with advances in the use of polarimetric radar to map regions in storms where hail exists, presents the opportunity to use routine radar observations to do analyses of hail production in storms over the United States that only a decade ago required specialized research radars. In principle, a large number of storms can be analyzed efficiently using archived polarimetric WSR 88-D data, including output from standard hydrometeor identification algorithms (Straka et al. 2000, Park et al. 2009), and other radar-based parameters or combinations of parameters correlated with hail presence and size. Using these quantities the characteristics of hail in storms that were seeded can be compared in a quantitative manner to those in similar storms in the same region in a similar meteorological setting that were not seeded.

We present below polarimetric radar-based observations of hail in a large supercellular thunderstorm that was seeded using silver iodide (AgI) smoke generators and dry ice pellets by five aircraft during the Western Kansas Weather Modification Program (WKWMP). This storm occurred in northwestern Kansas on June 29, 2000. It was observed by an extensive array of observing systems assembled for the Severe Thunderstorm Electrification and Precipitation Study (STEPS) (Lang et al., 2004). The primary goal of the WKWMP is to decrease hail damage using cloud seeding with glaciogenic agents. These operations are based on the hypothesis that such seed-

ing reduces damaging hail via the beneficial competition process (Smith and Beer, 2000). Analysis of polarimetric radar observations will show that the storm intensified and hail production rapidly increased after seeding operations began. From the analysis it is not possible to confidently attribute the increase in hail production to seeding or to one or several other influences on the storm, such as changing near-storm environment, interaction with outflows from neighboring storms, etc. However, analyses like this one on a population of seeded and unseeded storms will be useful for a more thorough study of the effects of glaciogenic seeding on hail production by supercellular thunderstorms.

2. OBSERVATIONS

2.1 Western Kansas Weather Modification Program

The WKWMP began operations in 1975 and has covered various areas of western Kansas up to the present. In 2000 there were two operational areas, one served by a radar and several aircraft based in Colby (northwest Kansas), and the other by several aircraft in Lakin and other airports in west central Kansas, supported by a radar in Lakin (see Figure 1). When large storms having long durations were present, such as the storms observed on this day, aircraft based at several different airports could be deployed on the same storm or storm complex. A project meteorologist at the radar in Colby helped direct pilots toward bases of updrafts in flanking cells where they ignited their AgI generators and pyrotechnic flares at altitudes from 5-8,000 ft. MSL. One twin-engine aircraft was available to drop dry ice pellets into rising flanking convective turrets from 16-18,000 ft. MSL. Flight tracks and seeding equipment operation statistics are compiled for each flight, along with a record of waypoints associated with each seeding run.
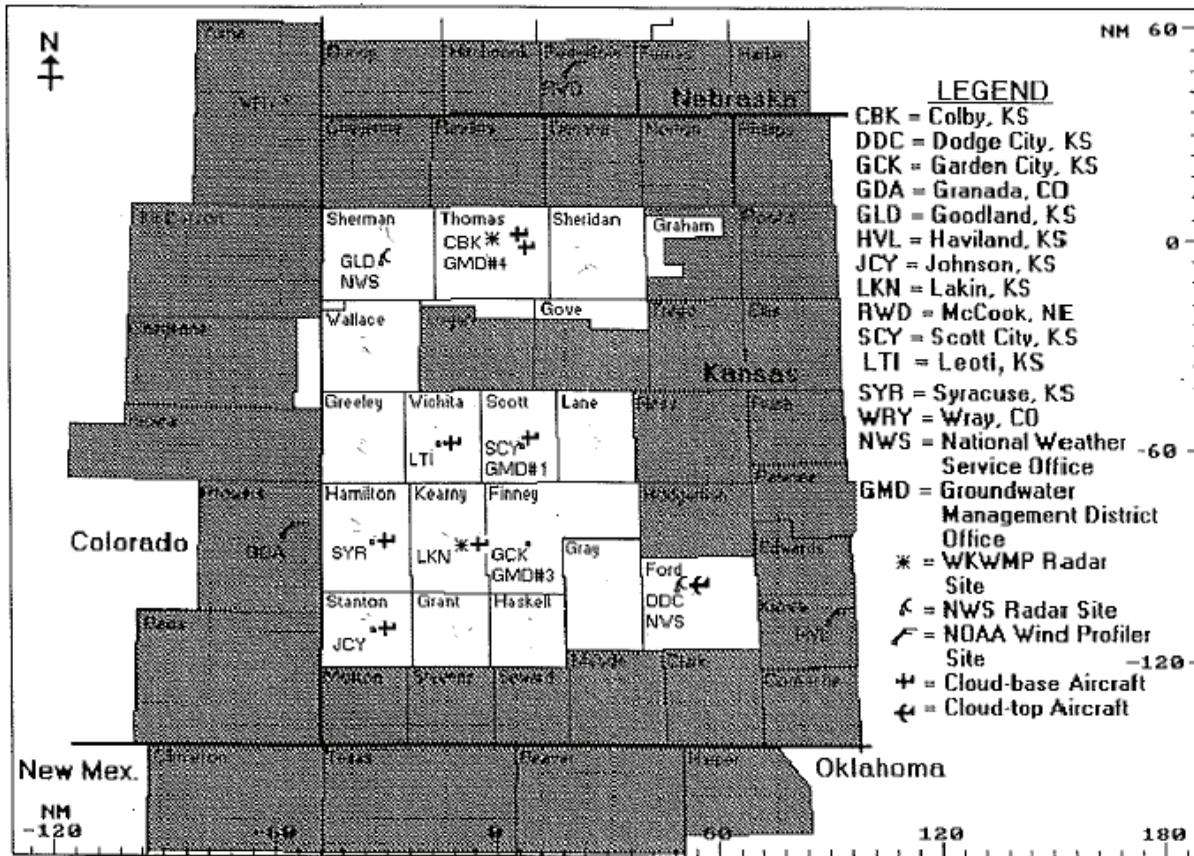
Figure 1: A reproduction from Smith and Beer (2000) showing the operational areas for the WKWMP in 2000.

In 2000, the WKWMP used a variety of airborne glaciogenic seeding systems (Smith and Beers, 2000). Carly-type wing-tip generators were used to burn an acetone solution containing 2% AgI along with unspecified amounts of NaI and $C_6H_4C_{l2}$ (paradichlorobenzene). The rate at which the solution was burned produced 2.8 g/min AgI complexed with NaCl . They also employed burn-in-place 120 g pyrotechnic flares that released AgI aerosol when ignited while held in under-wing racks. Some flares were manufactured by Weather Modification Group, Inc. (near Calgary, AB, Canada) and others by Concho Cartridge (San Angelo, TX). The twin-engine cloud-top seeder had a system for dispersing dry ice pellets at the rate of 5 lbs/min (2.3 kg/min).

2.2 Severe Thunderstorm Electricity and Precipitation Study

STEPS operations are discussed in Lang et al. (2004). A network consisting of three 10-cm-wavelength Doppler radars, two of them polarimetric, was used to observe storms propagating through northeastern Colorado and northwestern Kansas. These included the CSU-CHILL polarimetric Doppler research radar operated by Colorado State University, the Spol polarimetric Doppler radar operated by the National Center for Atmospheric Research (NCAR), and the WSR-88D operational Doppler radar at the site of the Goodland NWS office. A mobile mesonet of automobile-borne instrumentation, a mobile

balloon-sounding team with rawinsondes capable of electrical as well as thermodynamic observations, additional thermodynamic and wind soundings, and an instrumented armored aircraft also probed regions of the storms and storm environment. Much of the STEPS observational record is maintained in field project archives at the NCAR Earth Observing Laboratory (See http://data.eol.ucar.edu/codiac/projs?STEPS and http://data.eol.ucar.edu/master_lists/generated/t28/dataset_list.html#category-230). The discussion below focuses on radar observations.

2.3 Meteorological Setting

A large storm began to develop in northeastern Colorado in the mid-afternoon of 29 June 2000. Tessendorf et al. (2005) and Wiens et al. (2005) provide a summary of regional meteorology and overall storm evolution. The storm began as a group of several smaller cells forming along a surface boundary with support from a short-wave aloft. Initial radar echoes were noted at 2130 UT in northeast Colorado, north of Burlington and moving eastward. Surface temperatures reached 29°C with dew points near 20°C in the region at this time. The wind was veering from south near the surface to northwest aloft. Convective Available Potential Energy (CAPE) in the region was estimated to be between 1500 and 2000 J/kg based on project soundings. This storm moved eastward into Kansas and two cells began to dominate. Large (> 2 cm) hail was first reported on the ground at 2235 UT north of Goodland, KS. Larger hail (>4.5 cm) was first reported at the surface at 2307 UT. At 2325 UT the storm organized into a distinctly supercellular radar reflectivity structure and turned to the south southeast. (See Marwitz, 1972, Browning and Foote, 1976, and Browning, 1977, for discussions of characteristics of supercellular storms.) A weaker left-moving cell split away from the main cell at this time. The main cell maintained a quasi-steady reflectivity structure for several hours during the remainder of its lifetime. Hail reports associated with this storm came in to the Goodland NWS office through 0108 UT on 30 June. The storm still contained regions with radar reflectivities exceeding 60 dBZ at 0300 UT on 30 June as it moved southeastward from a position south of Colby, Kansas, after sunset. At this time it merged with an even larger storm to the northeast that was moving southward and the combined storm evolved into a mesoscale convective system (MCS) that propagated southeastward across Kansas overnight, developing a distinct bow echo feature. (See Maddox, 1980, for description of mesoscale convective systems.) Wind gusts as high as 80 mph (129 km/hr.) were reported overnight associated with this MCS. The MCS finally decayed before sunrise near the southeast corner of Kansas.

A reflectivity swath diagram (see Figure 2) shows the footprint of highest radar reflectivities observed over a given point during the lifetime of the storm as it passed through the STEPS region. The organization into supercellular form and the turn to the right occurred at about 2325 UT. An EF-2 tornado was reported under the storm at this time. Hail to 4.5 cm diameter was observed at the surface for the next one and one-half hours. There were 31 crop insurance hail claims filed within the target seeding area on this day (Smith and Beers, 2000). In terms of hail damage, there were six other days in the northern target area in 2000 with more claims.
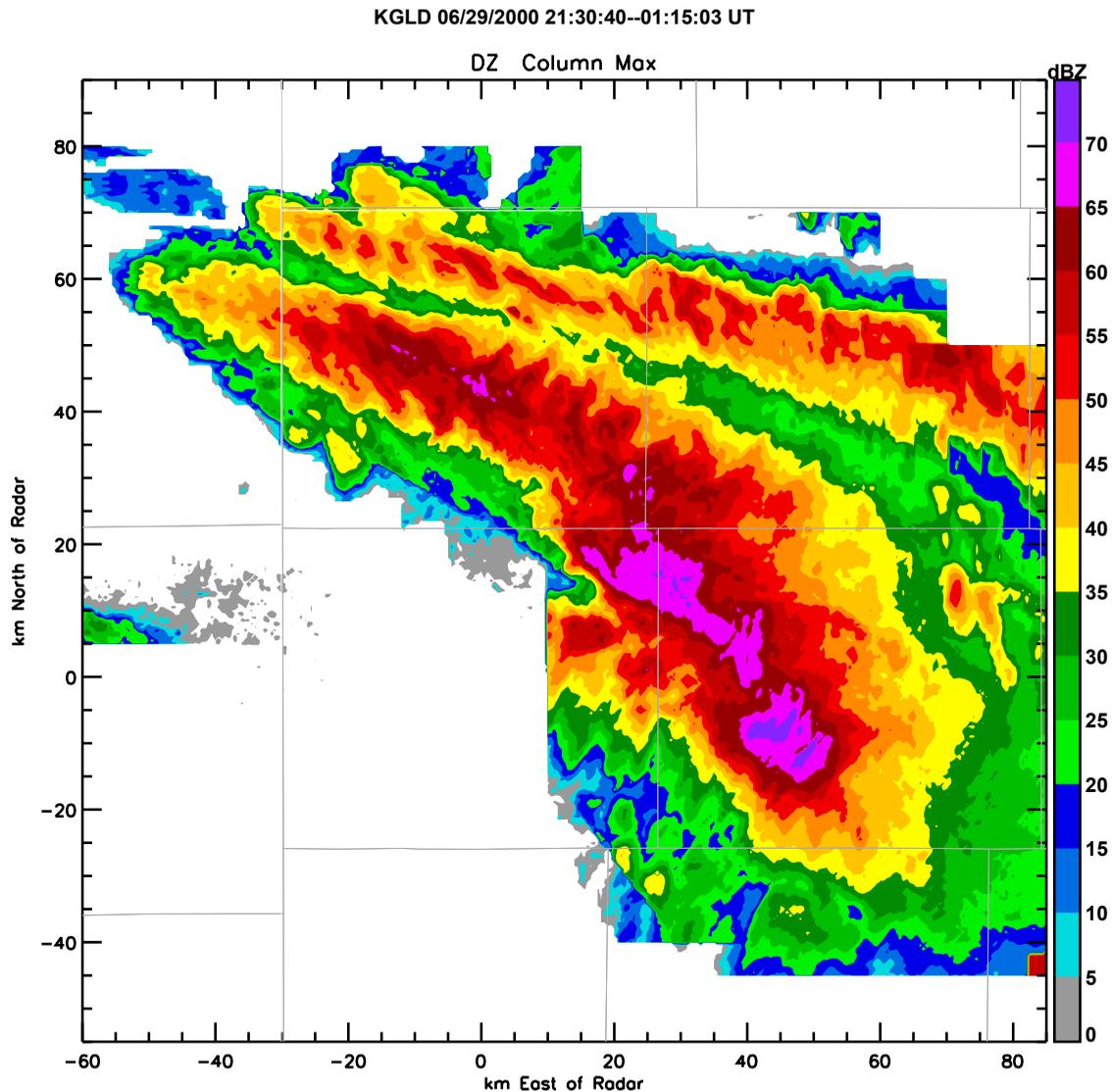
JOURNAL OF WEATHER MODIFICATION

KGLD 06/29/2000 21:30:40--01:15:03 UT

Figure 2: A Hovemuller-type diagram showing maximum reflectivity observed over any location between 2130 UT on 29 June and 0115 UT on 30 June, 2000 in the region of interest based on observations of the NWS WSR-88-D KGLD radar at Goodland, KS. State and county borders are shown, with Colorado to the west, Nebraska to the north, and most of the diagram covering northwestern Kansas. The reflectivity pattern indicates the movement of the storm of interest over this time period. Axes are labeled in distance from the radar. The color scale for equivalent reflectivity is indicated on the right.

A series of radar plan-position-indicator (PPI) images in Figure 3 from the NWS WSR-88D at Goodland, KS (KGLD) depict the movement of the storm from a regional perspective. In its early development the storm had an evolving multicellular structure. The storm maintained a quasi-steady reflectivity structure from the time of the turn to the south southeast around 2325 UT, for the next several hours. During this time new cells formed on the southern flank and merged into the main storm body. Following the period covered in Figure 3, the storm eventually merged with the larger storm to the east, formed an MCS, and crossed the state of Kansas overnight, as described above.
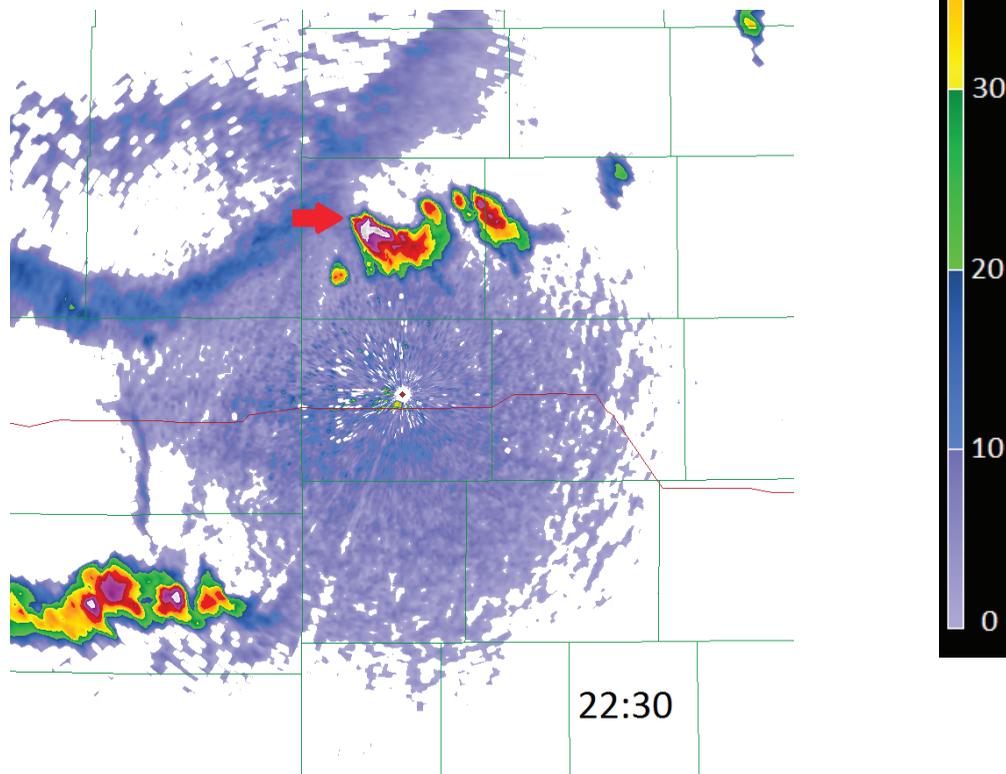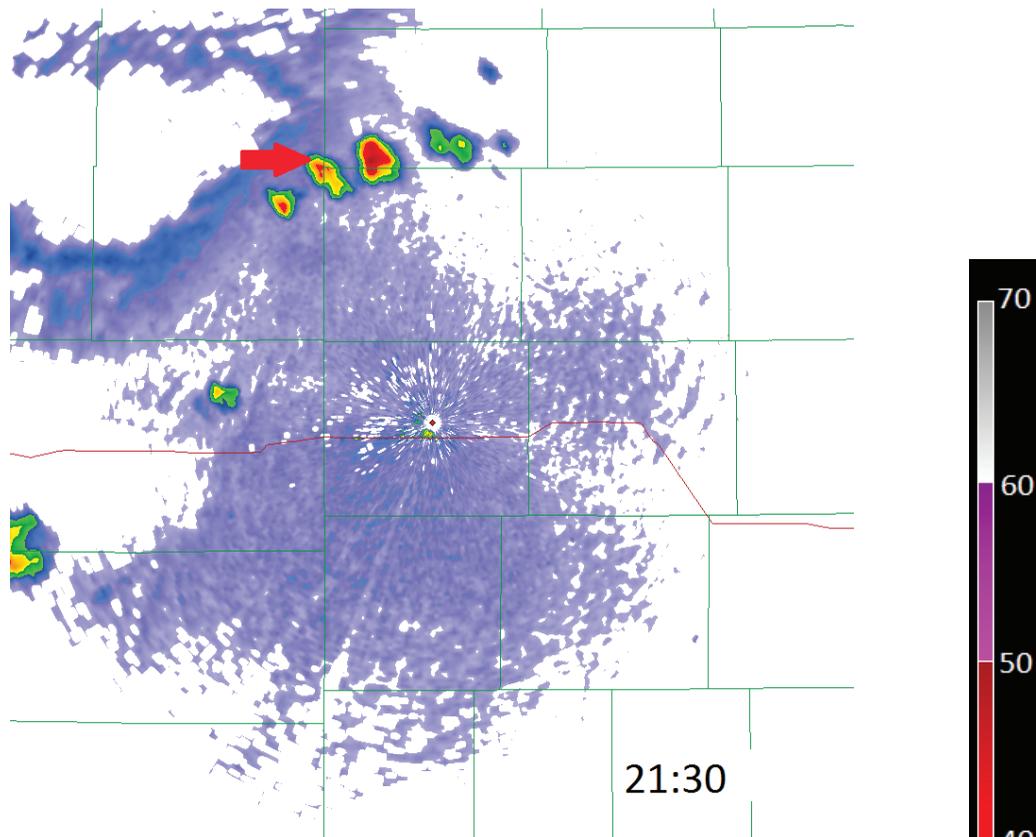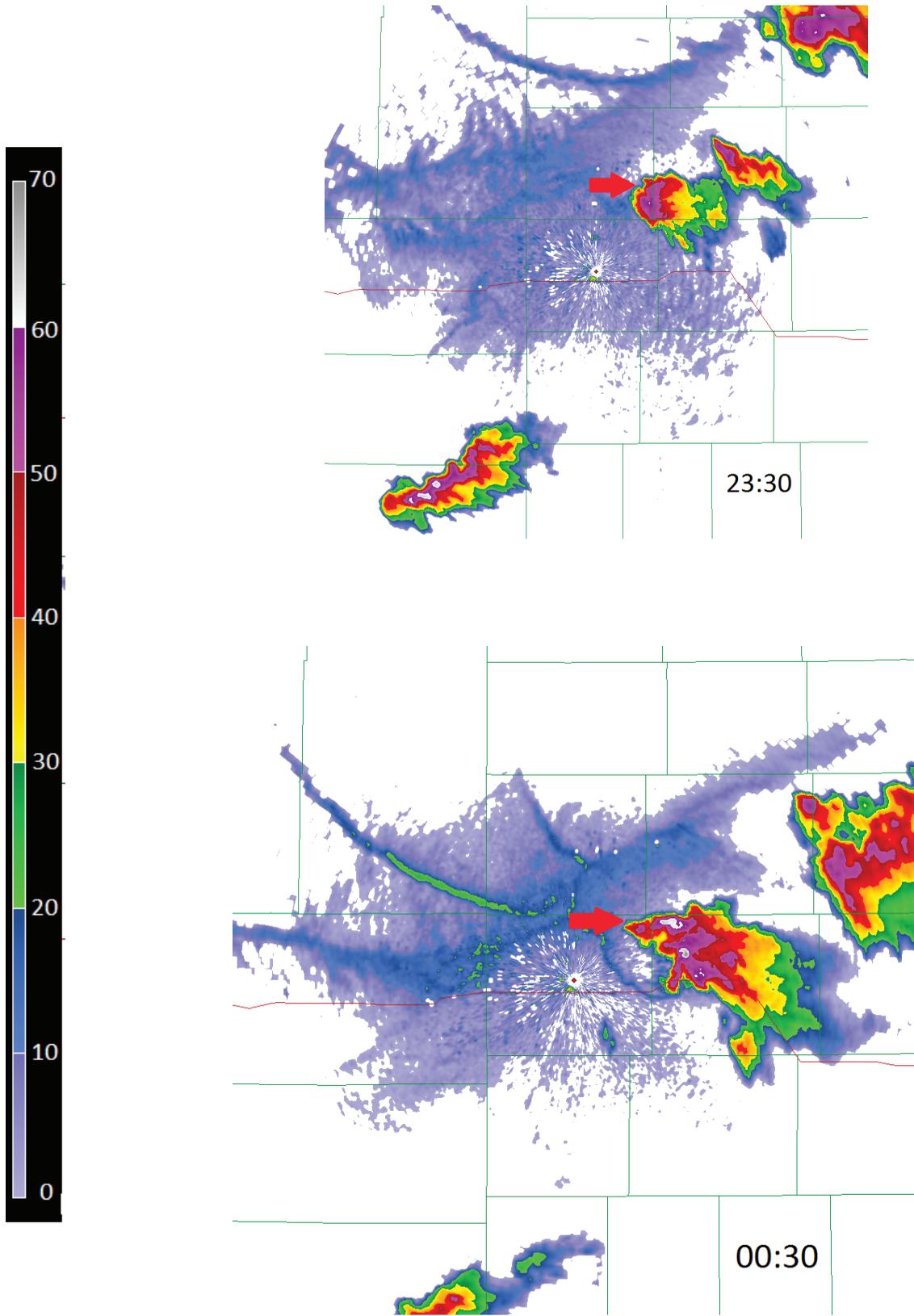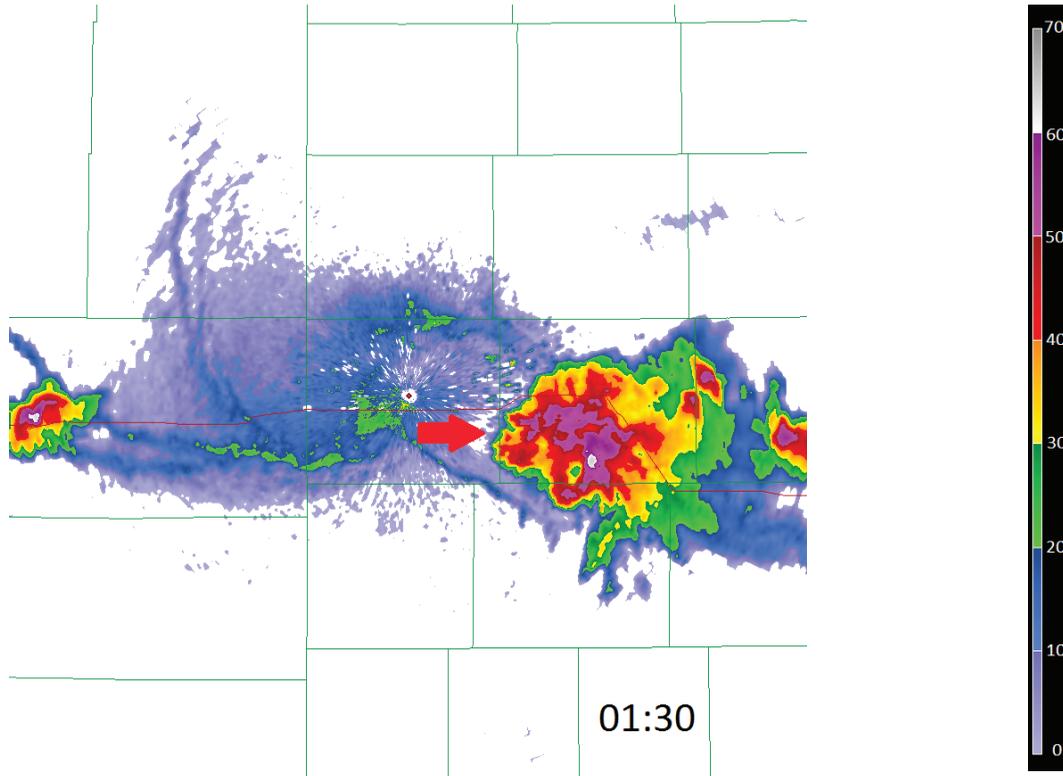
Figure 3: Five 0.5° elevation angle scans from KGLD covering northeast Colorado and northwest Kansas, spanning the period 21:30 UT on 29 June to 01:30 UT on 30 June, 2000, at one hour intervals. The reflectivity color code is common to all panels. The cell that becomes or is the main storm is indicated by a red arrow in each panel. Four isolated cells form along a boundary at 21:30 UT in Panel A. By 22:30 UT a new cell has formed but has already started to decay at the southwest end of the line, and the strongest cell is the next to the northeast. By 23:30 UT the strongest cell is becoming supercellular and itself is starting to split, while a weaker cell persists northeast and adjacent it. A larger storm is further northeast from the storm in the STEPS area, and moving southward from Nebraska into Kansas. At 00:30 UT on 30 June the two cells in the STEPS area have evolved into one cell that is being approached by the larger storm to the northeast. Finally, at 01:30 UT, the STEPS storm is starting to merge with the larger storm to the east. This complex becomes an MCS and moves south southeastward across Kansas overnight.

2.4 Summary of Seeding Operations

As the multicellular storm approached the target seeding area in northwest Kansas from the east, several aircraft patrolled along the northeastern boundary of the project area, dispersing seeding material into the clear air feeding northward into the base of the advancing storms. Once the storm entered the seeding area, additional aircraft joined the mission and four cloud base aircraft dispersed glaciogenic material directly under the bases of flanking cells on the south side of this storm for more than three hours. A "cloud top" aircraft dispersed dry ice pellets into the upper regions of these flanking cells during one flight.

Flight and seeding records are available as paper records. Figure 4 shows the complete flight track for the first flight of seeding aircraft N7805P plotted on an aeronautical chart background. It took off at 2230 UT on June 29 as multiple cells were organizing along the Colorado-Kansas border. A patrol leg was made up to the St. Francis area. It then returned to the northern border of Sherman County, the northeastern edge of the operational seeding area, to await the arrival of the storm. While waiting, it commenced east-west legs in clear air along this border while running generators, dispersing AgI nuclei at flight level into the inflow air feeding the approaching storm. As the storm organized into a supercell, turning south-

eastward and moved into the operational area, the aircraft switched to cloud-base seeding of flanking cells on the southern flank of the storm. Figure 4 shows that the N7805P track follows the south-

eastward trajectory of the storm track shown in Figure 2 until 0047 UT on June 30 when it breaks away from this storm and moves to treat a larger storm to the east near Hill City.
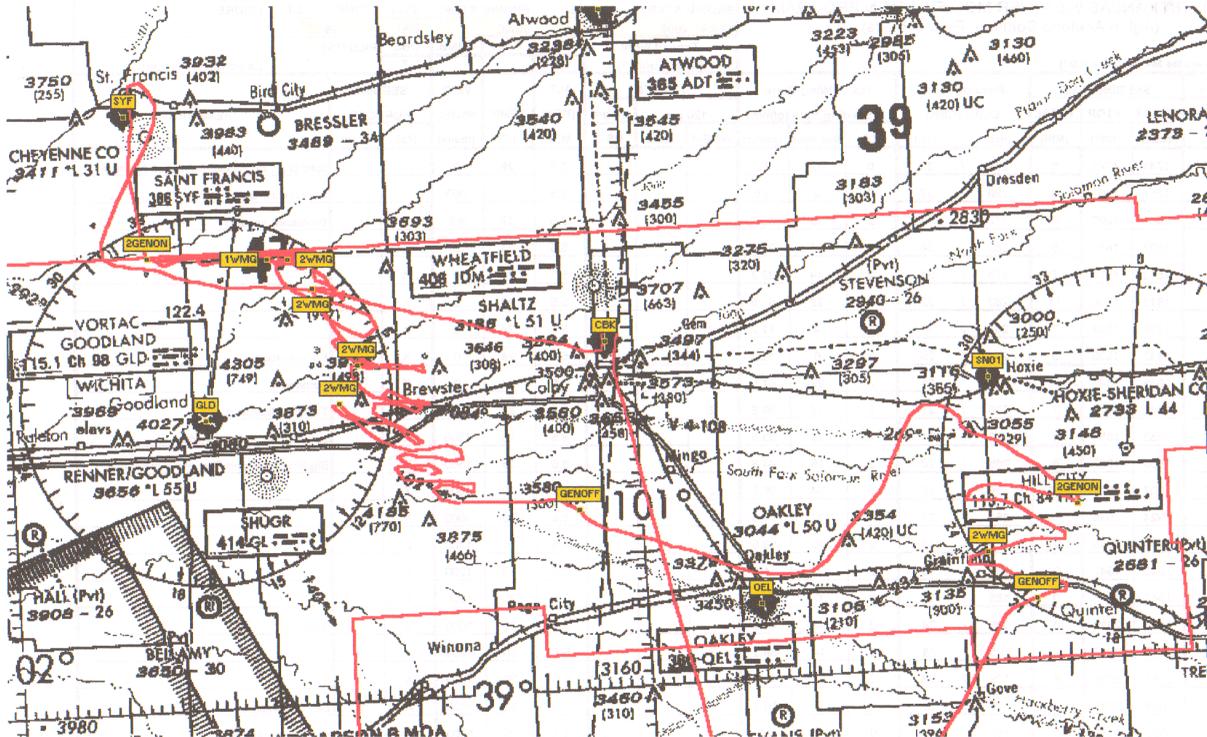

Figure 4: Flight track of seeding aircraft N7804P on June 29, 2000. The flight track is the curving red line heading west northwest from Colby, then north to St. Francis, then back into the operational area (also outlined in straight red lines) where the aircraft initially conducted broadcast seeding while waiting for the storm to enter the operational area. The aircraft then switched to seeding the bases of flanking cells as the storm moved into the operational area. "GENON" and "GENOFF" denote turning the acetone burners on and off. "WMG" denotes ignition of burn-in-place flares.

An example of the flight data summaries available for that day is shown in Figure 5 (this one for the same flight of N7805P shown in Figure 4). Seeding times and waypoints, along with an indication of generator and flare use, are shown for each seeding pass. Although digital flight track information is not available, the waypoints indicated in Figure 5 in terms of range and magnetic bearing from Colby give a precise indication of storm-relative seeding locations. An example is shown in Figure 6. This figure shows two waypoints corresponding to the eastern and western extent of the fifth seeding episode from 2335-

2346 UT, superimposed over the KGLD 0.5^0 elevation angle storm reflectivity pattern at 2335 UT. The waypoints in Figure 5 are connected with a straight line for clarity, but in actuality the aircraft operated below cloud base back and forth between these two waypoints for this 11-minute period of time.

In summary, broadcast seeding into the low-level inflow of the approaching storm occurred from 2301 UT until 2325 UT, when the storm entered the operational seeding area. Then seeding under the bases of cells in the flanking line and adjacent

to the main body of the storm occurred from 2325 UT June 29 – 0130 UT June 30. Dispersal of dry ice into tops of flanking cells was conducted from 2352 UT June29 – 0045 UT June 30. The seeding operations were conducted aggressively with five aircraft in an attempt to modify precipitation evolution in feeder cells and the main storm into which these cells merged. Smith and Beers (2000) report that there were 21 flight hours of seeding. There were 3068 grams of AgI dispersed into the storm by wing-tip generators, and 4560 grams dispersed by burning flares between 2300 UT on the 29th and 0200 UT on the 30th. Figure 7 displays to AgI released in half-hour intervals

for the entire treatment of this storm. In addition, 50.8 kg of dry ice pellets were dropped into tops of flanking cells between 2352 and 0045 UT. Waypoints for all aircraft were overlaid on low-level KGLD PPI's, in the format of Figure 6. These plots (not shown) confirm that cloud base and cloud top seeding operations were focused on the flanking/feeder cells, as specified by the beneficial competition hypothesis and WKWMP operational procedures.

We now consider hail production by this storm.

FLIGHT SUMMARY *WESTERN KANSAS WEATHER MODIFICATION PROGRAM (Agl in Acetone Solution, Pyrotechnics)													AIRCRAFT: N7805P PROJ. FLIGHT# 38 SEEDING FLIGHT # 15						

Western Kansas Weather Modification Program

FLIGHT SUMMARY
*WESTERN KANSAS WEATHER MODIFICATION PROGRAM
(Agl in Acetone Solution, Pyrotechnics)

AIRCRAFT: N7805P PROJ. FLIGHT# 38 SEEDING FLIGHT # 15
ENGINE START: 1725 ENGINE STOP: 2106 TIME: 3.7 HOURS
YEAR: 2000 MONTH: JUNE DAY: 29

Note: All times use the 24-hour Clock (CDT)

Type of Flight (Check only 1): HAIL X RAIN COMB. OBS. X
PILOT(S): LaFontaine / Rogers

CLOUD TYPE		SEEDING TIME			Position From Colby (CBK)		No. of Wing Gens & Seeding Rate (g/min)			FLARES			ALT. (KFT)	TEMP (C)	VERT. VELOC. (ft/min)	SEEDING PURPOSE		REMARKS
ISOLD	LINE	START (CDT)	STOP (CDT)	TOTAL (MIN)	(deg. /	n.m.)	2.8	Gen Mins	(grams)	120 gm WMG-1	RS-3	40 gm RS-3	MSL	(C)	(ft/min)	Hail	Rain	
X		1741	1741	0	275 /	25	0	0	0.0				5.0	28	0			Iced Out, No Bases, Rain shaft North of
X		1751	1751	0	290 /	37	0	0	0.0				8.5	17	900			St. Frances, Bases at 9.5
X		1801	1807	6	275 /	34	2	12	33.6				8.5	17	900	X		Broadcast seeding
X		1807	1812	5	280 /	24	2	10	28.0				5.5	24	0	X		
X		1812	1819	7	275 /	34	2	14	39.2				5.5	24	0	X		
X		1819	1830	11	283 /	22	2	22	61.6				5.5	24	0	X		
X		1830	1832	2	281 /	22	2	4	11.2				5.5	24	0	X		
X		1832	1835	3	278 /	25	2	6	16.8	1			5.5	24	0	X		Funnel cloud
X		1835	1846	11	279 /	25	2	22	61.6	2			5.5	24	0	X		Tornado
X		1846	1853	7	276 /	21	2	14	39.2	2			5.5	24	1200+	X		Tornado disapated
	X	1853	1859	6	270 /	21	2	12	33.6				9.5	15	1500	X		Lowered base, Rain shaft
	X	1859	1907	8	265 /	20	2	16	44.8				9.5	15	1500	X		Big Scud Low and Fast moving/dvfping
	X	1907	1924	17	259 /	19	2	34	95.2	2			8.5	20	1000	X		
	X	1924	1935	11	251 /	21	2	22	61.6	2			8.5	20	1000	X		
	X	1935	1945	10	228 /	16	2	20	56.0				8.5	20	1200	X		
	X	1945	1947	2	204 /	13	2	4	11.2				8.5	20	1200	X		
	X	1947	1947	0	185 /	12	0	0	0.0				8.5	20	1200	X		
	X	2002	2010	8	098 /	24	2	16	44.8				5.5	20	1000	X		Shelf
	X	2010	2017	7	105 /	38	2	14	39.2	2			5.5	20	1000	X		
	X	2017	2025	8	109 /	29	2	16	44.8				5.5	20	1000	X		
	X	2025	2032	7	115 /	32	1	7	19.6				5.5	20	1000	X		Left Generator empty
	X	2032	2032	0	117 /	37	0	0	0.0				5.5	20	1000			Right Generator empty
		0000		0	/			0	0.0									

Total Generator Time: 265 Minutes
Seeding Output: 742.0 grams Agl
Seeding Period: 136 Minutes NOTE: This is the total time of seeding: if breaks occur, you must add times of all seeding periods to obtain a total.
Total No. Flares Burned: 11 Flares
WMG-1: 11 Flares NOTE: When seeding with WMG-1 or RS-3 flares (only) use a stop time as 6 minutes after the start time.
Concho RS-3/120: 0 Flares
Concho RS-3/40: 0 Flares

Page 1 of 1 Pages

Figure 5: Flight summary for the first flight of N7805P on June 29, 2000. Times are in Central Daylight Time. This graph was reproduced for a clearer copy.
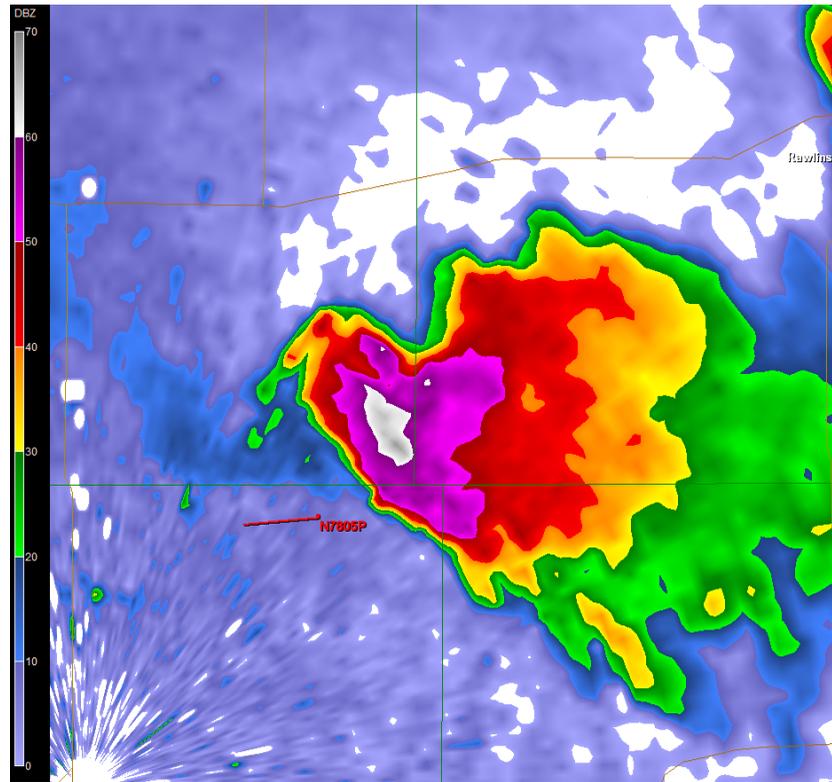
Figure 6: A portion of the 0.5º elevation angle scan of KGLD showing waypoints at the ends of the fifth seeding flight segment of aircraft N7805P from 2335 – 2346 UT on June 29, 2000. The two waypoints are connected by a straight red line. Storm-relative low-level inflow is from the south.
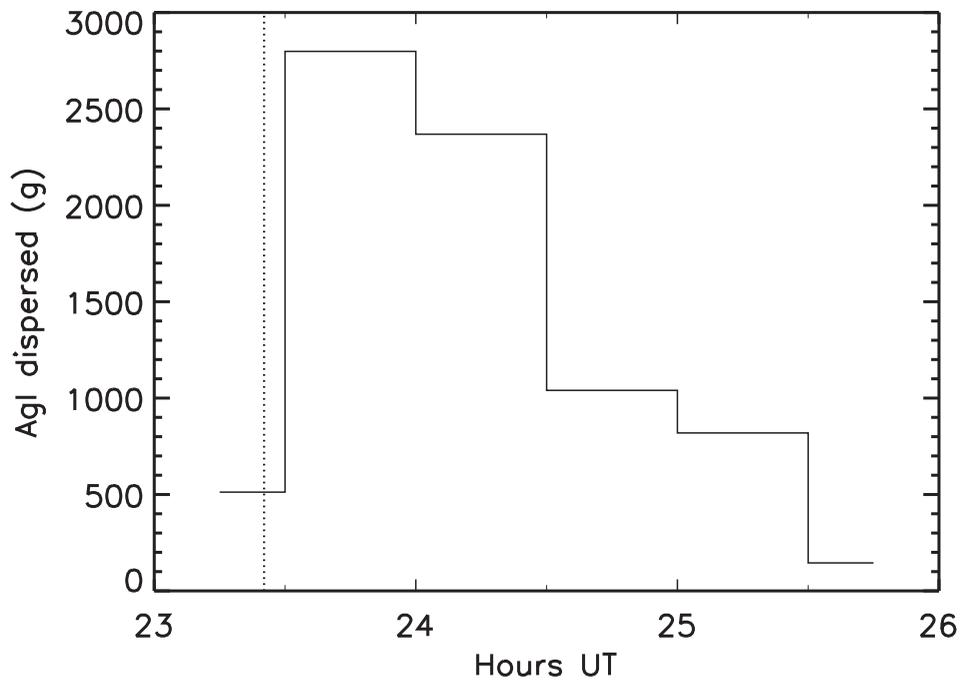

Figure 7: Histogram display of half-hourly amounts of AgI dispersed by WKWMP seeding aircraft into the storm of interest in this study. The vertical dotted line indicates the time the storm turned to the right and became supercellular. Starting with 00 UT on June 30 hours have 24 added to them.

2.5 Polarimetric Radar Mapping of Hail

Tessendorf et al. (2005) and Wiens et al. (2005) used polarimetric and Doppler radar observations from the three STEPS radars to analyze the evolution of circulations, reflectivity patterns, and hydrometeor type spatial distribution in this storm. In order to do so, they interpolated radar observations to a Cartesian grid with 0.5 km unit cell size.

Figure 8, based on data extracted from Figure 5 in Wiens et al. (2005) shows the total volume occupied by the storm, represented as the volume occupied by radar reflectivity greater than 0 dBZ, and the volume within the storm containing hail. Hail was identified using a fuzzy-logic-based hydrometeor identification scheme adapted from Liu and Chandrasekar (2000) and Straka et al. (2000). See Tessendorf et al. (2005) for details. There is a dramatic increase in both storm and hail volumes beginning near 2325 UT when the

storm intensified, organized into a supercell, produced a tornado, and turned rightward. This also was the time when 30 minutes of broadcast seeding by two aircraft ended, and three additional aircraft joined the operation to conduct coordinated cloud base and cloud top seeding of flanking cells over the next two hours. Tessendorf et al. (2005), in their Figures 13 and 14, show that prior to 2325 UT hail was found in these storms predominantly near cloud base. They also show that storm updrafts during the subsequent rapid intensification phase increased dramatically with peak magnitudes reached at altitudes above 9 km MSL. By 2345 UT, 15 minutes after cloud base seeding began and this intensification and reorganization occurred, much larger volumes containing hail were observed. Hail was identified in the storm as high as 10 km MSL. After 0000 UT hail was found distributed through the entire vertical extent of the storm, but occupying decreasing volumes at each level as time progressed.
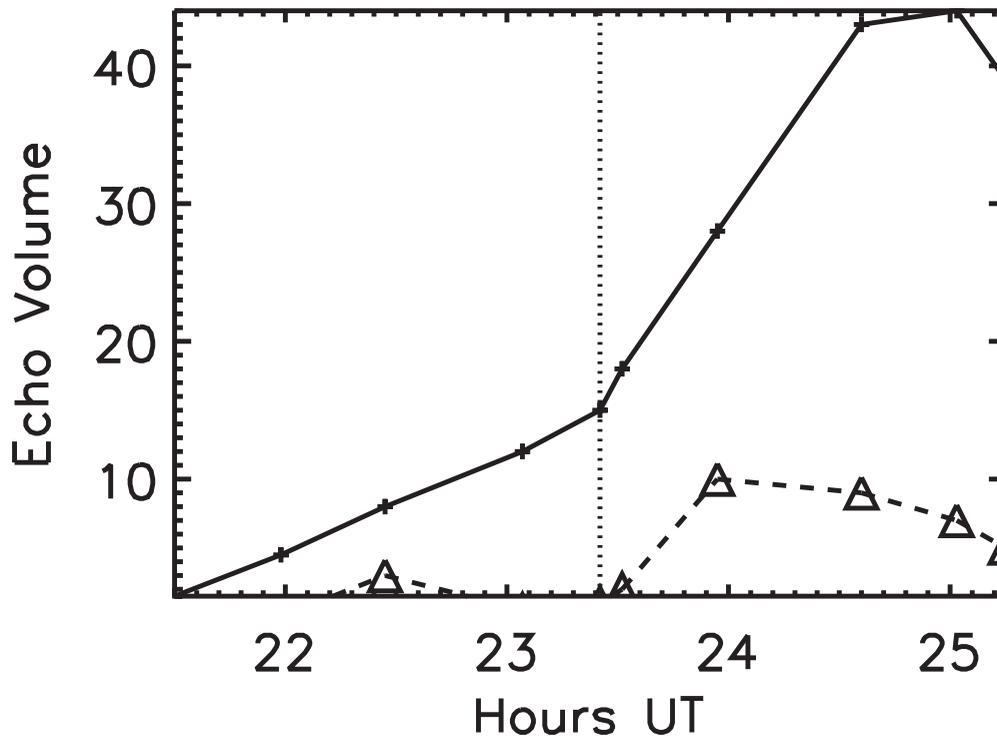

Figure 8: Volume in units of 10^3 km^3 of regions of storm with Z > 0 dBZ (solid line with + symbols) and containing small or large hail as identified using a polarimetric radar hydrometeor identification algorithm (dashed line with triangle symbols). To better discern trends, hail volume is multiplied by 10x. Data have been re-plotted based on analysis of Figure 5 in Wiens et al. (2005). Glaciogenic seeding began at 2301 UT. Starting with 00 UT on June 30 hours have 24 added to them.

3. DISCUSSION

3.1 Seeding Procedures Followed Conceptual Model

Following the WKWMP beneficial competition conceptual model, the airborne broadcast seeding into the low-level inflow air, followed by airborne dispersal of seeding material into the base of flanking cell updrafts, and dispersal of dry ice into the upper regions of flanking towers, were all intended to produce enhancement of embryo formation in flanking cells. Strong storm-relative low-level inflow carried these flanking cells (containing the embryos) into the main storm echo complex. There is no rigorous way to calculate how many additional embryos resulted from the seeding. If embryo concentration in the flanking cells indeed was increased by seeding, these additional embryos should have been introduced into the hail growth regions associated with the main storm.

3.2 Effects of Seeding on Hail Production

The behavior of the storm, particularly its change at 2325 UT from a multicellular cluster to a vigorous tornadic hail-producing supercell with a rotating updraft, suggests that as the storm propagated from Colorado into Kansas it moved into a region with higher vertical shear of the horizontal wind and perhaps higher CAPE. The observed changes in storm circulation and vigor strongly enhanced the prospects for developing large hail. It is highly unlikely that seeding by itself, in a constant storm environment, can lead to a multicellular storm organizing into a supercell. Glaciogenic seeding might have resulted in increased release of latent heat of freezing at lower levels, increasing updraft buoyancy in flanking cells and even in the main updraft region, but it is difficult to understand how it might have enhanced the rotation of the storm, a key factor in supporting supercellular development. Even with special STEPS project soundings in addition to the scheduled NWS soundings, and a STEPS project mobile mesonet at the surface, this mesoscale environmental variation cannot be resolved using the available surface and upper air data. In fact, changing storm environment might best be inferred from observed storm behavior.

Bulk analysis of multiparameter radar observations (Tessendorf et al., 2005, and Wiens et al., 2005) shows clearly that the volume of storm containing strong updrafts, and the volume containing hail, both increased dramatically at the time the storm evolved into a supercell. This clearly indicates a dramatic increase in hail production within the storm driven by dramatic increases in updraft strength and volume. Results presented by Wiens et al. (2005) do not include any estimates of hail size. The hydrometeor identification scheme of Liu and Chandrasekar (2000) attempts to distinguish between small hail, large hail, and a mixture of rain and hail. Straka et al. (2000) attempt to distinguish between dry and wet hail, as well as small, large, and giant hail. However, the current scheme implemented by the NWS distinguishes only hail and a mixture of hail/rain. If archived NWS WSR-88D data are used to study a storm, only an analysis similar to that of Wiens et al. (2005) is possible. Such an analysis cannot be used to study the detailed physical chain of events beginning with the introduction of glaciogenic seeding material into the flanking cells, and ending with hail found through the much of the vertical extent of the storm and on the ground, or the impact of seeding on hail size or concentration at the ground.

3.3 What was the impact of seeding on hail production in this storm?

Several interpretations of the observations presented above are possible.
- Seeding had negligible effect on the storm. Storm behavior, including the rapid increase in hail production after seeding began, was driven by the changing mesoscale environment surrounding the storm as it moved from Colorado into Kansas which caused it to become more vigorous and supercellular.
- Seeding had the effect of invigorating hail production in the storm, possibly by delivering more embryos to regions with excess supercooled cloud water, or possibly by some other process or processes.
- Seeding had the effect of mitigating the natural tendency for increased hail production as the storm invigorated. Less damaging hail fell

from the storm than would have fallen if there had been no seeding. If there had been no seeding there would have been more and/or larger hail from this storm, and more hail insurance claims.

It is difficult to establish one interpretation as clearly superior to the others, based only on observations of this one storm and generally understood aspects of storm behavior. If one had observations like these from a large sample of similar storms, some seeded, and some not, it might be possible to distinguish whether seeding (on average) has significant influence on hail production from storms similar to this one. With the network of operational WSR-88D polarimetric Doppler radars, analyses much like those conducted by Tessendorf, Wiens, and colleagues, could be implemented in regions where weather modification operations are conducted. A large data set could be compiled from freely available operational data. Polarimetric radar observations could be used to compute time series of volumes of storms containing hail, graupel, etc. for a population of storms, some seeded, some not. Statistics on these quantities could be compiled for a large number of storms as part of hail suppression operational programs. Statistical tests for significant differences in hail volumes between seeded and unseeded storms could be performed using these data. With a large enough population of cases, the effects of factors other than seeding will average out, and it may be possible to isolate an effect due to seeding.

Work by Liu and Chandrasekar (2000) and Straka et al. (2000) suggests that finer discrimination between hail sizes and distinction between wet/dry hail is possible with polarimetric radar data. Area covered by radar indication of hail in the base scan, and time of coverage, also may be explored as a perhaps more relevant metric for comparing hail production between storms.

It is unfortunate that one of the longest running hail suppression programs in the United States, the North Dakota Cloud Modification Project (NDCMP), is conducted in an area with poor radar coverage by the operational WSR-88D net-

work. Texas, where the only other long-running hail suppression operations in the United States are conducted, has better coverage. Operational polarimetric radar data is not available near Calgary where the Alberta Hail Suppression Project is conducted.

The number of cases needed to statistically verify a hail reduction due to seeding depends on the magnitude of the reduction. This number was estimated for the National Hail Research Experiment (NHRE), conducted in northeastern Colorado in the early to mid-1970's, by Foote and Knight (1979). The NHRE was designed based on preliminary statistical studies suggesting that a randomized experiment with 75 cases could verify a 40% reduction in a metric of hail damage at the 5% significance level. In the northeastern Colorado area where this experiment was conducted, it was estimated that five years would be needed to accumulate a sample of this size. In an operational program covering a similar area, one might assume that a storm sample of roughly 75 cases containing roughly equal numbers of seeded and unseeded storms would be required to show a reduction of this magnitude in some measure of hail on the ground. In most project areas in North America (e.g. Alberta, North Dakota, and Texas), it could take from 5 to 10 years to acquire a sufficient sample of storm observations with good radar coverage. If unseeded storms forming in similar mesoscale meteorological environments outside of the project area can be used to compare to seeded storms in the project area, a smaller number of years might be required to obtain a sufficiently large sample. Further study is needed to verify which meteorological parameters are the best ones to be used to define "similar" environments. A good starting set would be the environmental parameters used by convective weather forecasters to determine the likelihood of hail, such as CAPE, shear, helicity, cloud-base height, wet-bulb zero, etc.

Another consideration is that not all storms will be "perfectly" seeded. Due to logistical and nowcasting limitations, seeding is likely to be more effective in some cases than in others at introducing seeding material into the desired locations in

flanking cells. This variability in operational effectiveness could further extend the time needed to resolve a seeding effect.

4. CONCLUSIONS

- Due to the chaotic dynamical nature of large convective storms, with many physical processes interacting in non-linear ways, one cannot draw firm conclusions about the overall effects of cloud seeding on hail production from just one case. A large number of cases, both seeded and unseeded, need to be studied and results analyzed.
- Polarimetric radar data can provide quantitative information on hail occurrence in storms. The volume of a storm containing hail is one metric. An example of one analysis based on this metric is taken from the work of Tessendorf et al. (2005) and Wiens et al. (2005), in which the bulk storm volumes containing hail, and other radar-derived storm characteristics over the storm's lifetime, are analyzed to characterize storm hail production in a seeded thunderstorm. Other metrics may prove more useful and should be investigated.
- Once an analysis procedure is established, it will be possible to analyze development of hail in a large number of storms inexpensively using operational polarimetric radar data and automated computational procedures. Statistical tests for differences in hail production between populations of seeded and unseeded storms can then be conducted.

5. ACKNOWLEDGEMENTS

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