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Exploratory analysis of the effect of hail suppression operations on precipitation in Alberta

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Abstract

An operational hail suppression program has been based in southern Alberta, Canada, since 1996. The program is designed to reduce hail damage to property in towns and cities. The analysis of the effect of the cloud seeding on the rainfall was motivated by concerns that hail suppression operations might reduce rainfall and thus offset any economic gain offered by a reduction of hail damage. An exploratory analysis of volume-scan, C-band radar data using sophisticated storm cell tracking software was used to calculate radar-derived rainfall characteristics from 160 seeded and 1167 non-seeded storms, on 82 days with seeding, during the summers of 2001 and 2002. The seeded storms (stratified according to maximum radar-derived cell top height) have greater mean durations (+50%), have greater mean precipitation rates (+29%) and have a greater mean total rain area–time integral (+54%). There is statistical evidence to reject the null hypothesis of no effect of cloud seeding on the total volume of rainfall. The data support the claim that seeding causes an increase in rainfall. The seeding effect is estimated to increase the mean rainfall volume (averaged for categories 7.5–11.5-km height storms) by a factor of 2.2, with an average 95% confidence interval of (1.4, 3.4).

Keywords: Hail suppression; Cloud seeding; Radar-derived rainfall characteristics

1. Introduction

Hailstorms pose a serious threat to the province of Alberta, Canada. Annual losses to agriculture due to hail amount to approximately 5% of production and direct costs to agriculture range from CAD$50 million to CAD$100 million (Alberta Agriculture Financial Services, private communication). More recently, the high insurance costs of urban hailstorms have escalated due to the replacement cost clauses in homeowner policies. The insurance costs associated with the severe hailstorm that struck Calgary on 7 September

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1991 have been estimated at \$400 million (Charlton et al., 1995). The direct costs due to hail damage to property now exceed agricultural losses in Alberta, and even small positive mitigation effects would be extremely beneficial economically. As a result, an operational hail suppression program was introduced in 1996, entirely funded by private insurance companies, with the sole objective of reducing the damage to property by hail.

The new Alberta program incorporates several notable improvements over earlier hail suppression projects in the province. These improvements include the following:

- Faster acting "condensation freezing" formulation silver iodide (AgI) flares which provide approximately 100 times more ice nuclei per gram of seeding material (4×10^{13} ice nuclei per gram of pyrotechnic at -10 °C and the ability to nucleate ice as warm as -4 °C), and 90% activation within 1–2 min of introduction at temperatures between -6 and -10 °C.
- Injection of the seeding material directly into the developing cloud turrets using high-performance, twin-engine aircraft for quick response and timely seeding.
- Use of GPS tracking and computer technology to display the aircraft locations on the radar displays to improve the targeting of seeding operations to the most critical "new growth" regions of the storms.

The program ran from June 15 to September 15 during 1996 and 1997 and from June 1 to September 15 during 1998 to 2002. The seeding area covers approximately 26,000 km^2 in the Calgary to Red Deer region of southern Alberta. The economic evaluation of the hail program is undertaken by the insurance industry using claims data. The hail program was renewed in 2001 following their determination of a reduction in the losses due to hail damage.

This paper presents an exploratory analysis of the effect of the cloud seeding on the rainfall. The study was motivated by concerns from some rural constituents during the drought of 2001 and 2002 that the hail suppression operations might be reducing rainfall. This analysis uses volume-scan C-band radar data and sophisticated storm cell tracking software to obtain radar-derived rainfall characteristics from seeded and non-seeded storms, on days with seeding, during the summers of 2001 and 2002. The radar data are used in order to capture the spatial and temporal resolution of the convective clouds that produce the majority of summertime rainfall in Alberta. The existing surface rain gauge networks are not sufficient to resolve convective cloud scales associated with the cloud seeding.

2. Conceptual hail model

The cloud-seeding methodology used in Alberta is based upon the techniques, methods and results of the long-term hail research project conducted by the Alberta Research Council from the late 1960s to 1985 (Alberta Research Council, 1986). The conceptual model for Alberta hailstorms has evolved from the observations by Chisholm (1970), Chisholm and Renick (1972), Barge and Bergwall (1976), Krauss and Marwitz (1984), and English (1986). Direct observational evidence from instrumented aircraft penetrations of Alberta and Colorado storms in the 1970s and early 1980s indicated that hail embryos grow within the time evolving "main" updraft of single cell storms and within the updrafts of developing "feeder clouds" or cumulus towers that flank mature "multi-cell" and "supercell" storms (see, e.g., Foote, 1984; Krauss and Marwitz, 1984). The computation of hail growth trajectories within the context of measured storm wind fields has integrated many hail growth theories and illustrated a striking complexity in the hail growth process (Foote, 1985). The growth to large hail in Alberta is hypothesized to primarily occur along the edges of the main storm updraft where the merging feeder clouds interact with the main storm updraft (as described in WMO, 1995).

3. Cloud seeding hypothesis

The hail suppression hypothesis in Alberta is based on the concept of beneficial competition. Beneficial competition assumes a deficiency of natural ice nuclei in the environment and that the injection of silver iodide (AgI) will result in the production of a significant number of "artificial" ice nuclei. The natural and artificial ice crystals compete for the available supercooled liquid cloud water within the storm. Hence, the hailstones that are formed within the seeded clouds should be smaller and produce less damage. In addition, if sufficient nuclei are introduced into the new growth region of the storm, the hailstones may be small enough to melt completely before reaching the ground. Cloud seeding operations are intended to alter the microphysics of the treated clouds, assuming that the present precipitation process is inefficient due to a deficiency of natural ice nuclei. Seeding with AgI initiates the precipitation process earlier in the lifetime of a cloud, and once seeded, the cloud should be more efficient in converting a greater proportion of its vapor to precipitation, resulting in an increase in the rainfall. Cloud seeding does not attempt to compete directly with the energy and dynamics of the storm. Any alteration of the storm dynamics occurs as a consequence of the increased ice crystal concentration and initiation of riming and precipitation-sized ice particles earlier in the cloud's lifetime.

4. Seeding materials

Silver iodide is primarily dispensed using droppable and/or end-burning pyrotechnics. The silver iodide formulation flares are manufactured by Ice Crystal Engineering (ICE) of Davenport, ND. The ejectable flares contain 20 g of seeding material and burn for approximately 37 s, and the end-burning flares contain 150 g of seeding material and burn for approximately 6 min. The ice-nucleating effectiveness of the flares manufactured by ICE has been tested at the Cloud Simulation and Aerosol Laboratory at Colorado State University (DeMott, 1999). The laboratory tests determine the number of ice crystals formed per gram of nucleant as a function of cloud temperature. Specified temperatures for testing in the isothermal cloud chamber are typically -4, -6, -8, -10 and -12 °C. The ICE flares produce between 10^{12} and 10^{13} ice nuclei per gram of pyrotechnic between -6 and -10 °C. The new-generation ICE pyrotechnic produces >10^{12} ice nuclei per gram of AgI at -4 °C. The number of ice nuclei per gram of AgI is >2×10^{14} at -10 °C. Rates of ice crystal formation for the ICE flare in the CSU isothermal cloud chamber were extremely fast. At a temperature of -4.2 °C, 63% of the nuclei were active at 0.77 min and 90% active at 4.33 min. The ice formation mechanism was identified as condensation–freezing nucleation (DeMott, 1999). High yield and fast-acting agents are important for hail suppression because the time window of opportunity in order to seed feeder-clouds before merging with a parent storm is often less than 10 min (Krauss and Marwitz, 1984). The flares used during this study had the same formulation described in DeMott (1999) and were freshly made just prior to the beginning of the 2001 program.

Silver iodide is also dispensed in limited quantities within the inflow region at cloud base using airborne acetone generators and a seeding solution with the chemical formulation: 2% AgI–0.5 NH_4I–0.1 $C_6H_4Cl_2$–1.0 $NaClO_4$. The ice formation effectiveness of the acetone solution is comparable with the pyrotechnic formulation.

5. Weather radar

The project radar is a WR-100 Enterprise Electronics Corp. (EEC) C-band radar system mounted on a 12-m tower at the Olds-Didsbury Airport (51°N latitude, 114°W longitude). The radar is enclosed in a radome to provide safe, all-weather operation. The nominal specifications of the C-band radar are frequency = 5580 MHz, wavelength = 5.4 cm, peak power = 250 kW, pulse duration = 2 μs, pulse repetition frequency = 258Hz, beam width = 1.65° (circular), antenna gain = 40 dB, minimum detectable signal = -105 dBm. The minimum detectable signal represents approximately 10 dBZ at 100-km range, or 0.5-mm-diameter water drops with 1 l^{-1} concentration. The radar was operated 24 h/day during the operational period. A complete volume scan was performed every 4.4 min.

6. Titan radar software

A software package called TITAN (for Thunderstorm, Identification, Tracking, Analysis and Nowcasting) was added to the EEC WR-100 C-band radar system in 1997. TITAN is a software system that ingests radar data, converts it into Cartesian coordinates, identifies storms, tracks them and displays the tracks and forecasts (Dixon and Wiener, 1993). TITAN makes it possible to compute a number of relatively sophisticated storm and track parameters very easily in real time (as detailed in Mather et al., 1996).

The radar reflectivity data were transformed into rainfall amounts using the Marshall–Palmer relationship: $Z = 200R^{1.6}$ where Z is in mm^6/m^3 and R is in mm/h (Marshall and Palmer, 1948). To avoid hail contamination, the maximum Z for the rain calculation was truncated at 50 dBZ. The ability of single polarization radar to measure rainfall has been well documented in the literature (e.g., Wilson and Brandes, 1979; Austin, 1987; Atlas et al., 1990; Rosenfeld et al., 1990; Seed and Austin, 1990; Joss and Waldvogel, 1990).

Empirical values of radar reflectivity vs. rain intensity relations and their variations for geographical location, storm to storm, or even within individual storms have been the subject of many studies (a list of empirical Z–R relations can be found in Battan, 1973). The Marshall and Palmer relation is the most widely used description of the size distribution of raindrops and fits measured raindrop spectra typical for a wide range of rainfalls reasonably well (Joss and Waldvogel, 1990). Attempts to optimize Z–R relationships for a specific region between gage and radar estimates have not yielded substantial improvement and are generally not the major issue in radar rainfall measurements (Smith et al., 1975). Schnur et al. (1997) documented the capabilities of the same EEC WR-100 radar used in this study to quantify the temporal and spatial distribution of rain for the southern modeling subarea of BOREAS during the period May–September 1994, using the Marshall–Palmer Z–R relationship. The cumulative difference for the study period between radar and gauge area averages was 14% of the radar estimate, and the area-averaged monthly rain accumulations estimated using gauges and radar agreed to within 8.7% for the month of July 1994. Similar accuracy is expected for this study because the southern BOREAS modeling area has a similar summer climate to the Alberta project area and is only about 500 km to the east.

TITAN objectively computes cell statistics for all storms within the radar viewing area. This feature allows the comparison of seeded storm cells with many natural (non-seeded) storm cells in an objective manner. The only difference between the seeded and non-seeded cells is their location. Storms were not seeded if they did not threaten a town or city. Otherwise, the geographical and meteorological conditions were the same.

6.1. Cell identification and tracking criteria

TITAN was set to objectively identify and track cells defined by radar reflectivity >40 dBZ, with volume >10 km^3, above 3 km MSL. Furthermore, only storm cells that existed longer than 10 min were chosen to eliminate the very many small cells that pulse up and down for only one or two radar scans, which generally would not be seeded. In addition, only storm cells that had a maximum top height (as defined by the height of the 40-dBZ contour) greater than or equal to 7.5 km were chosen for this analysis in order to choose similar natural clouds to seeded clouds and also to avoid the occasional ground clutter. In this way, seeded cells were compared with similar, non-seeded cells that could have been seeded but were not because they did not threaten a town or city inside the project area. Storms were called "seeded" if they were seeded at any time during their lifetime; however, most of the seeding was done in the early, developing stages of the storm's lifetime.

7. Cloud seeding methodology

Storm cells (as defined by TITAN) located within the project area are seeding candidates if they are deemed to be a potential hail threat to a community. Radar meteorologists are responsible for making the "seed" decision and directing the cloud seeding missions, incorporating the observations of the pilots into their decisions. Patrol flights are often launched before clouds within the target area meet the radar reflectivity seeding criteria. These patrol flights are meant to provide a quicker response to developing cells. Sometimes, seeding is started before the radar reflectivity cell criteria is met, if the pilots report vigorous, dynamic growing clouds located directly upwind of the cities of Calgary or Red Deer.

Cloud top seeding is typically conducted at an altitude corresponding to the -10 °C level. The seeding aircraft penetrate the tops of the developing cumulus towers on the upshear sides of convective cells as they grow through the -10 °C altitude. The 20-g pencil flares fall approximately 1200 m during their 37 s burn time. The 1200-m fall zone covers a temperature range of approximately 8 °C; therefore, the seeding material is dispensed in a vertical curtain covering the temperature range at which the glaciogenic nuclei first become active. The seeding aircraft penetrate the center of single convective cells. For multi-cell storms, or storms with feeder clouds, the seeding aircraft penetrate the tops of the developing cumulus towers on the upshear sides of the more mature convective cells, as they grow up through the -10 °C altitude. Seeding is also conducted at cloud base in the updraft region associated with the flanking line of feeder clouds and developing new growth zone of the mature storm, or the leading edge of the main updraft. Large, long-lived storms are often seeded by two aircraft; one seeding at cloud base and the other aircraft at the -10 °C level, seeding the developing feeder clouds. The seeding continues until the storm no longer poses a hail threat or no longer threatens an urban center.

8. Seeding rates and amounts

The ejectable flares are typically dropped at a rate of one 20-g flare every 5 s during a cloud penetration. This translates to a seeding rate of approximately 240 g of seeding material per minute. Burn-in-place flares are usually burnt one flare at a time, dispensing 150 g of material in 6 min, or 25 g min^{-1}. The acetone solution airborne generators emit a continuous plume at a rate of 2.9 g AgI per minute.

The seeded clouds in this study were seeded during 126 flights totaling 279.8 flight hours. A total of 7944 ejectable flares (158.9 kg seeding material), 848 burn-in-place flares (127.2 kg seeding material), and 210 gal of acetone solution (14.4 kg seeding material) were used. The total amount of seeding material dispensed was 300.5 kg. The average seeding rate was 1073 g h^{-1}or 17.9 g min^{-1}. Given that 160 cells were seeded in this study, the average amount of seeding material per cell was 1.88 kg. In all cases, the seeding material was injected directly into the clouds or updrafts.

9. Meteorological conditions

A summary of the important daily atmospheric parameters on the 82 days with hail during 2001 and 2002 is given in Table 1. Alberta clouds are characterized by continental cloud drop distributions (e.g., English and Marwitz, 1981; Krauss and Marwitz, 1984). The mean cloud-base temperature was 5.6 °C for the storms included in this analysis. These statistics of the meteorological conditions in which the Alberta

Table 1
Meteorological parameters for the 82 days on which hail was reported during 2001 and 2002

	Average	Standard deviation	Maximum	Minimum
Precipitable water (mm)	18.8	4.9	32.8	8.6
Freezing level (km above MSL)	3.3	0.5	4.7	2.4
− 5 C (km)	4.1	0.5	5.0	3.0
− 10 C (km)	4.8	0.5	5.8	3.7
Cloud base height (km)	2.6	0.4	3.4	1.5
Cloud base temperature (°C)	5.6	3.7	12.0	− 4.0
Temperature maximum (°C)	23.0	4.3	33	11
Dew point (°C)	8.8	3.1	14.0	0.0
Convective temperature (°C)	22.0	4.5	36.5	12.5
CAPE (J/kg)	781	620	3549	17
Total totals	54.0	2.4	60.0	45.0
Lifted index	− 3.0	2.1	1.3	− 8.3
Showalter	− 1.3	1.5	2.6	− 5.2
Cell direction (°)	257	53	350	0
Cell speed (m/s)	10.6	3.9	20.6	2.6
Storm direction (°)	273	59	350	0
Storm speed (m/s)	8.6	3.0	15.4	2.6
700 mb wind direction (°)	254	59.4	350	0.
700 mb wind speed (m/s)	7.7	3.4	15.4	1.5
500 mb wind direction (°)	253	51.7	350	0.
500 mb wind speed (m/s)	14.1	6.0	30.3	2.6
250 mb wind direction (°)	243	51.5	350	15
250 mb wind speed (m/s)	26.9	13.6	56.6	1.0

storms form help place the Alberta project storms in context with other locations in the world and represent the primary reference conditions for Alberta hailstorms.

10. Data analysis

The storm data were collected for the months of June, July and August during 2001 and 2002. The data set encompasses 95% of all the seeded storms; therefore, this analysis represents a comprehensive picture of all storm activity for the summers of 2001 and 2002. The remaining 5% of seeded clouds did not achieve the 40-dBZ cell criteria or live long enough to meet the selection criteria. The data set consists of 160 seeded storms (as objectively defined by TITAN) and 1167 non-seeded storm complexes that also met the selection criteria. A total of 85 of the 160 seeded complexes are from 2001 and 75 from 2002. Exactly 825 of the 1167 non-seeded storms are from 2001, and 342 are from 2002. The non-seeded storms are chosen only from the days on which seeding took place in order to have similar meteorological conditions for the seeded and non-seeded cases. The non-seeded clouds are considered to be independent from the seeded clouds because the seeding is applied directly to specific clouds, and TITAN includes all merging or splitting echoes as part of the same seeded storm complex. The seeded clouds represent 12% of the total number of cells that satisfied the selection criteria.

The relationships between the seeded and non-seeded storms were investigated further by stratifying the data according to maximum radar-derived cell top height. On any given day, thunderstorms have maximum top heights determined by the tropopause or an intermediate stable layer that would affect all clouds equally. Dennis et al. (1975) found that AgI seeding may lead to increases in maximum cloud heights averaging 600 m. This analysis assumes that the seeding does not significantly affect the distribution of maximum cell top height by using 1-km-size categories. In this way, seeded clouds are compared with non-seeded clouds that had similar dynamics and thermodynamics to achieve comparable cell top heights. Any differences between the seeded and non-seeded clouds should be due to the microphysical effects associated with the seeding. The data were separated into height categories to avoid a bias against the non-seeded clouds, because there were many more non-seeded small clouds that met the selection criteria than seeded small clouds. The majority of smaller clouds would heavily bias the average values for the non-seeded cloud population as a whole.

10.1. Storm duration

The descriptive statistics for Storm Duration of the 160 seeded and 1167 non-seeded storms of 2001 and 2002, according to maximum cell top height, are given in Table 2.

Natural cells with maximum top heights of 8.5 km and lower had storm durations that satisfied the selection criteria, on average, for less than half an hour. Natural storm

Table 2
Descriptive statistics for storm duration (h) of the 160 seeded and 1167 non-seeded storms, according to maximum cell top height (km)

Height (km)	*N*	Mean	Median	Standard Deviation	Minimum	Maximum	Q1	Q3
Seed storm duration vs. maximum top height								
7.5	39	0.46	0.37	0.30	0.21	1.95	0.22	0.52
8.5	37	0.81	0.52	0.74	0.21	4.19	0.33	1.08
9.5	39	0.94	0.72	0.68	0.21	3.54	0.57	1.23
10.5	24	1.19	1.20	0.67	0.28	2.85	0.65	1.61
11.5	12	1.45	0.96	1.23	0.44	5.09	0.87	1.74
12.5	7	1.70	1.68	0.54	0.73	2.31	1.39	2.20
13.5	1	3.46	3.46	*	3.46	3.46	*	*
14.5	1	1.83	1.83	*	1.83	1.83	*	*
	160							
No-seed duration vs. maximum top height								
7.5	511	0.36	0.29	0.18	0.21	2.38	0.22	0.43
8.5	331	0.45	0.36	0.27	0.21	1.89	0.29	0.51
9.5	172	0.61	0.47	0.44	0.21	2.57	0.36	0.66
10.5	87	0.74	0.59	0.53	0.21	2.84	0.36	0.95
11.5	36	1.04	0.88	0.69	0.21	3.16	0.58	1.40
12.5	18	1.23	1.08	0.66	0.36	2.82	0.86	1.59
13.5	10	2.19	1.46	1.35	1.17	4.83	1.22	3.27
14.5	2	1.28	1.28	0.37	1.01	1.54	*	*
	1167							

cells lived for more than 1 h only when reaching heights of 11.5 km or greater. These times agree favorably with the radar observations and numerical model simulations from Colorado: ~ 15 min for weak storms, ~ 25 min for multicellular storms and >50 min for long-lived unicellular storms (Fankhauser and Wade, 1982; Knight et al, 1982); the southern plains: < 50 min for single cell, >50 min for multi-cell, and >120 min for supercell storms (Weisman and Klemp, 1982); and Switzerland: ~ 70 min average duration for severe Swiss storms (Houze et al., 1993).

The mean storm duration is greater for the seeded storms than for non-seeded storms for each height category. The positive differences between seeded and non-seeded storm duration are consistent in the mean, median and the first (Q1) and third (Q3) quartiles. The relatively short (< 60 min) mean and median storm duration for the vast majority (~ 95%) of natural storm cells helps explain the large temporal and spatial variability of summertime convective precipitation.

10.2. Precipitation flux

The descriptive statistics for Mean Precipitation Flux of the 160 seeded and 1167 non-seeded storms from 2001 and 2002, according to maximum cell top height, are given in Table 3. Even the smallest (7.5 km maximum height) category of cells produced precipitation fluxes greater than 100 m^3 s^{-1}, which is comparable to the flow rate of many rivers. Summertime convective storms produce significant amounts of precipitation

Table 3
Descriptive statistics for mean precipitation flux (m^3/s) of the 160 seeded and 1167 non-seeded storms, according to maximum cell top height (km)

Height (km)	*N*	Mean	Median	Standard deviation	Minimum	Maximum	Q1	Q3
Seed mean precipitation flux vs. maximum top height								
7.5	39	146.4	135.9	73.9	41.2	321.6	82.7	183.9
8.5	37	252.5	210.6	168.5	68.4	708.7	124.3	353
9.5	39	443.9	310	391.7	53.2	1369.8	194.9	662.7
10.5	24	536.6	451.8	430.8	95.2	1914.8	277.7	626.7
11.5	12	669.9	646.1	269.3	233	1086	469.2	904.4
12.5	7	836	909	360	329	1253	537	1185
13.5	1	732.3	732.3	*	732.3	732.3	*	*
14.5	1	1275.7	1275.7	*	1275.7	1275.7	*	*
	160							
No-seed mean precipitation flux vs. maximum top height								
7.5	511	118.3	102.9	66.6	21.0	429.7	71.3	151.3
8.5	331	167.6	145.0	104.5	20.9	648.5	90.0	212.7
9.5	172	237.2	193.7	162.4	36.3	1039.1	125.7	292.9
10.5	87	356.9	279.6	228.8	62.9	963.7	169.4	519.7
11.5	36	471.3	479.8	196	159.8	912.1	323.4	557.6
12.5	18	745.3	829.6	414.6	80	1597.1	396.1	998.5
13.5	10	1190	1073	448	763	2000	803	1533
14.5	2	1218	1218	965	536	1901	*	*
	1167							

Table 4
Descriptive statistics for area–time integral (km^2 h) of the 160 seeded and 1167 non-seeded storms, according to maximum cell top height (km)

Height (km)	*N*	Mean	Median	Standard deviation	Minimum	Maximum	Q1	Q3
Seed area–time integral vs. seed maximum top height								
7.5	39	6.17	4.01	5.93	0.93	32.40	2.31	10.33
8.5	37	19.22	7.8	28.99	1.13	163.43	4.07	24.77
9.5	39	30.2	17.77	35.2	1.16	179.93	9.31	39.79
10.5	24	44.13	36.6	42.5	1.7	167.99	12.66	52.64
11.5	12	73.7	39.9	109	10.7	411.1	23.6	72.3
12.5	7	83.8	82.5	48.3	25.1	145.7	38.4	137.2
13.5	1	149.87	149.87	*	149.87	149.87	*	*
14.5	1	107.5	107.5	*	107.5	107.5	*	*
	160							
No-seed area-time integral vs. maximum top height								
7.5	511	4.80	3.41	4.68	0.28	66.11	2.17	6.00
8.5	331	8.25	5.39	8.43	0.37	53.38	3.02	10.21
9.5	172	15.21	8.05	20.98	1.41	147.01	4.2	16.85
10.5	87	24.16	16.01	24.59	0.51	101.6	6.64	31.71
11.5	36	41.55	28.67	38.63	0.44	144.36	13.77	54.89
12.5	18	75.7	69.6	64.6	3.3	235.2	32.8	85.6
13.5	10	172.5	126.4	129	61.4	433.3	82.8	229.4
14.5	2	95	95	58	54	136	*	*
	1167							

flux and represent very important sources of water for continental regions in spite of their high spatial and temporal variability.

The mean storm precipitation flux is greater for the seeded storms than for non-seeded storms for each height category except the 13.5-km height, which had only one seeded storm. The sample size for all height categories of 11.5 km and lower are greater than 10; therefore, some associations or inferences can be drawn. The positive differences between seeded and non-seeded storm precipitation fluxes are evident in the mean, median and the first and third quartiles.

Table 5
Seed/no-seed ratios for mean precipitation flux, cell duration and area–time Integral (ATI) according to maximum cell height

Maximum height (km)	Seed/no-seed ratio		
	Precipitation flux	Duration	ATI
7.5	1.24	1.27	1.29
8.5	1.51	1.79	2.33
9.5	1.87	1.55	1.99
10.5	1.50	1.61	1.83
11.5	1.42	1.39	1.77
12.5	1.12	1.38	1.11
13.5	0.62	1.58	0.87
14.5	1.05	1.44	1.13
Average	1.29	1.50	1.54

10.3. Area–time integral

Doneaud et al. (1981, 1984) showed a strong correlation between the area–time integral (ATI) and the rain volume for convective complexes. The descriptive statistics for ATI of the 160 seeded and 1167 non-seeded storms from 2001 and 2002, according to maximum cell top height, are given in Table 4. The area–time integral is greater for the seeded storms than for non-seeded storms of similar height, except for the one seeded storm in the 13.5-km height category.

10.4. Seed/no-seed ratios

Seed/no-seed (S/NS) ratios for mean precipitation flux, cell duration, and ATI according to maximum cell height are given in Table 5. The average S/NS for cell duration equals 1.50 for all size categories. The average S/NS of mean precipitation flux equals 1.29 for all size categories. The average S/NS of area–time integral equals 1.54 for all size categories. The results are consistently positive for cell-height categories 7.5–12.5 km. The higher height category ratios are not as reliable since there was only one seeded storm in the 13.5- and 14.5-km categories.

10.5. Transforming the rain volume data

The distribution of precipitation data such as storm duration, precipitation flux, or ATI is generally positively skewed. This affects the calculations of various parameters such as the mean because the mean value is greater than the most probable value due to the influence of the relatively few values of large magnitude and the many values of small magnitude. As a result, the use of classical statistical tests cannot be strictly applied, because they depend on the assumption that the data are normally distributed and centered equally about the mean. A common practice when dealing with skewed data is to perform a log-transform of the data. The log values are then more normally distributed and classical statistical tests can then be performed on the log-transformed values. A log transform was performed on the parameter rain-volume because it incorporates the combined effects of cell duration, precipitation flux and area–time integral.

The box plots of the log-transformed total rain-volume values for the 1167 non-seeded and 160 seeded storms of 2001 and 2002, stratified according to maximum cell top height, are shown in Fig. 1 (no-seed) and Fig. 2 (seed). The distributions within each height category have approximately the same shape and spread. Furthermore, the seeded storms appear to have an additive effect that holds true for the log-transformed data, which would translate directly into a treatment effect on the original scale of measurements.

10.6. Statistical analysis

The Student's t-test was used to test the null hypothesis of no seeding effect on rain volume. The assumptions of the t-test are that both groups are independent of one another and that the distributions are normal. We have applied the t-test on the log scale because the log-transformed rain volumes have distributions that are satisfactory for using the test, and

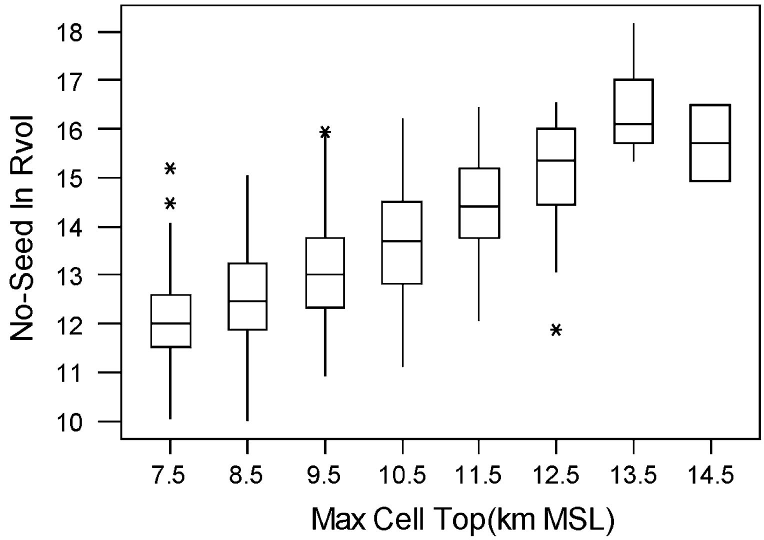

Fig. 1. Box plots of the log(base e)-transformed rain volume (m^3) measurements of 1167 non-seeded storms. The line across the box is at the median. The bottom of the box is at the first quartile (Q1), and the top is at the third quartile (Q3). The lines that extend from the top and bottom of the box are defined by the lower limit Q1 − 1.5 (Q3 − Q1) and the upper limit Q1 + 1.5 (Q3 − Q1). Outliers are plotted with asterisks (*).

the equality of variances assumption has not been violated for the height categories 7.5 – 11.5 km. The mean differences (seed minus no-seed), confidence intervals, *P*-values (probability that the difference occurred by chance) and the seeding factors for rain volumes of each

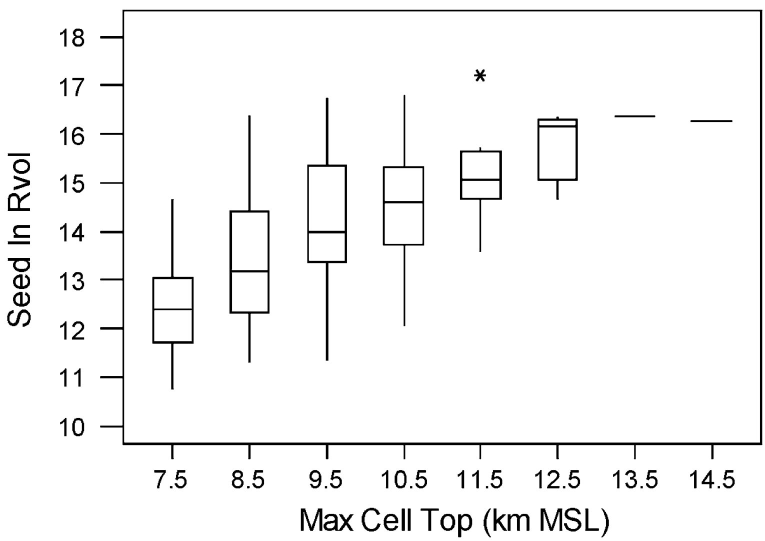

Fig. 2. Box plots of the log(base e)-transformed rain volume (m^3) measurements of 160 seeded storms.

Table 6
Mean differences (seed minus no-seed), *P*-values (probability that the difference occurred by chance) and the seeding factor for rain volumes of each category of maximum storm top height

Maximum top height (km)		Natural log	*P*-value	Seed/no-seed factor
7.5	mean difference	0.411	0.001	1.51
	95% high	0.672		1.96
	95% low	0.151		1.16
8.5	mean difference	0.818	< 0.0001	2.27
	95% high	1.153		3.17
	95% low	0.482		1.62
9.5	mean difference	0.956	< 0.0001	2.60
	95% high	1.348		3.85
	95% low	0.565		1.76
10.5	mean difference	0.941	0.0005	2.56
	95% high	1.474		4.37
	95% low	0.408		1.50
11.5	mean difference	0.633	0.032	1.88
	95% high	1.303		3.68
	95% low	− 3.73E − 02		0.96
12.5	mean difference	0.313	0.2395	1.37
	95% high	1.201		3.32
	95% low	− 0.5746		0.56

maximum storm top height category are given in Table 6. The one-sided *P*-values are < 5% for all size categories up to and including 11.5 km. This suggests that there is sufficient evidence to reject the null hypothesis of no effect of cloud seeding on the log-transformed rainfall volume. The data support the claim that seeding caused the increase in rainfall. The average increase in the mean rainfall volume (7.5–11.5-km cells) is a factor increase of 2.2 with an average 95% confidence interval of (1.4, 3.4).

11. Discussion and conclusions

An exploratory analysis of volume-scan C-band radar data, using sophisticated storm cell tracking software, was used to obtain radar-derived rainfall and storm characteristics from 160 seeded and 1167 non-seeded storms, on 82 days with seeding, during the summers of 2001 and 2002 in Alberta. The seeded storms (stratified according to maximum radar-derived cell top height) have greater mean durations (+ 50%), have greater mean precipitation fluxes (+ 29%) and have a greater mean total area–time integral of precipitation (+ 54%). There is statistical evidence to reject the null hypothesis of no effect of cloud seeding on the total volume of rainfall. The data support the claim that seeding caused an increase in rainfall. The seeding effect is estimated to be a factor of 2.2 increase in the mean rainfall volume (averaged for categories 7.5–11.5-km height storms) with an average 95% confidence interval of (1.4, 3.4). The effect on point rainfall is less than the effect on rain volume because the seeding effect is composed of increases in the mean area and duration of the precipitation as well as the flux. The average increase in rainfall depth is approximately 12% for the seeded storms as computed by TITAN.

These results agree favorably with those reported by Dennis (1990), which indicated that silver iodide seeding could increase total rainfall from isolated convective clouds in South Dakota by a factor between 1.5 and 2.5 from moderate shower clouds or small thunderstorms with tops from 7 to 10 km MSL. The effects of seeding also dropped off for the larger clouds with tops >10 km MSL in the Dennis (1990) study.

A cloud's lifetime is controlled by the magnitude and speed of the combined thermodynamics and microphysics of the precipitation formation processes and limited by the negative effects of entrainment of dry environmental air that works to return the cloud liquid water to the vapor phase. This analysis supports the radar and microphysical observations of English and Marwitz (1981) in Alberta, indicating that the AgI seeding continues to generate ice crystals in such a manner as to first initiate and then prolong the lifetime of precipitation. These results are consistent with the observations of Krauss et al. (1987) and Bruintjes et al. (1987), and the modeling results of Hudak and List (1988) indicating increases in the precipitation efficiency due to seeding in the continental clouds of the Bethlehem region of South Africa.

The results of Huston et al, (1991) and Dennis et al, (1975) indicated that AgI seeding accelerates precipitation formation in US High Plains storms, and Farley (1987) showed increases in surface rainfall for the numerical simulation of Alberta hail storms. The present analysis supports those findings and supports the hypothesis that seeding with AgI initiates the precipitation process earlier in the lifetime of a cloud, and once seeded, the cloud is more efficient in converting a greater proportion of its vapor to precipitation over a prolonged period of time.

Only a small fraction of the total number of storms was actually seeded because the objective of the Alberta Hail Suppression Project is solely to reduce the damage to property by hail in urban centers. Increases in precipitation have been demonstrated on a storm-cell basis using radar to capture the high temporal and spatial variability of convection. The convective storms have been shown to be relatively short-lived and cover small areas, although substantial precipitation fluxes are produced over the limited areas covered by each storm. The effect on area rainfall is not measurable using the present sparse network of surface recording gauges. This analysis indicates that increases in precipitation are a beneficial side effect to agriculture in Alberta due to the hail suppression activities. However, deliberate attempts to increase the precipitation over the larger agricultural area would necessitate a considerable increase in resources in order to seed a greater fraction of the total number of storms available.

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