

TWENTY SEASONS OF AIRBORNE HAIL SUPPRESSION IN ALBERTA, CANADA

Daniel B. Gilbert¹, Bruce A. Boe¹, Terrence W. Krauss²

¹Weather Modification, Inc., Fargo, North Dakota, USA

²Krauss Weather Services, Inc., Red Deer, Alberta, Canada

ABSTRACT: After a catastrophic late-season hailstorm hit the Calgary, Alberta, metropolitan area in September 1991, causing about half a billion dollars (Canadian) in damage, the property and casualty insurance industry began actively seeking ways to actively mitigate hail damage. After nearly four years of intensive study and intra-industry negotiation, the Alberta Severe Weather Management Society (ASWMS) was born. The ASWMS was and is comprised of representatives of all the insurance companies making up >90% market share in southern Alberta, and through levies based on their market share, annually fund an airborne cloud seeding program having the exclusive purpose of reducing damaging hailfalls in metropolitan areas, the Alberta Hail Suppression Project (AHSP). Beginning in 1996, this program has become an annual endeavor conducted from June through mid-September. This paper summarizes the current structure and operations of the AHSP, and through radar data compares seeded and unseeded storms that occurred on 21 July 2015, one of the most active days of the 2015 storm season.

1. BACKGROUND

1.1 Overview of Hail Climatology, Hail Suppression

Hail has long been a problem for both agriculture and municipalities in the Province of Alberta. Figure 1 shows the average number of hail days throughout Canada. It is notable that there is a “bull’s eye” on the area from Calgary to Red Deer, which also coincides with the greatest population density of the province, which continues to increase. In 1956, under the aegis of the Alberta Research Council, a research program was undertaken that sought to develop and evaluate the effectiveness of cloud seeding from aircraft to mitigate crop-hail damage. The program continued to conduct cloud seeding and research the hail problem and ways to reduce the hail impact on agriculture until 1985, when it was discontinued due to cut-backs in Provincial Government spending.

The hail problem did not end with the hail research program, and in 1991 a severe hailstorm caused

several hundred million dollars damage in the City of Calgary and adjacent metropolitan areas. This storm, though by no means the first of its kind, was of sufficient magnitude to rekindle interest in hail damage mitigation through cloud seeding.

1.2 The Alberta Severe Weather Management Society

A consortium of underwriters of property and casualty insurance in Alberta was formed in the wake of the 1991 Calgary storm, and named itself the Alberta Severe Weather Management Society (ASWMS). From its formation, the ASWMS was focused on establishing a renewed Alberta Hail Suppression Program through cloud seeding. This time, the focus was to be on protecting municipalities, not crops. The necessity for such a program was presented to the Insurance Bureau of Canada (IBC), and though the IBC was encouraging, it offered no financial support. The Province of Alberta was itself approached for funding of the program. Though the need was acknowledged by the provincial leaders, funding was not forthcoming.

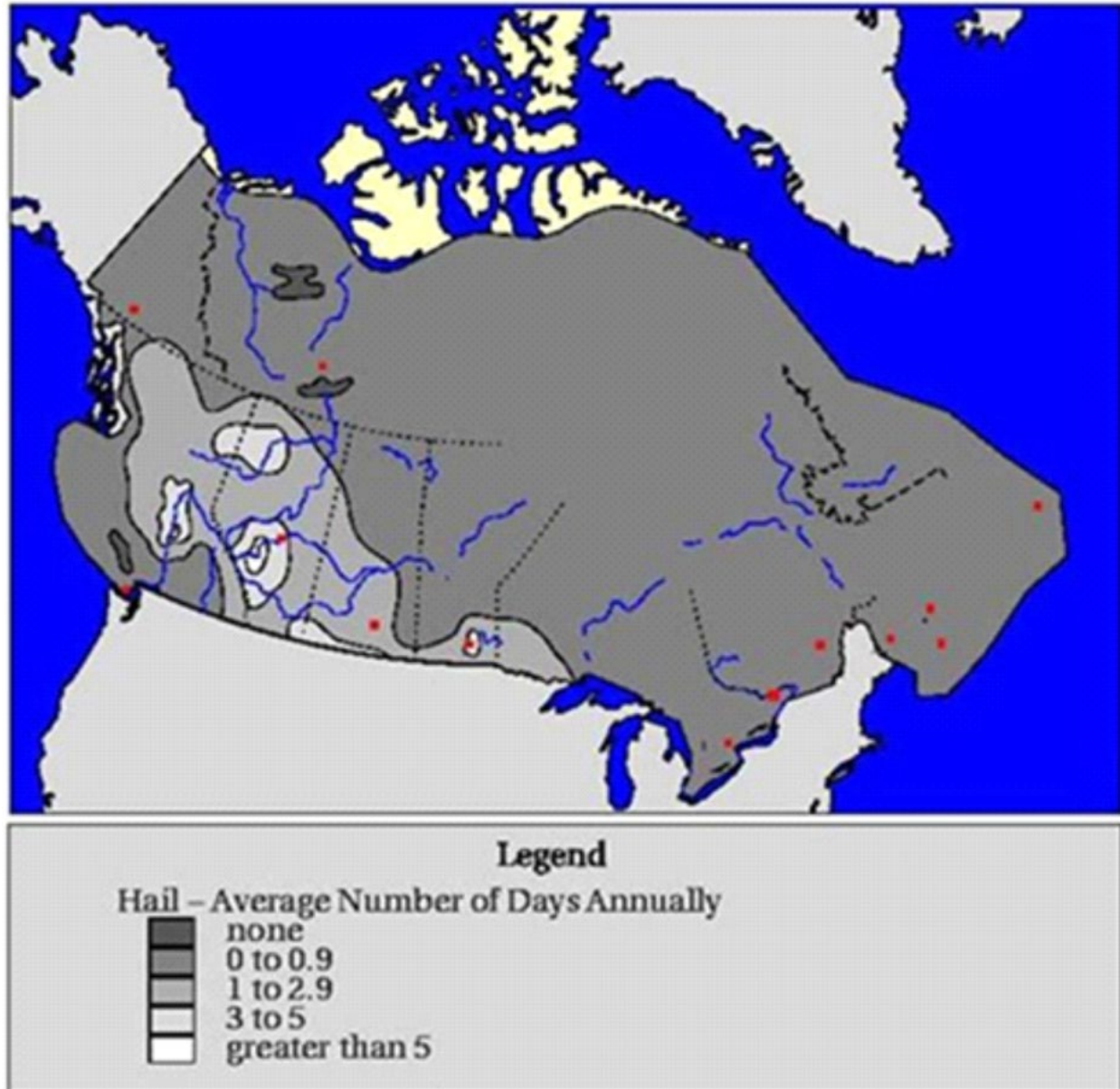


Figure 1. The hail climatology of Canada, from Etkin and Brun (1999). The average number of hail days per year, based on the 1951-1980 climate normal of Environment Canada (1987).

In 1995, the ASWMS developed a protocol through which its members would pay into a common project fund, amount proportional with market share, and the current Alberta Hail Suppression Project finally became possible. An international tender was issued, and Weather Modification, Inc. (WMI) was awarded an initial five-year contract to conduct operations from June 15 through September 15 each summer, beginning in 1996.

1.3 Initial Program (1996)

The goal of the project from the beginning has been the protection from the ravages of hailstorms to property concentrated in urban areas, to the maximum extent technology and safety will allow. The two largest such areas within the project target area are Calgary and Red Deer, but there are dozens of additional cities and towns that also warrant atten-

tion. To do this, the project established a weather radar and Operations Centre at the Olds-Didsbury Airport, approximately halfway between the two largest metropolitan areas (Figure 2). Two aircraft were based in Calgary, a third in Red Deer.

1.4 Recent Alberta Urban Hail Damage

The most notable urban storms (Insurance Bureau of Canada 2015) are listed below, with losses in 2014 Canadian Dollars.

- 2014 Aug. 7–8, southern Alberta, Calgary, wind/thunderstorm (hail): \$568.9 million
- 2012 Aug. 12, region around Calgary, wind/thunderstorm (hail): \$578.1 million
- 2010 July 12–13, Calgary and southern Alberta, wind/thunderstorm (hail): \$569.5 million
- 1996 July 16–18, Calgary, hail: \$167.7 million
- 1996 July 24–25, Calgary, hail: \$120.0 million
- 1991 Sept. 7, Calgary, hail: \$518.2 million

The most recent (the top bullet), was the #7 Top National Weather Story of 2014, according to Environment Canada <https://www.ec.gc.ca/meteo-weather/default.asp?lang=En&n=C8D88613-1&offset=8&toc=show>.

2. CURRENT PROGRAM STRUCTURE

The contract, originally let in 1996, was awarded to Weather Modification, Inc. The original contract was to provide airborne hail-suppression services with three aircraft, to be guided by meteorologists from a radar-equipped operations center. The scientific basis for the program was established largely on the basis of the long-term Alberta Research Council hail program, which had conducted hail and hail suppression research from 1956 through 1985.

The project is staffed and run by the contractor, under continuous oversight of the ASWMS Director. Operations are conducted solely by the contractor, on a 24 hours-per-day, 7-days-a-week basis. There

is no down time. Prior to project start-up on June 1 each year, a full day pre-project ground school for all project personnel and administrative staff is hosted by the ASWMS.

2.1 Infrastructure

Six significant changes have been made to the project scope during the first twenty seasons. Early on (season 2) it was recognized that the hail problem begins earlier in the year than June 15, so since 1998, the project has begun each season on June 1.

Beginning in the 2006 season, the protected area was expanded somewhat to the east, to include the town of Strathmore and communities east of Calgary.

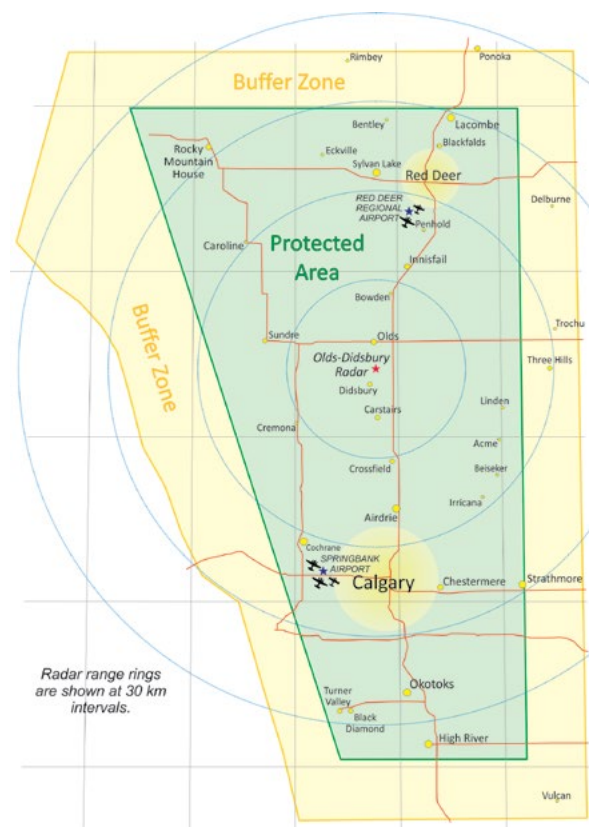


Figure 2. Southern Alberta, showing the project protected area (approximately 21,000 km²) through the 2015 season. The major cities and towns in and near the protected area are shown, along with the location of the Olds-Didsbury Operations Radar Centre (red star). Aircraft bases are shown by aircraft symbols.

The third change did not occur until the 13th season, 2008. The unrelenting expansion of the metropolitan areas within the project area meant increasing risk, and a fourth cloud seeding aircraft was added to the project. This aircraft is based in Red Deer.

The fourth change was the replacement, in 2011, of an aging WR-100 weather radar with a new C-band radar built by WMI. This radar possessed significantly increased sensitivity which meant that clouds could be detected sooner (earlier in their development), and Doppler capability. The fifth change was implemented in 2013, with the addition of a fifth aircraft to the project, another King Air, based at the Springbank Airport.

The last significant change occurred in 2014, with the replacement of the 2011 Doppler radar with an even-newer C-band radar having increased sensitivity (minimum detectable signal < 10 dBZ). Improvements included implementation of the latest version of the TITAN radar software, state-of-the-science radar antenna control, improved data processing, and volume scans completed every four minutes instead of every five minutes.

2.2 Current resources

Five aircraft are presently employed; all are twin-engine, and pressurized. Three are based at the Springbank Airport just west of Calgary; the other two are based at the Red Deer Regional Airport located near Penhold, just southwest of Red Deer. Three of the five aircraft are King Air model C90 turboprop aircraft, used primarily for top seeding using 20 gram glaciogenic pyrotechnics that are ignited as they are dropped, and fall ~ 1 km before being consumed. The King Airs also carry 48-place racks for 150 gram glaciogenic pyrotechnics, which are burned while remaining affixed to the aircraft wings. The other two aircraft are Cessna model 340A, and used primarily at cloud base, though they are also equipped with the racks for the 20 gram ejectable pyrotechnics. These aircraft also carry burn-in-place pyrotechnics on the wings, and for more extended, lower-rate seeding, also use solution-burning ice nucleus generators on each wing tip. These generators can each operate

for about 2.5 hours. The locations of the aircraft relative to the protected area and larger buffer area are given in Figure 2. The equipment is operated by a cohesive team of pilots, meteorologists, technicians, and mechanics. Each aircraft is operated by a two-person flight crew. Flying, recordkeeping, and aircraft readiness duties are shared. Pilots are trained either by exposure to convective seeding techniques on other WMI projects, and/or by flying with a senior, experienced captain. Safety is of paramount importance. The project operations team consists of three meteorologists. The most senior person directs most of the operations, particularly when multiple aircraft are deployed. The other two prepare the daily forecasts and updates, archive weather data, provide operational support, and share weather monitoring duties. An electronics technician maintains the radar, computers, and seeding equipment. Services for aircraft maintenance are provided through an on-site maintenance organization (local FBO).

3. OPERATIONS

The AHSP staff is responsible for seeding hailstorms threatening a protected city on a 24 hour-per-day, 7 day-per-week basis. This requires constant communication and coordination among the meteorologists and between meteorologists and pilots. Cell phones and text messaging are the primary method of communication, and all crew members are required to be reachable at all times. Weather and radar are monitored remotely when there is minimal threat of thunderstorms. Crews are required to be at the airport or radar office when there is a significant and immediate threat of damaging hail. Threat recognition and reliable clear communications are keys to the timely seeding of hailstorms.

3.1 Forecasting

Threat recognition begins with the daily forecast which is issued daily at 11 am local time as a pdf document emailed to all crew members and posted to a designated website. As numerical weather models have improved over recent years, forecasting of hail has improved. During the five year period from 2011-2015, the AHSP meteorologists

have averaged a Probability of Detection of 0.91 with a False Alarm Ratio of 0.20. This means forecasters identified the threat of any size hail (5 mm or larger) correctly 91% of the time.

The vast majority of hailstorms on the AHSP occur between 11 am and 11 pm local time (Figure 3). While elevated non-severe nocturnal thunderstorms are not uncommon in Alberta, there are typically less than five nocturnal hailstorms requiring seeding in any given season.

Assembly of the daily forecast begins at 8 am MDT. An example of the daily forecast sheet can be found in Figure 4. Forecasts are valid for a 24 hour period from 12 UTC to 12 UTC (the official “storm day” begins and ends at 6am MDT). The forecast also includes a brief day 2 outlook for planning purposes.

Along with the written summary page, a modified WRF model sounding is included which indicates the worst case scenario for the day at the time of maximum threat. Four other weather maps are included with the forecast including a surface depiction, an 850 hPa Theta-E chart, a 500 hPa chart with heights and vorticity, and a 250 hPa jet level chart. The upper air charts are model data from the 12 UTC run of the operational NAM (WRF) model from NCEP, valid for the time of peak instability/threat which is frequently 00 UTC. Forecasters are allowed to use their favorite websites to view model data. However, the project favorite is typically that of the College of DuPage, since it has readily available charts for Alberta that are centered over the project area. As time allows, forecasters are encouraged to view other model data beyond the WRF, including the HRRR, RUC/RAP, GFS, and European and Canadian models (ECMWF and GEM). However, these charts are not included with the issued forecast.

The daily WRF model sounding is the most valuable forecasting tool for the project. The raw data are obtained from either Northern Illinois University’s “Storm Machine” website, or that of Plymouth State University. The model sounding files are analyzed with RAOB. A skewT/logP thermodynamic diagram is created, and surface conditions

modified to reflect the maximum temperature and dew point for the day. Typically, the peak instability and hail threat will occur in the late afternoon during the time of peak heating, and the 00 UTC sounding will show the most threatening thermodynamic profile. Model soundings are available for both Red Deer and Calgary, and either can be utilized depending on where the more significant threat will be.

When conditions indicate a possibility of thunderstorms, the model sounding data are sometimes analyzed with HAILCAST (Brimelow et al., 2006) which is a 2D model that predicts hail size. Project studies have shown this model works well with some conditions, but has been found to have difficulty in assessing the strength and effectiveness of convective inhibition parameters. To determine whether or not to run the model, a decision tree is used (Figure 5). The decision tree (Mills and Colquhoun 1998) is meant to remove situations where the model has been found to yield misleading results. If the decision tree indicates HAILCAST should be run, the forecast sounding is converted to the requisite HAILCAST format, and the model is run with the forecast high temperature and dew point for the day. The average hail size output from the model is then included on the forecast sheet and considered in the final step of the forecast process.

Once all data have been analyzed and the forecaster has a clear idea of the weather scenario for the day, the final step is to determine the “Convective Day Category” or CDC. The CDC (Strong 1979) is an index that gives the potential for hailstorm activity, hail size and thus the likelihood of seeding operations. The characteristics of each CDC are given in Table 1.

The maximum vertically-integrated liquid (VIL) radar parameter criteria recorded by TITAN (Thunderstorm Identification Tracking Analysis and Nowcasting) radar software (Dixon and Wiener, 1993) was added to the CDC definitions after the comparison of VIL with Alberta surface hail reports by Krauss et al. (1998). It has been used since 1998 for forecast verification of hail size in the absence of surface hail reports. Radar VIL

values are used within the project area or buffer zones on the north, east, and south sides (not including the mountains or foothills of the western buffer zone). By convention, the +1 category minimum hail size is assumed to be 5 mm. The CDC is most valuable as an indicator of the threat level for project pilots. Days with a CDC from +2 to +5 require extreme vigilance, constant awareness of the developing weather, and rapid responses. Days with a very low CDC allow project personnel time to attend to personal tasks away from the airport or radar office. It should be noted that while the forecasters have a high probability of detection for hail (over 90%), surprise storms can occur. Human forecasters and imperfect numerical models can both fail to predict hail from time to time. This means that even on days when no hail is forecast, project personnel cannot completely let their guard down or ignore the skies.

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The maximum vertically-integrated liquid (VIL) radar parameter criteria recorded by TITAN

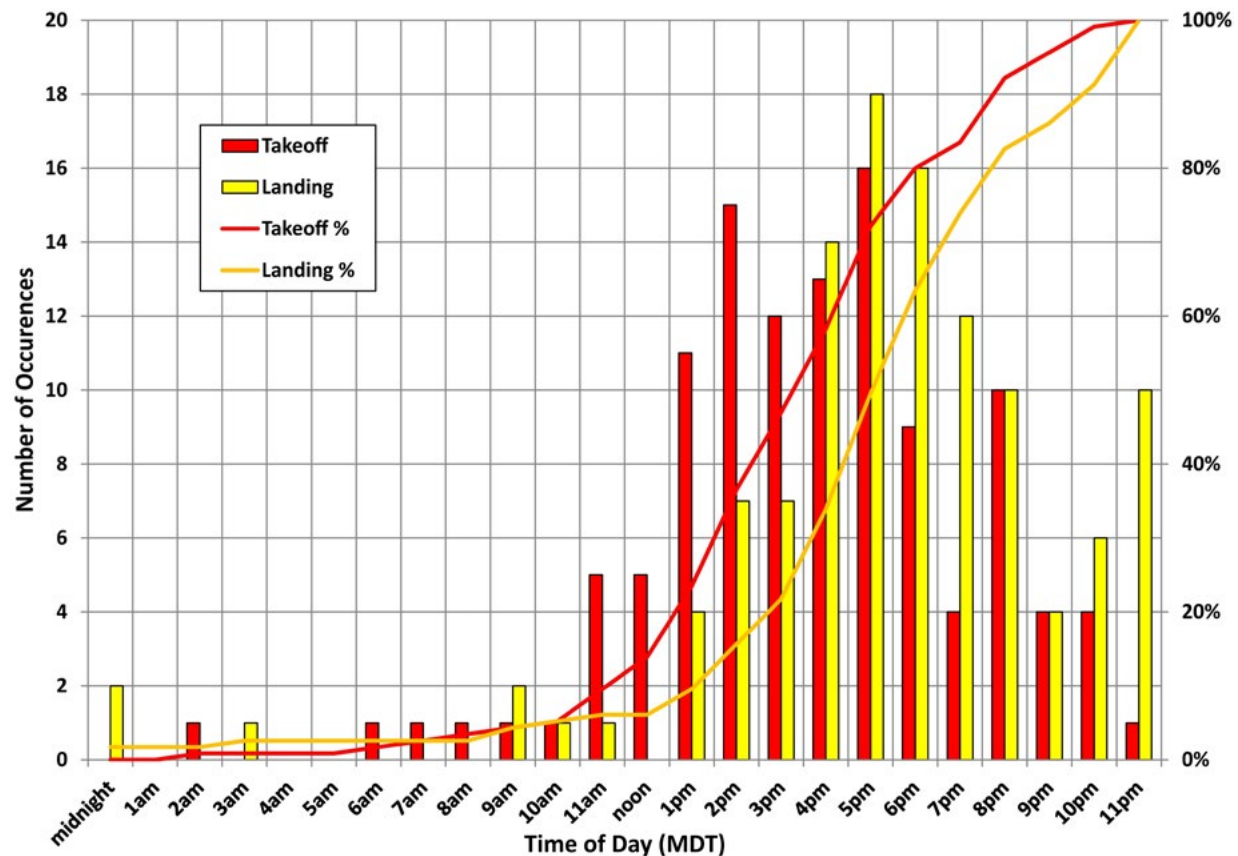


Figure 3. Diurnal variation in takeoff and landings, 2015 (Mountain Daylight Time). The 115 seeding and patrol flights are included. As is the norm, nocturnal flight operations were limited, especially after midnight.



Today's CDC +4	Synopsis: An upper level trough and jet streak will advance into our area today. Vorticity advection will be neutral through the day, but will turn positive late this evening. Lee cyclogenesis is expected this afternoon, and will create a significant meridional moisture gradient in the region. Extremely high instability is expected on and north of this moisture boundary, and east to northeast flow will aid in convective initiation along the foothills. Wind shear is robust today, strong in both direction and speed, and supercell thunderstorm development seems likely. Strong shear and significant moisture remain tomorrow, with strong PVA expected in the mid morning hours.
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Forecast:
 Conditional but extremely volatile day ahead. Strong insolation will gradually weaken the cap this afternoon, and convective initiation is expected over the foothills. This development will likely become supercellular and severe, and poses a significant threat to the project area as it moves in. The greatest threat lies in the north, where better moisture and forcing exist, and no activity is expected south of the dry line. Strong thunderstorms are again possible after dawn Wednesday.

Day 2 Outlook CDC: +4

Model Sounding	YQF	00Z
Freezing Level:	12.2	kft
-5°C Level:	15.2	kft
-10°C Level:	17.7	kft
Equilibrium Level:	39.2	kft
Tropopause:	39.5	kft
Cloud Base Height:	7.8	kft
Cloud Base Temp:	10.9	°C
Cell Motion:	246 @	30 kts
Storm Motion:	260 @	17 kts
Temp Max:	25.0	°C
Dew Point:	14.0	°C
Convective Temp:	24.5	°C
CAPE:	2089	J/Kg
CIN:	0	J/Kg
Lifted Index:	-6.0	
Showalter Index:	-4.4	
Total Totals:	56.0	
Precipitable Water:	1.03	inches
WINDEX:	63.0	mph

Hailcast Model Output

CALGARY: 2.7cm; used a temperature of 26.5C and a mixed dew point of 11C.

RED DEER: 4.0cm; used a temperature of 25C and a mixed dew point of 13C.

- | | |
|--|--|
| <input type="checkbox"/> Jet PVA | <input type="checkbox"/> Morning Fog |
| <input checked="" type="checkbox"/> Short Wave Trof | <input type="checkbox"/> Gusty SFC Winds |
| <input checked="" type="checkbox"/> Lee Cyclogenesis | <input checked="" type="checkbox"/> Loaded Gun |
| <input checked="" type="checkbox"/> Directional Wind Shear | <input checked="" type="checkbox"/> Theta E Ridge |
| <input checked="" type="checkbox"/> Speed Shear | <input type="checkbox"/> Chinook |
| <input checked="" type="checkbox"/> PM Radiative Cooling | <input type="checkbox"/> Cloud Cover |
| <input type="checkbox"/> AM ACC or Cloud Streets | <input checked="" type="checkbox"/> Insolation (sfc heating) |
| <input checked="" type="checkbox"/> NE/SE Moisture Advection | <input checked="" type="checkbox"/> Latent Instability |
| <input type="checkbox"/> Cooling at 500mb | <input type="checkbox"/> Frontal Lift |
| <input type="checkbox"/> Warming at 500mb | <input checked="" type="checkbox"/> Upslope Flow |
| <input checked="" type="checkbox"/> Dry Line or Dry Slot | <input type="checkbox"/> Low Ceilings |
| <input type="checkbox"/> Smoke/Haze | <input type="checkbox"/> Flood Potential |

Verification

Observed CDC:
 Max TITAN cell top: km
 Max reflectivity: dBz
 Max VIL: kg/m²
 YYC:
 YQF:
 Radar:
 Hail Reports:

Convective Day Category (CDC)		
-3	No Seeding	Clear skies, fair weather cumulus, or stratus without rain, no deep convection
-2	No Seeding	Towering Cumulus, altocumulus, alto-stratus, or nimbostratus producing rain for several hours or weak echoes (e.g. virga)
-1	No Seeding	Scattered convective rain showers but no threat of hail. No reports of lightning.
0	Patrol/Seeding	Thunderstorms (at least one) but no hail. VIL < 20 kg/m ² within the project area or buffer zones
+1	Seeding	Thunderstorms with pea or shot size hail (0.5 to 1.2 cm diameter). 20 kg/m ² < VIL < 30 kg/m ²
+2	Seeding	Thunderstorms with grape size hail (1.3 to 2.0 cm diameter). 30 kg/m ² < VIL < 70 kg/m ²
+3	Seeding	Thunderstorms with walnut size hail (2.1 to 3.2 cm diameter). 70 kg/m ² < VIL < 100 kg/m ²
+4	Seeding	Thunderstorms with golf ball size hail (3.3 to 5.2 cm diameter). VIL > 100 kg/m ²
+5	Seeding	Thunderstorms with greater than golf ball size hail (>5.2 cm diameter).

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Figure 4. The daily forecast for Tuesday, 21 July 2015 is shown.

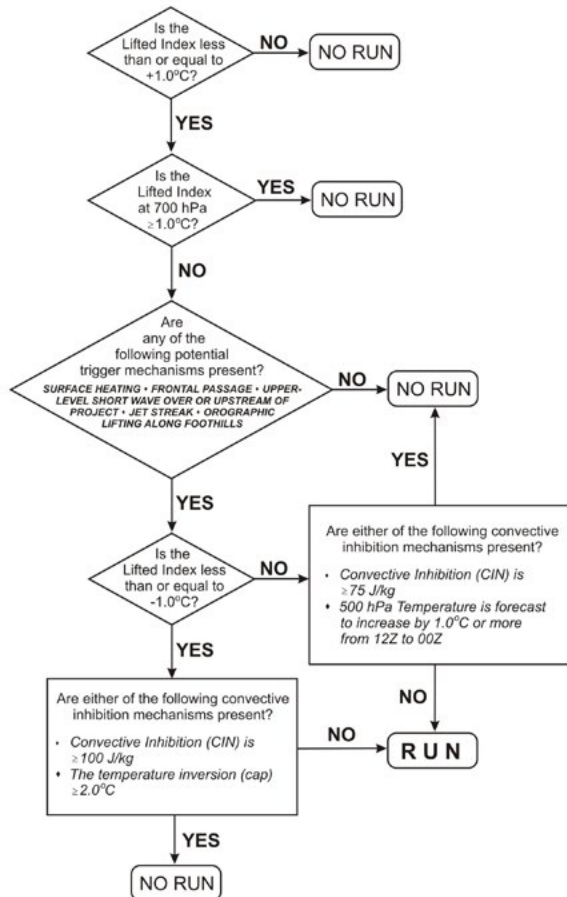


Figure 5. The decision tree used to determine if HAILCAST should be used for the daily forecast.

can both fail to predict hail from time to time. This means that even on days when no hail is forecast, project personnel cannot completely let their guard down or ignore the skies.

3.2 Briefings

The daily forecast is issued a few minutes before the daily 11 am (MDT) briefing to allow crew members to read it and prepare any questions or comments. The briefing is conducted via web conferencing, or by telephone as a backup option. All project offices are equipped with computers, high-speed internet, microphones, and webcams. All crew are required to attend the daily briefings unless there are extenuating circumstances, in which case they may call in remotely from a laptop or phone. The daily briefing is split into three sections: Debriefing of past operations, presentation

of the forecast, and planning of operations for the current day.

Briefings begin with a quick introduction of everyone present at each site including any guests that may be observing and listening. After introduction, the lead meteorologist debriefs the crew regarding the previous day's seeding operations (if any) and double-checks operations records including takeoff times, landing times, and amount of seeding material released. A candid discussion often occurs amongst the aircrews and meteorologists involved with the operations to resolve any issues regarding equipment, communication, seeding strategies, ATC conflicts, etc. Archived TITAN radar images with flight tracks can be posted to the shared web-conferencing screen to aid in discussions.

The daily forecast is then presented by the forecasting meteorologist. The forecast sheet and various charts and maps are posted to the shared web conferencing screen for group reference while the forecaster spends 5 to 10 minutes talking through the significant weather features for the day that support the selected Convective Day Category (CDC).

The lead meteorologist then runs through a quick checklist for each Hailstop crew and aircraft, and notes equipment status, aircraft maintenance issues, or changes to pilot duty schedules. If all systems are operational and all crew members are ready to fly, each particular aircrew and their plane will be designated "Good to go". Depending on the hail threat and timing of storms for the day, each aircrew will be assigned Airport Standby or Telephone Standby. This is typically the end of the briefing unless there are other non-routine issues to discuss.

3.3 Standby and Flights

Airport Standby: If hailstorms are expected to develop shortly after briefing, multiple aircrews remain at the airport to await seeding operations while meteorologists remain at the radar. If aircrews are not at the airport when a convective threat is identified, they will be called to the airport to await launch orders. The main goal of utilizing

Table 1. The Convective Day Category (CDC).

CDC	Strategy	Description
-3	No Seed	Clear skies, fair weather cumulus, or stratus (with no rain). No deep convection.
-2	No Seed	Towering cumulus, altocumulus, alto-stratus, or nimbostratus producing rain for several hours or weak echoes (e.g. virga).
-1	No Seed	Scattered convective rain showers but no threat of hail. No reports of lightning.
0	Patrol flights and potential seeding.	Thunderstorms (at least one) but no hail. VIL < 20 kg/m ² within the project area or buffer zones on north, east, and south sides.
+1	Seed	Thunderstorms with pea or shot size hail (0.5 to 1.2 cm diameter). 20 kg/m ² < VIL < 30 kg/m ²
+2	Seed	Thunderstorms with grape size hail (1.3 to 2.0 cm diameter). 30 kg/m ² < VIL < 70 kg/m ²
+3	Seed	Thunderstorms with walnut size hail (2.1 to 3.2 cm diameter). 70 kg/m ² < VIL < 100 kg/m ²
+4	Seed	Thunderstorms with golf ball size hail (3.3 to 5.2 cm diameter). VIL > 100 kg/m ²
+5	Seed	Thunderstorms with greater than golf ball size hail (>5.2 cm diameter).

Airport Standby is to have crews ready to go at a moment's notice once a threat is identified. This greatly improves response time and allows seeding to begin as soon as possible, minimizing the risk of a missed or late seeding event. If the threat level for the day is extreme (*i.e.* very large hail expected, or very fast-moving storms), all aircrews may sit at the airport all day waiting to be launched. On days with more minor threat levels, this is generally not the case.

Telephone Standby: If no convection is expected until much later in the day (or not at all), crews may be released to leave their posts so long as they are reachable on cell phones. Crews are generally expected to remain within 30 minutes travel time from the airport.

When convection is imminent, (*i.e.* reaching convective temperature, approaching shortwave, frontal passage, existing cells moving off the foothills) intensive radar watch and weather watch occur. If radar echoes or towering cumulus are deemed to indicate developing thunderstorms, flights may or may not be launched to the area depending on their location relative to cities and the expected threat level for the day. Since the primary project objective is to reduce hail damage over the major popu-

lation centers, nearly all developing storms upwind of the large cities of Calgary and Red Deer will warrant launch of aircraft. When the CDC indicates large hail likely, meteorologists are more aggressive with launches. When only small hail or short-lived or slow moving convection is forecast, meteorologists may hold off with launches unless cells indicate damaging hail signatures.

Operational flights fall into two categories, patrol and seeding flights. Patrol flights are launched in anticipation of possible damaging hailstorms in order to have aircraft airborne and strategically located if seeding needs to be initiated. If a decision is made to begin seeding, having the aircraft airborne and in place saves valuable time. This can save 20 or 30 minutes of travel time depending on the location of the cell. Seeding flights are simply flights where seeding occurs after a cell has been deemed to pose a threat to a protected city. As a general rule, seeding is usually initiated for any cell with TITAN cell tops above 7.6 km (25 kft) located upwind of a protected city.

When flights are launched, meteorologists use TITAN software to obtain coordinates for the desired patrol or seeding operations. Pilots are provided a radial and distance from known navigational aids.

For more experienced crews, landmarks or a particular city name are all that is needed. Once aircraft become airborne and establish radio communication with the radar meteorologist, more exact headings are often provided depending on storm evolution. A recommended altitude is also provided to pilots, near cloud base for base seeders, or near the -10°C altitude for top seeders. After instructing the aircrew to launch, meteorologists notify air traffic controllers that a “Hailstop” flight has been launched. While this is not an official filed flight plan, it helps ATC anticipate the needs of the seeding aircraft and reduces conflict with other nearby commercial and private aircraft. Anytime an aircraft is launched for seeding or patrol, at least one other aircrew is called to the airport as backup. When an aircraft is launched or placed on airport standby, a group text message is sent to all project staff to keep everyone informed of the developing situation.

For significant hailstorms, the preferred seeding strategy for the AHSP is to have a top seeder and at least one base seeder begin seeding a minimum of 20 minutes (absolute minimum) upwind of the city. Due to ATC restrictions regarding instrument flight rules with top seeding aircraft, only one top seeder is allowed to operate in an area at a particular altitude within a radius of approximately 30 nautical miles. However, base seeders can maintain visual separation and it is safe to operate with multiple base seeders in the same inflow region of a storm if it is large enough. Responsibility for safe separation of aircraft is not a responsibility of the project meteorologists, though they monitor the relative positions in real-time through the AirLink tracking system and offer some guidance. This responsibility lies with the flight crews. The project utilizes five aircraft to provide uninterrupted seeding coverage (at either cloud-base or cloud-top) and/or to seed multiple storms simultaneously, when required. Factors that determine which seeding strategies are feasible (top or base seeding) include: storm structure, visibility, cloud base height, proximity to terrain or other aircraft, and/or time necessary for Hailstop aircraft to reach seeding altitude. When there are too many storms

present at once and there are not enough aircraft resources available for all to be seeded effectively, priority is given to storms approaching the largest cities. A seeding priorities list of protected project cities is readily available to the radar meteorologist for quick reference in such cases.

Cloud base seeding is conducted by flying just below the cloud base within the developing inflow of growing cumulus congestus (towering cumulus) clouds, or the inflow associated with the new growth zone in advance of the shelf cloud located on the upshear side of linear multicell storms (squall lines). Care is taken not to seed the strong updrafts of mature storms, for such clouds are too advanced in their ice phase process and the seeding material would most likely be swept rapidly upward into the storm’s anvil without providing significant ice nuclei to the hail growth zone.

The cloud top seeding aircraft penetrate or skim the tops of developing, supercooled, largely ice-free (and therefore free of radar echo), cumulus congestus cells as they mature. When multicell storms are present or when more isolated storms have feeder clouds, the seeding aircraft penetrate or skim the tops of the developing cumulus towers as they grow up through the -10°C flight level. The direction of seeding runs is determined by the location of mature, adjacent cells, which cannot be safely penetrated. Aircraft radar is beneficial for avoiding dangerous areas in embedded or instrument meteorological conditions (IMC). Cloud top seeding is usually conducted at altitudes where cloud temperatures are between the -5°C and -15°C and closer to the former when possible, typically at altitudes of about 16,000 to 18,000 feet MSL. Cloud top seeding is done primarily with ejectable pyrotechnics comprised of 20 grams of silver iodide seeding agent, which are released into updrafts in the upper regions of developing supercooled cloud towers. Each flare burns for ~ 37 seconds, while falling a maximum of 2,700 ft (0.8 km). Nevertheless, a minimum 3,000 ft vertical separation (~ 1.5 km) is always maintained between cloud top and cloud base seeding aircraft (or other nearby aircraft) as illustrated in Figure 6.

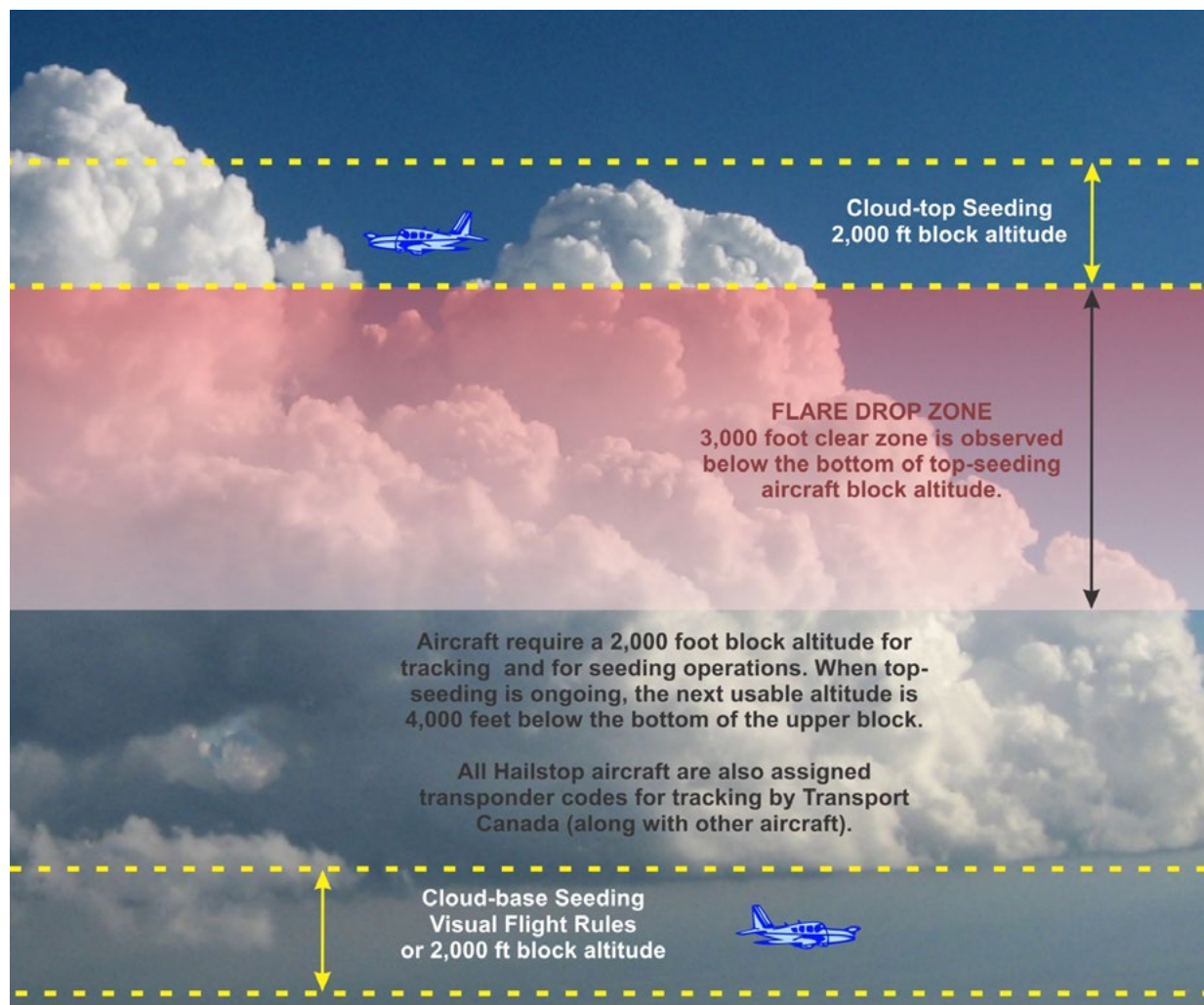


Figure 6. Vertical separation of aircraft for cloud-top and cloud-base seeding operations is illustrated. Top seeding is supplemented with burn-in-place 150 g pyrotechnics, particularly in low visibility or embedded conditions when targeting is difficult, or along a flanking lines when extended seeding runs are possible.

As seeding material is depleted and/or fuel levels become low, aircraft must eventually return to base for seeding agent and refueling. Replacement aircraft must be launched with enough time to reach the storms before the first depart. Every effort is made to provide continuous, uninterrupted seeding at both top and base. When a top seeding aircraft is approaching a storm with intention of replacing another top seeder, the replacement crew always approaches the storm from an altitude 1,000 to 2,000 feet above the top of the seeding plane's altitude block. This strategy keeps the reinforcement plane from flying through the flare drop zone of the seeding aircraft which would interrupt seeding and cause ATC conflicts. Once the seeding aircraft is finished seeding, they are then able to cancel their block with ATC and rapidly descend, vacating the

seeding zone. When they are clear of the area, the new plane simply drops down several thousand feet and starts seeding in the same area as the first plane. When this is done properly, the planes are able to hand off the top seeding operations with no interruptions in seeding. Hand-off of base-seeding operations is not as complex since pilots are able to maintain visual separation and are accustomed to working together in close proximity.

Seeding is terminated once a cell is no longer deemed a threat to a protected city. Seeding may be terminated if a cell weakens below hail threat criteria and atmospheric conditions are such that re-intensification is unlikely (i.e. stabilizing atmosphere after sunset, or cell moving into a less unstable air mass). In rare cases, seeding can be terminated

for reasons of pilot safety such as rapidly lowering ceilings, extreme turbulence, severe downdrafts, poor visibility at cloud base, etc. Once seeding of a cell has ended, aircraft may be redirected to other cells for seeding or patrol at the discretion of the radar meteorologist. Otherwise they return to base if no other threats are present.

All seeding directives given by the radar meteorologist are recorded in a hand-written log, as they occur. The exact time and detailed description of instruction are included. Examples of log entries include launch times (when aircraft were instructed to take off), airborne times, beginning of patrol or seeding, type of seeding (cloud top or base), seeding equipment utilized, altitude, times aircraft were redirected to a different area, cessation of seeding, return to base directives, and landing times. These same details are recorded by pilots during their flights. After missions have ended, logs are carefully reviewed to ensure accuracy and to reconcile any differences. All operational logs are then converted to digital formats and archived in the project record for purposes of reporting and post-analysis.

4. SCIENTIFIC BASIS

The understanding of the development of hail includes knowledge gained from work in Alberta by Chisholm (1970), Chisholm and Renick (1972), Marwitz (1972a, b, and c), Barge and Bergwall (1976), Krauss and Marwitz (1984), and English (1986). Direct observational evidence from the instrumented aircraft penetrations of Colorado and Alberta storms in the 1970s and early 1980s indicates that hail embryos grow within the evolving main updraft of single cell storms and within the updrafts of developing feeder clouds (the cumulus towers) that flank mature multi cell and supercell storms (see e.g. Browning, 1977, Foote 1984, Krauss and Marwitz 1984). The computation of hail growth trajectories within the context of measured storm wind fields provided a powerful tool for integrating certain parts of hail growth theories, and illustrated a striking complexity in the hail growth process.

In most severe hailstorms, the hail embryos develop in the feeder or daughter clouds/cells upwind of the mature cell (Heymsfield et al. 1980; Krauss and Marwitz, 1984; Cheng and Rogers, 1988).

The hail suppression conceptual model utilized in the Alberta Hail Suppression Project is based on the results of the former research program of the Alberta Research Council and the experiences of WMI in the USA, Canada, Argentina, and Greece. It involves the use of glaciogenic (ice-forming) materials to seed the developing feeder clouds near the -10°C level in the upshear, new growth “propagation” region of hailstorms. The glaciogenic reagents initiate the rapid development of small ice particles through the condensation-freezing nucleation process, and thus produce enhanced concentrations of ice crystals that compete for the available, supercooled liquid water in storms. This helps prevent the growth of large, damaging hail. The seeding also stimulates the precipitation process by speeding the growth of ice-phase hydrometeors, initially into snow pellets (also called graupel) which fall from the cloud earlier, melt, and reach the ground as rain, instead of continuing to grow into large ice particles that reach the ground as damaging hail.

5. HIGH EFFICIENCY SEEDING AGENT

Seeding is glaciogenic, and conducted with two seeding agents. A silver-iodide seeding solution is burned in ice nucleus generators attached to the wingtips of cloud based seeding aircraft. Higher-dose seeding is accomplished with pyrotechnics manufactured by Ice Crystal Engineering, LLC (ICE), of Kindred, North Dakota (DeMott 1999). This reagent is used in two ways. The DeMott (1999) CSU isothermal cloud chamber tests indicate that, on a per gram basis of pyrotechnic, the output and effectiveness indicate that these flares are among the best available worldwide. High yield and fast acting agents are important for hail suppression since the time window of opportunity for successful intervention of the hail growth process is often less than 10 minutes. More information about the ICE glaciogenic pyrotechnics can be

found on the internet at www.iceflares.com. The pyrotechnic yields are given in Table 2.

It should be noted that the ICE pyrotechnics presently used on the project produce more ice nuclei per gram of AgI and are much more active at warmer cloud temperatures (*i.e.* between -4°C and -10°C) than the AgI flares used in the previous Alberta Research Council program.

6. DATA COLLECTION

6.1 Weather Radar

C-band radar has been and continues to be used in the AHSP. Key throughout the project has been the use of the TITAN (Thunderstorm Identification Tracking Analysis and Nowcasting) radar software (Dixon and Wiener, 1993). This software is highly configurable, and allows bulk statistics to be examined. In Alberta, TITAN is set to identify and track all storm cells having 45 dBZ reflectivity volume greater than 10 km^3 above 4 km altitude (MSL).

The specifications of the current Doppler/TITAN-equipped weather radar, sited at the Olds-Didsbury Airport, are given in Table 3.

6.2 Hail Size Estimation / Verification

Hail reports from a variety of sources are utilized. Environment Canada data are available on-line, and these consist of public reports as well as those from “official” sites, such as airports. Radar-calculated VIL is available from the project radar, and is used for estimation of hail sizes in the absence of surface reports. Of course, first-hand reports from project staff, the news media, and persons familiar with the project (and/or who know project personnel) are always welcomed. Finally, reports from social media may also be used if they are verified (*i.e.* accompanied by photographs).

7. EVALUATION CASE STUDY - 21 JULY 2015

This case study evaluates the effects of seeding of a severe storm that occurred on 21 July 2015, when

three severe storms tracked across the project area very close in space and time. Two of the storms were seeded, but the third was not seeded because it was tracking just outside the project area. All were well-within radar range. Storm intensities are compared to see if the intensities were affected with respect to the timing and amount of seeding. This provides an example of a practical evaluation of the Alberta cloud seeding, of great interest to the sponsoring insurance industry because this was the most severe storm day of the 2015 season.

7.1 Synoptic Weather Conditions

On the morning of 21 July 2015, the project forecaster predicted the potential for golf ball-sized hail. The severe weather threat was enhanced by an intrusion of high theta-e air from the southeast that lay across the northern project area, north of a west-to-east dryline across the central project region. The NAM-WRF model forecast sounding (Figure 7) for the afternoon indicated $> 2000\text{ J/Kg}$ CAPE, and a Lifted Index of -6°C , with a cloud base temperature of 10.9°C . A mid-level trough was approaching from the west, and a surface low was forming over southern Alberta.

The 850 hPa theta-e chart depicted moisture being drawn around the southern surface low, and into the northern project area. At the upper levels, a jet streak was pushing through central Alberta, revealed by 50-60 knot winds near Red Deer. The vertical wind shear profile indicated strong speed and directional shear. Southeast surface winds were expected to create upslope flow along the western project boundary, which would be the primary trigger for initial afternoon thunderstorms. A moderate capping inversion was expected to suppress convection during the morning and early afternoon. Cells were expected to initiate over the foothills, rapidly becoming severe supercells, and then move east through the northern project area with a storm motion vector of 260° at 17 knots (see Figure 4 for the complete forecast for the day, issued at 11:00 MDT). The HAILCAST model predicted 2.7 cm diameter hail for Calgary and 4.0 cm size hail for Red Deer on 21 July 2015.

Table 2. Activation Rate (Time to nucleate 90% of the nuclei) and Yield (per gram) of the ICE Glaciogenic Pyrotechnic (DeMott 1999).

Temp (°C)	LWC (g m ⁻³)	T90% (min)	Yield (g ⁻¹ pyro)
-4.0	1.5	4.32	1.04x10 ¹¹
-6.3	1.5	1.12	6.00x10 ¹²
-10.5	1.5	0.73	3.07x10 ¹³

Table 3. Characteristics of the AHSP Project Radar, Olds-Didsbury Airport

Parameter	dBm	
Radar Constant	77.2577	
Noise	-64.5418	
Minimum Detectable Signal	-106.945	
Receiver Gain	42.4013	
Minimum dBZ at 1 km Range	-29.6555	
System Specifications		
Frequency (C-band)	5.975	GHz
Peak Power	250	KW
Average Power	150	W
Range Gate (length)	150	m
Pulse Repetition Frequency	600	sec ⁻¹
Pulse Width	1.0	µsec
Range	180	km
Beam Width	1.65	deg
Volume Scans	15	per hour

On this day, Environment Canada issued tornado warnings and several threatening funnel clouds were spotted, but there were no reports of any tornados touching down. Environment Canada received multiple reports of hail from the storms that formed, ranging in size from golf ball to hen egg size hail at Lacombe, Blackfalds, and Gull Lake

(north of Red Deer), loonie¹ (2.7 cm) size hail in Sylvan Lake (due west of Red Deer) and toonie (3 cm) size hail in Donalda (west of Red Deer), and hen egg size hail from the north side of Red Deer. For city locations, see again Figure 2.

Preliminary estimates of damage to property from the storms on 21 July 2015, provided by the Insurance Bureau of Canada Property Claims Service in August 2015, is estimated at >\$200 Million (Canadian dollars).

7.2 Operations Summary

Storms initiated along the foothills west of the project at 12:45 MDT. The first aircraft was launched at 14:09 (MDT). By 15:00 a line of cells was moving eastward into the protected area. As the line gradually moved eastward, cells intensified into severe, well-organized severe cells with damaging hail. Seeding was concentrated on three areas. Cell #1 tracked over the north part of Red Deer and impacted the town of Blackfalds, located approximately 8 km north of Red Deer. Cell #2 tracked across the town of Lacombe located approximately 18 km north of Red Deer. Cell #5 was a severe storm that tracked just north of Ponoka, located approximately 45 km north of Red Deer, just outside the protected project border, and was not seeded. (Several severe cells also passed south of the radar which were seeded, but are not part of this case study because of their separation in space and time.)

All five aircraft were utilized for at least one seeding flight, two aircraft flew two seeding missions, and one flew three seeding flights. With 23 hours and 15 minutes of seeding flight time recorded, 21 July 2015 was the most heavily seeded storm day of the season. Seeding agent released included 1,238 ejectable 20 g AgI flares (from cloud top), and 153 burn-in-place 150 g AgI flares (cloud base and on top). In addition, the base-seeding aircraft logged a total of 729 minutes of wingtip generator time. On this day, a total of 49,188 grams of silver

¹ The "loonie" is the 2 cm diameter Canadian dollar coin, so called because of the loon that graces the obverse side of the coin. The "toonie" is the sister two-dollar coin ~3 cm in diameter. The spellings "twonie" and "twoonie" are sometimes also used, but the Royal Canadian Mint uses "toonie".

Our experience in Alberta relating VIL and hail size observed at the ground indicates that the VIL values $>70 \text{ kg m}^{-2}$ are highly correlated with reports of walnut size hail ($>2 \text{ cm}$ diameter), and that $\text{VIL} >100 \text{ kg m}^{-2}$ is highly correlated with golf ball size ($>3.3 \text{ cm}$ diameter) hail.

The accumulated 24 hour maximum vertically-integrated liquid (VIL) measured by the radar on 21 July 2015 is shown in Figure 9.

The largest hail swaths (VIL tracks) were associated with the tracks of the three severe cells that tracked through Ponoka, Lacombe, Blackfalds, and northern Red Deer. The VIL tracks also indicate smaller hail occurred from the storms south of

the radar, and multiple reports of small and large hail were reported from this area.

Radar reflectivity and VIL parameters related to hail size indicate that the most severe cell of the day was the one that passed through the Ponoka area approximately 50 km north of Red Deer (TITAN cell #5). This cell had significantly greater VIL than the seeded cells within the project area. The northernmost (Ponoka) cell was not seeded, as it was just outside the project protected area. When the adjacent seeded storm tracks were compared with the unseeded track near Ponoka, there is a strong suggestion that the seeded storms had reduced hail size.

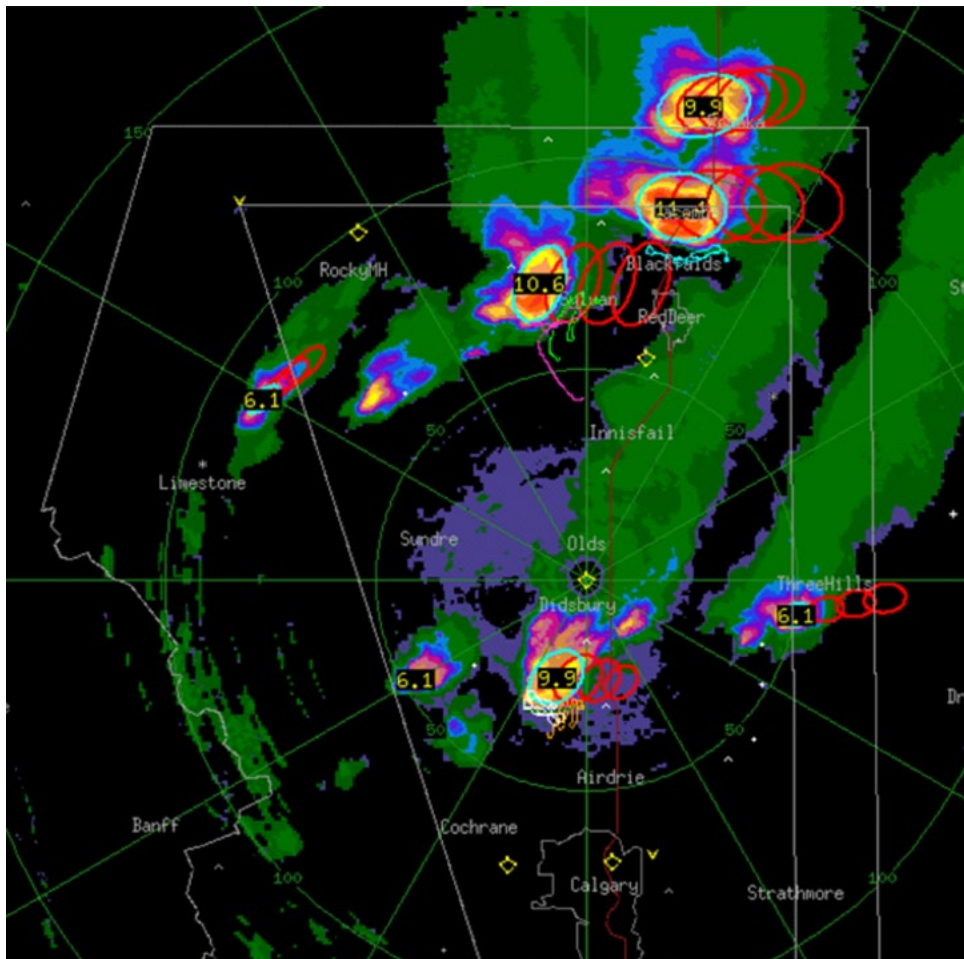


Figure 8. The Olds-Didsbury radar display at 19:26 MDT (01:26 UTC) indicated four severe thunderstorm cells within the radar coverage area. All five Hailstop (HS) aircraft were seeding at this time. Hailstop 3 (light blue track) was near Blackfalds (seeding Cell #2 located approximately 25 km north of Red Deer), HS4 and HS5 (green and pink tracks, respectively) were near Sylvan Lake (seeding Cell #1 located approximately 25 km west of Red Deer), and HS1 and HS2 (white and orange tracks, respectively) were seeding a storm located just south of the radar.

7.3 Radar Characteristics

The most important radar characteristics of cells #1 (seeded), #2 (seeded), and #5 (not seeded) are presented in this section. The statistics for cell top height, maximum reflectivity, maximum VIL, and cell area >60 dBZ for the seeded cells (#1 and #2), and the non-seeded cell (#5) are given in Table 4.

Maximum cell top (45 dBZ) heights ranged from 11.4 to 12.1 km. The mean cell top heights were 9.6

to 10.4 km. Maximum radar reflectivities ranged from 65.4 to 67 dBZ, and the average maximum reflectivities were 60.9 to 62.1 dBZ. The maximum cell areas >60 dBZ ranged from 74.7 to 129.8 km², and the average cell areas >60 dBZ ranged from 30.3 to 55.8 km². In all cases, the non-seeded cell #5 had the highest values. The number of volume scans (N) for each cell is indicated, and volume scans were completed approximately every 4 min for the life of each storm.

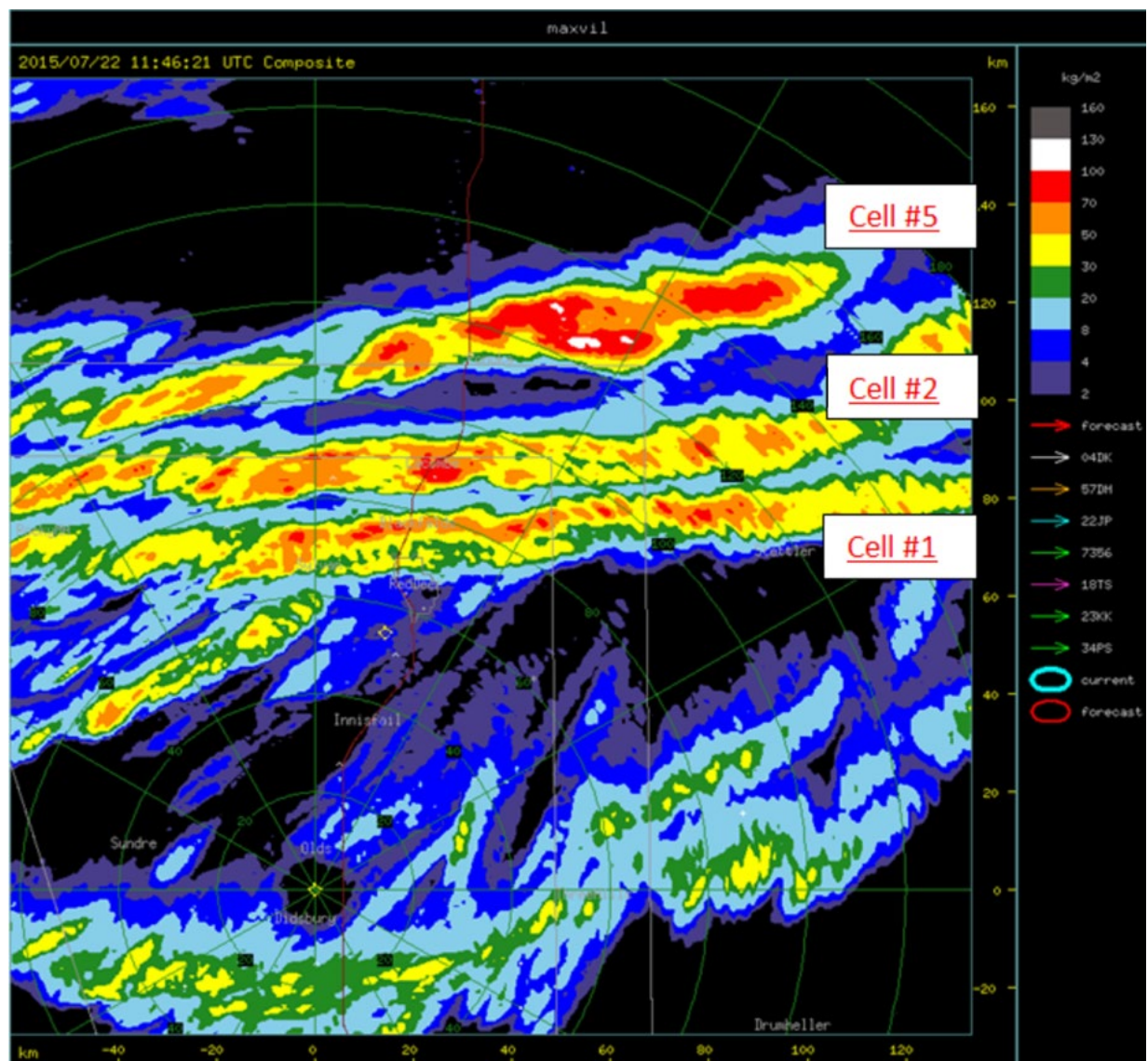


Figure 9. The 24-hour maximum vertically-integrated liquid (VIL) measured by the radar on 21 July 2015 is shown. Range rings are at 20 km intervals.

8. PRELIMINARY EVALUATION

The cell maximum radar reflectivity (dBZ) for each volume scan, for each cell, is shown in Figure 10. The total time covered is from 17:03 to 22:48 (MDT) 21 July 2015 (23:03 UTC 21 July 2015 to 04:48 UTC 22 July 2015). Each radar volume scan required 4 min to complete.

HAILSTOP seeding aircraft are directed to seed a hailstorm if it is a damage threat and moving towards a town or city within the project area. Figure 10 displays the maximum reflectivity and that cell #1 and #2 had exceeded 60 dBZ before the seeding started. The effects of AgI seeding are not instantaneous, and time is required for the seeding material to nucleate and have its ice particles significantly compete for the cloud supercooled liquid water. Secondly, the storm contains growing hail particles at the time seeding starts, and the trajectories of those existing hail particles will not be affected by the seeding, and the complete growth of those hail particles will be observed by the radar for the remainder of their lifetime, until they fall from the cloud.

The effects of seeding take time before they are visible on radar. Silver iodide nucleates ice crystals relatively quickly (within approximately 1 min) and then starts to grow approximately 1 micron per sec. Therefore, several minutes are required before the cloud liquid water starts to be significantly depleted. A radar reflectivity of 20 dBZ due to the growth of seeded ice crystals using ICE AgI flares took approximately 12 min in a study by Krauss et al. (2000).

The growth rate of the hail diameter is proportional to the cloud liquid water content (LWC). The time required for hail to grow from 0.5 cm to 3 cm is about 10 minutes for a LWC of 5 g m⁻³, or 20 minutes for 2.5 g m⁻³ (Knight et al., 1982). Using a conservative LWC of 2 g m⁻³, Knight et al. (1982) estimated the growth time from a cloud droplet to a 3 cm hailstone to be 45-50 minutes, and this lies within the range of updraft lifetimes typically observed in severe Alberta hailstorms (Chisholm and Renick, 1972).

Table 4. Radar Parameters of Cell #1, Cell #2, and Cell #5, 21-22 July 2016

Variable	Complex Number	Mean	Standard Deviation	Minimum	Median	Third Quartile	Maximum
Cell Top (km)	1-seed	9.7	1.4	6.1	10.3	10.6	11.4
	2-seed	10.4	1.2	6.1	10.6	11.4	12.1
	5-no seed	9.6	1.5	6.1	9.9	10.6	12.1
Maximum Reflectivity (dBZ)	1-seed	60.9	3.3	50.5	61.5	63.3	65.5
	2-seed	61.3	3.2	52.6	62.4	63.5	65.4
	5-no seed	62.1	4.4	46.5	63.8	65.1	67.0
Maximum VIL (kg m ⁻²)	1-seed	47.6	20.8	6.4	47.8	62.5	90.1
	2-seed	53.6	21.3	7.3	57.5	67.6	102.4
	5-no seed	57.4	29.6	4.6	56.8	77.9	121.7
Area >60 dBZ (km ²)	1-seed	30.3	23.3	0.0	27.5	52.6	74.7
	2-seed	45.8	32.1	0.0	47.5	61.9	112.2
	5-no seed	55.8	37.1	0.0	53.4	83.0	129.8
Cell #1: Seeded, 23:03:34 UTC to 04:48:10 UTC. (17:03 to 22:48 MDT) 90 volume scans.							
Cell #2: Seeded, 23:03:34 UTC to 04:09:27 UTC. (17:03 to 22:09 MDT) 83 volume scans.							
Cell #5: Unseeded, 23:03:34 UTC to 03:53:58 UTC. (17:03 to 21:53 MDT) 77 volume scans.							

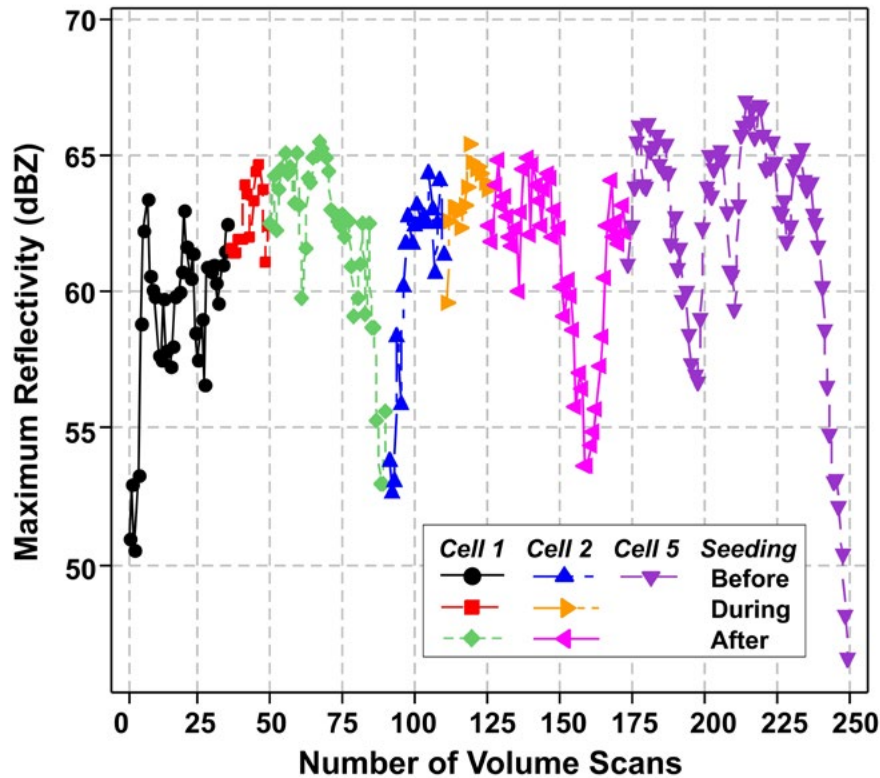


Figure 10. Cell maximum radar reflectivity (dBZ) for each volume scan, for Cells #1, #2, and #5, before seeding, during the seeding, and after the seeding stopped (i.e. post-seeding). Cell #5 was not seeded. Volume scans were performed every four minutes, and the total time covered is from 17:03 to 22:48 (MDT) 21 July 2015. Cell #1: lifetime 23:03:34 UTC to 04:48:10 UTC. (17:03 to 22:48 MDT) 90 volume scans. Cell #2: lifetime 23:03:34 UTC to 04:09:27 UTC. (17:03 to 22:09 MDT) 83 volume scans. Cell #5: lifetime 23:03:34 UTC to 03:53:58 UTC. (17:03 to 21:53 MDT) 77 volume scans.

From initial seeding it can take 20 to 45 min for the particles that were present in the cloud prior to the seeding to complete their growth and fall from the storm. Therefore, the effects of seeding on an existing severe thunderstorm are not expected to be readily visible on radar for approximately 20 to 45 min.

The maximum reflectivity for the seeded cells #1 and #2 continued to increase for 8 to 9 volume scans (32 to 36 minutes) after the seeding started, and this is consistent with the time required for the removal of the pre-existing hail particles in the storm, developing hydrometeors that would not be affected by the seeding.

Cell #1 tended to have reflectivity >60 dBZ for 57 volume scans (3.68 hours), cell #2 tended to have reflectivity >60 dBZ for 58 volume scans (3.75 hours), and cell #5 tended to have reflectivity >60 dBZ for 68 volume scans (4.5 hours). Certainly

cell #5 had maximum reflectivity >65 dBZ for more volume scans than cells #1 and #2. Cell #5 had 20 volume scans with maximum reflectivity >65 dBZ, compared with 5 volume scans >65 dBZ for Cell #1, and only 1 volume scan >65 dBZ for Cell #2. This observation is consistent with the hypothesis that seeding will reduce the time of large hail production within the storm cell.

The composite radar cell area (km²) with radar reflectivity >60 dBZ for each volume scan, for each cell, is shown in Figure 11.

Severe hail damage is undoubtedly associated with radar reflectivity areas >60 dBZ, and one can see that cell #5 (not seeded) had more volume scans with larger areas >60 dBZ than the seeded cells #1 and #2. The amount of storm area >60 dBZ over time should definitely be related to the amount of damage that would be incurred, and the authors strongly recommend that further analyses be con-

ducted to relate the areas of high radar reflectivity to property damage.

The cell maximum VIL, computed using the maximum reflectivity is shown in Figure 12. The vertical integration of liquid (VIL, kg m^{-2}), computed as a cell value using the maximum reflectivity at each altitude level, is a good indication of the total, vertically integrated intensity of the cell. Individual radar pixel VIL values have been shown to be highly correlated to hail at the surface, therefore, the cell VIL maximum is also highly correlated to the severity of the storm cell and the probability of large hail at the surface.

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The cell maximum VIL plot vs time (Figure 12) also shows that the seeded cells #1 and #2 had fewer extremely high values (i.e. >80 kg m^{-2}). Cell #5 had 17 volume scans with maximum VIL >80 kg m^{-2} , compared with 6 volume scans with maximum VIL >80 kg m^{-2} for Cell #1, and 7 volume scans with maximum VIL >80 kg m^{-2} for Cell #2. Extremely high values of VIL are associated with larger and/or numerous hailstones. Larger and/or numerous hail stones are more likely to have high damage potential. Therefore, this should also be an

indicator of the reduced damage potential of the seeded storm cells, compared with the max VIL of the unseeded storm (cell #5).

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In many ways, a practical assessment of a potential seeding effect involves the observed empirical cumulative distribution of a parameter highly correlated with hail at the ground and potential hail damage, comparing seeded storms with non-seeded storms, e.g. area > 60 dBZ.

The empirical cumulative distribution function of the cell area >60 dBZ data for cell #1, #2, and #5 is shown in Figure 13. The normal probability distribution curves computed using the parameters computed from the observed radar data are also shown in Figure 13. The normal distribution fits very well to the data. The mean cell area >60 dBZ for the seeded Cell #1 was 45.7% less than the non-seed Cell #5 area >60 dBZ. The mean cell area >60 dBZ for the seeded Cell #2 was 17.9% less than the non-seed Cell #5 area >60 dBZ.

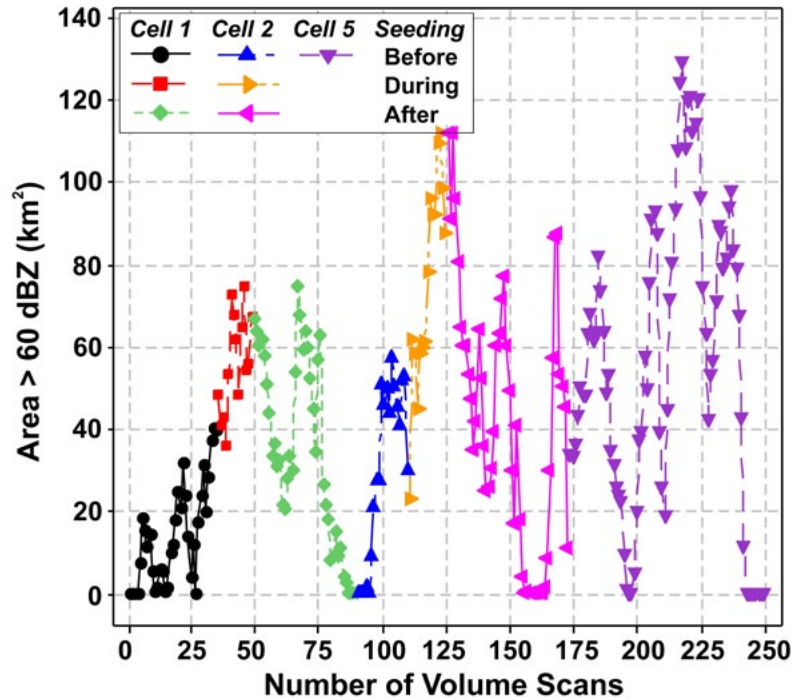


Figure 11. Composite radar cell area (km^2) with radar reflectivity >60 dBZ for each volume scan, for Cells #1, #2, and #5, before seeding, during the seeding, and after the seeding stopped. Cell #5 was not seeded. Cell #1: lifetime 23:03:34 UTC to 04:48:10 UTC. (17:03 to 22:48 MDT) 90 volume scans. Cell #2: lifetime 23:03:34 UTC to 04:09:27 UTC. (17:03 to 22:09 MDT) 83 volume scans. Cell #5: lifetime 23:03:34 UTC to 03:53:58 UTC. (17:03 to 21:53 MDT) 77 volume scans.

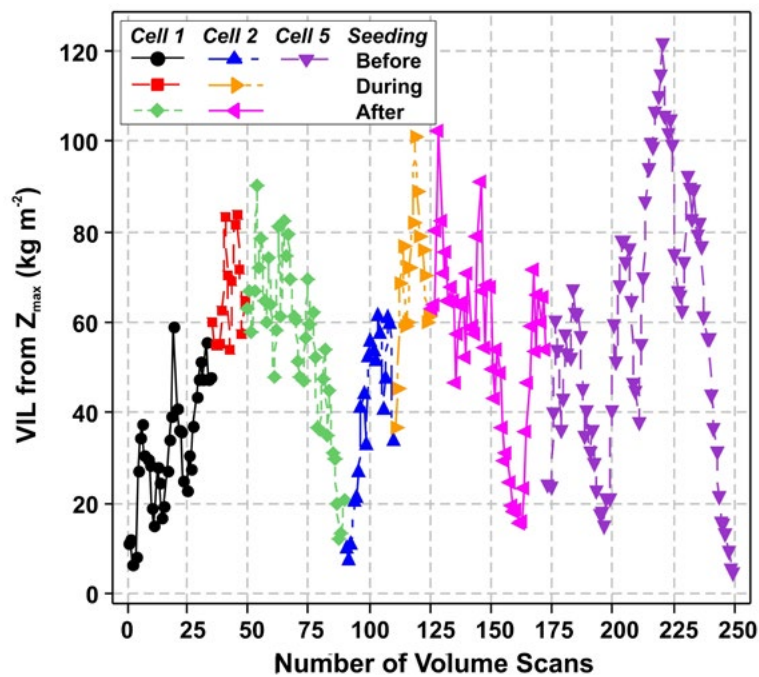


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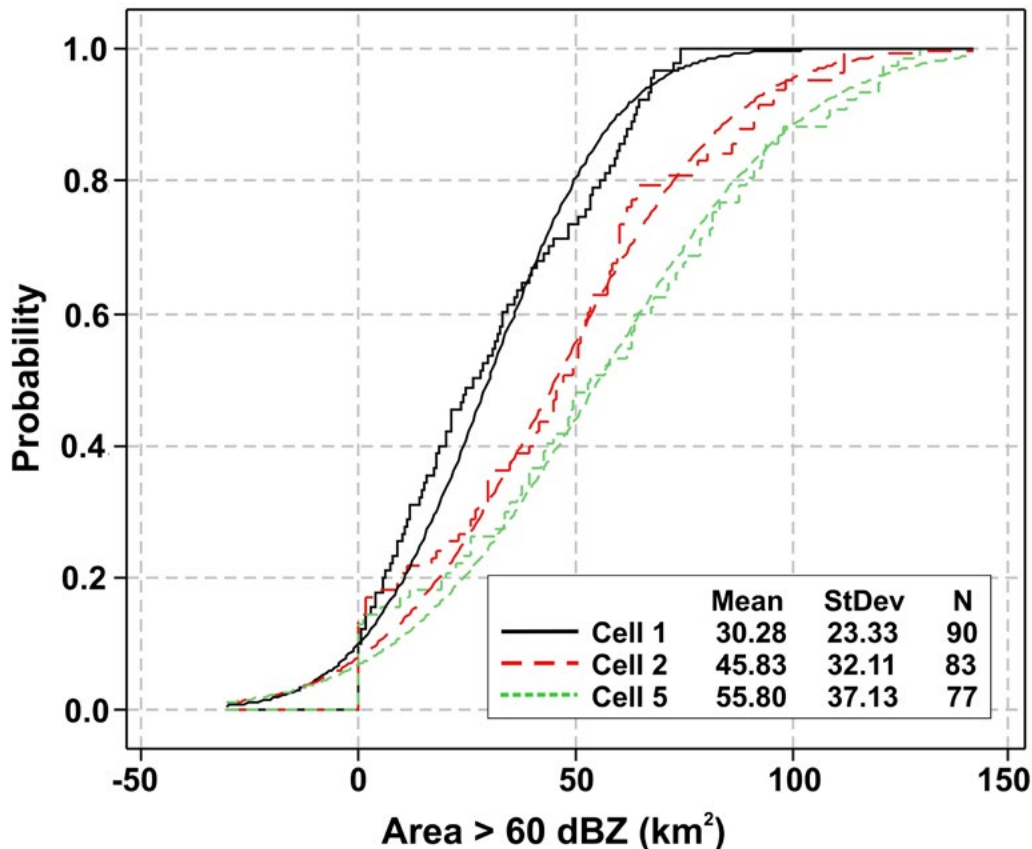


Figure 13. The empirical cumulative distribution functions of the cell area >60 dBZ data for Cell #1 (seeded), #2 (seeded), and #5 (not seeded). The normal probability distribution curves (dashed) computed using the mean and standard deviation parameters computed from the observed radar data are also shown.

The statistical T-test of the area >60 dBZ distributions indicates that the probability that the mean area >60 dBZ of Cell #1 was less than Cell #5, and was significant at the 99% level. The probability that the mean of Cell #2 was less than the mean of Cell #5 was only significant at the 90% level.

9. CONCLUSIONS

Evaluation of hail suppression programs continues to be a challenge due to the complex nature of severe thunderstorms and the difficulty in measuring effective response variables to cloud seeding.

The American Meteorological Society (AMS) official society statement regarding weather modification (2010) states that in complex cloud systems it is often difficult to determine a seeding effect on a cloud-by-cloud basis. In complex situations, large numbers of events must be analyzed to separate the

response to cloud seeding from natural variability in cloud behavior. Rigorous attention to evaluation is needed to develop a more effective understanding of the effects of cloud seeding.

The most recent Statement on Weather Modification from the World Meteorological Organization (WMO) Expert Team (2015) states that glaciogenic seeding technologies have been used operationally in many parts of the world to reduce hail damage. However, scientific evidence to date is inconclusive and evaluation of the results has proven difficult.

There is a long history of weather modification programs in Alberta. A 50th Anniversary article was published in the Bulletin of the Canadian Meteorological and Oceanographic Society (Strong et al. 2007). In 1980-85, the Alberta Research Council (ARC) conducted a research study of the

physical processes occurring in storms and the effects of cloud seeding on them. Humphries, et al., (1987) stated that weather modification technology had been solidly demonstrated on a limited scale. The hail problem is the most complex and difficult to solve, but substantial progress had been made and hail suppression looked feasible at least for some types of storms. The complexities of the hail suppression evaluation were elucidated further in the official final report of the Alberta Research Council (1986). The official ARC report that presented analyses of crop damage data from the Alberta Hail and Crop Insurance Corporation suggested a decrease in the loss to risk ratio of the order of 20% could be attributed to cloud seeding if no significant changes in weather patterns had occurred in central Alberta in the past 50 years and if no other factors had contributed to the observed decrease. Trends due to climate change, cloud seeding and changes in insurance practices are difficult to isolate.

The current Weather Modification Association (WMA) Statement on Weather Modification Capabilities (2011) states that the capability to suppress damaging hail continues to improve. Attracted by potentially large benefit/cost ratios, many countries are conducting projects where hailstorms are seeded to reduce the damage caused by hail.

The detailed analysis of three severe storms that occurred very close in space and time on July 21, 2015 indicates that the two seeded storms had less severe area (45.7% and 17.9% less mean area >60 dBZ) than the neighboring non-seeded storm. The seeded storms also had less maximum reflectivity, and less maximum Vil (as detailed in Table 4, and shown in Figures 10 and 12).

Severe hailstorms have caused >\$500 Million damage in 2012 and 2014 in Alberta, therefore, a 1% decrease in insured hail damage more than pays for the current program, and the results of this case study evaluation provides sufficient incentive and support for the hail suppression program.

The AHSP has continued to be funded by the private insurance companies of Alberta for the past 20 years, and the project is thought to be successful

in reducing the costs associated with hail damage to insured property, in spite of recent increases in the number of severe hailstorms. Evaluations of severe storm events, conducted on a case by case basis, comparing radar parameters between seeded and non-seeded storms has provided sufficient evidence to warrant the continuation of the program.

ACKNOWLEDGEMENTS

WMI acknowledges the continuing, kind support of the entire Board of Directors of the Alberta Severe Weather Management Society (ASWMS). The understanding, support, and cooperation of the ASWMS are greatly appreciated. A number of organizations and people deserve recognition and thanks. The cooperation of these persons and agencies is very important in making the project successful, in positive working environments.

- *Edmonton Area Control Center and Calgary Terminal Air Operations.* Through the years, the excellent cooperation by the ATC has played a very important role in allowing the project pilots to treat the threatening storms in an efficient and timely manner as required, often directly over the city of Calgary.
- *The Alberta Financial Services Corp. (AFSC)* in Lacombe has annually provided the crop insurance information. This has been helpful in assessing climatological hail trends.
- For all twenty seasons, Bob Jackson has provided office space for the Operations Center, at the Olds-Didsbury airport.

Weather Modification, Inc., wishes to acknowledge the contributions of all the staff who served through the years.

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