A cloud seeding pass is repeated immediately if there are visual signs of new cloud growth or radar reflectivity gradients remain tight (indicative of persistent updrafts). A 5 to 10 min waiting period may be used, to allow for the seeding material to take effect and the storm to dissipate, if visual signs of glaciation appear or radar reflectivity values decrease and gradients weaken. This waiting period precludes the waste of seeding material and ensures its optimum usage.

For cloud base seeding, a typical seeding rate of 1 burn-in-place flare (150 g each) is used. Cloud seeding runs are repeated until no further inflow is found. Wing-tip seeding solution burners will also be used to provide continuous silver iodide seeding if extensive regions of weak updraft are observed at cloud base and the shelf cloud region. Base seeding is not conducted if only downdrafts are encountered at cloud base, since this would waste seeding material.

The cloud seeding flares are silver-iodide pyrotechnics with an ice nuclei effectiveness of approximately 10^{14} nuclei per gram of pyrotechnic, active at -10°C, as determined by independent cloud chamber tests at Colorado State University.

Sufficient dispersion of the particles is required for AgI plume overlap from consecutive flares by the time the cloud particles reach hail size for effective hail suppression. The work by Grandia et al. (1979) based on turbulence measurements within Alberta feeder clouds indicated that the time for the diameter of the diffusing line of AgI to reach the integral length scale (200 m) in the inertial subrange size scales of mixing, was 140 seconds. This is insufficient time for ice particles to grow to hail size. Therefore, dropping flares at 5 sec intervals should effectively deplete the supercooled liquid water and prevent the growth of hail particles. The use of the 20 gram flares and a frequent drop rate provides better seeding coverage than using larger flares with greater time/distance spacing between flare drops. In fact, the above calculations are conservative when one considers that the center of the ice crystal plume center will have a higher concentration of crystals.

B. EQUIPMENT

Type:

- one Advanced Radar Corporation C-band Doppler weather radar, 250 kw peak power, with 1.65 deg. beam width, located at the Olds-Didsbury airport, 50ft tower-mounted, including radome.
- Three Beechcraft C90 King-Air prop-jet aircraft (two in Springbank and one in Red Deer).
- Two Cessna 340 aircraft (one in Springbank and one in Red Deer).

C. MATERIALS TO BE EMITTED:

- Cloud top (ejectable) pyrotechnic flares are 20g AgI formulation manufactured by Ice Crystal Engineering (ICE) of Kindred, North Dakota, USA (www.iceflares.com)
- Cloud base (burn-in-place) flares are 150g AgI formulation manufactured by Ice Crystal Engineering (ICE) of Kindred, North Dakota, USA (www.iceflares.com)
- A solution of acetone, silver iodide, sodium perchlorate, paradichlorobenzene, and ammonium iodide will also be burned for continuous seeding at cloud base. The products of combustion yield silver iodide (AgI) ice nuclei, carbon dioxide (CO_2), and water (H_2O).

Activation tests performed at Colorado State University indicate greater than10^{14} ice crystals per gram of seeding agent burned, active at -10°C.

Total flight hours and quantities to be dispersed: We estimate the project may use 8,500 twenty-gram flares and 1,000 one hundred-fifty gram flares, plus approximately 250 gallons of the seeding solution (2% AgI by volume) will be burned. The number of operational days, flights, and amount of seeding material dispensed over the past fifteen years is summarized in the attached table. No harmful effects from these materials is expected. This is based on years of studies (both in the USA and Canada) to detect silver in precipitation (above background levels) following cloud seeding. The amount of silver distributed by the cloud seeding is small compared to the output from industry. Silver amounts from cloud seeding are far, far less than the USA EPA guidelines.

PART 8. GENERAL INFORMATION CONCERNING USE OF AIRCRAFT.

- Three C90 King Air prop-jet aircraft, two in Springbank (N904DK and N518TS) and one based in Red Deer (N522JP).
- Two Cessna 340 aircraft, one in Springbank (N457DM) and one in Red Deer (N37356).

PART 9. GENERAL INFORMATION CONCERNING USE OF GROUND VEHICLES.

No special project ground vehicles will be deployed for the project. (Only private vehicles for personal transportation will be used.)

PART 10. GENERAL INFORMATION CONCERNING ANY MEASUREMENTS OR OBSERVATION INSTRUMENTATION.

No special surface observations are planned for this project. The primary instrumentation is the weather radar and special aircraft instrumentation. Daily weather charts will be recorded for documentation and reporting purposes.

AIRCRAFT TRACKING GLOBAL POSITIONING SYSTEM (GPS): The WMI weather radar control and communications center will be equipped to receive and record data from the GPS aircraft tracking system. The GPS system displays the exact position of aircraft superimposed on the radar display to enable the controller to accurately direct the seeding aircraft to optimum seeding locations within the storm system. The color-coded aircraft position on the PPI will be marked with a small symbol. Electronic coding will enable radar controllers to discriminate between all project aircraft.

TEMPERATURE INSTRUMENTATION: Each of the cloud seeding aircraft will have a temperature sensor to ensure that the cloud penetration seeding runs are conducted at the proper temperature levels.

WEATHER RADAR: The C-band Doppler radar will be equipped with a computerized radar recording and display system. The radar recording system will be capable of providing numerous cell statistics and colour products including plots of radar PPI displays and maximum reflectivity maps. The sophisticated radar tracking software called TITAN (Thunderstorm Identification, Tracking, Analysis, and Nowcasting) has been used since 1997 and has proved to be very useful. TITAN is licensed from the U.S. National Center for Atmospheric Research (NCAR).

PART 11. CERTIFICATION BY ORGANIZATION FOR WHOM ACTIVITY IS TO BE CONDUCTED:

State type of working agreement entered into with the weather modifier: Contract.

I HEREBY CERTIFY THAT ALL STATEMENTS MADE IN THIS NOTIFICATION OF INTENT TO ENGAGE IN WEATHER MODIFICATION ACTIVITIES ARE TRUE AND COMPLETE TO THE BEST OF MY KNOWLEDGE, AND REPRESENT IN SUBSTANCE AN ACCURATE DESCRIPTION OF A PROPOSAL TO UNDERTAKE WEATHER MODIFICATION ACTIVITIES ON BEHALF OF THE ORGANIZATION NAMED HEREIN.

Name of organization: Alberta Severe Weather Management Society

Full name of certifying officer and title:

Todd Klapak
President, Alberta Severe Weather Management Society
(403) 231-1357, Todd.Klapak@intact.net

29 TK

Signature: Date: May ~~16~~, 2017

PART 12. CERTIFICATION BY PERSON PROPOSING TO CONDUCT ACTIVITY.

I HEREBY CERTIFY THAT INFORMATION PROVIDED IN THIS NOTIFICATION OF INTENT TO ENGAGE IN WEATHER MODIFICATION ACTIVITIES IS A TRUE AND COMPLETE DESCRIPTION OF MY PROPOSED PLANS TO ENGAGE IN THE SPECIFIC WEATHER MODIFICATION ACTIVITIES HEREIN DESCRIBED.

Name of organization: Weather Modification, Inc.

Full name of certifying officer:
Bruce A. Boe
Vice President of Meteorology
(701) 235-5500

Signature: Date: May 16, 2017

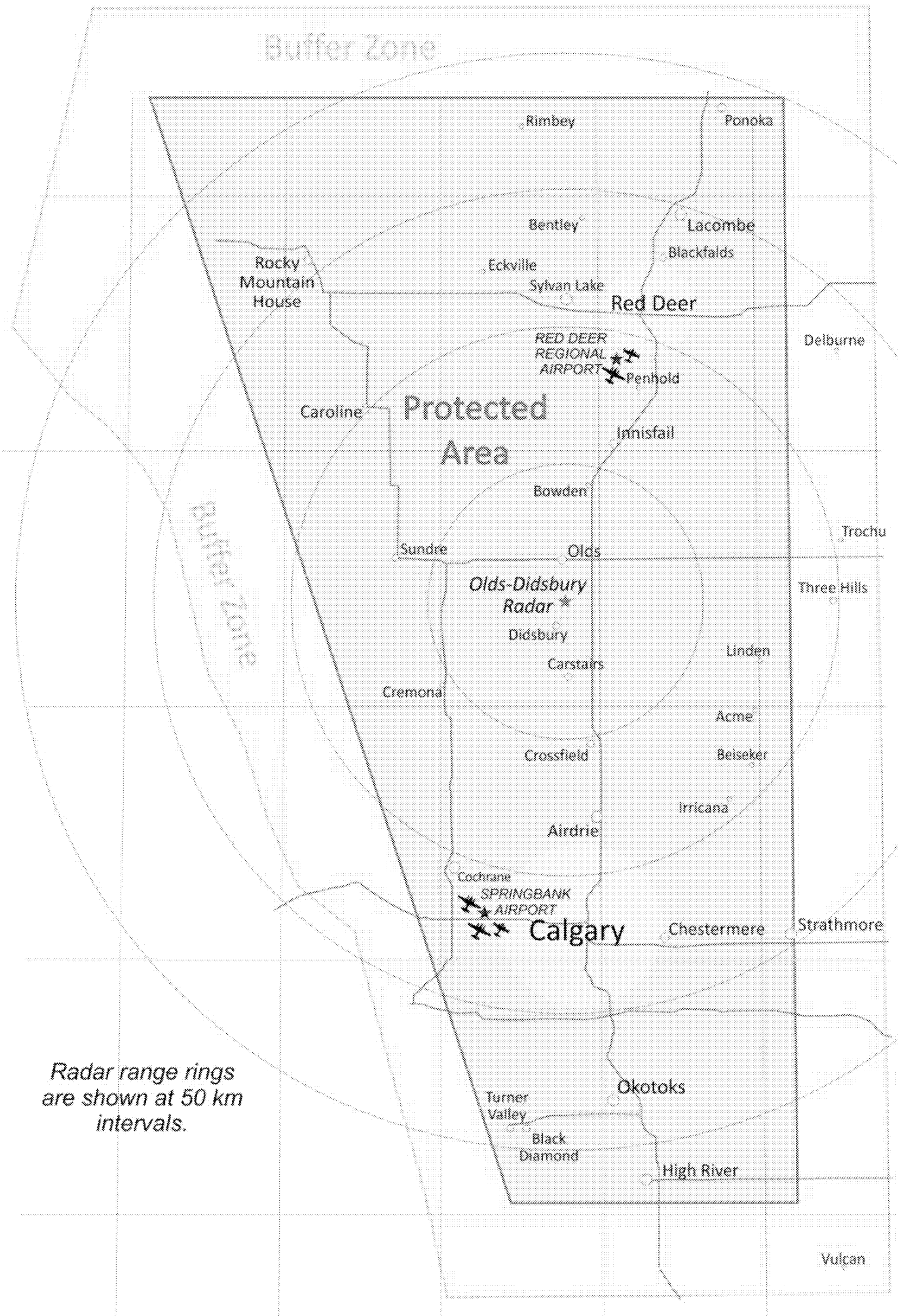

Figure 1: Map of south-central Alberta showing the project area, outlined in green, covered by the Hail Suppression activities.

Table 1. Operations Summary by Season, 1996-2016

Season	Storm Days With Seeding	Aircraft Missions (Seeding & Patrol)	Total Flight Time (hours)	Number of Storms Seeded	Total Seeding Agent (kg)	Seeding Agent Per Day (kg)	Seeding Agent Per Hour (kg)	Seeding Agent Per Storm (kg)	Ejectable Flares	Burn-in-place Flares	Seeding Solutions (gallons)	Season Activity Rank
2016	35	139	277.1	96	294.9	8.4	1.06	3.07	6496	1000	246.9	5
Mean	31.1	105.0	215.8	92.0	218.5	6.9	1.00	2.5	5242.3	682.1	166.6	
2015	26	115	233.3	79	349.2	14.6	1.37	4.42	8127	1138	262.9	8
2014	32	128	259.5	101	382.5	12.0	1.47	3.79	10782	1020	228.6	3
2013	26	103	229.6	70	233.3	9.0	1.02	3.33	6311	636	131.7	11
2012	37	143	300.1	116	314.6	8.5	1.16	2.70	7717	914	260.3	2
2011	48	158	383.0	134	400.1	8.3	1.13	3.00	10779	1020	350.2	1
2010	42	115	271.8	118	263.8	6.3	1.10	2.20	5837	851	227.5	7
2009	20	38	109.3	30	48.4	2.4	0.84	1.60	451	237	56.5	21
2008	26	112	194.7	56	122.9	4.7	1.00	2.20	1648	548	113.5	16
2007	19	76	115.3	41	99.7	5.2	0.90	2.40	1622	413	77	20
2006	28	92	190.2	65	214	7.6	1.10	3.30	4929	703	145.4	13
2005	27	80	157.9	70	159.1	5.9	1.00	2.30	3770	515	94.2	18
2004	29	105	227.5	90	270.9	9.3	1.20	3.00	6513	877	132.7	9
2003	26	92	163.6	79	173.4	6.7	1.10	2.20	4465	518	92.6	15
2002	27	92	157.4	54	124.2	4.6	0.80	2.30	3108	377	80.3	19
2001	36	109	208.3	98	195	5.4	0.90	2.00	5225	533	140.8	10
2000	33	130	265.2	136	343.8	10.4	1.30	2.50	9653	940	141.3	4
1999	39	118	251.3	162	212.7	5.5	0.80	1.30	4439	690	297.5	6
1998	31	96	189.9	153	111.1	3.6	0.60	0.70	2023	496	193.8	12
1997*	38	92	188.1	108	110.8	2.9	0.60	1.00	2376	356	144.3	14
1996*	29	71	159.1	75	163.3	5.6	1.00	2.20	3817	542	80.5	17

**The 1996 and 1997 seasons began on June 15, not June 1, which has been the norm ever since.*

2018 FINAL OPERATIONS REPORT

AHSP

ALBERTA HAIL SUPPRESSION PROJECT

ALBERTA SEVERE WEATHER MANAGMENT SOCIETY

WEATHER MODIFICATION INTERNATIONAL

ALBERTA HAIL SUPPRESSION PROJECT
FINAL OPERATIONS REPORT 2018

A PROGRAM DESIGNED FOR SEEDING CONVECTIVE CLOUDS
WITH GLACIOGENIC NUCLEI TO MITIGATE URBAN HAIL DAMAGE
IN THE PROVINCE OF ALBERTA, CANADA

by

WEATHER MODIFICATION INTERNATIONAL

Weather Modification LLC
3802 20th Street North
Fargo, North Dakota
U.S.A. 58102

for the

Alberta Severe Weather Management Society
Calgary, Alberta
Canada

DECEMBER 2018

EXECUTIVE SUMMARY

This report summarizes the activities during the 2018 field operations of the Alberta Hail Suppression Project. This was the twenty-third season of operations by Weather Modification LLC, dba Weather Modification International (WMI) of Fargo, North Dakota, under contract with the Alberta Severe Weather Management Society (ASWMS) of Calgary, Alberta. This season was the third season of the latest 5-year contract cycle for this on-going program; WMI has been the contractor since operations began in 1996. The program was again directed for the ASWMS by Dr. Terry Krauss. The program continues to be funded entirely by private insurance companies in Alberta with the sole intent to mitigate the damage to urban property caused by hail.

The cloud-seeding contract with WMI was renewed in 2001, 2006, 2011, and again in 2016. Calgary, Red Deer and many of the surrounding communities have seen significant growth in population and area since 1996. Calgary's population exceeded 1 million in 2006, and property values have more than doubled since the program's inception. In 2008 it was estimated that a hail storm similar to that which caused $400 million damage in Calgary in 1991 would now cause more than $1 billion damage. New record Alberta hailstorms have recently occurred in 2009 and 2010, and in 2012. On August 7, 2014, a severe storm hit Airdrie and other areas in southern Alberta caused more than $580 million dollars damage (IBC Facts 2017), indicating that a billion dollar storm within Calgary is certainly now possible.

The project design has remained the same throughout the period, but a fourth seeding aircraft (Hailstop 4) was added to the project in the summer of 2008 to increase seeding coverage on active storm days. In 2013, a fifth aircraft (Hailstop 5) was added, another twin-engine turboprop King Air, the same model aircraft as Hailstop 1 and 3 have been in recent seasons. This fifth aircraft was based in Springbank (CYBW) with Hailstop 1 and Hailstop 2. Hailstop 3 and Hailstop 4 were once again based at the Red Deer Regional Airport (CYQF).

The program was operational from June 1st to September 15th, 2018. Only storms that posed a hail threat to an urban area, as identified by the project's weather radar sited at the Olds-Didsbury Airport (CEA3), were seeded. The project target area covers the region from High River in the south to Ponoka in the north, with priority given to the two largest cities of Calgary and Red Deer. The project area is shown in Fig. 4.

Seven industry-accredited tours of the Operations Centre located at the Olds-Didsbury Airport were conducted for insurance brokers and insurance company staff. At each, a lecture on the history and science of the hail suppression program was given. The radar facility was explained and demonstrated, and one of the five Hailstop aircraft flew in to provide first-hand observation of the seeding equipment and allow some interaction with a flight crew. A total of 145 people attended the 2018 tours.

Hail was reported within the project area (protected area and buffer area) on 41 days. Larger than golf ball size hail was reported near Bowden on July 13th and on August 2nd in southeast Calgary.

Golf ball size hail was reported or observed by radar signature on July 1st in Didsbury, July 23rd in southwestern Calgary, and in Langdon on the 1st of August.

Walnut size hail was reported or observed by radar signature on June 9th in Irricana, in Olds on July 18th, on July 20th in Rimbey, southwest of High River on July 24th, and at the Springbank airport on July 30th.

There were 26 seeding days, whereas the mean is 31. A total of 127 seeding and patrol missions were flown, well above average, primarily because of the unusually large number of patrol flights (33). August was very warm in 2018, with many southern Alberta locations reporting all-time record maximum temperatures. The wildfire season in British Columbia began early and was very serious producing, in August, extremely smoky conditions in Alberta that persisted for weeks. At times, visibility was so low that seeding flights by cloud base seeding aircraft would have been extremely difficult, if not impossible. Fortunately, these days were characterized largely by stable air masses, and storms did not develop.

Of the 26 seeding days, all five Hailstop aircraft flew on eight days, and all five aircraft seeded on six of those eight days. When the weather was active, it was very active.

In June, 21 seeding missions were flown on 9 days, and an additional 14 flights flown for patrol on six days. A "patrol" flight is a flight flown to check cloud intensity or in anticipation of clouds becoming intense enough to warrant seeding, but during which no seeding was actually conducted.

July was the most active month, as is usually the case. Fifty-two seeding missions were flown on 13 days, and 15 more patrol flights on 11 days.

The most serious hailstorm of the season occurred on August 2nd, when thunderstorms developed west of Calgary and proceeded to move through the southern portion of the city. All five aircraft flew and seeded these storms. Ten seeding missions were flown, with each Hailstop aircraft flying twice. A detailed analysis of the August 2nd storm is provided as a case study in this report.

Activity diminished sharply after August 2nd. Only a single seeding mission was flown during the remainder of the month.

The final seeding mission of the season was flown on September 11th.

There were thunderstorms reported within the project area on 55 days during the summer of 2018, compared with 59 days in 2017. Hail fell on 41 days, with hail of walnut size or larger on 10 days. During this season, there were 262.5 hours of project operations accrued on 35 days with seeding and/or patrol operations. A total of 77 storms were seeded during 94 seeding flights on the 26 seeding days. There were 33 patrol flights, and 13 short "public relations" flights on which one aircraft was flown to the Olds-Didsbury Airport to be available for viewing by insurance company employees attending tours of the Operations Centre and radar. The distribution of flight time by purpose is given in Fig. 34.

The amount of silver-iodide nucleating agent dispensed during the 2018 field season totaled 248.0 kg. This was dispensed in the form of 4,663 ejectable (cloud-top) flares (93.3 kg seeding agent), 951 burn-in-place (cloud-base) flares (142.6 kg seeding agent), and 198.0 gallons of silver iodide seeding solution (12.0 kg seeding agent).

Five specially equipped cloud seeding aircraft were dedicated to the project. Two Beech C90A King Airs and one Cessna 340A were based in Springbank, and a C90A and another C340A were based in Red Deer. The procedures used in 2018 remained the same as the previous years. The Springbank office and aircraft were at Springbank Aero Services, at that airport. The WMI Red Deer office was again set up in the Air Spray hangar at the Red Deer Regional Airport, as has been done in recent seasons.

The aircraft and crews provided a 24-hour service, seven days a week throughout the period. Eleven full-time pilots and three meteorologists were assigned to the project this season. In addition, WMI's Director of Flight Operations, Mr. Jody Fischer, provided additional operational support throughout the season.

The 2018 crew was very experienced. The Red Deer aircraft team was led by Mr. Joel Zimmer, who has been with the Alberta program for 16 seasons, Ms. Jenelle Newman, and Mr. Mike Torris. The Springbank team was anchored by Mr. Brian Kindrat (onsite WMI Project Manager), Mr. Brook Mueller, and Mr. Andrew Brice. The radar crew was led by WMI's Chief Meteorologist, Mr. Daniel Gilbert, now with nine seasons' experience in Alberta, in addition to seven previous seasons' work in a similar capacity on a hail suppression program in North Dakota.

Overall, the personnel, aircraft, and radar performed well and there were no interruptions of service. A lightning strike to an engine on Hailstop 1 on July 10th resulted in that aircraft being grounded while the engine was inspected, but a replacement aircraft of the same type was on station and ready for action on July 12th. No seeding opportunities were missed. A radar calibration just prior to the beginning of the project season ensured that data was correctly displayed and recorded during the 2018 season.

High-speed Internet service was once again obtained at the Springbank and Red Deer pilot offices for the daily 11:00 AM weather briefings, so that they could closely monitor the storm evolution and motion using the radar images on the web prior to take-off. All of the project's radar data, meteorological data, and reports have been recorded onto a portable hard drive as a permanent archive for the Alberta Severe Weather Management Society. These data include the daily reports, radar maps, aircraft flight tracks, as well as meteorological charts for each day. The data can be made available for outside research purposes through special requests to the Alberta Severe Weather Management Society. In addition, the season's radar (TITAN) data are available to ASWMS Program Director Dr. Terry Krauss. Thus, Dr. Krauss has access to all data in the off-season, should the need arise.

ACKNOWLEDGEMENTS

WMI acknowledges the continuing, kind support of *Todd Klapak*, *Sherre Newell*, *Catherine Janssen*, *Dr. Terry Krauss*, and 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 for the project success, and in creating positive working environments.

- *Edmonton Area Control Center and Calgary Terminal Air Operations*. The excellent cooperation by the ATC once again 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.
- For the twenty-third season, special thanks go to *Bob Jackson* for sharing his office and hangar at the Olds-Didsbury airport, used for the radar and communications control center.
- *Sarah Newell* (AVIVA Canada) is thanked for organizing the seven informational seminars that were conducted at the Olds radar this summer as part of the Alberta Insurance Council accreditation program.
- *Perry Dancause*, *Andrew Robertson*, *Dennis Nava*, and the *staff of Air Spray Ltd* are sincerely thanked for providing offices, ramp space, and timely reliable aircraft maintenance this season at the Red Deer Airport.
- *Gary Hillman* of *Hillman Air* is thanked for allowing WMI to use his self-serve fuel tank at the Red Deer Regional Airport.
- The *staff* and manager, *Andreas Bertoni*, of Springbank Aero are thanked for providing office space, ramp space, and other operational support to the project at the Springbank Airport.

Weather Modification International wishes to acknowledge the contributions of the staff who served on the project during the summer of 2018: WMI Director of Flight Operations *Jody Fischer*, project manager *Brian Kindrat*, meteorologists *Dan Gilbert*, *Brad Waller*, and *Adam Brainard;* electronics-radar technicians *Barry Robinson* and *Todd Schulz;* pilots in command, *Brian Kindrat*, *Andrew Brice*, *Michael Torris*, *Brook Mueller, Andrew Wilkes, Jenelle Newman* and *Joel Zimmer*; and the co-pilots, *Michael Benson*, *Matt Burrus*, *John Proppe*, *Mitchell Donst*, and *Trevor Black*. The staff performed very well as a team. The support of the WMI corporate head office in Fargo, North Dakota is also acknowledged, specifically, the efforts of *Erin Fischer*, *Jake Van Ornum*, *Cindy Dobbs*, *Neil Brackin*, *James Sweeney, Randy Jenson*, *Dennis Afseth*, *Bruce Boe*, *Mike Clancy, Mark Grove,* and *Robin Tinnie* are greatly appreciated.

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1. INTRODUCTION

Hail has long been a problem for both agriculture and municipalities in the Province of Alberta. Fig. 1 shows the average number of hail days throughout Canada. It is notable that there is a bullseye 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. Though never "operational", the program continued to research the hail problem and ways to reduce the hail impact on agriculture until 1985, when it was discontinued.

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.

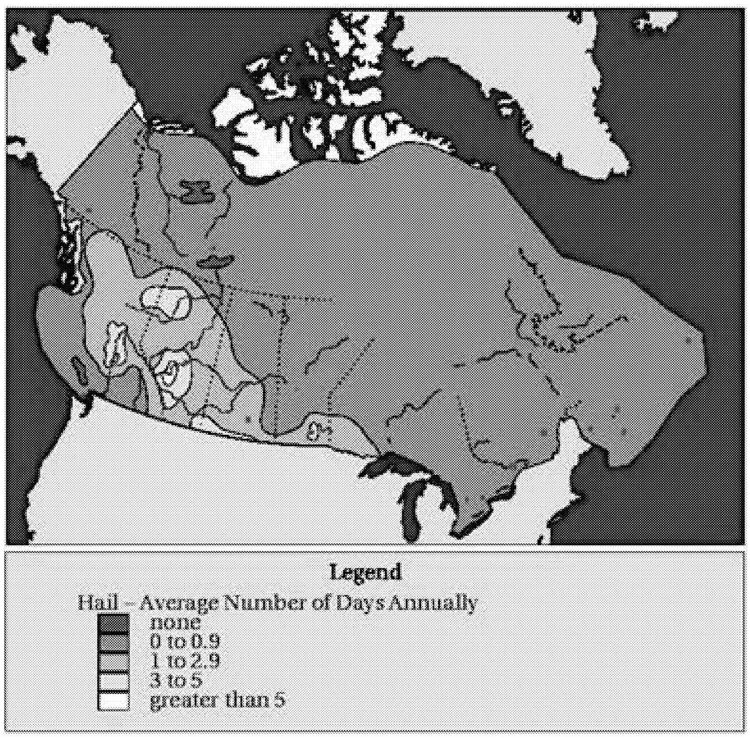


Fig. 1. The hail climatology of Canada, from Etkin and Brun (1999). The average number of hail days per year, based on the 1951-1980 climate normal of Environment Canada (1987).

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 utilizing cloud seeding, but 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.

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

The goal of the project from the beginning has been the protection of urban property from the ravages of hailstorms 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 attention. 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. Two aircraft were based in

Calgary, a third in Red Deer. At the conclusion of the initial five-year period the contract between the ASWMS and WMI was renewed for a second 5-year period (2001-2005), a third (2006-2010), in 2011, a fourth (2011-2015), and in 2016, a fifth (2016-2020). The 2018 season marked the 23rd consecutive season of operations.

Eight significant changes have been made to the project scope during the first twenty-two 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 been scheduled to begin each season on June 1.

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

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 the aging weather radar with a new set built by WMI. This radar possessed significantly increased sensitivity which meant that clouds could be detected sooner than they were previously (earlier in cloud development), and Doppler capability meant that internal storm motions could also be observed.

Fig. 2. This nocturnal image was captured in the late evening of July 20th. The in-cloud lighting is provided by lightning, silhouetting the aircraft wingtip. In such circumstances, lightning (at a distance from the aircraft) can be helpful. (WMI photograph by Trevor Black.)

In 2012, midway through the 17th season, the two aircraft that were based at the Calgary International Airport were permanently relocated to the Springbank Airport. The Calgary International Airport was experiencing increasing commercial flight operations, so the airport decided to put new, aircraft-arrival scheduling procedures in place. These scheduling procedures would have significantly impaired Hailstop flight operations, so the two project aircraft were moved to the Springbank Airport near Cochrane, west of Calgary.

The sixth change was implemented in 2013, with the addition of the fifth aircraft to the project, another King Air, based at the Springbank Airport.

The seventh significant change occurred in 2014, with the replacement of the 2011 Doppler radar with an even-newer Doppler weather radar. This newest Doppler weather radar was installed in May, prior to the 2014 project start. Improvements, in addition to the new transmitter and receiver, included a new antenna pedestal. The pedestal precisely rotates and elevates the radar antenna. This new radar system was developed and is supported by Advanced Radar Corporation (ARC), of Boulder, Colorado. During 2012 and 2013 there had been pedestal drive failures that had to be repaired "on the fly", while operations were imminent. Though operations those seasons were not compromised, the upgrade included the new pedestal in part to avoid any further gear failures. Improvements realized from the radar included implementation of the latest version of the TITAN radar software, state-of-the-science radar antenna control, and improved data processing. The last allowed the time required for each volume scan to be decreased from five to less than four minutes, which means the radar now updates 15 times per hour, rather than 12. In addition, the porting of real-time data to the WMI website was also improved.

The most recent and eight significant modification to the program occurred in 2016, when the northern border of the protected area was pushed north a short distance to include Ponoka in the protected area. Ponoka had previously been in the buffer area, and this modification allows inclusion of that community as well.

This final operations report summarizes, in detail, all the activities during the 2018 field operations of the Alberta Hail Suppression Project, the twenty-third summer of operations.

Fig. 3. On June 4th a double-rainbow was captured southeast of the Operations Centre at the Olds-Didsbury Airport in the wake of a cluster of northeast-moving thundershowers. (WMI photograph by Daniel Gilbert.)

2. THE 2018 FIELD PROGRAM

The project conducted operations to mitigate hail storms threatening cities and towns from June 1st through September 15th, 2018. Only those storms posing hail threats to an urban area were treated by the project aircraft. The project target area covers the region from High River in the south to Ponoka in the north, with priority given to the two largest cities, Calgary and Red Deer.

The program utilizes the latest cloud seeding technology available, incorporating several notable improvements over previous projects in the province. These improvements include:

- Fast-acting, high-yield mixtures for the glaciogenic cloud seeding flares and the liquid seeding solution. The flares are manufactured by Ice Crystal Engineering (ICE) of Kindred, North Dakota. The new generation ICE pyrotechnics produce $>10^{11}$ ice nuclei per gram of seeding agent, active at a temperature of -4°C, and produce between 10^{13} and 10^{14} ice nuclei per gram of pyrotechnic active between cloud temperatures of -6°C and -10°C. Colorado State University (CSU) isothermal cloud chamber tests (DeMott 1999) indicate that at a temperature of -6.3°C, 63% of the nuclei are active in <1 min, and 90% are active within 68 seconds. This high-yield, fast-acting agent is important for hail suppression since the time window of opportunity for successful intervention of the hail growth process may be less than 10 minutes for each maturing cloud turret.
- Use of the latest GPS tracking and advanced TITAN (Thunderstorm Identification Tracking Analysis and Nowcasting) computer software to accurately display the aircraft locations on the radar displays to improve the controlling of aircraft and facilitate the direction of seeding operations to the most critical regions of the storms.
- Injection of the seeding material directly into the developing "feeder" cloud turrets as the most frequent seeding method.
- Use of experienced meteorologists and pilots to direct and conduct the seeding operations.
- Sensitive, state-of-the-science Doppler weather radar.

Five aircraft specially equipped to dispense the seeding agents were utilized. Three aircraft, two Beech King Air C90s and one Cessna 340 (C340), were based at the Springbank Airport west of Calgary. Two additional aircraft, one Beechcraft King Air C90 and one C340, were based at the Red Deer Regional Airport near Red Deer. The radar remained located at the Olds-Didsbury airport. The radar coordinates are 51.71° N latitude, 114.11° W longitude, with a station elevation of 1,024 m above sea level. The WMO station identifier is 71359, and the ICAO identifier is CEA3. The protected project area dimension is approximately 242 km (N-S) by 97 km (E-W), 23,474 km^2.

3. PROJECT OBJECTIVES

The project has two main objectives:

- To conduct cloud seeding operations to suppress hail and reduce property damage, and
- To develop a data archive that may eventually be used for the scientific assessment of the program's effectiveness.

The first of these objectives is to utilize the five aircraft and experienced personnel to recognize potential threats and react appropriately. The second is being achieved through the operation of a C-band Doppler weather radar with full archival, and the collection of other weather information by project meteorologists. These efforts include the comprehensive archival of all project decision records, as well as a wealth of additional weather data from the internet and other sources.

The project operations area is illustrated in Fig. 4. The boundaries of flight operations (actual seeding) are indicated by the broad yellow line, which actually includes the foothills of the Rocky Mountains, west of the protected area. This "buffer" area is very important, for the foothills are an important zone for storm genesis. The broad green line denotes the boundary of the protected area, i.e., storms threatening any of the communities within this area will be seeded, as resources allow, with priority assigned according to population.

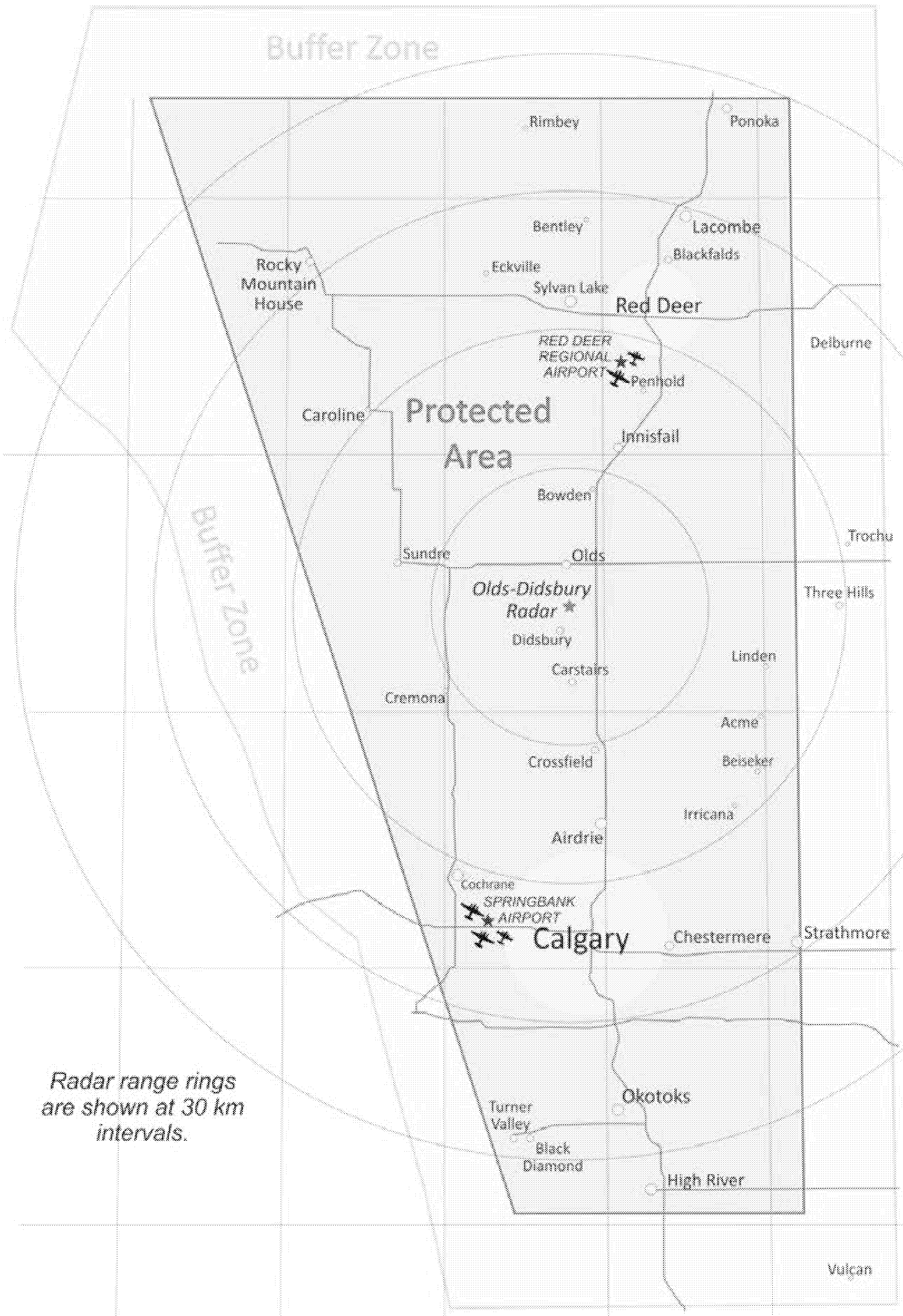


Fig. 4. A map of southern Alberta showing the project protected area. The major cities and towns in and near the protected area are shown, along with the location of the Olds-Didsbury Operations Centre (red star). Aircraft bases are shown by aircraft symbols.

4. PRIORITIES

Cities and towns are protected according to priority and proximity of aircraft, with greatest attention given to Calgary and Red Deer. Priority is determined based on rank in population, as shown in Table 1, below. Most storms are not seeded after they cross the QE II highway, except for storms east of Airdrie and Calgary that might threaten Strathmore. Since the project start in 1996 urban population growth within the protected area has increased by 74.2%.

AHSP Priority List Based on City Population

Priority	City/Town Name	Population		Change Since Project Start (1996)	
		1996	2017	Percentage	More People
1	Calgary	767,059	1,246,337	62.5%	479,278
2	Red Deer	59,834	100,418	67.8%	40,584
3	Airdrie	14,506	64,922	347.6%	50,416
4	Okotoks	7,789	28,881	270.8%	21,092
5	Cochrane	6,612	26,320	298.1%	19,708
6	Chestermere	1,603	20,331	1168.3%	18,728
7	Sylvan Lake	4,815	14,816	207.7%	10,001
8	Strathmore	5,273	13,756	160.9%	8,483
9	High River	6,893	13,584	87.4%	6,027
10	Lacombe	7,580	13,057	67.9%	5,148
11	Blackfalds	1,769	9,916	460.5%	8,147
12	Olds	5,542	9,184	55.5%	3,075
13	Innisfail	6,064	7,847	29.4%	1,783
14	Ponoka	5,861	7,229	14.2%	899
15	Rocky Mountain House	5,684	6,635	16.7%	1,616
16	Didsbury	3,399	5,268	45.8%	1,558
17	Turner Valley & Black Diamond	3,269	5,259	38.9%	1,271
18	Carstairs	1,796	4,077	91.6%	1,646
19	Penhold	1,609	3,277	76.6%	1,233
20	Crossfield	1,800	3,055	62.1%	1,118
21	Sundre	2,027	2,729	33.0%	668
22	Bowden	936	1,240	32.6%	305
23	Irricana	822	1,216	41.4%	340
24	Eckville	899	1,125	25.1%	226
25	Bentley	930	1,078	20.6%	192
26	Linden	563	828	28.8%	162
27	Beiseker	640	819	22.7%	145
28	Acme	590	653	10.7%	63
29	Caroline	452	512	10.8%	49
30	Cremona	393	444	16.3%	64
	Total Urban Population in Area	927,009	1,614,813	74.2%	684,025

Table 1. AHSP Priority List Based on City Population.

5. THE SCIENTIFIC BASIS FOR HAIL SUPPRESSION

Hail is formed when small ice particles are held aloft by strong thunderstorm updrafts within regions of unfrozen supercooled cloud water. This supercooled cloud water is collected by these "hail embryos" and freezes to them, resulting in growth to hail (greater than 5 mm diameter) sizes. Growth continues until (1) the supporting storm updraft weakens, (2) the in-storm motion of the growing hailstone moves it to the downdraft side from whence it can fall, or (3) the hailstone grows so large that the updraft can no longer support it.

In most situations the subcloud layer is relatively warm (much warmer than 0°C) so hailstones begin to melt during the final portion of their plummet to earth, but in many cases the hailstones are too large for melting to be complete, and hail reaches the ground.

5.1 THE FORMATION OF HAIL

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. Foote 1984, Krauss and Marwitz 1984). The computation of hail growth trajectories within the context of measured storm wind fields provided a powerful new tool for integrating certain parts of hail growth theories, and illustrated a striking complexity in the hail growth process.

Fig. 5. Light precipitation—likely snow pellets or rain—falls from a high-based shower near Olds on August 30th. The apparent color of convective precipitation depends mostly upon lighting, not phase (whether or not the precipitation is water or ice). (WMI photograph by Brad Waller.)

Some of this complexity is reviewed in the paper of Foote (1985) that classifies a broad spectrum of storm types according to both dynamic and microphysical processes thought to be critical to hail production.

Hail embryo sources identified by Foote (1985) include the following:

- Embryos from first-ice in a time-developing updraft
- Embryos from first-ice in the core of a long-lived updraft
- Embryos from flanking cumulus congestus
- Embryos from a merging mature cell
- Embryos from a mature cell positioned upwind
- Embryos from the edges of the main updraft
- Embryos created by melting and shedding
- Embryos from entrainment of stratiform cloud
- Embryos from embedded small-scale updrafts and downdrafts
- Recirculation of embryos that have made a first pass through the updraft core

Hail embryos grow into hailstones by collecting unfrozen, supercooled liquid water through collisions. This water freezes to the already-frozen embryo, increasing the size, weight, and fall speed, and also the potential for damage at the surface. This growth to large hail is theorized to occur primarily along the edges of the main storm updraft where the merging feeder clouds interact with the main storm updraft (WMO 1995). However, the mature hailstorm most certainly consists of complicated airflow patterns and particle trajectories.

Studies of the internal structure of large hailstones in Alberta and elsewhere have shown that hailstones can have either a graupel (snow pellet) embryo or a frozen-drop embryo. The different hail embryos indicate different growth histories and trajectories, and illustrate the complexity within hailstorms.

Fig. 6. Hailstop 4 sits on the ramp at sunset on July 6th, just after landing from a seeding mission that ranged from Olds, to Sundre, and then northeast toward Red Deer. Careful examination reveals the remnants of expended burn-in-place flares, still attached to the left wing rack. (WMI photograph by Trevor Black.)

5.2 HAIL SUPPRESSION CONCEPTS

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 in the -5 to -10°C zone 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.

The AHSP seeding methodology modifies the graupel embryo hail development process. Frozen-drop hail embryos are thought to originate from secondary sources (shedding from large existing hailstones, or via recirculation processes at the edge of the main updraft). Cloud seeding can only reduce the hail that grows from frozen drop embryos if the liquid water available for hail growth is reduced, or if the dynamics of the storm can be affected to eliminate the recirculation processes that formed the drop embryo in the first place. Both are extremely complex, and exploring them is not the primary focus of the Alberta project.

Fig. 7. On June 29th Hailstop 2, Hailstop 1, and Hailstop 5 (left to right) bask in the morning sun, prior to the development of afternoon thunderstorms that moved over Airdrie and Calgary. Hailstop 1 and Hailstop 2 both flew on the CDC +2 day. (WMI photograph by Andrew Wilkes.)

The governing premise of the Alberta cloud seeding operations is the cloud microphysical concept called beneficial competition. The premise of beneficial competition is that the well-documented natural deficiency of ice nuclei (ice-forming particles) in the atmosphere can be corrected by the release of additional ice nuclei (glaciogenic seeding material) into developing storm clouds. This is done by the combustion of small amounts of reagent and/or solutions containing silver iodide (AgI), either as pyrotechnics (flares) or from wing-borne solution-burning ice nucleus generators (Fig. 8) With either method, from 10^{13} to 10^{14} (or from 10,000,000,000,000 to

100,000,000,000,000) ice nuclei are produced for each gram of seeding agent burned. This potentially increases greatly the number of precipitation embryos in the cloud.

These natural and human-induced ice crystals, many of which become precipitation, then "compete" for the available supercooled liquid cloud water within the storm. Because the total amount of supercooled liquid remains essentially unchanged, that same mass is divided among the increased number of embryos, meaning the final maximum size of each individual ice particle is significantly decreased. Hence, the hailstones that form within seeded clouds will be smaller and produce less damage if they survive (don't melt during) the fall to the surface. If they are sufficiently small, they will melt completely in the warmer subcloud layer and reach the ground as rain.

Cloud seeding alters the microphysics of the treated clouds, assuming that the existing precipitation process is inefficient due to a lack of natural ice nuclei. This deficiency of natural ice has been documented in the new growth zone of Alberta storms (Krauss 1981). Cloud seeding does not alter directly the energy or dynamics of the storm. Any alteration of the storm dynamics that does occur results as a consequence of the increased ice crystal concentrations and the development of additional precipitation-size ice particles earlier in the cloud's lifetime.

Fig. 8. A mid-season thunderstorm brings rain and threatens hail on the late afternoon of July 19th, while Hailstop 2 seeds with wing-tip ice nucleus generators and burn-in-place flares at cloud base, southwest of Innisfail. (WMI photograph by Matt Burrus.)

Because the mature hailstorm consists of complex airflows and precipitation trajectories, cloud seeding does not affect all hail embryo sources. It does, however, modify the primary hail formation process. In other words; the cloud seeding cannot eliminate all of the hail, but can reduce the size, amount, and the extent of the area affected by hail.

A schematic diagram of the conceptual storm model showing the hail origins and growth processes within a hailstorm is shown in Fig. 9. The cloud seeding methodology applied to the new growth zone of the storm is illustrated. As mentioned previously, cloud seeding cannot prevent or completely eliminate the occurrence of damaging hail. We presently do not have the ability to predict with any certainty exactly the amounts and sizes of hail that would occur if cloud seeding did not take place. Therefore, we do not have the ability to predict or determine by measurements with confidence the net effect of the seeding. The new growth zones of potential hailstorms are seeded, and the amounts and types of precipitation at the surface are observed, as well as the radar reflectivity characteristics of the storm before, during, and after seeding.

It is anticipated that the successful application of the technology will yield a decrease of damaging hail by approximately 50% from what would have occurred if seeding had not taken place.

This expectation is consistent with the results reported in North Dakota (Smith *et al.* 1997) and in Greece (Rudolph *et al.* 1994). The decrease in hail can only be measured as an average over time (e.g. 5 years or more) within the operations area, and then compared with the historical values for the same area. Because of these uncertainties, the evaluation of any hail mitigation program requires a statistical analysis. The characteristics of both seeded and unseeded storms vary considerably, such that any storm trait can be found in either category.

A meaningful evaluation of the project might be feasible if insurance loss data for hailstorms was made available. However, such data are considered proprietary and this presents obstacles to analyses. (This kind of evaluation is mentioned further in the recommendations at the conclusion of this report.) An additional complicating factor is that hail, by itself, is not always differentiated as the cause of the insured damage, e.g., a window might be broken by hail, high winds, or by surface-based debris borne by the high winds, and to the insurance adjuster it makes little difference; storm damage has occurred.

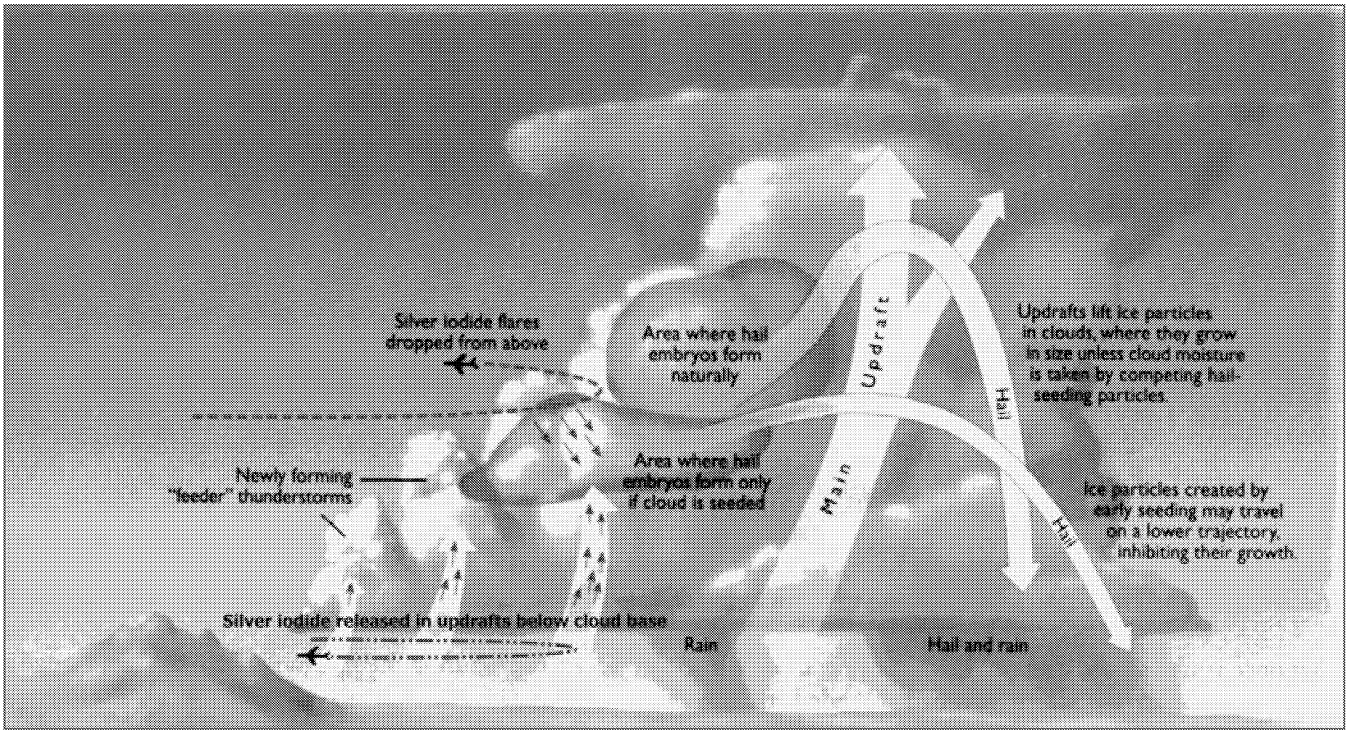


Fig. 9. Conceptual model for hail suppression is illustrated graphically, as adapted from WMO (1995). This schematic shows generalized cloud seeding locations at cloud base and at cloud tops, as employed for mature multi-cellular thunderstorms. (Modified from an original graphic prepared by Canadian Geographic.)

5.3 EFFECTS OF HAIL SUPPRESSION EFFORTS ON RAINFALL

A common question about cloud seeding concerns the effect on the rainfall. The effects of seeding to mitigate hail damage on storm rainfall are not dramatic, but slightly positive. The target area specifically, and Alberta as a whole, lack the high density time-resolved precipitation measurements necessary to provide a scientifically-meaningful rainfall analysis. However, evaluation of another long-term hail suppression program in neighboring North Dakota that does have such a precipitation network found that rainfall is increased about 5 to 10 percent compared to that from similar unseeded clouds (Johnson 1985). Since methodology, seasons, and seeding agents are the same, and since the storms themselves are very similar, it is reasonable to believe that effects in rainfall in Alberta are similar. All this is wholly consistent with the concept that the number of precipitation embryos is increased by glaciogenic seeding.

There is a common yet quite false belief that thunderstorms operate at near 100% efficiency in producing rainfall. This is not logical, for 100% efficiency would require that all moisture processed by a storm would fall to the ground; no cloud, even, could remain. This is far from the case. There have been numerous studies of the fluxes of air and water vapor through convective clouds; these are summarized in Fig. 10.

Precipitation efficiencies can vary widely from as little as 2% for storms studied by Marwitz (1972) and Dennis *et al.* (1970) to near 100% for a select few. Marwitz (1972d) and Foote and Fankhauser (1973) show that in the case of High Plains storms there is an inverse relation between the precipitation efficiency and the environmental wind shear in the cloud-bearing layer. [Wind shear is the change in wind speed and direction at various altitudes.] The least efficient storms tend to be supercell hailstorms; the highly efficient storms tend not to produce hail at all. The average wind shear on hail days in Alberta is approximately 2.5 x 10^{-3} sec^{-1}. This average shear value corresponds to an average precipitation efficiency of approximately 50% (see again Fig. 10). For reasons previously stated, it logically follows that the production of large, damaging hail is largely a result of natural storm inefficiency.

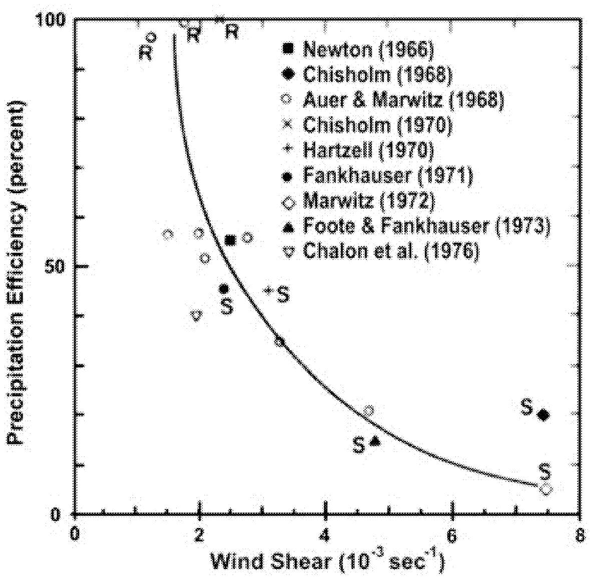


Fig. 10. Precipitation efficiency for High Plains thunderstorms, from Browning (1977). Known supercells are labeled "S". Storms that produced only rain are labeled "R". (Copyright American Meteorological Society, Boston, MA, used by permission.)

Krauss and Santos (2004) performed an exploratory analysis of the project volume-scan C-band radar data, using the TITAN storm tracking software, to obtain radar-derived rainfall 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) had greater mean durations (+50%), greater mean precipitation fluxes (+29%) and had greater mean total area–time integral of precipitation (+54%). There was statistical evidence to support the claim that seeding caused an increase in rainfall. The seeding effect was 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 was approximately 12% which agrees well with the results from North Dakota.

The introduction of more precipitation embryos through seeding earlier in a cloud's lifetime is generally highly advantageous, reducing the amount and size of any hail, and making the cloud more efficient as a rain producer in the process. Seeding a hailstorm means that less water is lost via the entrainment of dry environmental air through the sides and top of the cloud, or lost by ice crystals vented through the cloud anvil at high altitudes.

6. THE OPERATIONS PLAN

6.1 IDENTIFICATION OF HAIL-PRODUCING STORMS

The height of the 45 dBZ contour (a radar echo-intensity level) was a criterion tested in a Swiss hail suppression program. The Swiss research found that all hailstorms had 45 dBZ contours above the altitude of the -5°C temperature level (Waldvogel *et al.* 1979). There was a False Alarm Rate (FAR) of 50%, largely because some strong rainstorms also met the criterion. However, it is much preferable to assume that a heavy rainstorm is going to produce hail than to mistakenly believe that a hailstorm is only going to produce heavy rain. Studies of Alberta hailstorms also indicated that 50% of all Alberta hail storms had a maximum radar reflectivity greater than 45 dBZ, above the -5°C level (Humphries *et al.* 1987). The Russian criteria for hail identification stated that the height of the 45 dBZ contour had to exceed the height of the 0°C isotherm by more than 2 km (Abshaev 1999). Similarly, the criteria used by the National Hail Research Experiment in the USA (1972-1974) for a declared hail day was defined by radar maximum reflectivity greater than 45 dBZ above the -5°C level (Foote and Knight 1979). Our experience suggests that the Swiss/Alberta/Russian/USA criterion is reasonable (Makitov 1999). The physical reasoning behind it is simply that radar reflectivity (≥45 dBZ) implies that significant supercooled liquid water exists at temperatures cold enough for large hail growth.

In Alberta, the TITAN cell identification algorithm in 2015 was set to track any cell having more than 10 km^3 of 45 dBZ reflectivity, extending above 3.5 km altitude (MSL). In all previous seasons the reflectivity threshold had been 40 dBZ, to be "safe", absolutely certain that every cell having even a slight chance of producing hail would be recognized by the radar-processing software as such. The drawback to this was that many, many cells not realistically having much potential for hail were being flagged. With the latest radar upgrade, however, the project radar now has a more sensitive receiver, shorter pulse length, and other radar processing improvements, such that ASWMS Project Manager Dr. Terry Krauss became confident that the 45 dBZ threshold could be used. This decision has been supported by our observations since 2015. As such, each such cell tracked by TITAN is then considered to be a potential hail cell; therefore, this represents our seeding criterion. A storm is a candidate for immediate seeding if the storm cell within the project boundary (as identified by TITAN with the criteria above) is moving towards and is expected to reach a protected town or city.

The impact of this change on the project was immediate and very helpful. Shallow stratiform rains were no longer identified as TITAN cells. Also, when larger mesoscale convective systems developed, the updated reflectivity criterion resulted in far fewer immense, sprawling and complex TITAN cells. In previous seasons it was common to be tracking three or more cells, only to see TITAN merge them into one very large, convoluted entity as their developing anvils merged. Because the cells remain separate longer, this is a significant plus for post-analysis, concentrating on the radar reflectivity volumes associated with hail. That rain showers are no longer identified as cells is not operationally significant.

6.2 ONSET OF SEEDING

In order for cloud seeding to be successful, it is the goal of the program to seed (inject ice nucleating agents into) the developing "new growth" cloud towers of potential hail-producing storms at least 20 minutes before the storm cell moves over a town or city within the target zone. For the Alberta project, the principal targets are the towns and cities within the project area (Table 1). Since 20 minutes is the minimum time reasonably expected for the seeding material to nucleate, and have the seeded ice crystals grow to sufficient size to compete for the available supercooled liquid water (and yield positive results), a 30 minute or greater lead time is generally thought to be advisable.

Fig. 11. Hailstop 3 flies among developing cloud turrets while approaching a storm at 2:21 PM MDT on July 1st, 2018, northeast of Calgary. (WMI photograph by Trevor Black.)

6.3 CLOUD SEEDING METHODOLOGY

Meteorologists at the Operations Centre are responsible for initiating cloud seeding and patrol flights, alerting air crews of the presence of developing weather sufficiently in advance that aircraft will be ready for immediate flight when that time comes, in accordance with operational protocols. The meteorologists advise the Hailstop aircraft when to takeoff, and guide them to the storms of concern. Patrol flights are often launched before clouds within the target area meet the radar reflectivity seeding criteria, especially over or near the cities of Calgary and Red Deer.

These patrol flights ensure a quicker response to developing cells. In general, a patrol flight is launched in the event of visual reports of vigorous towering cumulus clouds, or when radar cell tops exceed 25 kft (7.6 km) height over the higher terrain in the western part of the operations area, especially on those days when the forecast calls for damaging hailstorms.

Launches of additional aircraft are determined by the number and spacing of storms and the flight time required for each seeding aircraft to reach the desired location and altitude. Overlap of coverage (airspace) and on-station time are also considered. In general, to avoid even the possibility of collisions, and to comply with air traffic control (ATC) rules, only one aircraft can work safely at cloud top for each active thunderstorm complex. If multiple storms develop that are sufficiently spaced, more than one aircraft can work at cloud top simultaneously. Horizontal separation must be sufficient to ensure there is no chance of either aircraft impinging on the other's assigned airspace. [Cloud top seeding is always done under instrument flight rules (IFR), so separation is required by regulation as well as for safety.]

When the storm clouds of interest are relatively small (especially common when storms first develop), there is often room only for one seeding aircraft to operate beneath the rain free cloud base as well. However, when storms are larger and visibility is good, multiple aircraft can often be used safely at cloud base on the same complex. This is possible because flight operations below cloud base are usually conducted under visual flight rules (VFR) and thus out of cloud, so separation of aircraft can be ensured visually. To accomplish this, all cloud-base seeding aircraft must be constantly aware of each other's locations. In addition, a landing light may be turned on to aid spotting by other Hailstop aircraft. Responsibility for safe separation of aircraft is not a responsibility of the project meteorologists, though they can usually monitor the relative positions in real-time through the *AirLink* tracking system. Rather, the flight crews have this responsibility. Multiple aircraft are most often used on the same storm when the storms assume a linear structure and develop new growth (towering cumulus) along the leading edge of the line. The project utilizes five aircraft to provide uninterrupted seeding coverage (at either cloud-base or cloud-top) and/or to seed multiple storms simultaneously, if required.

Factors that determine which seeding strategy is used (cloud top or cloud base seeding) include: storm structure, visibility, cloud base height, and/or time necessary for Hailstop aircraft to reach seeding altitude. 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 multi cell storms (squall lines). Care is taken not to seed the strong updrafts of mature storms, for such clouds are too advanced in their development and hail development, if it has occurred, is too far advanced to be averted, and the seeding material would most likely be swept upward into the storm anvil without providing "beneficial competition" to the developing hail zone.

6.4 SEEDING PROCEDURES

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 small pyrotechnics, comprised of 20 grams of seeding agent, which are ejected 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 (Fig. 12).

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 flight is determined by the location of any more mature, adjacent cells, which cannot be safely penetrated.

When the growing cells of interest are embedded within surrounding cloud, and also with most nocturnal convective complexes, there are no clearly defined feeder turrets visible to the flight crews. Seeding aircraft can use their on-board weather radars to help position themselves in these cases; however, aircraft radars are designed for weather avoidance, not for the detection of non-precipitating clouds, and so "see" only mature cells, those beyond the growth stage where seeding can be effective. In these instances, seeding aircraft will skim the storm edge at altitudes between -5°C and -10°C, near the region of tightest radar reflectivity gradient.

At cloud top, seeding is done primarily by ejecting multiple 20-gram flares into cloud elements when updrafts and liquid water are encountered. A burn-in-place flare may be ignited also, especially when turrets are closely spaced and seedable cloud volumes are frequently encountered. Nocturnal seeding may also be performed from below the cloud base altitude when visibility is sufficient.

An idea of what night seeding is like is provided by Fig. 13. Lightning can often help provide illumination at the cloud base and at cloud top, but such illumination is irregular, very brief, and by nature, "flat", meaning that human eyes struggle to perceive much depth and distance perception. Nevertheless, lightning does help in conducting nocturnal operations. On occasion, additional illumination may be provided by moonlight, especially if the upper reaches of the storm anvil do not shadow the developing turrets. In any case, the seedable clouds are those that have not yet produced precipitation, and therefore those devoid of radar echoes.

For safety reasons flight operations require aircraft to avoid heavily-electrified regions, and also close proximity to known hail and hail aloft, as indicated by the project radar. Wind shear and terrain clearance pose additional hazards. Though operations after dark are infrequent in Alberta because of the long summer days and lingering twilight hours, seeding operations are conducted whenever storms develop, even in the wee hours of the morning. Typically, this happens only a few times each season.

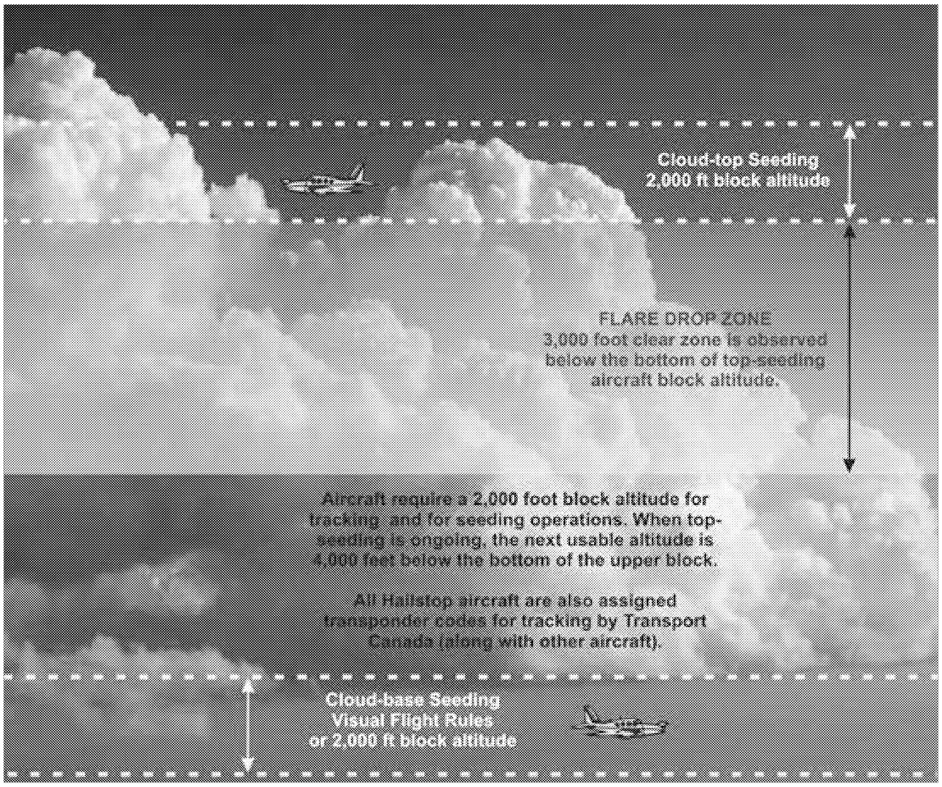


Fig. 12. Separation of aircraft by altitude. This diagram illustrates how vertical separation of cloud-base and seeding aircraft is achieved. (WMI graphic.)

6.5 CESSATION OF SEEDING

If the radar reflectivity criteria continue to be met, seeding of all cells still threatening to damage towns or cities is continued. However, seeding is effective only within cloud updrafts and in the presence of supercooled cloud water, i.e. the developing stage in the evolution of the thunderstorm. The mature and dissipating stages of a storm cannot be effectively seeded because seeding only works by enhancing ice development in clouds that are primarily ice-free, a characteristic only manifested in developing cloud turrets. Storm complexes having no new development are destined for decay. While a few storms simply develop, mature, and decay without initiating secondary development, those that have the potential to produce hail almost always produce cool outflows that initiate more new growth adjacent to the mature and dissipating portions of the storm. This new growth extends storm life and is seedable, so aircraft must operate in some proximity to mature, electrified clouds and dangerous wind shears, which include violent up- and downdrafts. Safety thus becomes of paramount importance. The history of aviation is filled with accounts of aircraft destroyed by thunder-storms, and the potential today is just as real as ever.

Safety of project aircraft and crews is ensured by strict adherence to flight policies that are designed to keep aircraft from ever entering mature portions of the storms and from flying into extreme winds, hail, or electrically-active regions.

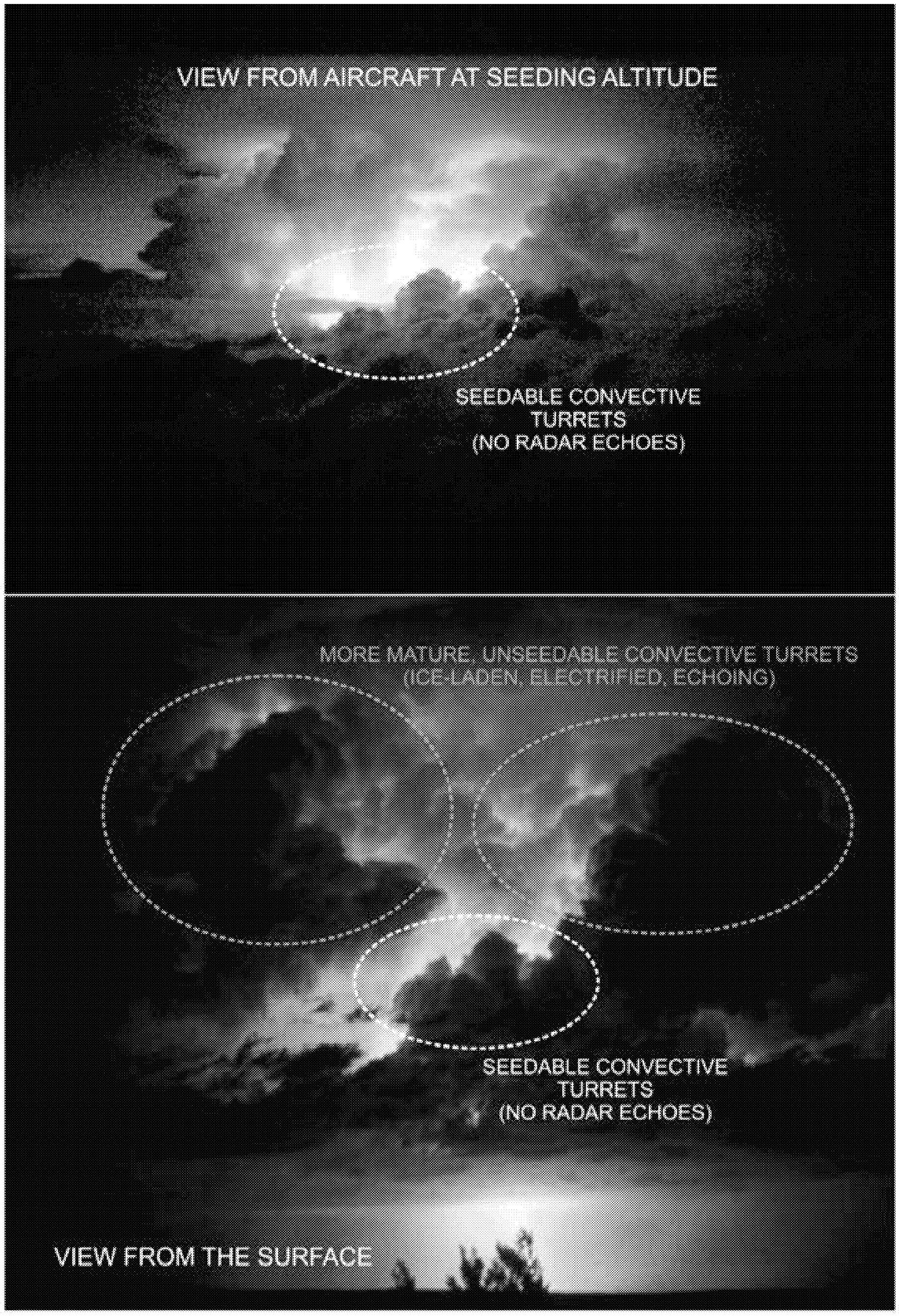


Fig. 13. Nocturnal lightning, as viewed from the air (top) and the ground (bottom).

Strong radar reflectivity can only persist when new cloud development continues; when it doesn't, decay is inevitable. Thus, when storms maintain their intensities, developing cloud regions must exist, even though it is sometimes hard to find them. Such mature storm complexes are seedable only when the developing clouds are accessible to the seeding aircraft. If they are embedded within the mature clouds, hidden by decaying clouds, and cannot be approached from below (cloud base), seeding cannot safely occur. Storm cells being tracked by radar are not seeded if there are no indications of developing updraft or supercooled liquid water, or when the storm does not threaten a town or city.

6.6 SEEDING RATES

The seeding agent is dispensed in three ways: (1) a silver-iodide seeding solution can be burned from wing-tip-borne ice nucleus generators, (2) pyrotechnics can be burned "in place", while held in special racks affixed to the trailing edges of the aircraft wings, and (3) small pyrotechnics can be ignited and ejected into cloud tops from racks mounted on the belly of the aircraft fuselage.

A seeding rate of one 20 gram flare every 5 sec while in supercooled updraft is typically used during cloud penetrations. A higher rate is used (*i.e*. 1 flare every 2 to 3 sec) if updrafts are very strong (i.e. greater than 2000 ft/min) or if the storm is particularly intense. Repeated cloud seeding passes in the same region are immediately warranted if there are visual signs of continued new cloud growth or if the radar reflectivity gradient of the parent cell remains tight (indicative of continued growth and persistent updrafts). If not, a 5 to 10 min waiting period may be used between penetrations, to allow the seeding to take effect and for visual signs of glaciation to appear, or for radar reflectivities to decrease and gradients to weaken. Such waiting reduces the amount of seeding material used. Calculations show that the seeding rate of one flare every 5 sec will produce >1300 ice crystals per litre averaged over the plume, within 2.5 min. This is more than sufficient to deplete the liquid water content produced by updrafts up to 10 m s^{-1} (2000 ft min^{-1}), thereby preventing the growth of hailstones within the seeded cloud volumes (Cooper and Marwitz 1980).

For effective hail suppression, sufficient dispersion of the particles from consecutive flares is required for the seeding plume to overlap by the time the cloud particles reach hail size. The work by Grandia *et al.* (1979), based on turbulence measurements within Alberta feeder clouds, indicated that the time for the diameter of the diffusing line of ice nuclei to reach the integral length scale (200 m) in the inertial subrange size scales of mixing, is 140 seconds. This is insufficient time for ice particles to grow to hail size, therefore, dropping flares at 5 sec intervals (assuming a true airspeed of 80 m s^{-1}) should provide sufficient nuclei and allow adequate dispersion to effectively deplete the supercooled liquid water and reduce the growth of hail particles. The use of the 20 gram flares and a frequent drop rate provides better seeding coverage than using larger flares with greater time/distance spacing between flare drops. In fact, the above calculations are conservative when one considers that the centre of the ice crystal plume will have a greater concentration of ice crystals.

For cloud base seeding a seeding rate using two solution-burning generators or one burn-in-place flare is typically used, dependent on the updraft speed at the cloud base. For an updraft >500 ft min^{-1}, generators and consecutive flares per seeding run are typically used. Cloud seeding runs are repeated until inflow (updraft area) has diminished or until the storm of concern has passed all urban areas. Solution-burning ice nucleus generators are used to provide continuous silver iodide seeding if extensive regions of light or moderate updraft are found at cloud base in advance of the shelf cloud region. Base seeding is not conducted if only downdrafts are encountered at cloud base, since the seeding agent would not be ingested by the cloud.

6.7 SEEDING AGENTS

The cloud seeding pyrotechnics used by WMI are exclusively manufactured by Ice Crystal Engineering (ICE) of Kindred, North Dakota. The ejectable flares contain 20 grams of seeding material and burn for approximately 37 sec and fall approximately 2700 ft before burning up. The burn-in-place (ICE-BIP®) flares contain 150 grams of seeding material, and burn for approximately 4 min. Arrangements were made with Solution Blend Services, a Calgary-based company, to pre-mix all silver iodide seeding solution from reagent grade raw materials provided by WMI. All handling, mixing, storage, and labelling requirements established by law and regulation were fully satisfied.

The Cloud Simulation and Aerosol Laboratory (SimLab) at Colorado State University (CSU) has tested the ice nucleating ability of aerosols produced from cloud seeding flares and solutions for many years (Garvey 1975, DeMott 1999). [Note: The SimLab is now closed and no longer performs such tests; a new testing facility to conduct these standardized tests is not yet available.] The current ICE pyrotechnics were tested at CSU in 1999 as reported by DeMott (1999). Aerosols were collected and tested at nominal temperatures of -4, -6 and -10°C. At least two tests were done at each temperature, with greater emphasis placed on warmer temperatures. The cloud chamber liquid water content (LWC) was 1.5 g m^{-3} for most tests, but 0.5 g m^{-3} for some, enough to confirm the independence of nucleation rate upon cloud droplet concentration. The primary product of the laboratory characterization is the "effectiveness plot" for the ice nucleant which gives the number of ice crystals formed per gram of nucleant as a function of cloud temperature. Yields for the ICE flares at two cloud water contents (LWC) are shown in Fig. 14 and are tabulated in Table 2. The nucleation capabilities of the solution-burning ice nucleus generators are also shown in Fig. 14.

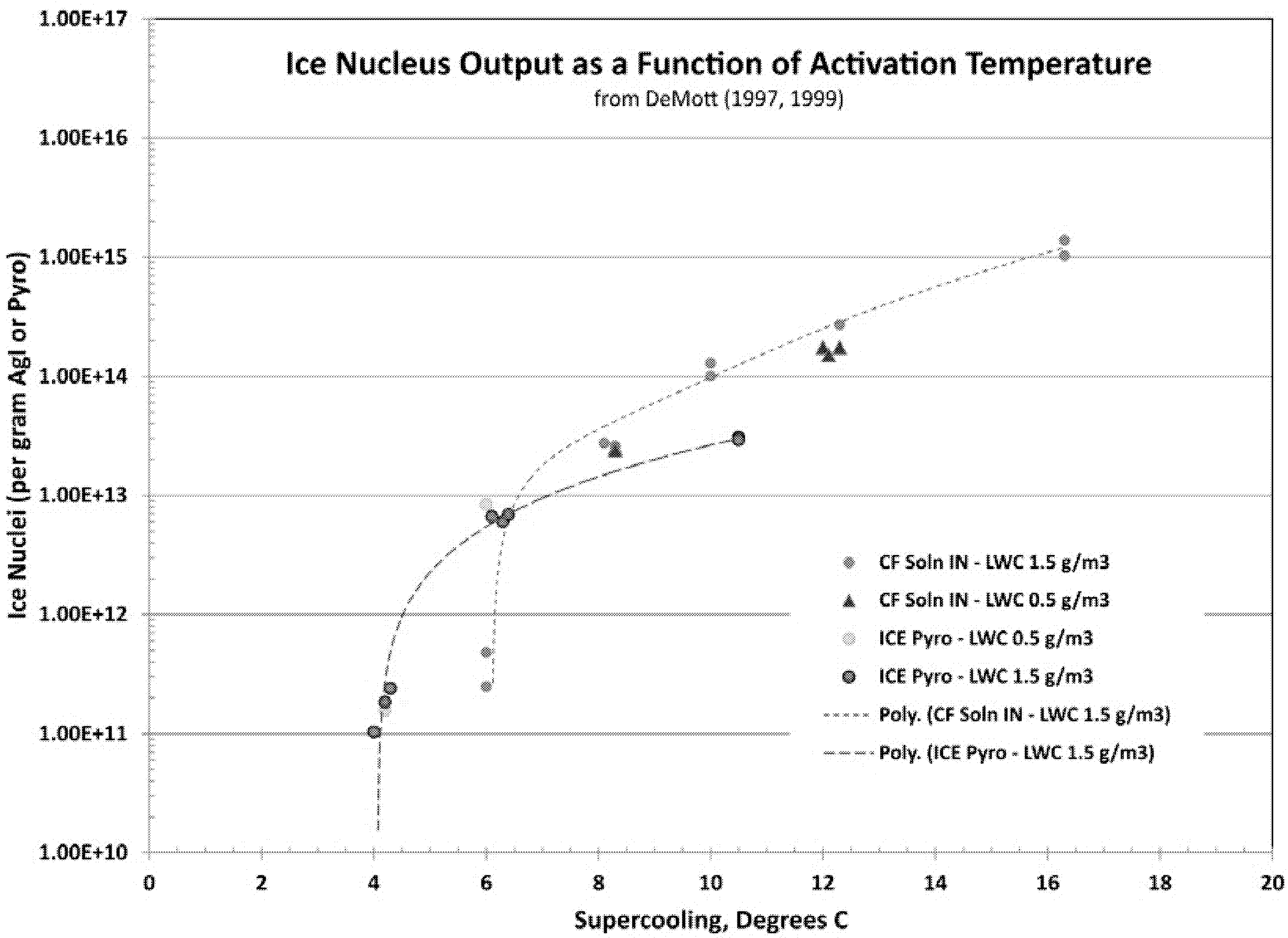


Fig. 14. Yield of ice crystals per gram of pyrotechnic as a function of supercooling (red curve, red and yellow data, DeMott 1999) and for the liquid solution burned in the wingtip ice nucleus generators, used at cloud base (blue curve, blue data, DeMott 1997).

Temp (°C)	LWC ($g\ m^{-3}$)	Raw Yield (g^{-1} AgI)	Corr. Yield (g^{-1} AgI)	Raw Yield (g^{-1} pyro)	Corr. Yield (g^{-1} pyro)	Yield (per pyro)
-3.8	1.5	3.72×10^{11}	3.87×10^{11}	4.01×10^{10}	4.18×10^{10}	8.36×10^{11}
-4.0	1.5	9.42×10^{11}	9.63×10^{11}	1.02×10^{11}	1.04×10^{11}	2.08×10^{12}
-4.2	1.5	1.66×10^{12}	1.70×10^{12}	1.80×10^{11}	1.84×10^{11}	3.67×10^{12}
-4.3	1.5	2.15×10^{12}	2.21×10^{12}	2.32×10^{11}	2.39×10^{11}	4.77×10^{12}
-6.1	1.5	6.01×10^{13}	6.13×10^{13}	6.49×10^{12}	6.62×10^{12}	1.32×10^{14}
-6.3	1.5	5.44×10^{13}	5.56×10^{13}	5.87×10^{12}	6.00×10^{12}	1.20×10^{14}
-6.4	1.5	6.22×10^{13}	6.34×10^{13}	6.72×10^{12}	6.85×10^{12}	1.37×10^{14}
-10.5	1.5	2.81×10^{14}	2.85×10^{14}	3.03×10^{13}	3.07×10^{13}	6.15×10^{14}
-10.5	1.5	2.34×10^{14}	2.37×10^{14}	2.87×10^{13}	2.91×10^{13}	5.81×10^{14}
-4.2	0.5	1.41×10^{12}	1.45×10^{12}	1.53×10^{11}	1.57×10^{11}	3.14×10^{12}
-6.0	0.5	7.42×10^{13}	7.73×10^{13}	8.01×10^{12}	8.34×10^{12}	1.67×10^{14}
-10.5	0.5	2.38×10^{14}	2.41×10^{14}	2.91×10^{13}	2.96×10^{13}	5.92×10^{14}

Table 2. Yield (per gram) of the ICE Glaciogenic Pyrotechnic (DeMott 1999).

Tests were also performed using the method of DeMott *et al.* (1983) to determine the characteristic times for effective ice nuclei activation; these are summarized in Fig. 15 and Table 3. The primary results of the CSU SimLab tests of the glaciogenic cloud seeding pyrotechnics manufactured by ICE are summarized as follows (from DeMott 1999):

- The aerosol particles produced by the new ICE pyrotechnics were highly efficient ice nucleating aerosols. Yield values were approximately 1×10^{12}, 5×10^{13} and 3×10^{14} ice crystals per gram pyrotechnic effective at -4, -6 and -10°C in 1.5 g m^{-3} clouds in the CSU isothermal cloud chamber. Improvement compared to the previous pyrotechnic formulation used by ICE was modest at -6°C, but most significant (factor of 3 increase in yield) at -4°C.
- The ICE pyrotechnics burned with a fine smoke and a highly consistent burn time of ~37 s.
- Rates of ice crystal formation were very fast, suggestive of a rapid condensation freezing process. The balance of observations showed no significant difference in the rate data obtained at varied cloud densities, supporting a conclusion that particles activate ice formation by condensation-freezing.

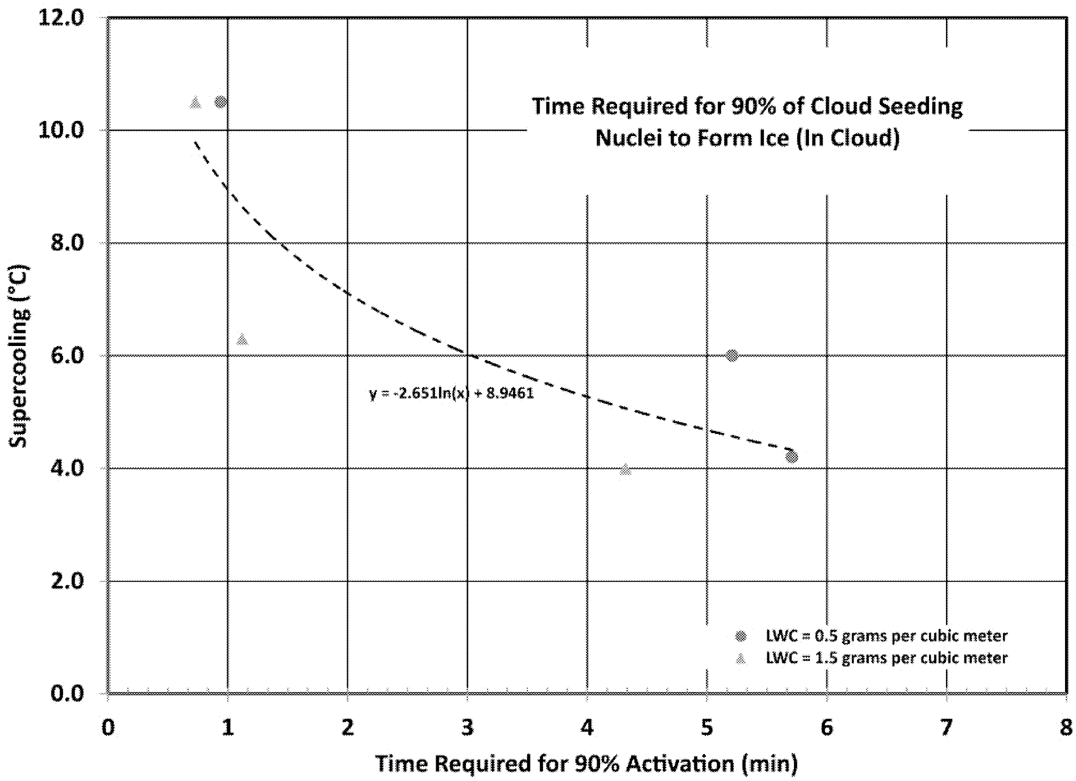


Fig. 15. The time required for 90% of the seeding agent (nuclei) to form ice, as a function of supercooling. At temperatures colder than about -9°C (9° supercooling), 90% of the seeding agent produces ice in cloud. (Data from DeMott 1999.)

The CSU isothermal cloud chamber tests indicate that, on a per gram basis of pyrotechnic, the output and effectiveness indicate that they are 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.

Temp (°C)	LWC (gm^{-3})	k (min^{-1})	kdil (min^{-1})	kact (min^{-1})	T1/e (min)	T90% (min)	Yield Correction
-4.0	1.5	1.093	0.023	0.935	0.94	4.32	1.023
-4.2	0.5	0.713	0.019	0.694	1.44	5.71	1.028
-6.3	1.5	1.775	0.038	1.737	0.48	1.12	1.020
-6.0	0.5	0.724	0.028	0.696	1.43	5.21	1.041
-10.5	1.5	3.200	0.045	3.155	0.32	0.73	1.014
-10.5	0.5	2.488	0.040	2.448	0.41	0.94	1.016

Table 3. Activation Rate of Nuclei Produced by ICE Pyrotechnic (DeMott 1999).

6.8 SUSPENSION

Criteria are in place that define when seeding should be stopped, or not be conducted. These criteria were developed in accordance with the Weather Modification Association (WMA) statement recommending such criteria be established for all projects.

The ASWMS suspension guidelines are as follows:

The following criteria and procedures for suspending operations in the face of impending severe weather to avoid contributing to, or appearing to contribute to, damaging weather situations shall be followed:

1. An emergency shutdown of seeding operations can be declared when there is a situation that poses an immediate threat to life and property. A logical criterion would be when a community is under a declared State of Emergency for flooding or tornado.
2. If the field meteorologist has any doubt about whether suspension criteria are met, he or she should order seeding stopped, and then contact the Project Director for clarification.
3. The Alberta Severe Weather Management Society policy of suspension of seeding during severe weather activity is strictly for reasons related to public perception and aircraft safety.
4. Resumption of normal seeding operations would be conditional on the emergency situation no longer posing a reasonable threat, such as a declared State of Emergency being lifted. However, if a storm forecast is of significant threat (3.3 cm diameter hail or greater), the Project Director has the authority to resume operations at any time.

7. PROGRAM ELEMENTS AND INFRASTRUCTURE

7.1 INFRASTRUCTURE

The flow of information within the project is illustrated in block diagram form in Fig. 16. The focal point of the project is the Operations Centre, located at the Olds-Didsbury Airport, approximately halfway between the two largest metropolitan areas, Calgary and Red Deer.

The ASWMS Board is comprised of individual insurance industry employees nominated by their respective companies. The ASWMS President serves as the primary liaison between the Board and Weather Modification International (WMI), though all Board members receive the project summary reports compiled and disseminated weekly by WMI during the operational period, which is June 1 through September 15, annually.

7.2 THE OPERATIONS CENTRE

Environment Canada operates two weather radars in Alberta, one in Carvel, near Edmonton, and the other at Strathmore, east of Calgary. While good for surveillance of the province, neither provides the detail and flexibility needed for hail suppression operations in the target area. Thus, radar support for the project required that a third radar be installed. Since the project's inception in 1996 the Operations Centre and radar have been based at the Olds-Didsbury Airport, centrally located in the target area (see again Fig. 4).

An illustrated schematic diagram (Fig. 17) of project activities occurring at and around the Operations Centre provides more detail about the origins and flow of data critical for operations. Technical specifications of all project-operated facilities and equipment are given in the appendix of this report.

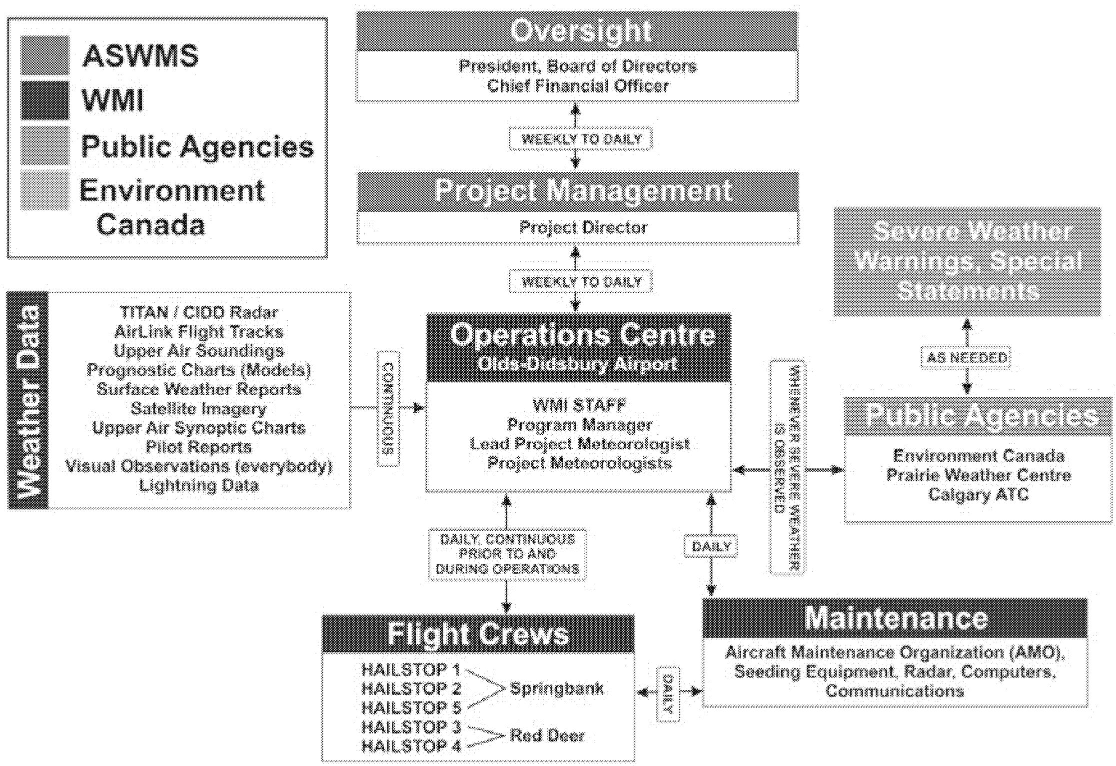


Fig. 16. Schematic of the Alberta Hail Suppression Program Infrastructure. Arrows denote direction of information flow. Arrow labels show typical frequency of communications.

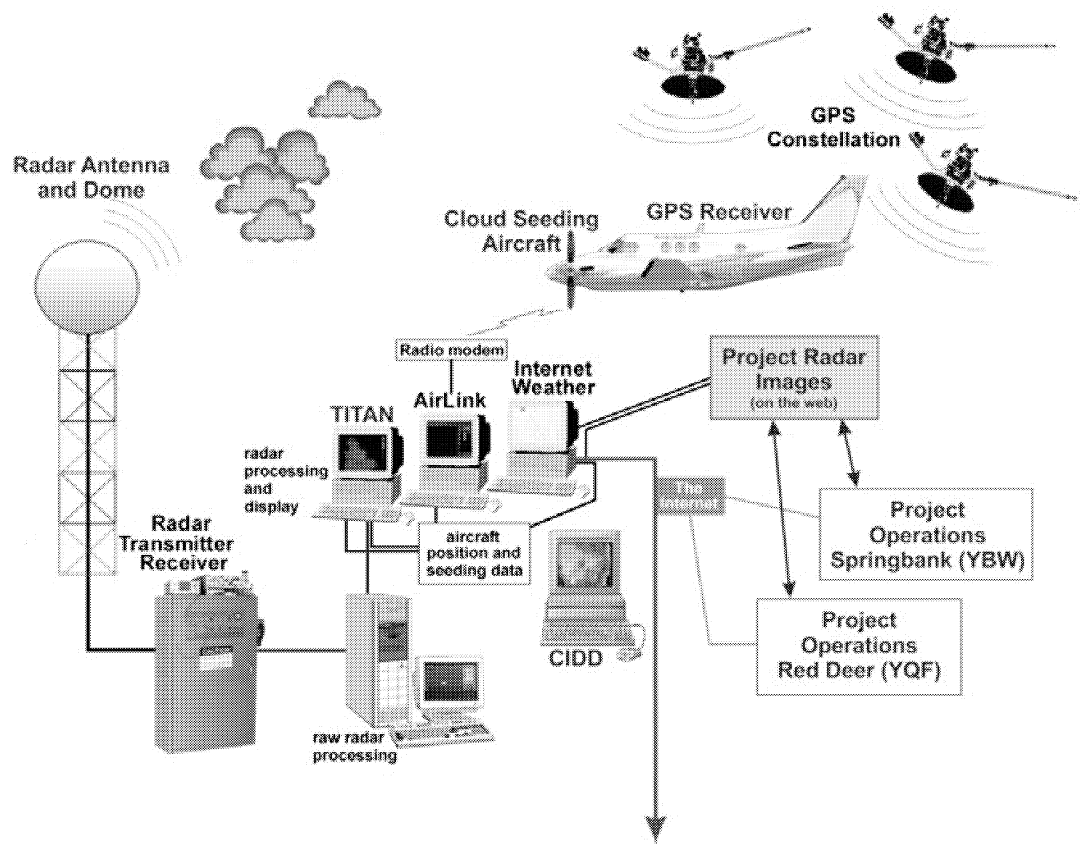


Fig. 17. AHSP Operational Elements. The radar and associated equipment shown are all at the Project Operations Centre, located at the Olds-Didsbury Airport, approximately halfway between Calgary and Red Deer.

All project operations are directed and monitored from the WMI radar installation at the Olds-Didsbury Airport (official airport identifier: CEA3). Project offices for radar operation and monitoring, weather forecasting, recordkeeping, and overall administration are located on the airfield just south of the main ramp. Immediately adjacent to the Operations Centre offices is the easily recognizable radar tower and radome (Fig. 18).

The project control room contains the following: radar displays and processing computers, the *AirLink* flight telemetry system, computers with internet connectivity for access to external weather data, VHF radios for direct communication with project aircraft, and telephone.

The primary radar display and control is achieved through the Thunderstorm Identification, Tracking, Analysis, and Nowcasting (TITAN) acquisition and processing software. The TITAN software processes and displays the full-sky volume scan radar data, producing a variety of graphical images that are useful in real-time as operations are conducted, and also in post-analysis. [Note: the term volume scan refers to radar data collected during a complete set of 360°, full-azimuth scans, each at progressively higher antenna elevation angles. About four minutes are required for the radar to complete each volume scan.]

Fig. 18. The bright morning sun bathes the radar at the Olds-Didsbury Airport on June 22nd, 2018, while inside the Operations Centre (left), the forecaster prepares for the 11:00 AM briefing. (WMI photograph by Brad Waller.)

7.3 DIGITAL WEATHER RADAR

The TITAN software helps the meteorologists identify potential hailstorms and, with the flight tracks of project aircraft superimposed, improves the guidance of aircraft to the hail-growth regions of active thunderstorms. The primary (and largest) TITAN display window is referred to as the RVIEW window. The operator can select the RVIEW window to display any of a number of TITAN parameters either as observed for specific constant altitude plan views (called CAPPIs), or as a composite view, that shows the maximum value observed at each coordinate anywhere above the surface. Composite reflectivity TITAN images are sent to the WMI web server after the completion of each volume scan.

Operating in tandem with TITAN is the Configurable Interactive Data Display (CIDD) radar processing system. The CIDD is similar to TITAN in function. There are advantages to both systems, so WMI uses both. The CIDD is typically set up to run a continuous animated 1-hour loop.

Both TITAN and CIDD are available in the operations room on dedicated displays, that is, flat-panel monitors dedicated full-time to those purposes. In addition, a supplemental TITAN RVIEW window is not used interactively, but used to port (send) TITAN data to the web upon the completion of each complete radar volume scan. This ensures that the web image is consistent from scan to scan.

7.4 GROUND SCHOOL

A ground school was conducted prior to the commencement of the project field operations on 30 May 2018, for project personnel at the Intact Insurance training room in downtown Calgary (Fig. 19).

Fig. 19. WMI Chief Meteorologist and Lead Project Meteorologist Dan Gilbert reviews a portion of the daily routine with AHSP project personnel during ground school on May 30^{th}, 2018. The day-long sessions, hosted by the ASWMS in downtown Calgary, include reviews of the plans, policies, and procedures, as well as project safety. ASWMS Board members are welcome to attend, and often do. (WMI photograph by Bruce Boe.)

Operational procedures about who does what, where, when and why, as well as general conduct and reporting requirements were presented and reviewed at the ground school. A representative of NAV Canada's Air Traffic Control Unit for Calgary participated in the ground school. A copy of the ground school program and samples of the flight log and radar log forms are included in the appendices.

The pre-project ground school training topics included:

i. program overview and design, project area, target areas, and priorities
ii. overview of operations and procedures
iii. cloud seeding hypotheses for hail suppression
iv. cloud seeding theory and techniques
v. aviation weather problems and special procedures
vi. aircraft controlling techniques and procedures
vii. seeding aircraft equipment and characteristics
viii. weather radar equipment and basic principles
ix. basic meteorological concepts and severe weather forecasting
x. weather phenomena, fronts, and storms
xi. daily routines and procedures
xii. communications procedures
xiii. computers, documentation, and reporting procedures
xiv. safety, security precautions and procedures

7.5 PUBLIC RELATIONS

A total of seven groups toured the project Operations Centre at the Olds-Didsbury airport as part of the Alberta Insurance Council accreditation program. Tours were conducted on June 21^{st}, and 28^{th}; August 9^{th}, 16^{th}, 22^{nd}, and 28^{th}; and September 6^{th}, 2018. In total 145 persons took part in this program, which helps those working in the industry understand the program.

The tours, organized and led by Ms. Sarah Newell (AVIVA Canada), each included a presentation by ASWMS Program Director Dr. Terry Krauss, a tour of the room and equipment used to direct the cloud seeding operations, and a chance to see one of the project seeding aircraft and its associated equipment (Fig. 20).

Fig. 20. Captain Jenelle Newman (hand on wing-tip ice nucleus generator) explains the seeding equipment on Hailstop 4 to some of the participants in the August 16th, 2018 continuing education tour and seminar at the Olds-Didsbury Airport, while another attendee waits at the base of the aircraft door her turn to check out the seeding aircraft interior. (WMI photograph by Adam Brainard.)

Recent storms were also replayed for the visitors on the radar (Fig. 21). In addition to the equipment used in the project, attendees learn about Alberta's long history in hail suppression research and operations, the scientific basis for the program, and how the seeding agent (silver iodide) functions to reduce hail. They also learn how the operations are conducted, hearing the information from the meteorologists and pilots who actually perform the operations. Another high point of the day includes a short lecture from ASWMS Director, Dr. Terry Krauss.

Fig. 21. Several members of the August 16th, 2018 continuing education tour listen as meteorologist Brad Waller (seated) explains the functionality of the Operations Room. (WMI photograph by Adam Brainard.)

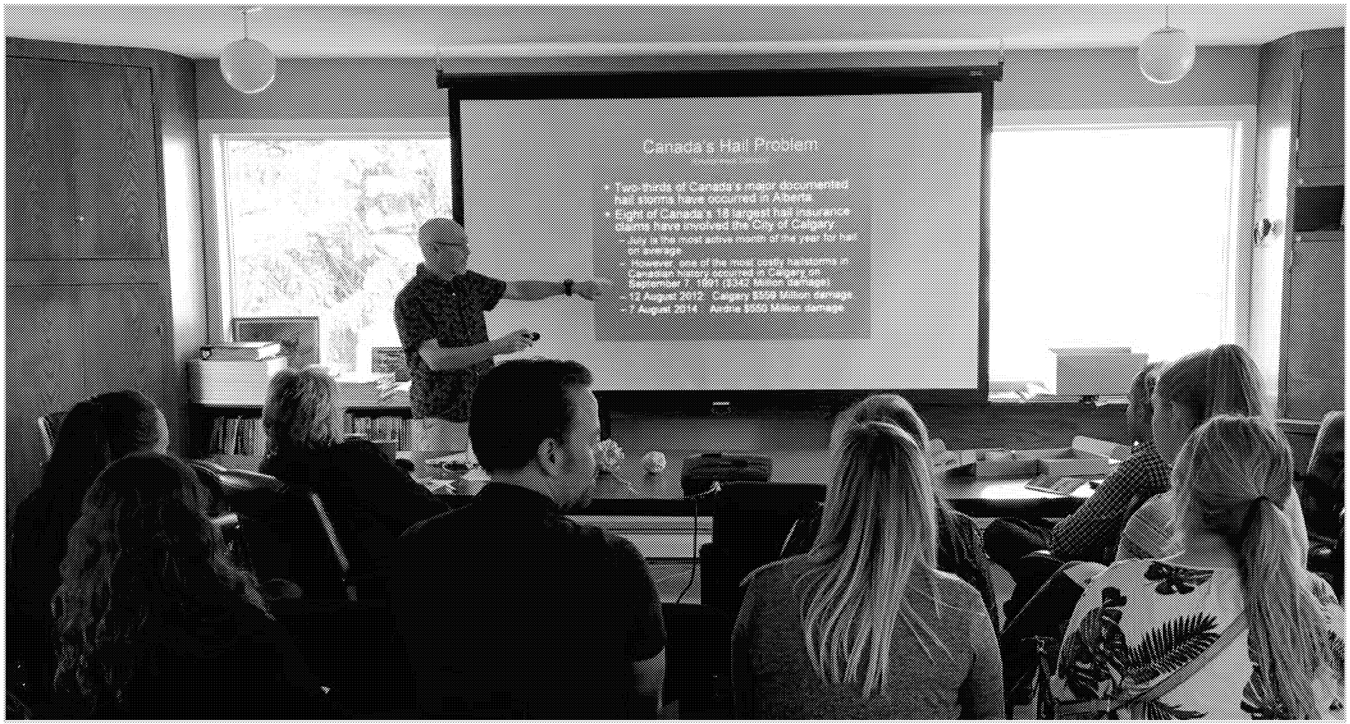


Fig. 22. Alberta Severe Weather Management Society Project Director Dr. Terry Krauss provides the history and science of the project to some of the attendees of the insurance industry-accredited operations centre tour on June 28th, 2018. (WMI photography by Bradley Waller).

Fig. 23. ASWMS Tour Director Sarah Newell and Dr. Terry Krauss, together after another successful season of continuing education tours, on September 6th, 2018. Each tour group completed the "circuit" which included a lecture from Dr. Krauss, an aircraft viewing, inside and out, hosted by a project flight crew, and a demonstration of the operations room by one of the project meteorologists. (WMI photograph by Dan Gilbert.)

8. FLIGHT OPERATIONS

Five specially equipped cloud seeding aircraft were dedicated to the project. Two Beech C90A King Airs and one Cessna 340A were based in Springbank, and a C90A and another C340A were based in Red Deer. The procedures used in 2018 remained the same as the previous years. The Springbank office and aircraft were at Springbank Aero Services, at that airport. The WMI Red Deer office was again set up in the Air Spray hangar at the Red Deer Regional Airport, as had been done in previous seasons.

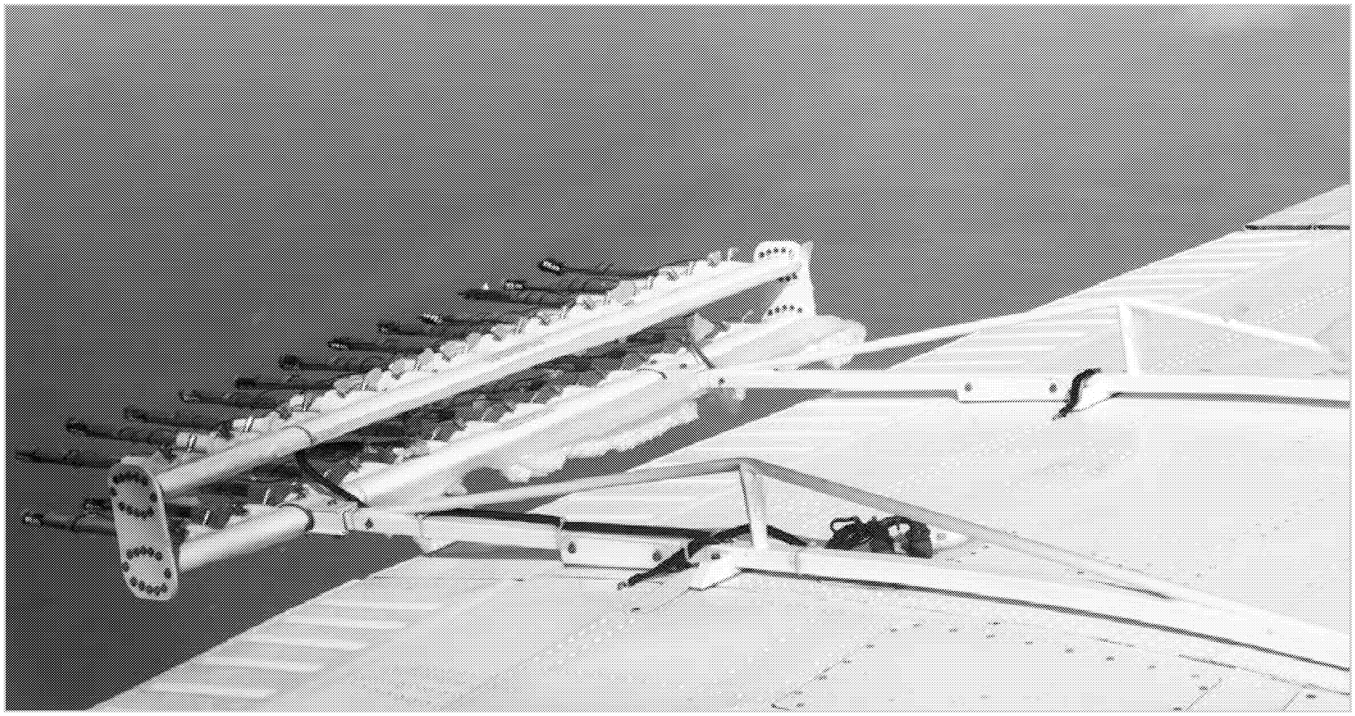


Fig. 24. On July 26th, Hailstop 5 seeded a vigorous thunderstorm as it moved from near Cochrane east across Calgary. In-cloud turbulence was heavy, and so was the supercooled liquid water, so the seeding rate was high. In this picture, taken at 5:36 PM Mountain Time, spent burn-in-place flares can be seen across most of the upper rack, as well as the rime ice build-up on the rack itself. (WMI photograph by Brian Kindrat.)

When convective clouds were detected by radar or visually observed to be developing, the seeding aircraft were placed on standby status, and the crew of at least one sent to their airport. Aircraft on standby status are able to launch and reach a target cloud within about 30 min after the request to launch has been made by the controlling meteorologist. When seedable clouds are imminent, the seeding aircraft are dispatched to investigate. Aircraft were available and prepared to commence a seeding mission at any time, and the seeding of storms often continued after dark, with due regard to safety (see again Fig. 13).

8.1 AIR TRAFFIC CONTROL

Prior to the start of field operations, arrangements were made with NAV Canada managers of Air Traffic Services in Calgary and Edmonton to coordinate the cloud seeding aircraft operations. Permission was granted to file pre-defined flight plans for the project aircraft, with special designations and fixed transponder codes. The designated aircraft were as follows: Hailstop 1 for the King Air C90 airplane (N904DK) based in Springbank, Hailstop 2 for the C340 aircraft (N234PS) based in Springbank, Hailstop 3 for the King Air C90 aircraft (N127ZW) stationed in Red Deer, Hailstop 4 for the C340 aircraft (N37356) based in Red Deer, and Hailstop 5 for the King Air C90 aircraft

(N518TS) based in Springbank. After a lightning strike to an engine on Hailstop 1 on July 10th, N904DK was replaced by King Air C90 N522JP for the duration of the project.

Direct-line telephone numbers were used to notify air traffic controllers of cloud seeding launches. Aircraft were launched to specific locations defined by VOR and DME coordinates. Distinct air traffic clearance was given to project aircraft within a 10 nautical mile radius of the specified storm location. Cloud top aircraft were given a 2,000 ft block with 6,000 ft clearance below bottom of their block. Cloud base aircraft were typically given a ± 1,000 ft altitude clearance (see again Fig. 12). This procedure works very well in general. On a few occasions, seeding aircraft may be asked to briefly climb to higher altitudes while passing over the city of Calgary, or to suspend seeding for a few minutes to allow other commercial aircraft to pass below them, but such interruptions are infrequent.

8.2 CLOUD SEEDING AIRCRAFT

Two different models of twin-engine aircraft were utilized on the project. Hailstop 1, Hailstop 3, and Hailstop 5, the cloud-top seeding aircraft, were Beech King Air C90s, turboprop (propjet) aircraft. Both cloud-base seeding aircraft (Hailstop 2 and 4) were Cessna model 340A aircraft. All five aircraft were equipped with fuselage-mounted flare racks carrying ejectable flares, and also wing racks for burn-in-place flares. The two Cessna 340As also were equipped with solution-burning ice nucleus generators affixed to their wingtips.

Beech King Air C90

A photo of one of the Beechcraft King Air C90 (Hailstop 1) is shown in Fig. 25. Complete aircraft specifications are given in the Appendix. The King Air C90 is a high-performance twin engine turboprop aircraft that has been proven repeatedly in seeding operations. Each of the King Airs was equipped with three belly-mounted racks each having the capacity for 102 twenty-gram ejectable cloud seeding flares, for an aircraft total of 306 flares.

Each also carried racks affixed to the trailing edges of the wings that held up to forty-eight 150-gram "burn-in-place" flares per wing. As this nomenclature implies, the burn-in-place pyrotechnics are not ejected, but are burned while attached to the wing rack.

The three turboprop King Air seeding aircraft (Hailstop 1 and 5, Springbank, and Hailstop 3, Red Deer) were used primarily for seeding at cloud top by direct penetration of growing cloud turrets, most often those flanking large storm complexes. Such turrets are precipitation-free at the time of seeding, and consequently (radar) echo-free as well, though more mature adjacent cells may be producing strong radar returns. This means that those monitoring operations will often see the flight tracks of properly positioned aircraft near the echoing storm complexes, but not necessarily in them. This direct targeting makes very effective use of these aircraft, which function most efficiently at higher altitudes.

In 2018 the King Airs were also sometimes used at cloud base, seeding with burn-in-place flares. There are several scenarios in which the King Airs are more effective at cloud base. The aircraft may drop down to cloud base after having seeded aggressively at cloud top depleting their supply of ejectable flares. They are able to continue seeding with remaining burn-in-place flares at cloud base so long as fuel supply is sufficient. For very severe storms, multiple base seeders are often deployed. For safety, only one top seeder is allowed to work in the airspace near a storm. King Airs can be utilized as base seeders along with the C340s while other King Airs work at cloud top above them. Sometimes the King Airs can switch places (top and base quickly swap altitudes) as ejectable flare supplies are used up. This practice provided better base-seeding coverage, as the Cessna 340s (next section) can carry only 24 burn-in-place flares per mission due to their lighter wings. At other times, weather conditions are less favorable for top seeding due to seedable targets being embedded within cloud layers. In such circumstances, base seeding is more effective due to more certain targeting. While seeding at cloud top in embedded conditions is possible, it presents challenges such significant aircraft icing and exposure to a heightened risk of lightning strikes. In these situations, base seeding is both safer and more effective. In some situations with cloud bases above 8,000 feet, ATC restrictions near Calgary can be avoided if the cloud base seeding aircraft changes altitude to 8,000 feet or above.

Fig. 25. A King Air model C90, Hailstop 3, sits on the Olds-Didsbury Airport ramp on August 9th, while Captain Joel Zimmer (in blue, facing camera) introduces the tour-goers to how the aircraft is used on the project. Racks of burn-in-place pyrotechnics are visible aft of the near wing. (WMI photograph by Adam Brainard.)

Cessna 340A

The two other seeding aircraft, Hailstop 2 (Springbank) and Hailstop 4 (Red Deer), were Cessna 340A aircraft (C340) whose primary role was seeding the growing cloud turrets while within updrafts just below cloud bases. The Cessna 340s are pressurized, twin engine, six cylinder, turbocharged and fuel-injected all-weather aircraft, equipped with weather-avoidance radar and GPS navigation system (Fig. 26). Complete specifications for the C340 are given in the Appendix.

The C340 aircraft both carry a 204-position belly rack for twenty-gram ejectable flares (used in cloud top seeding, which they also can do very effectively), and wing racks for twenty-four 150 gram burn-in-place flares, as well as two wing-tip ice nucleus generators that burn silver iodide seeding solution. Each generator has a capacity of 26.5 litres (7.0 U.S. gallons), sufficient for continuous seeding for about 2.5 hours. Although the C340 can seed effectively at cloud top, even in known icing conditions, these aircraft are not as fast or powerful as the turboprop aircraft and so are more efficient and cost-effective when utilized in cloud-base seeding operations, their primary role in Alberta.

Fig. 26. A Cessna model 340A, Hailstop 2, rests on the ramp at the Springbank Airport, after the season's first day on which all five Hailstop aircraft flew, June 9th. While the Springbank Aero crew refuels the aircraft, co-pilot Matt Burrus refills seeding solution for the far ice nucleus generator. (WMI photograph by Brian Kindrat.)

9. RADAR CONTROL AND COMMUNICATIONS CENTRE

The project Operations Centre was located at the Olds-Didsbury Airport (identifier CEA3), near the geographical centre of the protected area, and approximately equidistant from Calgary and Red Deer. The office contains a modest reception and work area, the operations room from which the weather is monitored and operations conducted, and a washroom. The reception/work area has two desks, telephone, a printer/copier/scanner/fax, and a TV monitor that allows viewing of the main radar display outside the rather small (staff only) operations room (Fig. 27). A small refrigerator, coffee pot, and water cooler were also available for staff use.

The project's radar control room contained an *AirLink* computer with radio telemetry modem for GPS aircraft tracking acquisition, as well as the TITAN computer and display for the radar, and the meteorological data acquisition (internet) computer. Controllers communicated with the seeding aircraft using VHF radio. The controlling duties were led by Dan Gilbert, who was assisted by Brad Waller and Adam Brainard.

The operations room was configured to place all the needed resources within easy reach of the operations director. Project reference and equipment manuals were shelved on the upper left. Telephones were available, with remote handsets. The desk top provides the space needed for data recording (logs) and data entry (keyboard/mouse). The VHF radio needed for ground-to-air communication was placed directly in front of the operations director. To the far right was a third computer with dual monitors (Fig. 27, I, J), for continuous, dedicated access to internet weather data from other sources. There was ample room for a second meteorologist in the operations room when needed to assist with radio communications, data entry, or general weather surveillance.

High speed internet was again installed at the Springbank and Red Deer airport offices so that the pilots could closely monitor the storm evolution and motion prior to takeoff. This gave crews better comprehension of the storm situation they were going to encounter once airborne.

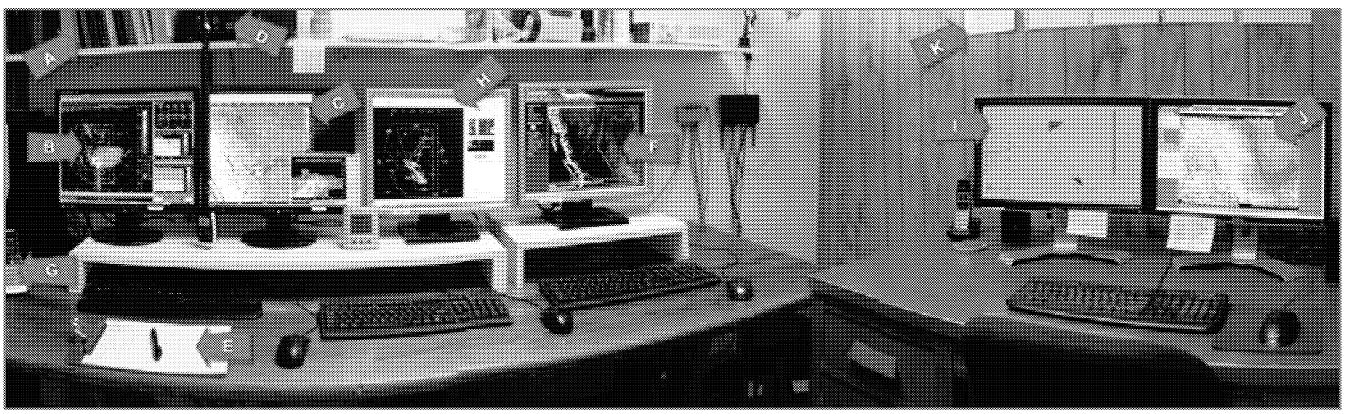


Fig. 27. The configuration of the Operations Room. Equipment includes (A) reference manuals, (B) TITAN displays, (C) CIDD, (D) VHF radio for communications with aircraft, (E) radar log, (F) internet data displays, (G) telephone, (H) *AirLink* display, (I and J) forecasting/nowcasting support displays, and (K) radio and radar licenses. (WMI wide-angle photograph by Daniel Gilbert.)

A Davis weather station installed at the Operations Centre, with wind sensors affixed to the sub-structure of the airport's non-directional radio beacon (NDB) tower, telemetered temperature, pressure, wind, and humidity into the office, where it was displayed in real-time and recorded. Data from the station were also made available in real-time through the Internet.

9.1 RADAR

The Doppler weather radar was installed in May 2014, prior to the project start. Improvements realized included implementation of the latest version of the TITAN radar software, state-of-the-science radar antenna control, and improved data processing. Volume scans require less than four minutes, so the radar updates 15 times per hour. A large battery backup system for the radar, TITAN, and the other mission-critical equipment in the operations room made it possible to hold all essential computers on battery more than long enough to start the backup generator and switch over from commercial power. The backup generator was run for a short period (10-15 minutes) each month during the season to ensure functionality for when it is needed. Radar calibration data and system specifications are given in Table 4.

WMI Radar, Olds-Didsbury Airport

CALIBRATIONS *Parameter*	*May 2018 (dBm)*	
Radar Constant	77.2577	
Noise	-62.1811	
Minimum Detectable Signal	-111.272	
Receiver Gain	49.0905	
Minimum dBZ at 1 km Range	-34.0116	
SYSTEM SPECIFICATIONS		
Frequency (C-band)	5.975	GHz
Peak Power	250	KW
Average Power	40	W
Range Gate (length)	150	m
Pulse Repetition Frequency	600	sec^{-1}
Pulse Width	1	µsec
Range	180	km
Beam Width	1.65	deg
Volume Scans	15	per hour

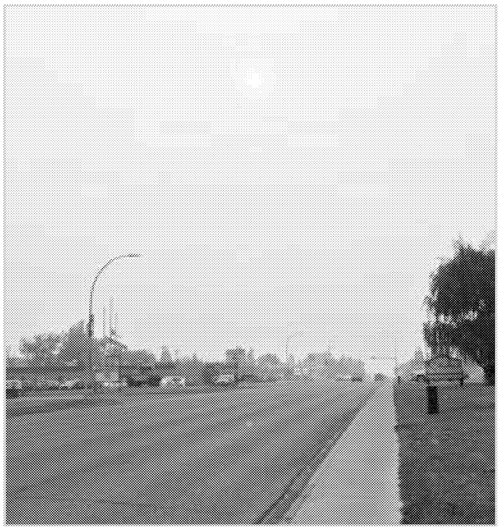
Table 4. 2018 Calibrations and Specifications of the Advanced Radar Corporation WMI Radar located at Olds-Didsbury Airport.

9.2 AIRCRAFT TRACKING

The project Operations Centre was equipped to receive and record data from all project aircraft, using data radio and WMI's *AirLink* tracking system. These GPS-based systems provided the exact real-time positions of the aircraft, allowing them to be superimposed on the TITAN RVIEW display. This allowed the meteorologist(s) controlling flight operations to accurately direct the aircraft to optimum seeding positions relative to each storm system. Each aircraft track was displayed in a different color, providing unambiguous identification. Examples of the raw *AirLink* data flight tracks, as well as 10-minute track segments superimposed on the TITAN displays are provided later in this report in the detailed descriptions of the storms of August 2nd, 2018, that struck southern Calgary. *AirLink* also displays where the seeding events took place, but these were not displayed on the tracks in the TITAN RVIEW because doing so adds excessive clutter to the already "busy" image. In addition to being telemetered to the Operations Centre, the position and seeding event data are recorded on board the aircraft, and thus are not lost if the telemetry between aircraft and radar is interrupted.

10. SUMMARY OF SEEDING OPERATIONS

A brief summary of each day recounting the weather and operational activities is given in the Appendix. Further details regarding flight times and the amount of seeding are given in the Flights and Operations Summary tables, also in the Appendix.



There were 26 seeding days, whereas the mean is 31. A total of 127 seeding and patrol missions were flown, well above average, primarily because of the unusually large number of patrol flights (33). August was very warm in 2018, with many southern Alberta locations reporting all-time record maximum temperatures. The wildfire season in British Columbia began early and was very serious producing, in August, extremely smoky conditions in Alberta that persisted for weeks (Fig. 28). At times, visibility was so low that seeding flights by cloud base seeding aircraft would have been extremely difficult, if not impossible. Fortunately, these days were characterized largely by stable air masses, and storms did not develop.

Fig. 28. Smoke from forest fires persisted for a good portion of August, greatly reducing visibility. On August 15th, Meteorologist Bradley Waller captured the late-afternoon sky in Olds. The sun is barely visible. (WMI photograph by Bradley Waller.)

Of the 26 seeding days, all five Hailstop aircraft flew on eight days, and all five aircraft seeded on six of those eight days. When the weather was active, it was very active.

In June, 21 seeding missions were flown on 9 days, and an additional 14 flights flown for patrol on six days. A "patrol" flight is a flight flown to check cloud intensity or in anticipation of clouds becoming intense enough to warrant seeding, but during which no seeding was actually conducted.

July was the most active month, as is usually the case. Fifty-two seeding missions were flown on 13 days, and 15 more patrol flights on 11 days.

The most serious hailstorm of the season occurred on August 2nd, when thunderstorms developed west of Calgary and proceeded to move through the southern portion of the city. All five aircraft flew and seeded these storms. Ten seeding missions were flown, with each Hailstop aircraft flying twice. A detailed analysis of the August 2nd storm is provided as a case study later in this report.

Activity diminished sharply after August 2nd. Only a single seeding mission was flown during the remainder of the month. The final seeding mission of the season was flown on September 11th.

Fig. 29. At 2:26 PM on July 21st, a moderate thunderstorm above Calgary was being seeded by Hailstop 5. The flat cloud base is indicative of updrafts, rising currents of moist air that feed the storm. (WMI photograph by Brook Mueller.)

The aircraft and crews provided a 24-hour service, seven days a week throughout the period. Twelve full-time pilots and three meteorologists were assigned to the project this season. In addition, WMI's Director of Flight Operations, Mr. Jody Fischer, served as overall project manager.

The 2018 crew was very experienced. The Red Deer aircraft team (Fig. 30) was led by Mr. Joel Zimmer, who has been with the Alberta program for 16 seasons, Ms. Jenelle Newman, and Mr. Mike Torris. The Springbank team (Fig. 31) was anchored by Mr. Brian Kindrat (onsite WMI Project Manager), Mr. Brook Mueller, and Mr. Andrew Brice. The radar crew (Fig. 32) was led by WMI's Chief Meteorologist, Mr. Daniel Gilbert, now with nine seasons' experience in Alberta, in addition to seven previous seasons' work in a similar capacity on a hail suppression program in North Dakota.

Fig. 30. The Red Deer pilots, from left to right and back to front: Michael Benson, Joel Zimmer, Trevor Black, and Jenelle Newman. Not pictured: Michael Torris.

Fig. 31. The Springbank pilots, from left to right: Matt Burrus, Jon Proppe, Andreas Bertoni, Brian Kindrat, Brook Mueller, Andrew Wilkes, and Andy Brice.

Fig. 32. The meteorologists who staffed the Operations Centre at the Olds-Didsbury Airport, from left to right: Bradley Waller, Daniel Gilbert, and Adam Brainard.

Fig. 33. Project administration was overseen by Terry Krauss (ASWMS, left), and Jody Fischer (WMI, right).

The 2018 project was managed by Dr. Terry Krauss on behalf of the ASWMS, and Mr. Jody Fischer of WMI (Fig. 33). Krauss and Fischer worked closely to coordinate operations throughout the season.

Overall, the personnel, aircraft, and radar performed well and there were no interruptions or missed opportunities. A radar calibration at the beginning of the project season ensured that during the 2018 season the radar was calibrated correctly.

All of the project's radar data, meteorological data, and reports have been recorded onto a portable hard drive as a permanent archive for the Alberta Severe Weather Management Society. These data include the daily reports, radar maps, aircraft flight tracks, as well as meteorological charts for each day. The data can be made available for outside research purposes through a special request to the Alberta Severe Weather Management Society. In addition, the season's radar (TITAN) data are available to ASWMS Program Director Dr. Terry Krauss. Thus, Dr. Krauss has access to all data in the off-season, should the need arise.

10.1 FLIGHTS

There were thunderstorms reported within the project area on 55 days during the summer of 2018, compared with 59 days in 2017. Hail fell on 41 days, with hail of walnut size or larger on 10 days. During this season, there were 262.5 hours of project operations accrued on 35 days with seeding and/or patrol operations. A total of 77 storms were seeded during 94 seeding flights on the 26 seeding days. There were 33 patrol flights, and 13 short "public relations" flights on which one aircraft was flown to the Olds-Didsbury Airport to be available for viewing by insurance company employees attending tours of the Operations Centre and radar. The distribution of flight time by purpose is given in Fig. 34.

The distribution of flights (takeoffs and landings) by time of day (Mountain Time) is shown in Fig. 35. As was the norm, storm activity, and thus flights, was strongly correlated with the diurnal convective cycle which sees storm development coincide with daytime surface heating, and persistence through the evening hours, but only occasionally, after midnight.

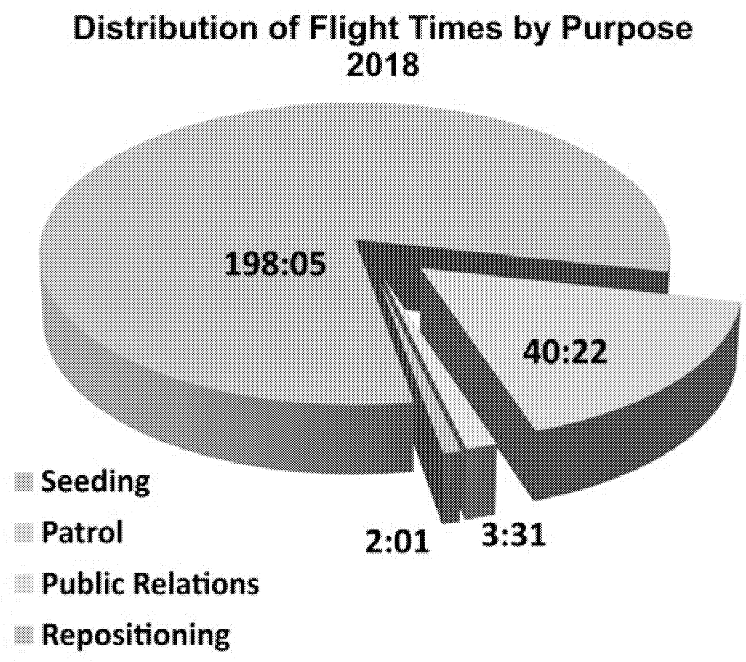


Fig. 34. The distribution of flight time during the 2018 season is shown, by purpose. "Public relations" flights were those from the aircraft's base to the Olds-Didsbury Airport on days that insurance industry continuing education training sessions were given. Times given are times from engine start to engine stop.

10.2 SEEDING AMOUNTS

The amount of glaciogenic nucleating agent dispensed during the 2018 field season totaled 248.0 kg. This was dispensed in the form of 4,663 ejectable (cloud-top) flares (93.3 kg seeding agent), 951 burn-in-place (cloud-base) flares (142.6 kg seeding agent), and 198.0 gallons of silver iodide seeding solution (12.0 kg seeding agent).

The amount of seeding agent dispensed on each day of operations in 2018 is shown in Fig. 36. There were 9 days on which more than 10 kg (10,000 grams) of seeding material was dispensed, one fewer day than in 2017. All of these were days on which a least four of the five Hailstop aircraft flew; on six of those days all five aircraft seeded. The amount of seeding agent dispensed per storm (3.23 kg) was well above the project mean (2.55 kg), perhaps a testament to 2018 storm intensity and duration, but also reflecting the collective experience of the project staff, as prompt arrival at storms meeting seeding criteria translates to better targeting and more sustained cloud treatment. This was still well below the 2015 value of 4.42 kg per storm, the highest of any season to date. The benefits of having five aircraft continue to be realized. This is especially demonstrated on those days when convection is widespread; more storms can be effectively treated.

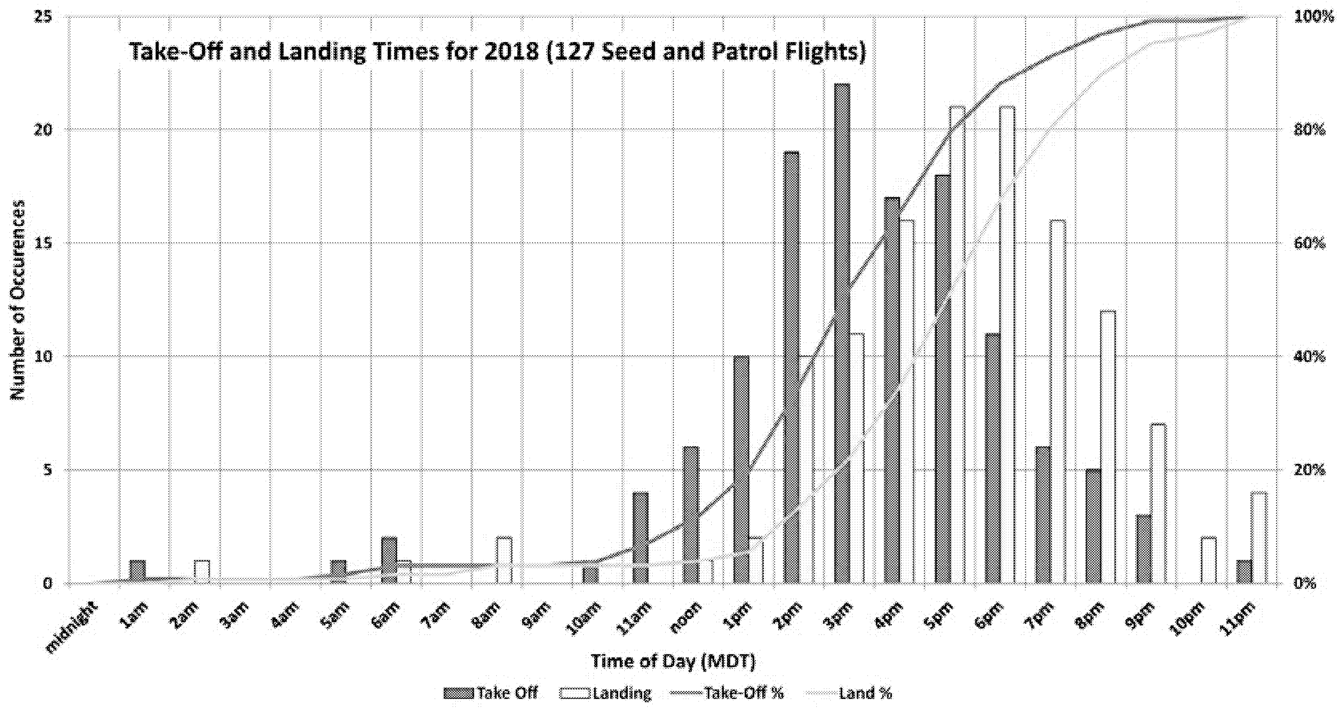


Fig. 35. Diurnal variation in takeoff and landings, 2018 (Mountain Daylight Time). The 127 seeding and patrol flights are included. As is the norm, nocturnal flight operations were limited, especially after midnight.

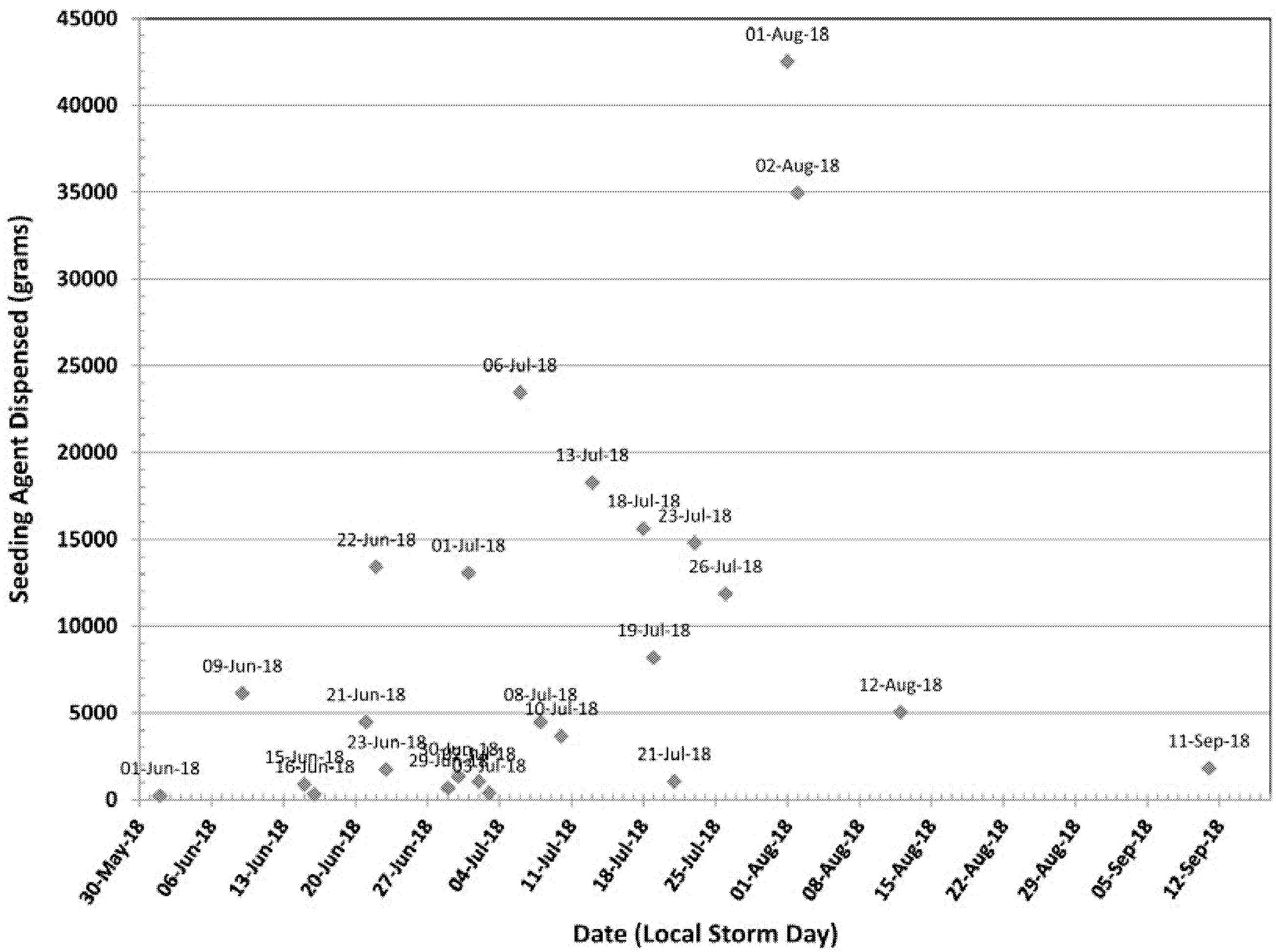


Fig. 36. The amount of seeding agent dispensed per operational day, 2018.

Table 5 gives a list of the operational statistics for all twenty-three seasons of the Alberta Hail Suppression Project. These statistics can be useful in understanding how the current season compared with those before, and for planning purposes. The 2018 summer ranked ninth all-time in terms of activity. Seeding occurred on 26 days [mean is 31 days, record (2011) was 48 days]; 127 project missions were flown for patrol and seeding. The distribution of flights by type and project day is shown in Fig. 37.

Seeding Activity by Season 1996-2018

Season	Storm Days with Seeding	Aircraft Missions (Seeding & Patrol)	Total Flight Time (hours)	Number of Storms Seeded	Total Seeding Agent (kg)	Seeding Agent Per Day (kg)	Seeding Agent Per Hour (kg)	Seeding Agent Per Storm (kg)	ICE-EJ® Flares	ICE-BIP® Flares	Seeding Solutions (gallons)	Season Activity Rank
2018	26	127	262.5	77	248.0	9.5	0.94	3.22	4663	951	198.0	9
Mean	31	106	218.2	90	221.4	7.2	1.02	2.55	5247	701	168.6	
2017	25	107	224.5	64	255.4	10.2	1.14	3.99	5939	842	170.2	11
2016	35	139	277.1	96	294.9	8.4	1.06	3.07	6496	1000	246.9	6
2015	26	115	233.3	79	349.2	14.6	1.37	4.42	8127	1138	262.9	8
2014	32	128	259.5	101	382.5	12.0	1.47	3.79	10782	1020	228.6	3
2013	26	103	229.6	70	233.3	9.0	1.02	3.33	6311	636	131.7	14
2012	37	143	300.1	116	314.6	8.5	1.16	2.70	7717	914	260.3	2
2011	48	158	383.0	134	400.1	8.3	1.13	3.00	10779	1020	350.2	1
2010	42	115	271.8	118	263.8	6.3	1.10	2.20	5837	851	227.5	7
2009	20	38	109.3	30	48.4	2.4	0.84	1.60	451	237	56.5	23
2008	26	112	194.7	56	122.9	4.7	1.00	2.20	1648	548	113.5	18
2007	19	76	115.3	41	99.7	5.2	0.90	2.40	1622	413	77	22
2006	28	92	190.2	65	214	7.6	1.10	3.30	4929	703	145.4	15
2005	27	80	157.9	70	159.1	5.9	1.00	2.30	3770	515	94.2	20
2004	29	105	227.5	90	270.9	9.3	1.20	3.00	6513	877	132.7	10
2003	26	92	163.6	79	173.4	6.7	1.10	2.20	4465	518	92.6	17
2002	27	92	157.4	54	124.2	4.6	0.80	2.30	3108	377	80.3	21
2001	36	109	208.3	98	195	5.4	0.90	2.00	5225	533	140.8	12
2000	33	130	265.2	136	343.8	10.4	1.30	2.50	9653	940	141.3	4
1999	39	118	251.3	162	212.7	5.5	0.80	1.30	4439	690	297.5	5
1998	31	96	189.9	153	111.1	3.6	0.60	0.70	2023	496	193.8	13
1997*	38	92	188.1	108	110.8	2.9	0.60	1.00	2376	356	144.3	16
1996*	29	71	159.1	75	163.3	5.6	1.00	2.20	3817	542	80.5	19

**The 1996 and 1997 seasons began on June 15, not June 1, which has been the norm ever since.*

Table 5. Operational statistics for seeding and patrol flights, 1996 through 2018.

The *Season Activity Rank* shown at the far right of Table 5 was calculated as follows: Each parameter for each year was divided by the project mean for that parameter to produce a normalized value. Then, the normalized values of *Storm Days with Seeding*, *Aircraft Missions*, *Total Flight Time*, *Number of Storms Seeded*, *Ejectable Flares*, *BIP Flares*, and *Seeding Solution* were summed for each season. The seasons were then ranked. *Total Seeding Agent*, *Seeding Agent per Day*, *Seeding Agent per Hour*, and *Seeding Agent per Storm* were not included in the ranking as those are all quantities derived from the others.

A summary of the flare usage, by aircraft, during the past 23 seasons is given in Table 6. The Cessna 340s (Hailstop 2 and Hailstop 4) are used mainly as cloud base seeding aircraft because they have lesser performance. There were no aircraft maintenance issues that impacted operations.

The best seeding coverage consists of seeding a storm simultaneously using two aircraft; one at cloud base and another at cloud top (-5 to -10°C) along the upwind "new growth" side of the storm. The King Air aircraft have proven themselves as excellent cloud-top seeders.

The seeding strategy has been to stagger the launch of the seeding aircraft, and use one aircraft to seed at cloud base and one aircraft at cloud top when the storm is immediately upwind or over the highest priority areas. However, if multiple storms threaten three or more areas at the same time, generally only one aircraft is used on each storm, or more aircraft are concentrated on the highest population area around Calgary.

AIRCRAFT LEGEND:	C340	CESSNA 340A	C90	BEECH KING AIR C90	CHEY	PIPER CHEYENNE II

hours = flight hours, EJ = ejectable pyrotechnic, BIP = burn-in-place pyrotechnic, gen hr = hours wingtip solution-burning seeding time

Season	***Hailstop 1***		***Hailstop 2***		***Hailstop 3***		***Hailstop 4***		***Hailstop 5***	
	Springbank (Calgary prior to 2012)		*Springbank* (Calgary prior to 2012)		*Red Deer*		*Red Deer*		*Springbank*	
	FLIGHT HOURS, EJ FLARES, BIP FLARES		FLIGHT HOURS, EJ FLARES, BIP FLARES, GEN HOURS		FLIGHT HOURS, EJ FLARES, BIP FLARES		FLIGHT HOURS, EJ FLARES, BIP FLARES, GEN HOURS		FLIGHT HOURS, EJ FLARES, BIP FLARES	
2018	C90	68 hours, 1937 EJ, 284 BIP	C340	66 hours, 0 EJ, 220 BIP, 59 gen hr	C90	39 hours, 1246 EJ, 89 BIP	C340	62 hours, 0 EJ, 133 BIP, 46 gen hr	C90	48 hours, 1480 EJ, 237 BIP
2017	C90	52 hours, 2071 EJ, 201 BIP	C340	57 hours, 0 EJ, 152 BIP, 47 gen hr	C90	39 hours, 2354 EJ, 203 BIP	C340	56 hours, 0 EJ, 117 BIP, 38 gen hr	C90	45 hours, 1514 EJ, 169 BIP
2016	C90	62 hours, 2460 EJ, 183 BIP	C340	78 hours, 0 EJ, 296 BIP, 82 gen hr	C90	49 hours, 1989 EJ, 164 BIP	C340	54 hours, 0 EJ, 132 BIP, 42 gen hr	C90	59 hours, 2047 EJ, 225 BIP
2015	C90	55 hours, 2798 EJ, 230 BIP	C340	76 hours, 0 EJ, 272 BIP, 76 gen hr	C90	47 hours, 2845 EJ, 208 BIP	C340	61 hours, 0 EJ, 199 BIP, 55 gen hr	C90	46 hours, 2484 EJ, 229 BIP
2014	C90	71 hours, 3554 EJ, 268 BIP	C340	60 hours, 0 EJ, 198 BIP, 57 gen hr	C90	41 hours, 3558 EJ, 207 BIP	C340	64 hours, 90 EJ, 190 BIP, 58 gen hr	C90	72 hours, 3580 EJ, 157 BIP
2013	C90	41 hours, 1149 EJ, 115 BIP	C340	58 hours, 0 EJ, 148 BIP, 37 gen hr	C90	42 hours, 3381 EJ, 166 BIP	C340	48 hours, 0 EJ, 78 BIP, 31 gen hr	C90	40 hours, 1781 EJ, 129 BIP
2012	C90	76 hours, 3250 EJ, 232 BIP	C340	87 hours, 0 EJ, 224 BIP, 72 gen hr	C90	83 hours, 4464 EJ, 198 BIP	C340	85 hours, 3 EJ, 260 BIP, 63 gen hr		
2011	C90	97 hours, 4783 EJ, 239 BIP	C340	105 hours, 244 EJ, 269 BIP, 91 gen hr	C90	99 hours, 5646 EJ, 273 BIP	C340	108 hours, 106 EJ, 239 BIP, 92 gen hr		
2010	CHEY	62 hours, 1612 EJ, 132 BIP	C340	82 hours, 74 EJ, 236 BIP, 53 gen hr	C90	96 hours, 4154 EJ, 200 BIP	C340	68 hours, 2 EJ, 286 BIP, 64 gen hr		
2009	CHEY	22 hours, 250 EJ, 27 BIP	C340	31 hours, 0 EJ, 65 BIP, 6 gen hr	C90	24 hours, 201 EJ, 48 BIP	C340	33 hours, 0 EJ, 97 BIP, 17 gen hr		
2008	CHEY	65 hours, 953 EJ, 88 BIP	C340	44 hours, 0 EJ, 171 BIP, 27 gen hr	C90	51 hours, 695 EJ, 169 BIP	C340	35 hours, 0 EJ, 120 BIP, 19 gen hr		
2007	CHEY	40 hours, 979 EJ, 81 BIP	C340	41 hours, 0 EJ, 155 BIP, 31 gen hr	C90	34 hours, 643 EJ, 177 BIP				
2006	CHEY	54 hours, 3217 EJ, 179 BIP	C340	70 hours, 72 EJ, 248 BIP, 58 gen hr	C90	66 hours, 1640 EJ, 276 BIP				
2005	CHEY	49 hours, 2750 EJ, 169 BIP	C340	45 hours, 0 EJ, 121 BIP, 38 gen hr	CHEY	64 hours, 1020 EJ, 225 BIP				

Table continued on next page.

AIRCRAFT LEGEND:	C340	**CESSNA 340A**	C90	**BEECH KING AIR C90**	CHEY	**PIPER CHEYENNE II**

hours = flight hours, EJ = ejectable pyrotechnic, BIP = burn-in-place pyrotechnic, gen hr = hours wingtip solution-burning seeding time

Season	*Hailstop 1*		*Hailstop 2*		*Hailstop 3*		*Hailstop 4*	*Hailstop 5*
	Springbank (Calgary prior to 2012)		*Springbank* (Calgary prior to 2012)		*Red Deer*		*Red Deer*	*Springbank*
	FLIGHT HOURS, EJ FLARES, BIP FLARES		FLIGHT HOURS, EJ FLARES, BIP FLARES, GEN HOURS		FLIGHT HOURS, EJ FLARES, BIP FLARES		FLIGHT HOURS, EJ FLARES, BIP FLARES, GEN HOURS	FLIGHT HOURS, EJ FLARES, BIP FLARES
2004	CHEY	83 hours, 5574 EJ, 359 BIP	C340	62 hours, 0 EJ, 196 BIP, 53 gen hr	C90	82 hours, 939 EJ, 322 BIP		
2003	CHEY	64 hours, 3598 EJ, 250 BIP	C340	54 hours, 0 EJ, 130 BIP, 37 gen hr	CHEY	46 hours, 867 EJ, 138 BIP		
2002	CHEY	57 hours, 1994 EJ, 163 BIP	C340	49 hours, 2 EJ, 73 BIP, 32 gen hr	CHEY	51 hours, 1112 EJ, 141 BIP		
2001	CHEY	62 hours, 3174 EJ, 216 BIP	C340	75 hours, 4 EJ, 215 BIP, 56 gen hr	CHEY	68 hours, 2093 EJ, 102 BIP		
2000	CHEY	90 hours, 4755 EJ, 379 BIP	C340	77 hours, 164 EJ, 193 BIP, 56 gen hr	CHEY	97 hours, 4734 EJ, 368 BIP		
1999	CHEY	91 hours, 3795 EJ, 313 BIP	C340	81 hours, 244 EJ, 197 BIP, 60 gen hr	C340	79 hours, 400 EJ, 180 BIP, 59 gen hr		
1998	CHEY	62 hours, 1880 EJ, 107 BIP	C340	68 hours, 134 EJ, 199 BIP, 29 gen hr	C340	59 hours, 9 EJ 190 BIP, 48 gen hr		
1997	CHEY	70 hours, 1828 EJ, 62 BIP	C340	58 hours, 264 EJ, 128 BIP, 26 gen hr	C340	60 hours, 284 EJ, 166 BIP, 32 gen hr		
1996	CHEY	62 hours, 2128 EJ, 143 BIP	C340	46 hours, 895 EJ, 192 BIP, 9 gen hr	C340	52 hours, 794 EJ, 207 BIP, 23 gen hr		

Table 6. Cloud seeding pyrotechnic and seeding solution usage by aircraft, through the 2018 season.

Seeding was conducted on the following 26 days in 2018: June 1st, 9th, 15th, 16th, 21st, 22nd, 23rd, 29th, and 30th; July 1st, 2nd, 3rd, 6th, 8th, 10th, 13th, 18th, 19th, 21st, 23rd, 26th, and 30th; August 1st, 2nd, and 12th, and September 11th.

All five aircraft were used for operations (seeding and/or patrol) on the following 8 days (local time) this season: June 9th, July 1st, 6th, 13th, 18th, and 30th, and August 1st and 2nd. Patrol flights were flown on June 3rd, 4th, 9th, 22nd, 25th, and 30th; July 1st, 6th, 10th, 18th, 19th, 20th, 21st, 23rd, 24th, 30th, and 31st; August 1st, 3rd, and 11th; and September 10th. Again, flight operations are summarized in Fig. 34 and 37.

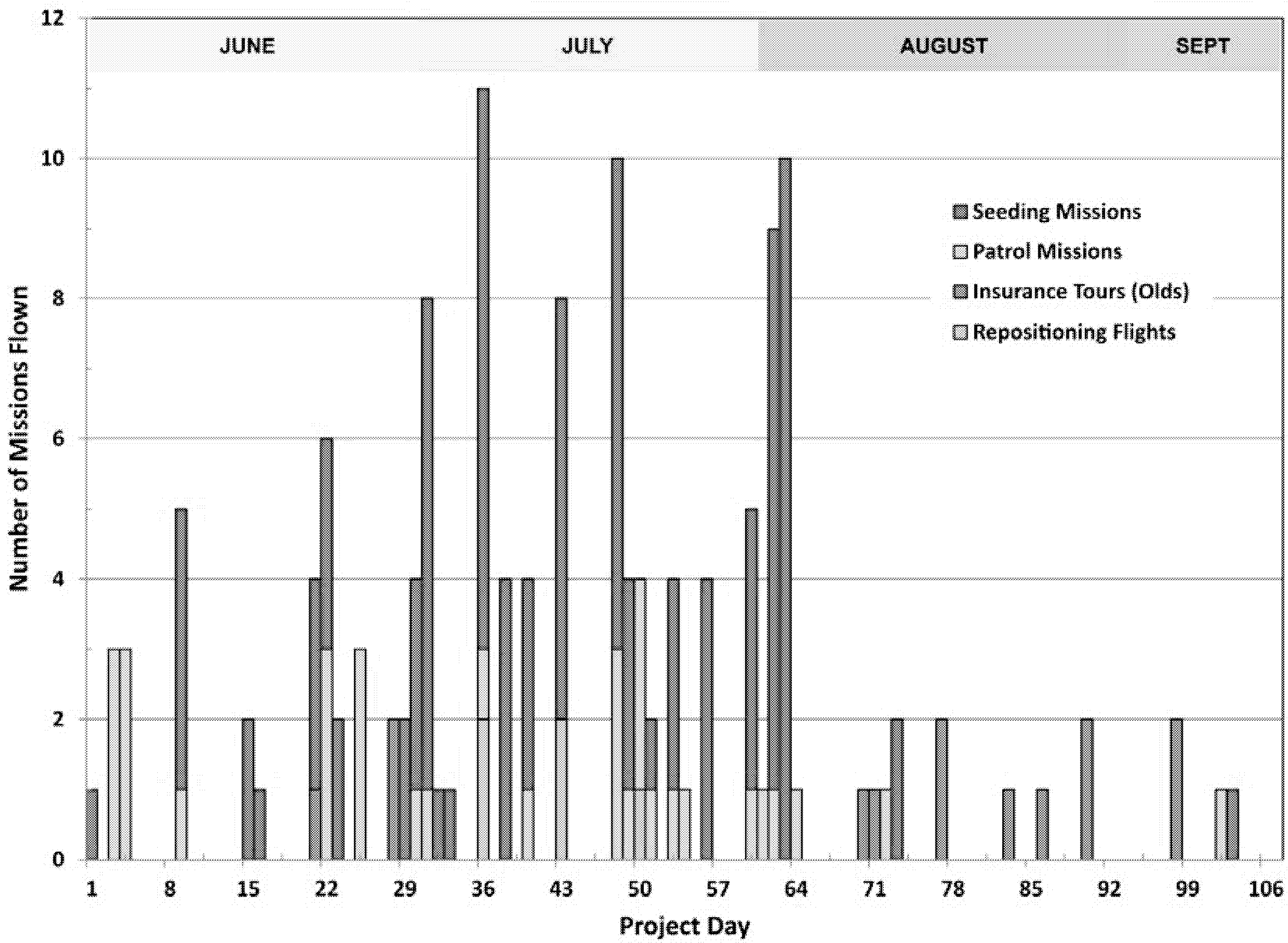


Fig. 37. The number of flights, by type, is shown for each project day of the 2018 season. Months are shown at the top of the graphic. The "Insurance Tours" flights were those made to the Operations Centre at the Olds-Didsbury Airport for the seven continuing education training sessions certified by the Alberta Insurance Industry. For two of the seven tours, the aircraft stayed at the Olds-Didsbury Airport overnight because the air was too hot to permit safe takeoffs due to density altitude considerations, or because visibility at the Red Deer Regional Airport was below minimums due to smoke. This was anticipated and posed no ramifications for operations.

10.3 STORM TRACKS

A map of all hailstorm tracks (representative of grape-size hail (1.3 cm diameter) and larger, determined by radar (VIL>30 kg/m^2) during 2018 is shown in Fig. 38. July was the stormiest month, which is the climatological normal. There were seven storms that tracked across or within the city limits of Calgary during the 2018 season. The central portion of the protected area experienced significantly fewer storms than the north or the south, apparently by natural chance. The most damaging storm of the season occurred on August 2nd. This storm day is reviewed in detail later in this report.

The number and distribution of storm tracks during 2018 were similar to previous seasons, with July once again easily being the most active month. Activity waned sharply after August 2nd. Only one seeding mission and one patrol flight were flown in September.

The plotted storm tracks shown in Fig. 38 include more than just start and end points when storms turned appreciably during their lifetimes. This gives a better indication of storm behavior.

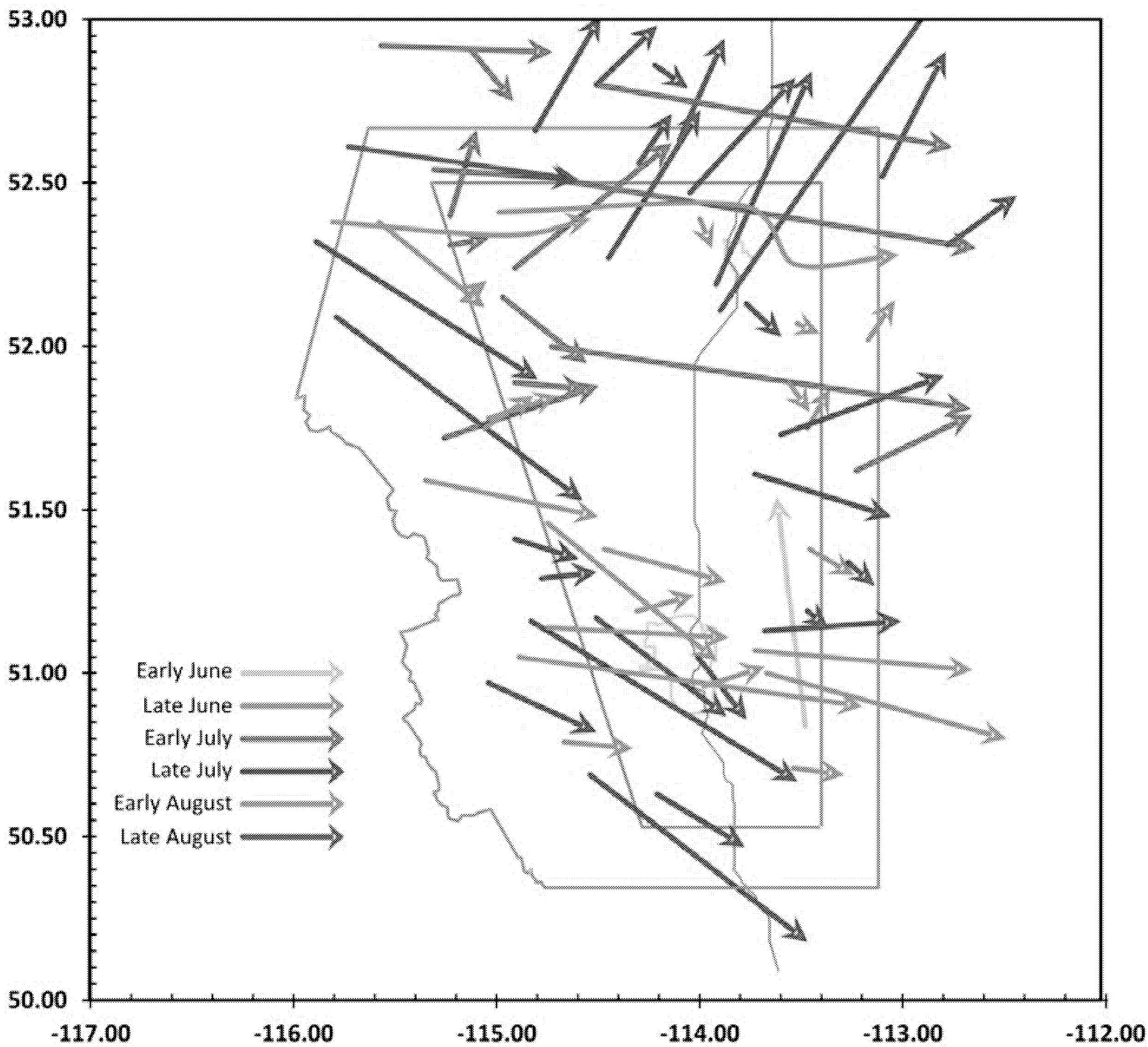


Fig. 38. All potential hailstorm tracks within the operations area during 2018 are shown. Tracks shown are those having a minimum vertically-integrated liquid (VIL, from the radar) of at least 30 kg/m^2, which corresponds to grape-sized hail and larger. This map does not show all of the 77 storms seeded because some are very sheared (they lean a lot) and VIL is less because the storm wasn't "vertical". Other, unseeded storms of hail potential that did not move near cities or towns are shown. All storms must be carefully monitored because, as the tracks show, direction of movement sometimes changes. June storms are green, July red, and August blue. September tracks are not shown because no storms having the requisite VIL minimum occurred.

Hail was reported within the project area (protected area and buffer area) on 41 days. Larger than golf ball size hail was reported near Bowden on July 13th and on August 2nd in southeast Calgary.

Golf ball size hail was reported or observed by radar signature on July 1st in Didsbury, July 23rd in southwestern Calgary, and in Langdon on the 1st of August.

Walnut size hail was reported or observed by radar signature on June 9th in Irricana, in Olds on July 18th, on July 20th in Rimbey, southwest of High River on July 24th, and at the Springbank airport on July 30th.

11. WEATHER FORECASTING

A project forecast was prepared each operational day throughout the project period by the assigned project meteorologist. In addition to the real-time information available from the project radar at the Olds-Didsbury Airport, the forecasting meteorologist used local weather observations as well as a vast array of weather data available on the internet.

11.1 COORDINATED UNIVERSAL TIME

The standard reference time chosen for the project field operations is universal time coordinates (UTC), also known as coordinated universal time (CUT), or Greenwich Mean Time (GMT). This is the accepted international standard of time for general aviation and meteorological observations, reporting, and communication. In Alberta, UTC is 6 hours ahead of local Mountain Daylight time. For example, 12:00 noon local Alberta time is equal to 18:00 UTC, and 6:00 PM local is equal to 24:00 or 00:00 UTC. This may cause some confusion with non-project personnel, since many of the thunderstorms occurred late in the day and continue beyond 6:00 PM local time, which is midnight or 00:00 hours UTC. The standard convention incorporated by the Alberta project is to report all aircraft, radar, and meteorological times in UTC; however, for convenience the summary tables are all organized according to the local calendar "storm" day with respect to Mountain Daylight Time.

11.2 PURPOSE

The primary function of the daily forecast is to impart to project personnel a general understanding of that day's meteorological situation, particularly as it relates to the potential for hail-producing storms. In this role it is useful, but because the data in hand are limited in temporal and spatial resolution, and because the forecasters themselves are human and thus fallible, the forecast can never be taken as the final word as to whether activity will or will not develop. Forecasts of no or limited convective activity do not relieve any project personnel of their hail-fighting responsibilities, and should not reduce vigilance or readiness of meteorological staff or flight crews. In theory, the project could function effectively without project forecasts. In practice, the forecasts are useful for a number of reasons:

- Elective maintenance of project-critical facilities (radar and aircraft) can be conducted on days when the probability of workable storms is less.
- Forecasts offer insight regarding the time at which convection is likely to initiate, thus allowing some intelligence in handling decisions about aircraft standby times.
- Preferred areas, e.g. northern, central, or southern portions of the protected area that are more prone to see action are identified in the forecasts, providing the logical basis for assignment of which aircraft are initially placed on standby.
- Forecasts attempt to quantify the available atmospheric instability, and thus the likelihood of explosive cloud/storm development. Days having high potential for rapid cloud growth require more immediate action.

Post-hoc forecast verification conducted by the meteorologists is a helpful tool to increase our understanding of Alberta thunderstorms, especially the atmospheric indicators (precursors) in the pre-storm environment. As this knowledge improves, so will our ability to anticipate and react to the initial deep convection.

So, while in theory the forecasts are not needed, they are useful and considered to be essential. The ultimate defense against the unexpected, unforecast, explosively-developing severe storm would be to always have aircraft airborne, patrolling the skies, scanning for the first sign of intense vertical cloud growth. More realistically, one might have flight crews constantly waiting, ready to scramble. The funding available for the project does not allow either of these, however, so the forecast becomes the primary tool through which the available resources can be allocated in the most effective manner.

It is also worth noting that even when equipment and personnel work together efficiently as a well-oiled, smooth-running machine, hail damage can still occur. A typical thunderstorm releases as much energy in its lifetime as a nuclear bomb. Cloud seeding can affect the microphysical (precipitation) processes, but we do not yet have the knowledge or tools to affect the energy released. Nature, in the end, sometimes offers more than can be handled.

11.3 CUSTOMIZED NUMERICAL MODELING

In early 2017, WMI began developing Weather Research and Forecasting model (WRF) domains to provide customized numerical modeling support for its cloud seeding operations. In this, the 2018 season, WMI expanded this effort to include the Alberta Hail Suppression Project. A convection-resolving high-resolution WRF (Weather Research and Forecasting model) domain was created covering south-central Alberta, and a suite of customized graphics and numerical weather prediction products were developed to explicitly help forecast convection and weather hazards important to the AHSP. Model runs were initiated two or three times per day (depending on the weather pattern) for a 48-hour forecast period. Table 7 summarizes information pertinent to this summer's WMI WRF operation. Some additional model settings and parameterization choices are detailed in Table 8.

WRF Version	Horizontal Resolution	Domain Size	Grid Center	Time Step	Model Initialization	Boundary Conditions
3.9.1	3km	540x540 km	51.8N 115.0W	Adaptive	NAM; with digital filter initialization	NAM

Table 7. The Weather Research and Forecasting (WRF) numerical model specifications and settings used by WMI for the AHSP in 2018 are shown.

Boundary Layer	Cumulus	Land Surface	Microphysics	Shortwave Radiation	Longwave Radiation
Yonsei (1)	None	NOAH LSM (2)	Thompson Aerosol-Aware (28)	Dudhia (1)	RRTM (1)

Table 8. Some additional model parameterization choices for the 2018 AHSP WMI WRF are given. They are included for those familiar with model parameterizations who will want to know.

WMI pursued development of its own in-house modeling capability for several reasons. First, it provides high-resolution numerical weather prediction information for our projects, anywhere in the world. This is extremely useful in regions outside the United States, where high-resolution model information may not exist or may be difficult or costly to access. Second, by establishing a unique WRF domain for the project area, a deep level of model customization can be employed. This customization can include changing all of the following:

- default parametrization schemes,
- initialization data sets, and
- domain settings.

This in turn results in model output customized to best prognosticate meteorological features of greatest importance to the project objectives. Finally, the internal execution of the WRF model opens unparalleled opportunities for customized, post-processed graphics to be created. These graphics can be overlaid with the project area boundaries and selected geopolitical features to give project personnel and clients a clearer understanding of where and when meteorological events are projected to occur in and around the project area. For example, on the evening of July 23, 2018, when greater-than-Loonie size hail was reported in southwestern Calgary, a WRF run initializing at almost 24 hours prior correctly identified a strong thunderstorm very near Calgary within an hour of when it in fact verified (Fig. 39). While such an accurate high-impact verification event is not yet the norm, the mere indication that there may be a powerful convective threat near Calgary with nearly a twenty-four hour lead time was beneficial to project personnel planning, and anticipating upcoming operations.

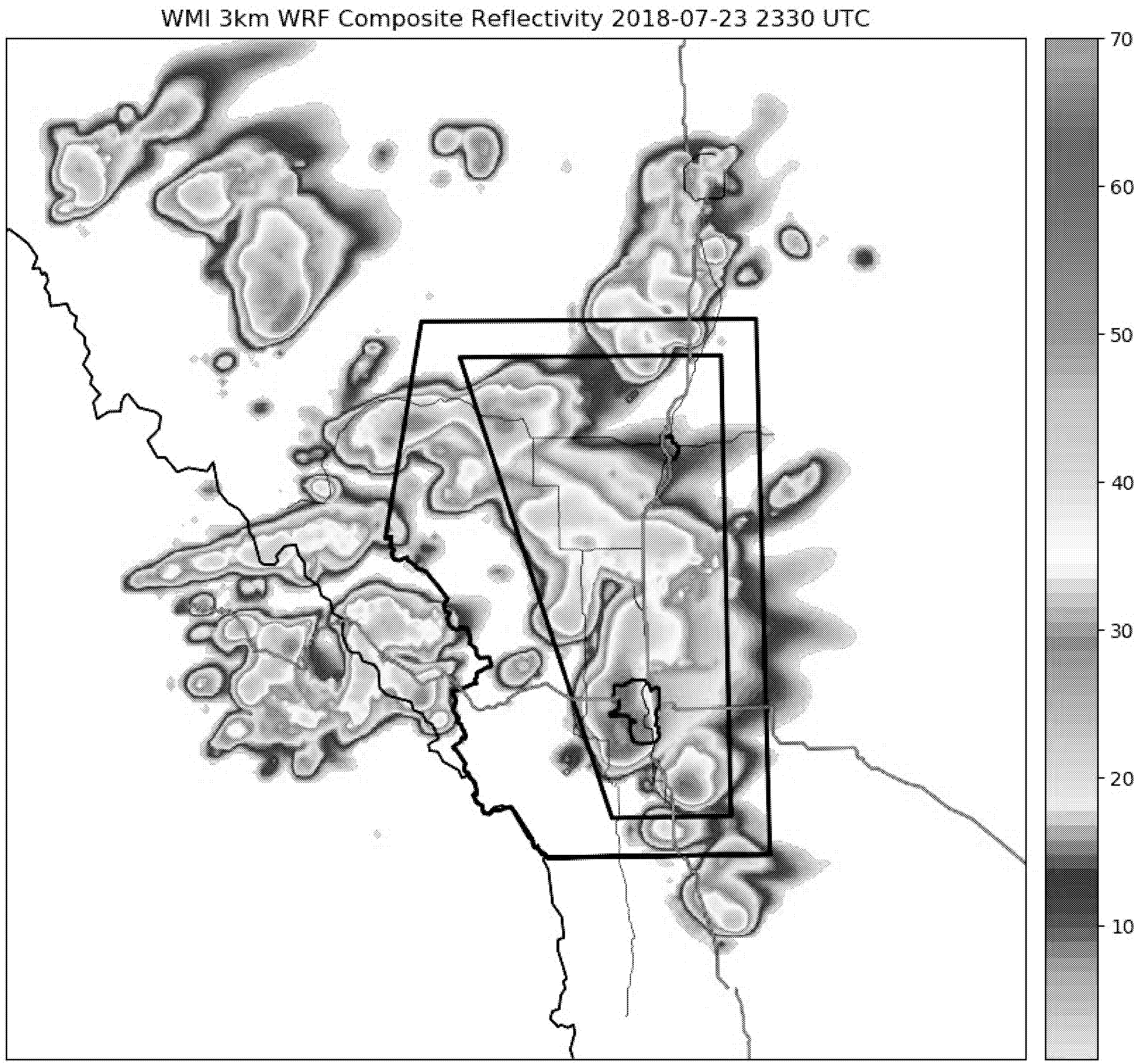


Fig. 39. The WMI WRF model run initialized at 0:00 UTC (6 PM) on July 22nd predicted severe thunderstorms over Calgary for the evening of July 23rd. Greater-than-Loonie size hail was reported in southwestern Calgary on the 23rd, about 24 hours later!

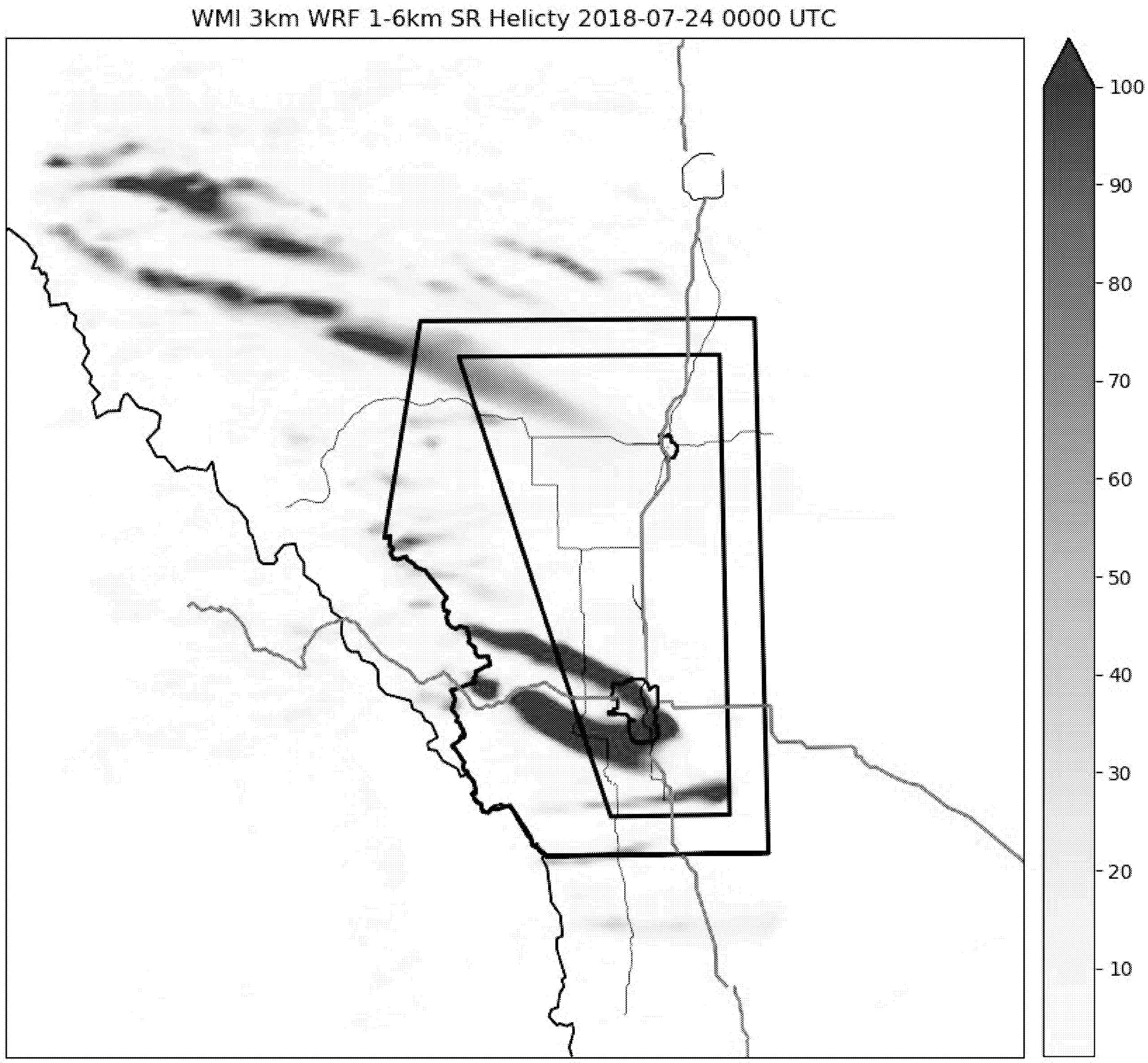


Fig. 40. An example of a project-specific prognostic chart not otherwise available is shown here. Depicted is the 1-6 km layer, storm-relative (SR) helicity (storm-scale rotation) map. This graphic, which shows the highest SR helicity in a twenty-four hour period, illuminates where the strongest rotating thunderstorms (supercell storms) were expected to develop on the July 23rd storm day. The strongest, most intense supercell thunderstorms were expected to be in and around Calgary.

Another custom product, showing storm-relative helicity (atmospheric spin in the mesoscale) is provided in Fig. 40. The meteorogram, also generated from the WMI WRF, is a time-series of meteorological parameters (Fig. 41). As aviation weather concerns are extremely important to the safety and efficiency of the program, a custom designed meteorogram of aviation-pertinent weather information is created for our project airports.

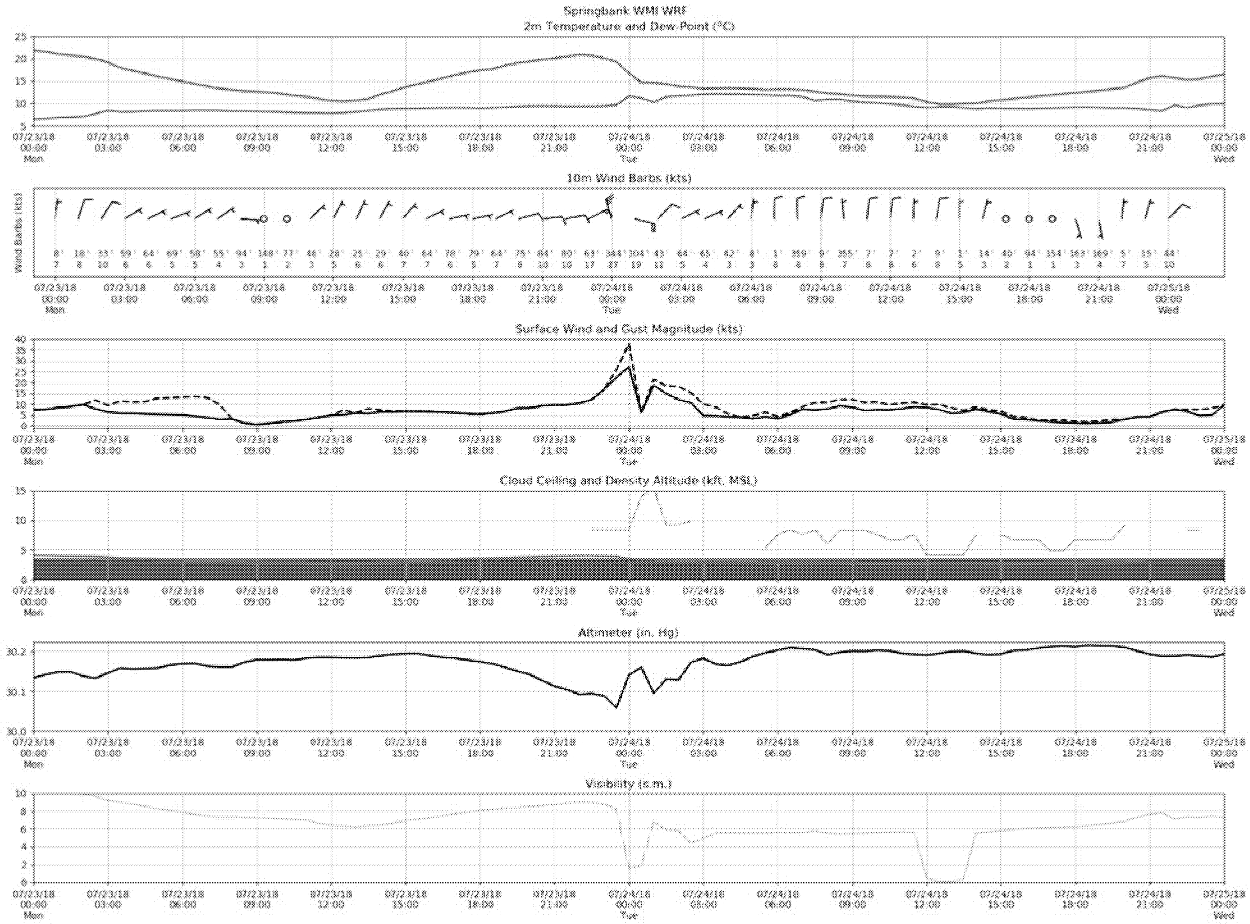


Fig. 41. This meteorogram for the Springbank Airport provides time-series graphics depicting an assortment of relevant meteorological parameters. The content of each time-series is shown centered above the plot. From top to bottom, the parameters are: temperature and dew point, near-surface (10 m) wind speed and direction, surface winds and gusts, ceiling (elevation of cloud base) and density altitude, altimeter setting (a surrogate for pressure), and visibility.

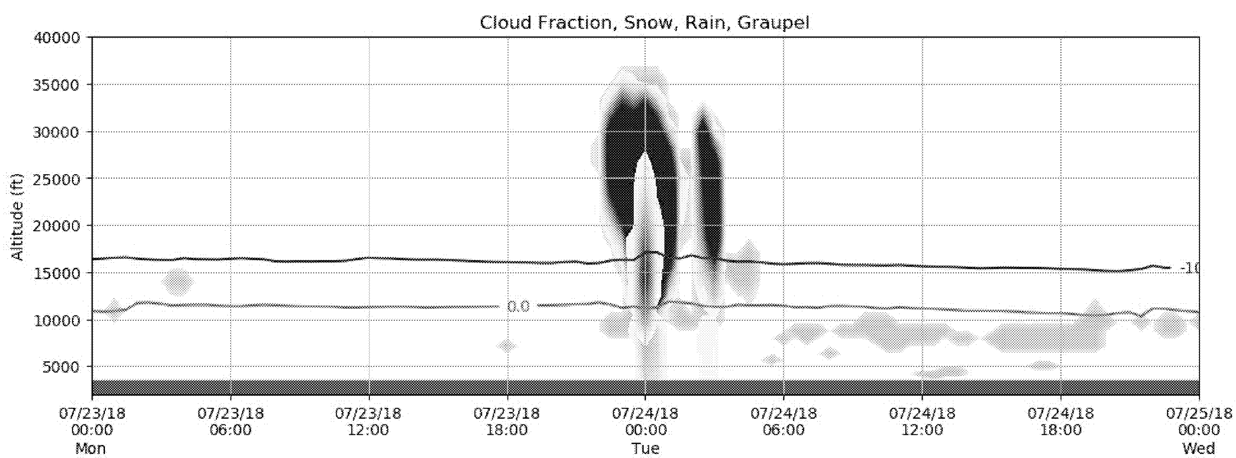


Fig. 42. Shown here is another time-series plot of cloud fraction (snow, rain, and graupel). Time is shown in the x-axis, while height is shown on the y-axis. This plot shows where the model believes cloud layers, rain, graupel/ice, and even snow will exist. The 0°C and -10°C isotherm heights are also shown (in red and blue respectively) for the 48-hour duration of the model.

11.4 PROCESS AND DISSEMINATION

Project forecasts were valid from 6:00 AM forecast day through 6:00 AM the next day, and also included a day-two outlook. The daily forecast preparation began with an assessment of the current weather conditions. The latest METARs (hourly surface weather reports), weather station data, radar and satellite imagery were noted and saved. The latest surface and upper air analysis maps were printed and saved. All data were saved with file names that utilize the proper WMI file naming procedures, with YYYYMMDD (year-month-day) at the beginning of the file name. Once the forecaster had a grasp of the current conditions, outside agency forecasts were examined in order to give a first-best-guess of the day's probable events. Often times, project personnel would request a "pre-forecast" before the official forecast is ready. NAV Canada, Environment Canada forecasts and BUFKIT soundings are always useful for this purpose.

The forecaster then examined the various operational prognostic model output. Typically, the WRF was the most up to date model in the early morning. All forecasters had their own preference for operational models, but some of the choices available include the WRF/NAM, GFS, ECMWF, SREF and the Canadian models. Model data were archived daily (but not printed) for the 250 mb, 500 mb, 700 mb, and surface pressure surfaces. Saved maps include the most current map (usually 12Z) through hour 48. Certain features are always of interest at certain levels:

- The 250 mb level best reflects the location of the upper jet stream winds, around 35,000 feet altitude. This map was analyzed for the general wave pattern (ridge/trough), upper level diffluence, and jet streaks. The right entrance and left exit quadrants of an upper jet streak are considered favorable regions for enhanced upward motions. Storm days with "upper support" tend to produce more vigorous convection than days without.

- The 500 mb level reflects the middle (pressure-wise) of the atmosphere around 18,000 feet, which is generally the boundary between upper- and lower-level weather features (aka: the level of non-divergence). The 500 mb charts were examined for temperatures, humidity, wave pattern, and especially vorticity (rotation). Advection of 500 mb vorticity from broad scale troughs, lows, or shortwaves tends to cause air to rise. This can be a trigger to help break through low level temperature inversions, or just simply enhance the amount of vertical motion in the atmosphere. Cold, dry conditions at this level are often indicative of an unstable atmosphere. Many convective stability indices utilize temperature and dew point between the surface and 500 mb. History shows that some of the worst Alberta hail storms occurred on days with only moderate instability but with strong 500 mb vorticity advection and upper jet support.

- 700 mb is the lower to mid-level of the atmosphere around 10,000 feet, usually near the height of the convective cloud base. The 700 mb charts are most typically used to determine the amount of low level moisture over a region. Lots of 700 mb moisture contributes to unstable atmospheres. Relative humidity, theta-E (equivalent potential temperature), and vertical velocity charts are all useful tools at this level. Shortwave troughs are sometimes evident on 700 mb vertical velocity charts when they are not easily identified at 500 mb. The presence of a theta-E ridge at or below 700 mb should be a red flag that nocturnal convection is possible. The 700 mb charts are also be analyzed for the presence of inversions or "caps" that inhibit surface-based convection, although this is usually more easily identified on a sounding than on a map.

Surface prognostic (forecast) charts (progs) were analyzed for the presence of lifting mechanisms such as troughs, lows, fronts, and dry lines. Such lifting mechanisms are triggers for initiating thunderstorms when the atmosphere is unstable. Moist, warm surface conditions are indicative of an unstable atmosphere. After sunset however, the lowest levels of the atmosphere tend to "decouple" from the upper and middle atmosphere as the air mass cools from the bottom up. This means that surface temperature and moisture are most important during the daytime and evening hours and can have less impact at night. It is a good idea to consult multiple sources for surface prognostic charts, as some analyses will omit important features. There can be major differences from one source to the next when it comes to surface analysis and timing. In general, surface dew points greater than 9°C are considered sufficient for large hail storms. Thunderstorm development becomes unlikely with dew points less than 5°C. Surface charts may also be utilized to determine areas with upslope flow. Low-level easterly winds flowing up the eastern slopes of the mountains are frequently the cause for storm initiation for the project.

After all model charts were saved, the forecaster created a daily meteorogram. This is a one-page graphic that includes multiple strip charts of the forecaster's choosing. Typical parameters for the meteorogram include temperature and dew point, cloud cover, wind direction/speed, CAPE, lifted index, convective inhibition, etc. The meteorogram is typically created for both Calgary and Red Deer every morning, but other locations can be utilized depending on where the forecaster thinks the best chance for deep convection (thunderstorms) will occur on that day. The meteorogram is printed and saved in the archives. The strip charts are valid through at least three days and can be a great tool for determining the extended outlook.

The next step was to create a daily sounding, or Skew-T diagram. Unfortunately, the closest real weather balloon (sounding) site is Edmonton, which is too far away to use for forecasting in the project area. Forecast soundings from the numerical models were thus preferred, which could be generated through a host of different internet sources.

The 12Z and 00Z WRF/NAM soundings were archived for both Red Deer and Calgary on a daily basis. These data were also utilized for running the HAILCAST model when necessary. The forecaster chose a location and valid time for the daily forecast soundings used in the forecasts. The sounding disseminated with the forecast was the one for the time and place with the worst-case scenario for the highest CDC (Convective Day Category) through the next 24 hours, typically Red Deer or Calgary. Most forecasts were made based on expected conditions at 00Z because the atmosphere is usually most unstable around that time, in the late afternoon. However, this may be sooner or later depending on the timing of surface features, etc. Once the sounding place and time were decided, the selected forecast sounding was analyzed with the RAOB software and modified as deemed physically plausible, to define a worst-case scenario (most intense convection possible). This often involved raising or lowering the surface temperature to best represent the expected maximum temperature for the day. The amount of surface moisture could be modified as well, but this was done with care so as not to overdo it. This has a large effect and can be the cause of busted forecasts. Once the sounding was modified, all convective parameters were recorded on the daily *metstats* sheet, and the sounding was printed. An image of the sounding was always saved, and was also included on the daily forecast sheet.

The forecaster then completed the daily forecast as a digital pdf document. Included in the daily forecast were mandatory level charts for the chosen valid time including: 500 mb height analysis for position of any shortwaves or vorticity lobes, surface analysis (including fronts, lows, highs, troughs, and dry lines), position of upper jet streaks at 300 mb, and 850 mb theta-e (equivalent potential temperature) to identify presence of low level moisture. The text body of the forecast appeared in two main sections including a synopsis of the overall weather features, and a section describing the expected weather through the next morning. The rest of the forecast thermodynamic parameters were taken directly from the modified sounding and were identical to the forecast sounding diagram that was also included in the forecast. The forecast sheet also includes a checklist to remind the forecaster not to inadvertently overlook any important weather features.

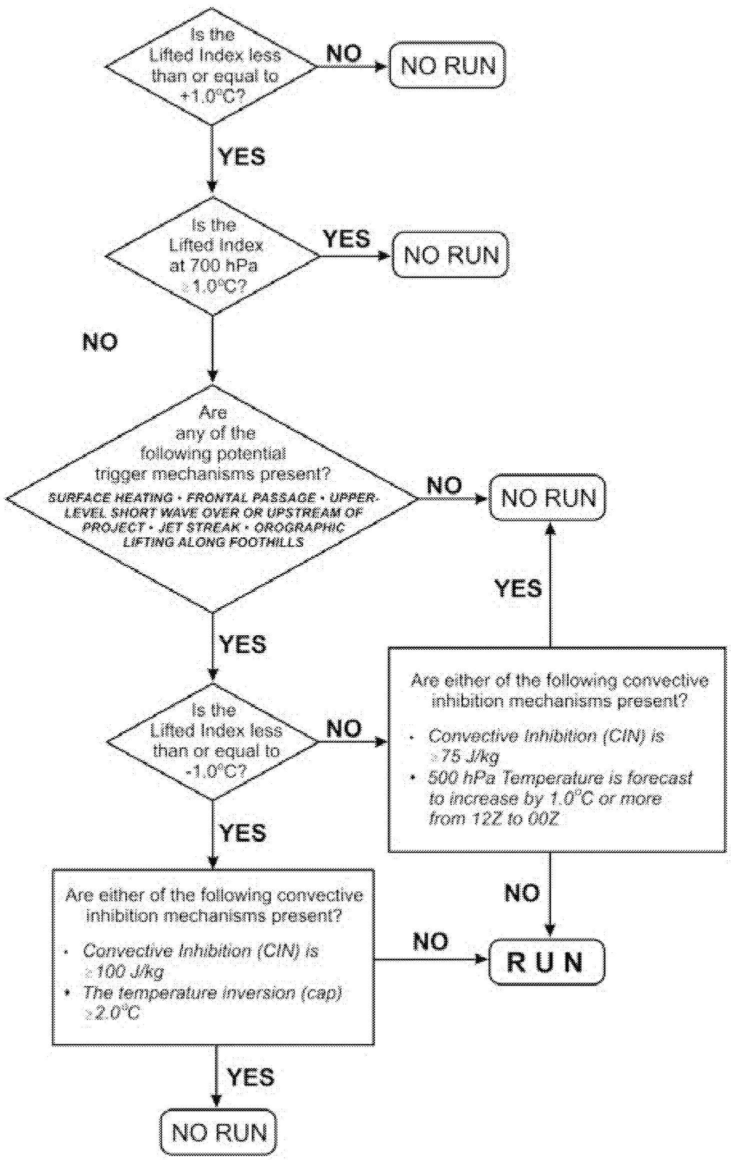


Fig. 43. Hailcast run/no-run flow chart.

Before making the final decision about the likelihood and size of hail, the forecaster sometimes needed to run the HAILCAST model (Brimelow *et al.,* 2006). To determine whether to run the model, a decision tree is used (Fig. 43). Research has shown that the model works well in many conditions but has been found lacking under certain scenarios. The decision tree is meant to remove situations where the model is not helpful. If the model is to be run, the forecast sounding data were modified to the required HAILCAST input format and saved as text files in the appropriate folder. The model was then run with the expected high temperature and dew point for the day. The average output from the models is included in the forecast.

Finally, the decision was made as to the Convective Day Category (CDC). This was the last decision before the forecast was sent out to project personnel. The CDC was marked on the forecast sheet, and the sheet scanned and saved according to WMI file-naming procedures. It was then emailed to the forecast recipients through the company email exchange using the Olds radar email account. The subject line of the email uses the format "YYYYMMDD AB forecast". The forecaster attached the forecast pdf file to the email and sent it at 10:45 local time, or about 15 minutes prior to the daily briefing.

11.5 DAILY BRIEFINGS

All project staff participated in a "GoToMeeting" visual weather briefing with full video support each day at 11:00 AM (local time). Teamwork depends on good communications, and so all personnel were required to attend the daily briefing at one of three locations: the radar, the Springbank Airport office, or the Red Deer Airport office. This briefing included a debriefing and summary of the previous day's operations (if any), discussion of the weather situation, presentation of the weather forecast and operational meteorological statistics, predicted hail threat, cloud base heights and temperatures, upper level winds, storm motion, equipment status reports, and operational plans for the day. After the briefing, crews were put on telephone standby or asked to remain at the airport on standby. All personnel were equipped with cellular telephones to allow quick access and constant communications, day or night.

If no seeding was expected within the next few hours after briefing (i.e. clear skies), flight crews were put on telephone standby. If operations were likely within the next few hours or actively growing cumulus were present, then crews were put on Airport Standby immediately following the briefing. During briefing, one crew at each site was always designated as "first up" or the first aircraft to be called if needed. Weather conditions and aircraft maintenance dictated which crews will be first up on any given day. If ceilings were very low, top seeders were designated as first up. If an aircraft was scheduled for maintenance, even if routine, then it would not be first up since it may have delays in launch time. When not on airport standby, crews were on telephone standby (maximum 60 minutes from airport) at any time unless other arrangements have been made after consulting with the project manager or meteorologists.

11.6 THE CONVECTIVE DAY CATEGORY (CDC)

The daily weather forecast established the Convective Day Category (CDC) that best described the conditions that were expected for each day. The CDC (Strong 1979) is an index that gives the potential for hailstorm activity and thus seeding operations. A description of the weather conditions for each CDC is given in Table 9. The distinction between the -2 and -1 category is sometimes difficult, since overcast or prolonged rains eventually break up into scattered showers. The maximum vertically-integrated liquid (VIL) recorded by TITAN is used 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). This may have increased the number of declared hail days from the early project years, which relied on a human report of hail fall at the surface; however, it is believed to be a more realistic measure of hail. The +1 category minimum hail size is assumed to be 5 mm since this is a common minimum size for hail used by numerical modelers, and also the recognized size threshold for hail. Smaller ice particles, those less than 5 mm diameter, are generally called snow pellets or graupel.

Various meteorological parameters were also forecast in addition to the CDC. These parameters were used in developing a seeding strategy and were passed on to pilots during the weather briefing. The meteorological parameters were recorded each day and archived for future analysis.

The Convective Day Category

CDC	Description	Verification
-3	Clear skies, fair weather cumulus, or stratus. No rain.	All echoes weaker than 30 dBz.
-2	Nimbostratus or weak embedded convection. No TITAN cells.	Rain and/or echoes ≥30 dBz.
-1	Discrete convective cell(s) and/or towering cumulus. May or may not reach TITAN cell criteria. No threat of hail. No lightning.	Discrete convection, TCU, or TITAN cell.
0	Thunderstorm(s) but no hail. VIL < 20 kg/m^2 inside the project area or in the north, east, or south buffer zones.	Lightning observation.
+1	Thunderstorm(s) with pea size hail (0.5 to 1.2 cm diameter).	Hail report and/or VIL between 20 and 30 kg/m^2.
+2	Thunderstorms with grape size hail (1.3 to 2.0 cm diameter).	Hail report and/or VIL between 30 and 70 kg/m^2.
+3	Thunderstorms with walnut size hail (2.1 to 3.2 cm diameter).	Hail report and/or VIL between 70 and 100 kg/m^2.
+4	Thunderstorms with golf ball size hail (3.3 to 5.2 cm diameter).	Hail report and/or VIL greater than 100 kg/m^2.
+5	Thunderstorms with greater than golf ball size hail (>5.2 cm diameter).	Hail report.

Table 9. The Convective Day Category (CDC).

11.7 METEOROLOGICAL STATISTICS

A complete listing of the daily meteorological statistics is given in Appendix I. A summary of the important daily atmospheric parameters used as inputs for the daily forecast of the CDC and threat of hail is given in Table 10. Hail days are defined by either a report of hail at the surface or by a vertically-integrated-liquid water (VIL) measurement from the radar of at least 20 kg/m^2.

The statistics exclusively for hail days are provided in the rightmost four columns of Table 10. Table 10 reveals what one would expect: hail is more common when moisture (precipitable water) is greater, when stability is less (Lifted Index), and when convective available potential energy, or CAPE, is greater.

Summary of Daily Atmospheric Parameters

Parameter	For All Days (107)				For Hail Days Only (41)			
	Avg	StdDev	Max	Min	Avg	StdDev	Max	Min
Forecast CDC	0.1	2.1	4	-3	2.0	1.2	4	0
Observed CDC	-0.1	2.1	5	-3	2.2	1.0	5	1
Precipitable Water (inches)	0.7	0.2	1.2	0.4	0.8	0.2	1.2	0.5
0°C Level (kft)	11.3	2.2	16.5	3.7	11.1	1.9	15	7.7
-5°C Level (kft)	13.7	2.3	18.9	5.5	13.5	2.0	17	9.6
-10°C Level (kft)	16.3	2.3	21.3	11.4	16	2	19.2	11.8
Cloud Base Height (kft)	9.9	2.8	22	4.2	8.7	2.3	17.4	5.4
Cloud Base Temp (°C)	3.2	4.6	11.6	-14.3	5.8	3.6	11.6	-6
Maximum Cloud Top Height (kft)	27.9	8.5	40.2	4.2	32.3	4.3	38.8	24
Temp. Maximum (°C)	21.7	5.9	35	2	21.4	4.9	31.5	13
Dew Point (°C)	7.8	3.5	15	0	9.8	3	15	3.5
Convective Temp (°C)	21.8	7	40	1.7	20.7	5.4	33.8	13
Conv. Avbl. Potential Energy (J/kg)	481.2	503.9	2536	0	862	551.5	2536	174
Total Totals	52.4	4.3	61.9	39.7	55.4	2.7	61.9	48.9
Lifted Index	-1.4	2.8	10	-8	-3.3	1.7	-1	-8
Showalter Index	-0.7	2.9	11	-7.8	-2.7	1.8	0.9	-7.8
Cell Direction (deg)	253	77	350	1	244	73	350	31
Cell Speed (knots)	20.8	9.5	55	1	20.3	10.3	55	7
Storm Direction (deg)	256	98	357	5	251	96	343	14
Storm Speed (knots)	13.5	6.7	36	2	12.8	7.3	36	2
Low Level Wind Direction (deg)	252	73	354	3	242	77	354	34
Low Level Wind Speed (knots)	14.7	7.5	45	2	14.4	7.1	45	2
Mid-Level Wind Direction (deg)	251	78	354	2	249	70	347	12
Mid-Level Wind Speed (knots)	25.1	12.6	68	4	23.7	14.9	68	4
High Level Wind Direction (deg)	245	71	356	9	250	45	327	50
High Level Wind Speed (knots)	46.1	25.2	106	3	44.1	26.7	97	3

Table 10. Summary of Daily Atmospheric Parameters.

Though a CDC of +5 was never forecast in 2017, two +5 days occurred. On both days, the forecast CDC was +4. The forecasting for the season is examined in greater detail in the following section.

11.8 FORECASTING PERFORMANCE

The following tables indicate the forecasting performance for the summer season with respect to the forecast and observed weather conditions as defined by the "Convective Day Category" or CDC within the project area. A CDC greater than zero indicates hail. The forecasts were verified by the weather observations as reported by Environment Canada, crop insurance reports received from the Agriculture Financial Services Corporation in Lacombe, and also by public reports of hail in the press, radio, television, and social media, as well as by the reports from project personnel. The Vertical Integrated Liquid (VIL) radar parameter was also used as a verification tool, but secondary to actual hail reports. The CDCs forecast compared to those actually observed in 2018 are summarized in Table 11.

		Observed Days		
Forecast Days		***No Hail***	***Hail***	***Totals***
	No Hail	53 [49.5%]	3 [3%]	56 [52%]
	Hail	13 [12%]	38 [35.5%]	51 [48%]
	Totals	66 [62%]	41 [38%]	107

Table 11. Comparison of CDCs Forecasts & Observations.

In 2018, hail fell within the project area on 41 of 107 days (38%), leaving 66 days without hail (62%). The forecast was correct in forecasting "hail" on 38 of the 41 observed hail days (93%) and failed to forecast hail on 3 hail days (7%). Of the three "misses" (days on which hail occurred but was not forecast) the hail was very small (CDC of +1) for two of them, and CDC of +2 for the third. On all three of the small-hail "miss" days, the forecaster predicted CDCs of zero. The forecast was correct in forecasting "no-hail" on 53 of 66 observed no-hail days (80%). The forecasters incorrectly predicted hail (false alarms) on 13 of the 66 days when no-hail was observed (20%). The WMI meteorologists did an excellent job with forecasting large hail in 2018 and missed no damaging hail days.

The Heidke Skill Score (HSS) for WMI this past year (from Table 12) was 0.70, a slight improvement from 0.69 in 2017. The HSS varies from –1 for no skill to +1 for perfect forecasts. The forecasting skill is considered significant if HSS is greater than 0.4, which was again greatly exceeded in 2018.

	2018	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008	2007	2006	2005	2004	2003	2002
POD (Hailcast)	.93	.70	.91	.81	.85	.89	.75	.72	.77	.91	.80	.82	.69	.84	.91	.76	.81
POD (WMI)	.93	.84	.80	.87	.90	.97	.98	.85	.85	.83	.68	.76	.69	.61	.60	.86	.83
FAR (Hailcast)	.21	.24	.20	.39	.19	.15	.22	.21	.31	.29	.35	.30	.31	.45	.47	.56	.34
FAR (WMI)	.25	.20	.15	.26	.19	.18	.23	.13	.14	.13	.20	.11	.14	.18	.30	.16	.33
HSS (Hailcast)	.57	.55	.23	.43	.35	.66	.51	.49	.46	.44	.43	.46	.35	.31	.39	.33	.56
HSS (WMI)	.70	.69	.52	.63	.66	.67	.68	.65	.72	.63	.49	.66	.55	.42	.51	.63	.59
CSI (Hailcast)	.74	.57	.74	.54	.71	.77	.62	.64	.56	.45	.52	.50	.42	.40	.51	.39	.57
CSI (WMI)	.70	.70	.70	.67	.74	.80	.76	.75	.73	.56	.52	.62	.53	.42	.49	.59	.59

Table 12. Probability of Detection (POD), False Alarm Ratio (FAR), Heidke Skill Score (HSS) and Critical Success Index (CSI) performance of Hailcast and WMI from 2002 to 2018.

The Critical Success Index (CSI) is the ratio of the successful hail forecasts divided by the sum of all hail forecasts plus the busts. The CSI does not incorporate the null event (no-hail forecast and no-hail observed), and is also a popular measure of the skill of forecasts. The CSI for WMI this past season was 0.70, the same as in 2016 and 2017.

Comparisons of the CDCs that were forecast and observed on a daily basis are made in Table 13. The exact forecast weather type (CDC) was observed on 59 of 107 days or 55% of the time. The forecast was correct or within one CDC category on 95 days or 89% of the time. There were three days when, according to the radar-estimated VIL, pea or grape size hail was indicated inside the project boundaries when hail was not forecast (not necessarily over a protected city). There was one day when hail as large as golf balls fell that was not well-predicted; pea size hail was forecast that day. Thus, there were no "surprise storms" this season.

The breakdown of CDC values for each of the 23 seasons is shown in Table 14. This year had 10 days on which large (walnut or larger) hail fell; the average is 12. There were 14 large-hail days in 2017. There were 55 thunderstorm days in 2018, (59 in 2017), while 63 is average. Golf ball or larger hail fell on 5 days in 2018; the average is 6 days.

For Table 14 and the other tabulations in this report, the "observed CDC" is taken to be the greater of the hail sizes reported by Environment Canada, and the Agricultural Financial Services in Lacombe, or the hail sizes estimated from the vertically-integrated liquid (VIL) measured by the project radar.

It should be noted that in 2018 the forecasters were either right onor within one CDC category on 95 out of the 107 project days, or 89% of the time. This is the highest accuracy yet achieved on the project.

Observed Convective Day Category (CDC) 2018

Green shading indicates that the forecast and observed CDCs were the same (perfect forecasts).
Gray shading indicates that the observed CDCs were greater than those forecast (underforecasts).
Blue shading indicates that the observed CDCs were less than those forecast (overforecasts).

Forecast CDC \ Observed CDC	-3	-2	-1	0	1	2	3	4	5	Total Days
-3	15		1							16
-2	2	10	1							13
-1	1	2	11	1						15
0		1	4	4	2	1				12
1		1	1	7	4	6		1		20
2	1		1	1	2	12	1			18
3				1		3	2	1		7
4						1	2	1	2	6
5									0	0
	19	14	19	14	8	23	5	3	2	107

Percent correct exact CDC category = 59/107 = 55% (49% in 2017)
Percent correct within one CDC category = 95/107 = 89% (82% in 2017)

Table 13. Forecast vs. Observed CDCs, 2018.

Summary of 2018 Observed Convective Day Categories (CDCs)

	DAYS WITH NO SEEDING			Thunder But No Hail	DAYS WITH HAIL (maximum hail size)					
	Mostly Clear Skies	Clouds, Virga	Showers		Pea	Grape	Walnut	Golf Ball	>Golf Ball	
Season	**CDC -3**	**CDC -2**	**CDC -1**	**CDC 0**	**CDC 1**	**CDC 2**	**CDC 3**	**CDC 4**	**CDC 5**	**Totals**
1996	27	21	12	11	5	12	3	1	1	93
1997	7	19	6	28	19	11	3	0	0	93
1998	14	24	2	29	23	8	2	4	1	107
1999	21	18	8	24	22	10	2	1	1	107
2000	13	21	8	26	18	9	2	9	1	107
2001	20	4	19	18	19	18	5	4	0	107
2002	27	8	20	16	15	17	3	1	0	107
2003	24	7	20	28	8	12	2	5	1	107
2004	11	4	28	29	15	11	3	5	1	107
2005	13	13	22	28	17	9	1	2	2	107
2006	19	14	15	24	19	5	6	3	2	107
2007	15	17	15	26	17	8	5	2	2	107
2008	15	7	10	34	17	15	2	6	1	107
2009	22	11	10	41	15	2	3	2	1	107
2010	3	10	9	37	11	27	8	1	1	107
2011	15	5	14	8	7	22	20	15	1	107
2012	8	7	22	14	4	16	12	22	2	107
2013	17	7	6	12	9	34	10	10	2	107
2014	11	9	22	7	11	19	6	18	4	107
2015	8	11	24	18	16	16	6	6	2	107
2016	8	6	9	15	25	29	9	2	4	107
2017	23	6	19	15	9	21	10	2	2	107
2018	19	14	19	14	8	23	5	3	2	107
Totals	**360**	**263**	**339**	**502**	**329**	**354**	**128**	**124**	**34**	**2433**
Average	**16**	**11**	**15**	**22**	**14**	**15**	**6**	**5**	**1**	
Maximum	**27**	**24**	**28**	**41**	**25**	**34**	**20**	**22**	**4**	
Minimum	**3**	**4**	**2**	**7**	**4**	**2**	**1**	**0**	**0**	

Table 14. Seasonal Summary for 2018 of Observed Convective Day Categories (CDCs).

11.9 THE HAILCAST MODEL

The Hailcast model (Brimelow, 1999, Brimelow *et al.,* 2006) was again used this summer to objectively forecast the maximum hail size over the project area. Hailcast consists of two components, namely a steady-state one-dimensional cloud model and a one-dimensional, time dependent hail model with detailed microphysics. The reader is referred to Brimelow (1999) for a detailed explanation of the model. Forecast soundings for Red Deer and Calgary were downloaded daily from the Plymouth State or Storm Machine website. A decision tree scheme was used to determine whether or not the soundings should be used to initialize the model. The decision tree is based on the work of Mills and Colquhoun (1998). The Hailcast model was not run if the atmospheric profile showed significant inhibition at 700 mb (approximately 10,000 feet) or warming greater than 1°C aloft during the day.

The performance of the HAILCAST model in 2018 was about normal, the HSS being +0.57, only slightly better than the +0.55 in 2017. [Recall that HSS values greater than +0.40 are considered skilled.] The probability of detection (POD) of hail events for Hailcast was 0.93, with a false alarm ratio (FAR) of 0.21.

The Critical Success Index (CSI) for Hailcast was +0.74, a wee bit better than the +0.70 for the WMI forecasters. These results demonstrate that while Hailcast is a useful tool it has weaknesses similar to many models and the results need to be interpreted within the context of the overall meteorological situation, taking into consideration other synoptic, mesoscale, and dynamic aspects that are not included in the one-dimensional model. One must also keep in mind that the input to Hailcast was routinely the 12-hour prognostic soundings of the WRF model. It is important to look at the full 24 hours of forecast soundings to use as input for Hailcast. Further research into the refinement of the Hailcast decision tree remains warranted, and of course, due care must be taken to input the proper sounding.

12. COMMUNICATIONS

Reliable communications for all project personnel and managers is essential for smooth and effective operations. These communications take place on a number of levels, with mixed urgencies. Real-time information-sharing and operational decision-making require immediate receipt of messages so appropriate actions can be taken. Time is of the essence. Routine daily activities such as completion of project paperwork and reports manifest less urgency, but still require due short-term attention. There are also project matters of importance on a weekly (or longer) time frame; these can be handled still more casually.

In the current age of widespread cellular telephone usage and coverage, mobile telephones have proven to be the most dependable means for project communications. Other real-time, project-essential communications occur between the Operations Centre and project aircraft; these are accomplished by voice radio transmissions. Aircraft positions and seeding actions are communicated to the Operations Centre via data radio.

For intra-project communications, all project personnel have cellular telephones. Pilots, who were on-call and had variable hours, always carried their mobile phones, and kept them well-charged and turned on. Meteorological staff did likewise, but because of their more structured hours and location (primarily the Operations Centre) were often reliably contactable via land (telephone) lines, especially while at the operations centre.

12.1 INTERNET ACCESS

High-speed internet access offices for the flight crews based in Springbank and Red Deer was established at the airports. Such access ensured real-time awareness of storm evolution and motion prior to launches, and gave the pilots better knowledge of the storm situations they would encounter once launched.

12.2 USE OF E-MAIL AND TEXT MESSAGES

E-mail and text messaging were discouraged when immediate receipt of information was essential, because the sender would not know with certainty if/when the recipient had received or would receive the message. Both were acceptable for non-urgent situations; however, in that context e-mail was preferred whenever any record of the message content and/or timeliness is needed. The on-site project lead meteorologist routinely sent blanket text message notifications of aircraft launches to all project field personnel, so everybody knew when operations commenced, and which aircraft was (were) flying.