"REVIEWED"

WEATHER MODIFICATION IN ALBERTA

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Abstract. The Alberta Research Council conducted a research and operational weather modification program in central Alberta during the period 1980 - 1985 inclusive. The year 1980 was a transition year in which the Alberta Research Council assumed management of the weather modification project. The current five-year experimental program started in 1981. Hail suppression through cloud seeding has been the focal point of this program, with exploratory studies of cloud seeding to increase rain and snow. The cost of the five year program was $22,730,000 -- of which $17,410,000 was contributed by Alberta Agriculture and $5,320,000 by the Alberta Research Council. This paper constitutes the summary report of the program which was submitted to the government of Alberta. It contains a brief history of weather modification activities in Alberta, the rationale for, and objectives of, the 1980 to 1985 program and the conclusions. A brief summary of applications of technology developed for weather modification research to non-weather-modification problems is also included. Since this report was originally written for politicians and the general public, it did not include formal references.

1. INTRODUCTION

1.1 The Potential of Weather Modification

The success of Alberta's $3 billion agricultural industry depends largely on the weather. Drought, hail, frost, floods and tornadoes cost Albertans hundreds of millions of dollars annually.

During the period 1980 to 1985, hailstorms caused an average $150 million annually in direct losses to crops. Secondary economic losses could add another $50 million to this amount. On the rare occassions when a severe hailstorm passes over a large city, the losses can be even more dramatic. A hailstorm that hit Calgary on July 28, 1981, caused an estimated $125 million damage and a hailstorm that passed over Munich, Germany on July 12, 1984 is thought to have caused one billion dollars damage.

Lost agricultural production due to insufficient moisture is also estimated at $150 million per year. The severe drought of 1985 is considered to have cost Alberta farmers $650 million.

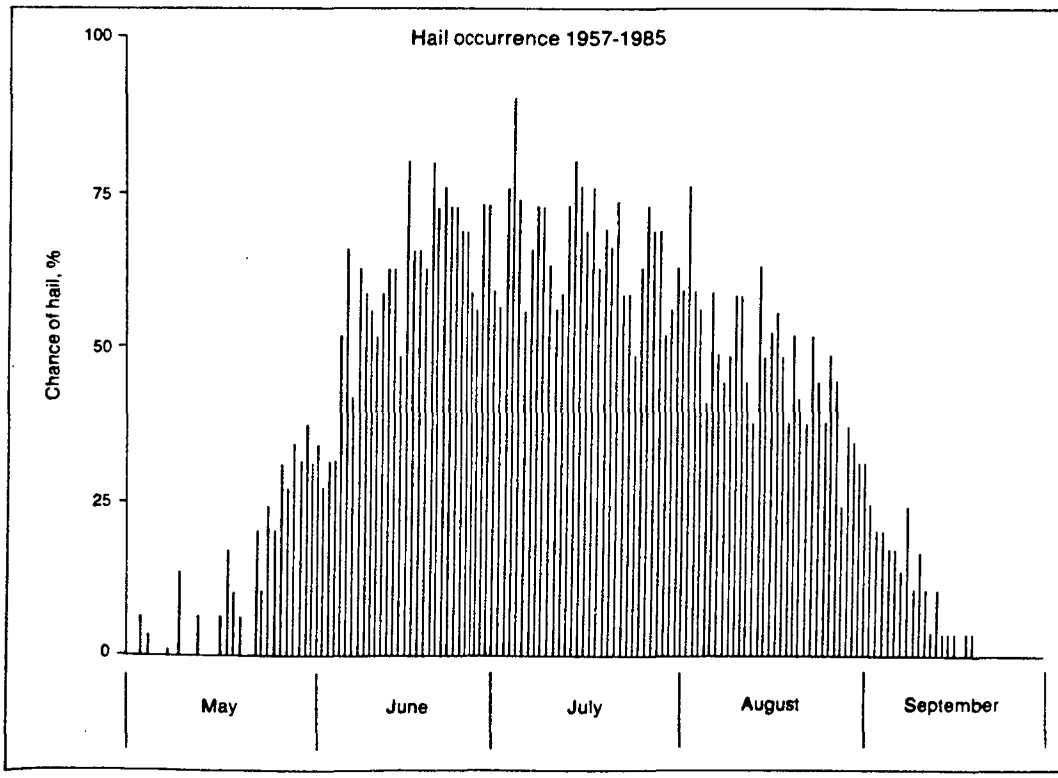

Figure 1 The climatological chance of hail occurring somewhere in central Alberta on any given date during the summer.

The devastating effects of hail and the lack of adequate water supplies coupled with the low cost to benefit ratio, have focused attention on the use of weather modification techniques to alleviate the problem. A five percent reduction in annual crop losses would be required to recover the capital and operating costs of a cloud seeding program.

1.2 The History of Weather Modification in Alberta

Crop losses due to hail damage in the early 1950s prompted farmers in the area north and east of Calgary to form the Alberta Weather Modification Co-operative and hire I.P. Krick and Associates to carry out a commercial hail-suppression program.

In 1956, a project was initiated by the Alberta Research Council to study Alberta hailstorms in order to design and test means for suppressing hail. Participants in this early project included the Atmospheric Environment Service of Environment Canada, the National Research Council and the Stormy Weather Group at McGill University. This phase of research continued until 1968. During these early years, fundamental information was collected on the characteristics of hail in Alberta such as its frequency at particular locations, the size of hailstones, the size and duration of hailstorms, and the weather patterns associated with hailstorms.

By 1969, it was believed the understanding of Alberta hailstorms was sufficient to begin a

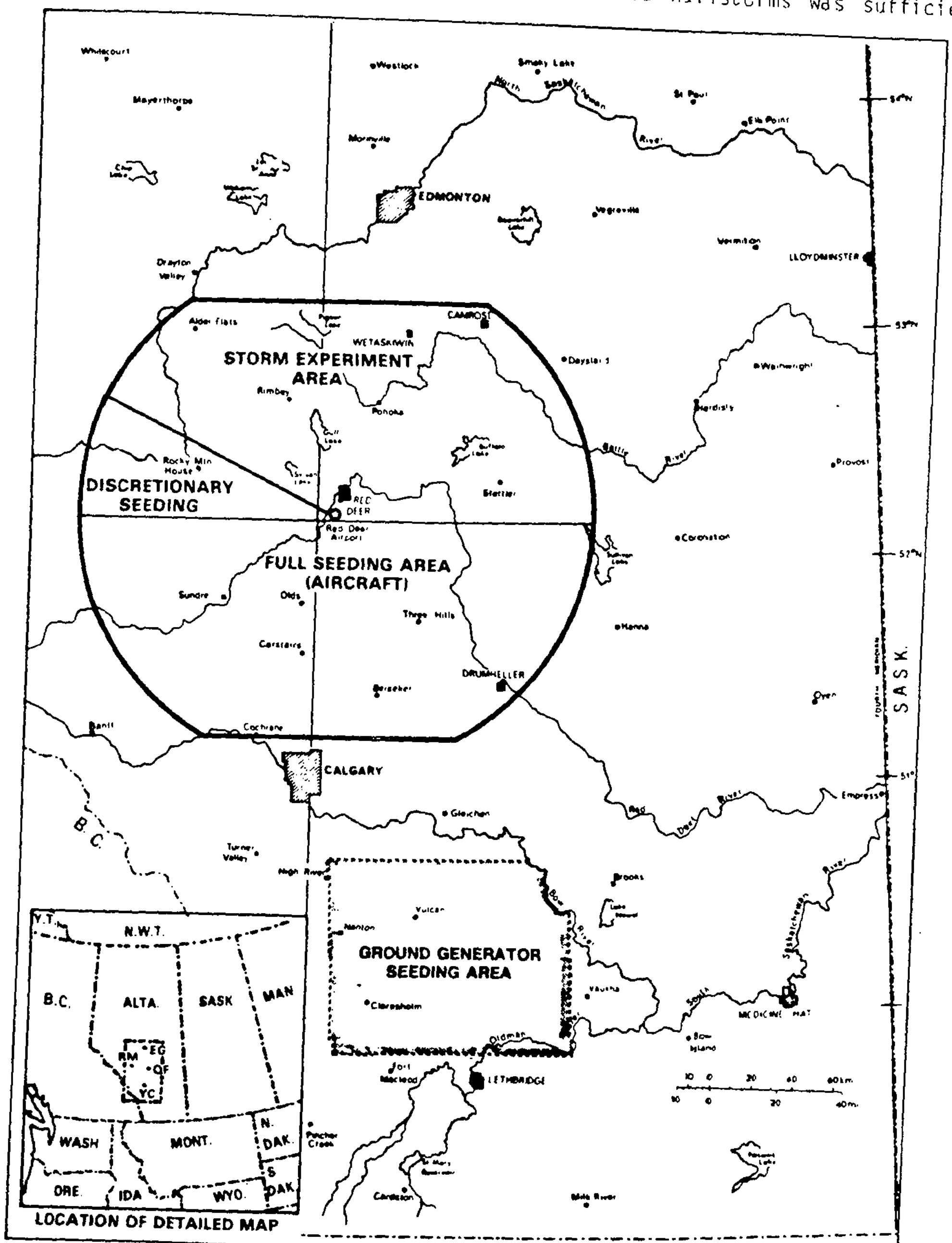

Figure 2. *Weather Modification Program experimental areas. The circular area between Edmonton and Calgary was the principal target zone of the Alberta Hail Project. All hailstorms that occurred in the southern half of this area were routinely seeded for hail suppression. Storms that occurred in the northern half were used for research. The area south of Calgary was the ground-based seeding target area.*

series of airborne cloud-seeding experiments called Project Hailstop. By 1973, a seeding technology had been developed whereby silver iodide flares were dropped into the tops of clouds developing on the edges of hailstorms.

The provincial government created the Alberta Weather Modification Board (under the Department of Agriculture) in 1973 to direct weather modification research and operations. The major emphasis of the research was a randomized seeding test. Using observations obtained by interviewing farmers about the time, location and nature of hailfall, and those obtained from weather radar, a statistical comparison of data from seeded and non-seeded storm days was conducted. Results were inconclusive because none of the various measurements of hailfall were accurate enough to reliably detect a seeding effect over the short time period of the project.

In 1980, after an interim year, the Alberta Research Council assumed full responsibility for research and operations in weather modification. An Advisory Committee on Weather Modification was formed by Alberta Agriculture to provide the Alberta Research Council with guidance on the general direction of the program from the point of view of the farm community. Up to this point the program had dealt exclusively with hail suppression, but it was now expanded to include rain and snow increase studies.

1.3 Objectives for the Period 1980 to 1985

During the period 1980 to 1985, the weather modification program emphasized a better understanding of the physical processes occurring in storms and the effects of cloud seeding upon them. This seemed essential to evaluate seeding effects reliably in a relatively short time period and to develop optimum seeding techniques. The overall goal of the program was to gain enough information to assess the feasibility of conducting, at a later date, a definitive cost/benefit analysis of weather modification in Alberta. Although the primary emphasis was on hail suppression, secondary objectives were rain increase and snowpack augmentation.

To understand the physical processes that produce hail, it is necessary to investigate the whole precipitation process right from the large-scale synoptic weather patterns associated with fronts and low pressure systems to the microscale precipitation processes that occur within a cloud. Hailstorms vary considerably in intensity, size and duration. These variations are now known to be determined by the environment in which the storm occurs and, for the most part, by processes that begin several hours before the storm forms. This investigation required a considerable amount of advanced technology.

The overall goal of the program incorporated five specific objectives.

1) To assess whether cloud seeding sufficiently influences hailstorms to cause a substantial change in hailfall. An aircraft equipped with cloud physics instrumentation and a weather radar facility were used. The aircraft facility was developed jointly by INTERA Technologies and the Alberta Research Council. In preparation for a future economic evaluation of cloud seeding for hail suppression, forecasting techniques were improved to provide methods to predict storm behaviour, help detect seeding effects and improve cloud seeding operations. New observational techniques were investigated to provide measurements of hailfall that could be used to evaluate cloud seeding.

2) To assess the potential for increasing rainfall by seeding cumulus clouds. For this, the same aircraft and radar facilities were used.

3) To investigate the potential for increasing snowfall in the Alberta Rocky Mountains by cloud seeding.

4) To investigate optimum seeding techniques for various types of weather modification, using two seeding materials (silver iodide and dry ice); as well as three delivery methods (seeding at cloud top; seeding at cloud base with aircraft; and seeding with ground-based generators). In particular, the ability of ground-based generators to inject suitable amounts of seeding material into clouds was evaluated.

5) To routinely seed hailstorms using aircraft.

1.4 Operational Cloud Seeding

During the program from 1980 to 1985, hailstorms were routinely seeded by aircraft from June 20 to August 31 in the region from Calgary to Red Deer, carrying on the earlier seeding program of the Alberta Weather Modification Board. Seeding was also conducted north of Red Deer until 1981. Seeding aircraft and operations staff were under contract to Intera Technologies of Calgary. Six seeding aircraft were used in 1980 and 1981 with five from 1982 to 1985, including a special "research seeder" for the rain and hail seeding experiments. Each aircraft was equipped with flares and acetone solution generators for seeding. Aircraft were directed to the storms from the radar control site at the Red Deer Airport.

1.5 Cloud Seeding Techniques

Since the discovery of silver iodide as an ice forming (nucleating) material in 1946, a number of cloud seeding techniques have been developed to generate the seeding material and dispense it into the clouds. Usually, the microscopic particles are generated by burning silver iodide rods in an electric arc, burning silver-iodide and acetone solution or by burning silver-iodide in a pyrotechnic mixture in flares or rockets. Rockets containing a silver-iodide charge are used extensively in the Soviet Union, and a number of its satellite countries, and in China for hail suppression seeding. Most other countries are using, or have used, ground-based generators or flares carried by aircraft to deliver seeding material to clouds.

1.5 Cloud-Top Seeding

Cloud-top seeding involves the discharge of small pyrotechnic flares, carried under the belly of the aircraft, into the tops of developing cloud towers (feeder clouds). Flares are dropped one km apart as the seeding aircraft flies over the cloud towers. The aircraft returns within a few minutes to make another pass.

The cloud-top seeding delivery system was developed in Alberta in the early 1970s based on studies of the structure and behaviour of Alberta hailstorms. The initial technique was modified twice to reflect changes in aircraft (from a jet to piston-engined aircraft), and again due to improved understanding of the hail-formation process in the storm. The technique is now being used on hail projects in other countries.

Because of timing and placement accuracy, this technique has generally been the preferred seeding method. Still, the actual seeding coverage achieved can vary from a high of near 75 percent for some storms to a low of near zero.

1.6 Cloud-Base Seeding

Cloud-base seeding uses flares or generators attached to the aircraft which burn silver iodide in acetone. The aircraft circles or flies below the cloud in the updraft area feeding it and the updraft carries the seeding material to the upper parts of the storm.

2 HAIL

2.1 Alberta Hailstorms

Investigations of the storm environment have shown that even though the various weather systems are vastly different in size (from single clouds to large frontal systems), they are intricately linked in a chain of events that ultimately leads to hail on the ground. Thus, in order to formulate a complete hail storm model, the various links needed to be isolated and understood. This new appreciation of the effects of large weather systems on the development of hailstorms has resulted in improved forecasts of storms and a potentially useful tool for the evaluation of cloud seeding effects.

Hail occurs in central Alberta (within a 130 km radius of Red Deer) on an average of 61 days during the summer. The majority of hailstorms (85 percent) occur between noon and 11:00 pm with 90 percent of hailswaths less than 30 km in length covering less than 200 sq. km. However, hailswaths can be over 300 km in length and 30 km in width from storms lasting for three or four hours. Hailstorms normally develop along the foothills during the afternoon, then move eastward over the farmlands and can continue producing hail into Saskatchewan.

Hailstorms result from energy imbalances in the atmosphere. These atmospheric forces are linked to hailfall by a complex chain of processes. Satellite imagery shows a clear tendency for convective clouds to develop within a framework of larger cloud complexes which in turn are associated with parent weather systems. These large systems influence the atmosphere on a regional scale, producing conditions favourable for the formation of hailstorms many hours before the actual storm develops.

Current theory suggests that these events, in conjunction with the influence the mountains have on the airflow and with solar heating, focus cloud development along the foothills. Airflow from over the mountains creates a "lid" that in the early stages suppresses cloud development. However, at the same time, the "lid" increases the potential instability of the atmosphere so

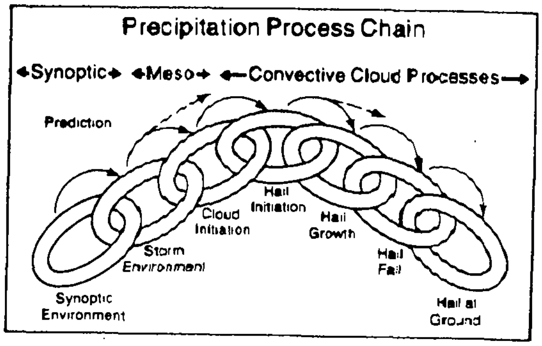

Figure 3. The "precipitation process chain" illustrating the sequence of weather events leading to hail. The synoptic weather determines the storm environment which in turn determines cloud development. The cloud development determines if or when hail growth starts, how fast it will be and how long it will continue. These factors determine the number and size of hailstones that fall to the ground.

that when it finally erodes, intense air currents capable of supporting large hailstones occur. The storms then move off the foothills depositing their hail load on the farmlands.

Most hailstorms in Alberta have a series of smaller clouds upwind of the main storm. The exact location of these clouds appears to depend upon the available moisture and winds in the environment. These clouds form at regular intervals in the same location relative to the storm and their formation appears to be determined by the interaction between the storm's downdraft (produced by rain and hail falling out of the cloud), its inflow (produced by warm air rising ahead of the storm) and the environmental winds. Because these clouds move towards and merge with the main storm, they are called feeder clouds. The growth of hailstones appears to start in these feeder clouds.

2.2 The Growth of a Hailstone

The growth of a hailstone occurs in two stages. The beginning stage, called embryo formation, must occur in young clouds with weak updrafts such as feeder clouds. The final growth to a hailstone, though, must occur in a strong and moist updraft such as in the main storm.

For a hailstone to form, a hail embryo must be caught and carried up by a strong and moist updraft. This happens when the feeder cloud, in which the embryos develop, merges with the main storm.

2.3 Hail Suppression Concepts

Modern hail suppression efforts do not attempt to control the storm itself, but seek to modify only the hail growth process within it. Most hail suppression theories involving cloud seeding are based on what is known as the "beneficial competition" or "competing embryo" hypothesis. This concept assumes that the amount of supercooled water (water colder than 0°C) in the hail cloud is the limiting factor on the amount of hail produced. Introducing enough artificial hail embryos can reduce the sizes of the hailstones reaching the ground by forcing natural hailstones to share the available liquid water with artificial ones. Artificial embyos are produced by seeding clouds with materials that produce additional ice nuclei.

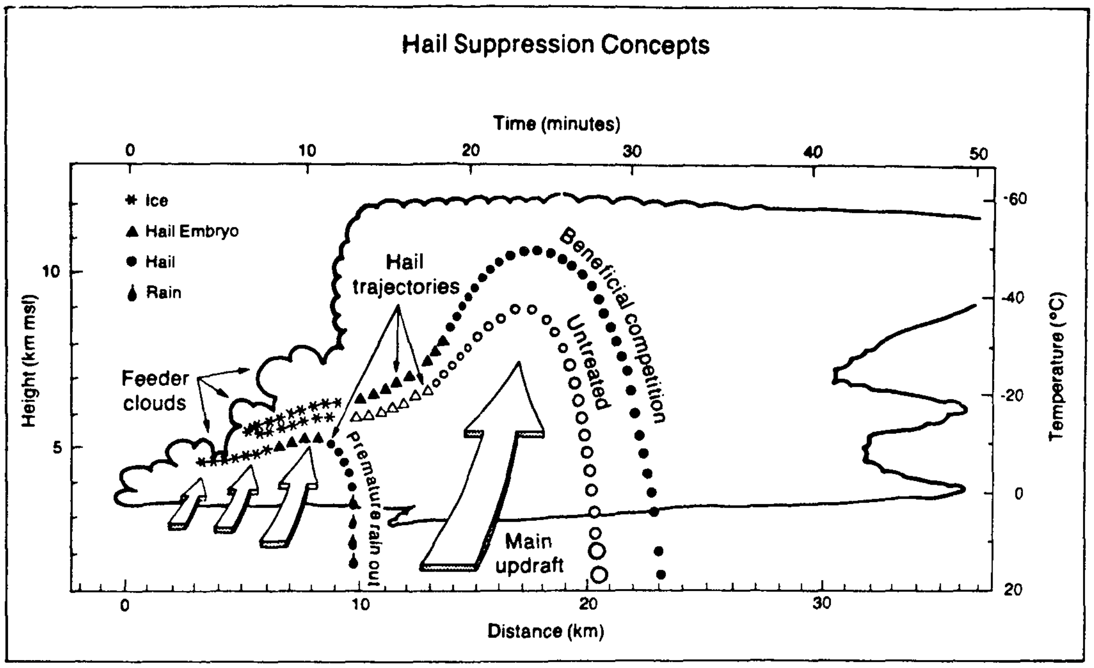

Figure 4 This illustrative slice through a typical hailstorm shows the expected paths of hailstones with and without seeding. After their beginning as embryos in the feeder cloud, the particles grow rapidly in the main updraft to fall as hailstones. Seeding the feeder clouds to introduce large numbers of ice crystals at the same time as natural ones are forming produces many artificial hail embryos that compete for the cloud's water supply. This competition limits the size of all embryos, resulting in smaller hailstones with a higher path through the storm. On this higher path (labelled beneficial competition), the stones grow slower and fall out of the storm as smaller hail. With some clouds, seeding the feeder cloud to cause ice crystals to form earlier allows hail embryos to precipitate out as rain before they reach the main updraft (premature rain out).

This has been the rationale behind the seeding operations and experiments in Alberta since the early 1970s. However, beneficial competition involves the risk of increasing the natural hailfall without ameliorating its effects if the natural embryos do not consume all the available liquid water or if too few artificial embryos are added.

More recently, an additional hail suppression concept, known as "premature rain out", has been proposed by Soviet and other scientists. This concept rests on the fact that ice nucleating materials such as silver iodide can initiate ice crystals at warmer temperatures than normal (i.e. close to 0°C) and therefore earlier in the lifetime of the cloud. This should start the precipitation process in the feeder clouds earlier and result in potential hail embryos falling out of the feeder cloud before it merges with the main storm so that fewer embryos are delivered to the updraft in the main storm.

2.4 <u>Testing the Concepts</u>

Because both concepts -- the beneficial competition and the premature rain out -- involve changing the number of embryos in feeder clouds, both concepts were tested through seeding experiments.

Hailstorm seeding experiments conducted in Alberta have involved treating a feeder cloud and then documenting the effect of the treatment with observations made by the cloud physics research aircraft. Once a feeder cloud became too vigorous and too much a part of the mature storm to permit the research aircraft to penetrate it, precipitation particles from the feeder cloud could usually be identified by weather radar. In addition, storm chase vehicles collected hailstone samples in the precipitation area. During the experiments carried out in 1985, observations were also made using an armoured aircraft (a T-28 from the South Dakota School of Mines and Technology), which was able to fly through the centre of the storm.

The treatments used in the seeding experiments included a placebo (no seed), droppable silver iodide flares, or dry ice pellets. With the dry ice pellets, a low and a high rate were used, so that a total of four different treatments were used. The treatment was usually applied at about the -10°C level; when the scientist onboard the research aircraft felt that there was a possibility of success with the premature rain out concept, the treatment was applied at the -5°C level.

Test clouds were required to satisfy certain criteria to ensure that all treated feeder clouds were similar. Ideally four feeder clouds from one storm were treated as part of one experiment -- each cloud receiving a different treatment -- so that differences measured could be attributed to the treatment.

A completely successful series of seeding experiments (four treatments) is extremely difficult to achieve since identification of a suitable feeder cloud, treatment and subsequent observation of the cloud can take as much as an hour. A storm will often change dramatically or move out of the project area before an experiment is completed. In addition, the radar data, research aircraft data, weather observations and observations of rain and hail at the ground result in several km of computer tape and millions of data values. Checks of data quality, extraction and analysis of relevant information, comparison of the various sources of information and interpretation of the results take months of effort for each case.

To date, six hailstorms have been analyzed. In four of these, a placebo as well as a seeding treatment were successfully applied. Data from six more successful hailstorm experiments and at least 10 additional partial experiments remain to be analyzed.

The seeding concepts can also be tested theoretically by using computer models to simulate atmospheric conditions. One such test was conducted with the assistance of The Institute of Atmospheric Sciences at the South Dakota School of Mines and Technology.

2.5 Experimental Results

2.51 Hailstorm Seeding Experiments

Results from the seeding experiments indicate that the current understanding of how hailstorms function is appropriate for Alberta and for the most part correct. Radar analysis of isolated storms indicates that 80 to 90 percent of storms that occur in Alberta are consistent with the model: storms have feeder clouds associated with them in which the precipitation process is initiated, and particles which form in the feeder clouds fall to the ground as hail.

An abundance of ice crystals was observed in all seeding experiments soon after seeding with either dry ice or silver iodide. The number of ice crystals in the seeded feeder clouds was very much greater than the number in unseeded clouds at comparable times in the cloud life. These high numbers of ice crystals were initially observed in a very small part of the cloud, but with time they spread and grew -- some of them becoming potential hail embryos within 10 minutes.

The number of potential hail embryos in the seeded feeder clouds was consistently about 10 times greater than the number in the unseeded clouds (beneficial competition concept). When seeded feeder clouds were sufficiently distant from the main storm, seeding encouraged the early formation of precipitable particles (premature rain out concept).

For safety reasons, the research aircraft cannot follow the treated feeder cloud once hail embryos have grown into centimeter-sized hailstones. Detailed analyses of the trajectories of radar reflectivity patterns (which are related to the particles growing within the feeder clouds) have led to the conclusion that such feeder clouds contribute particles which precipitate in the hailswath. Current radar analysis techniques are not sufficiently sensitive, however, to determine what effect additional hailstone embryos have upon the size and number of hailstones within the storm.

This problem was recognized after the third year of the program, and thus the armoured aircraft of the South Dakota School of Mines and Technology was brought to Alberta in 1985. However, this aircraft successfully participated in only one hailstorm-seeding experiment on July 11 -- an extremely severe storm. Analyses indicate that this storm was not sufficiently well-seeded using current techniques. This was due in part to the fact that the feeder clouds for this severe storm grew right on the edge of the storm, allowing insufficient time for artificially-produced embryos to prematurely rain out. In addition, exceptionally strong updrafts indicate that larger quantities of seeding material must be released over longer time intervals if beneficial competition is to be successful. These very intense storms appear to constitute less than 20 percent of the damaging hailstorms that occur in central Alberta.

Observations of hail collected at the ground from one operationally-seeded storm suggest that the number of hailstones on the ground was increased through cloud seeding. Not enough data was obtained to determine if the size of the hailstones was reduced to any significant degree.

2.52 Numerical Model

The Institute of Atmospheric Sciences at the South Dakota School of Mines and Technology used a computer model to simulate the seeding experiments that were carried out on a storm that occurred in Alberta on July 26, 1983. The calculations show that the feeder clouds were a source (although not the only one) of hailstone embryos; that seeding produced many ice crystals which spread through the cloud and grew with time; and that the seeded feeder cloud precipitated earlier than the unseeded feeder cloud. Futhermore, a temporary competition for the liquid water was seen. This suggests that seeding must be continuous, as it is in operational cloud seeding, to maintain this competition.

The computer simulations suggest that seeding one feeder cloud increased surface amounts of rain modestly (approximately seven percent) and decreased hail amounts somewhat (approximately nine percent). The computations also suggest that seeding with dry ice is more effective in inhibiting hail growth than seeding with silver iodide, but this may be a question of the amount rather than the type of seeding agent used. The computations verify that seeding resulted in the premature initiation of precipitation in this storm.

The results of these numerical tests cannot currently provide definitive answers regarding the effects of seeding because numerical models cannot yet simulate all the complexities of nature, but they do give indications of what seems reasonable to expect and what to look for in observations of the actual storms.

2.6 Economic Assessment of Hail Suppression Techniques

The experiments discussed in previous sections provide encouraging indications that cloud seeding can affect the amount of hail that falls on the ground, but the question of what economic benefit cloud seeding can provide can only be addressed in a properly designed statistical experiment.

One type of cost-benefit assessment involves the use of crop insurance data. A loss-to-risk ratio (L/R) is often used to assess hail damage. This is the ratio of crop loss caused by the hailstorm to the risk or insured value of the crop, and is usually expressed as a percentage. Many evaluations of hail suppression programs have used the L/R ratio, usually with mixed results, except in the Soviet Union and France where significant reduction in hail are claimed.

Alberta farmers have purchased insurance against crop losses since the first settlers began farming operations in the latter half of the nineteenth century. The most consistent records in the Province are those of the Alberta Hail and Crop Insurance Corporation and its predecessor, the Alberta Hail Insurance Board, spanning the period from 1938 to the present. These records represent the bulk of insurance policies purchased by farmers within the province.

Recent analyses of crop damage data from the Alberta Hail and Crop Insurance Corporation suggest a decrease in the L/R ratio of the order of 20 percent could be attributed to cloud seeding if no significant changes in weather patterns have occurred in central Alberta in the past 50 years and if no other factors have contributed to the observed decrease.

However, hail insurance data does not necessarily provide an accurate measurement of hailfall over an area because factors such as wind, crop type and growth stage determine how much damage will be caused by a given hailstorm. In addition, trends due to climate change, cloud seeding and changes in insurance practices are difficult to isolate. For this reason, a cost/benefit analysis of hail suppression should not rely primarily on insurance data.

Sequence of Events Leading to Hail Suppression

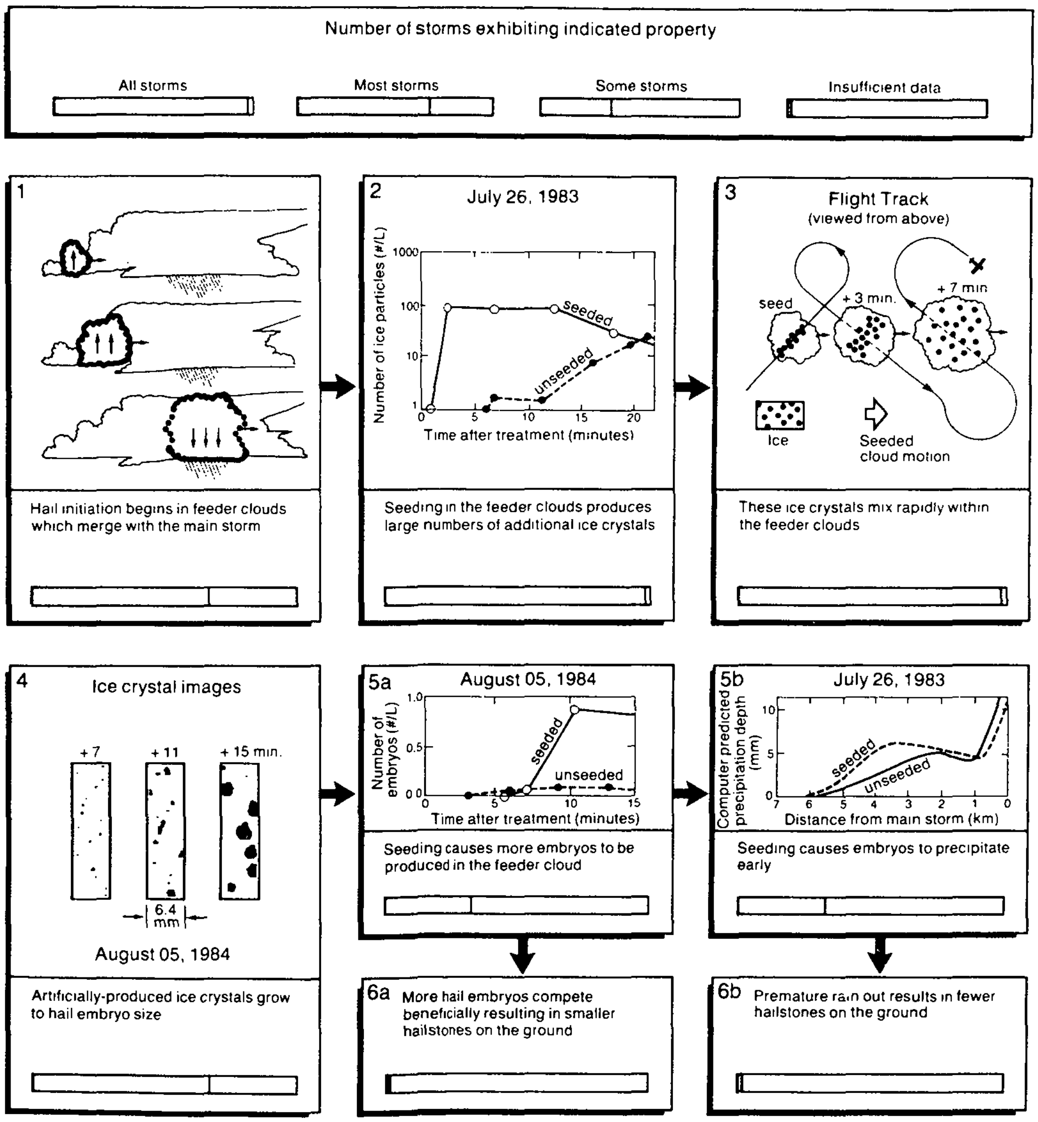

Figure 5 Sample results from testing the hail suppression concepts. Panel 1 illustrates the concept of hail formation. Panel 2 shows a comparison between the number of ice crystals in a seeded and unseeded feeder cloud as a function of time after treatment. Panel 3 indicates the spreading of ice crystals in a feeder cloud as determined from a sequence of aircraft passes through the cloud. Panel 4 shows the recorded images when ice particles intercept the laser beams onboard the research aircraft. Panel 5(a) (beneficial competition) illustrates the difference in numbers of hail embryos in seeded and unseeded feeder clouds. Panel 5(b) (premature rain out) shows the amount of computer-simulated precipitation from seeded and not seeded feeder clouds. Premature rain out is indicated in the seeded cloud. Panels 6(a) and 6(b) remain to be confirmed. The bars at the bottom of the panels indicate the degree to which that step of the suppression concept has been verified.

In preparation for a future definitive cost/benefit analysis, some effort has been devoted to determining optimum measurements of hailfall. Results obtained to date suggest that time-resolved hailstone samples and some radar parameters provide measurements of hailfall that are accurate enough to produce definitive results from a statistical experiment of relatively short duration (five to 10 years). Factors that influence hail, such as particular weather patterns and storm environments, have been identified and can be used in the future to separate effects due to changes in climate from those due to cloud seeding. Techniques have been developed to quantify the extent to which a storm is successfully seeded, so that an improper application of seeding material can be taken into account.

The Production and Economics Branch, Economic Services Division, Alberta Agriculture, has analyzed the effect of hail and drought on major crops in Alberta. In one analysis, the estimated average hail damage in 1985 dollars for the 1980 to 1985 period is 146 million. All analyses also show "that a loss recovery percentage of under 10 percent is sufficient to break even on hail suppression system costs". In particular, one analysis indicates that "benefits equivalent to 6.5 percent of premiums and administration costs are sufficient to pay for the total system cost". If secondary benefits and total crop value are considered, the loss recovery can decrease to less than three percent. Economic multipliers were not considered, which could lower the required loss recovery to below one percent.

2.7 Summary and Conclusions

The emphasis of the weather modification program over the past five years has been to better understand the hail formation process and the effect cloud seeding has upon it. A storm model was formulated which describes the current state of knowledge. This model has been shown to be appropriate for at least 80 percent of the hailstorms that occur in Alberta. Seeding concepts have been tested with seeding experiments and with computer calculations.

Results from the six hailstorm seeding experiments indicate that cloud seeding can increase the number of potential hail embryos produced by the feeder clouds or, in some storms, can cause potential hail embryos to precipitate out of the feeder cloud prematurely. Because of limitations in measuring and observing facilities, it has not yet been demonstrated that more hail embryos lead to smaller hail on the ground, nor that premature rain out of embryos results in fewer hailstones on the ground.

Computer calculations for one hailstorm have confirmed that premature rain out from the feeder cloud occurred. The calculations suggest that this resulted in a moderate decrease in the amount of hail (approximately nine percent) and a moderate increase in the amount of rain (approximately seven percent). These calculations also suggest that dry ice is more effective as an inhibitor to hail development than silver iodide.

Statistical analysis of crop damage data from the Alberta Hail and Crop Insurance Corporation suggests that a decrease in the L/R ratio of the order of 20 percent could be attributed to cloud seeding if changes in weather patterns and insurance practices have had no significant effect on this ratio.

Statistical analysis of hailstones from untreated storms and from one operationally-seeded storm shows that cloud seeding increased the number of hailstones on the ground. However, not enough data was obtained to determine if the size of the hailstones decreased significantly.

Aside from these results on the feasibility of suppressing hail through cloud seeding, significant progress has been made in other areas. The time and location of storm development and the size of hail can be more accurately forecast. A foundation of knowledge has been built up whereby it is now possible to study the effect of cloud seeding on the storm environment and hence on the development of new clouds and storms. A technique has been devised to separate effects of the storm environment and seeding coverage from effects due to cloud seeding on hailfall and a method of quantifying seeding effectiveness has been developed.

These results give reason to be optimistic about the possibility of suppressing hail to some extent in the most common types of storms and of detecting and economically assessing the suppression effect. The potential benefit to the agricultural community of cloud seeding for hail suppression is great and the cost of seeding is small in comparison. Although the final step in the hail suppression process (cloud seeding reduces hail damage) has not been validated, encouraging indications that cloud seeding can affect hailfall on the ground have been found. No evidence has been discovered that cloud seeding increases damage due to hail, nor has any evidence indicated that cloud seeding decreases rain. In fact, computer calculations suggest that rainfall is increased. Thus operational cloud seeding for hail suppression appears to be a positive tool for agriculture.

3 RAIN

3.1 The Potential of Rain Augmentation

Rainfall over much of southern Alberta is barely adequate in an average year, yet natural variations are such that the rain received in the growing season can be as much as 30 percent below normal once every five years. Even worse, much of this area can expect precipitation during July to be 60 percent below average once every five years.

Even when precipitation is averaged over five summers, large departures from the 30-year norm are frequently observed. Summers of the past decade have been characterized by below-average rain along the Bow River with above-average rain in the Drayton Valley area and the regions to the north and west of Edmonton. Southern Alberta has seen wide changes from very dry (as much as 40 percent below average in the late 1960s and early 1970s), to very wet (up to double the average rainfall in the mid-1970s) and back to dry again in the early 1980s. Departures of 30 or 40 percent above or below normal are common. During 1984 and 1985, the rainfall was very much below normal.

Weather modification is one means of increasing rainfall. Cloud seeding has been seen as a means of increasing the water supply in many areas of the world. Particularly well known is a project in Israel which used silver iodide to seed winter convective clouds. A statistical analysis showed that seasonal precipitation was increased by 15 percent.

In Canada, the Atmospheric Environment Service carried out seeding experiments on cumulus clouds in Yellowknife and Thunder Bay. Clouds in both areas showed increases in ice concentration with seeding and, in Yellowknife, 40 percent of the clouds produced rain.

Cumulus seeding experiments in Alberta in 1978 and 1979 produced dramatic radar evidence of rain augmentation through cloud seeding. These experiments and the encouraging results reported from elsewhere, led to the initiation of a series of rain seeding experiments in Alberta.

3.2 Rain Augmentation Concepts

Modern rain augmentation projects have been based on the belief that convective clouds are inefficient rain producers because of a lack of natural ice nuclei. It is believed that seeding convective clouds with an ice-nucleating material will convert more of the cloud water to ice. Ice particles will grow faster than water droplets and so will become heavy enough to fall out of the cloud faster than water droplets. The ice particles melt as they fall to the ground and arrive as rain.

Testing the rain augmentation concept through cumulus-cloud-seeding experiments has been a secondary objective of the weather modification program. These experiments were designed to document the processes of rain development in natural and seeded cumulus clouds, to determine the range of conditions under which clouds can be made to rain through cloud seeding, and to determine the most effective treatment.

Rainfall in Alberta is produced by widespread weather systems, thunderstorms and cumulus shower clouds. This rain is usually melted snow or graupel that grew in the cloud from tiny ice crystals. Measurements around the world have shown that few cumulus clouds with cloud-top temperatures of -15^{o}C and warmer rain naturally so isolated cumulus clouds containing little or no ice and with cloud-top temperatures of -15^{o}C or warmer were specifically selected for the experiments. As the clouds did not rain naturally, evaluating the seeding effects would be simpler.

Seeding experiments were carried out whenever isolated cumulus clouds or cumulus clouds embedded in a stratus cloud deck occurred in the project area and equipment was not required for hailstorm-seeding. The experiments involved choosing a test cloud according to characteristics measured by the research aircraft. An appropriate treatment of either silver iodide or dry ice pellets, or a placebo (no treatment), according to a random sequence, was applied to the test cloud. The treatment effects were observed by repeated flight through the treated cloud by the research aircaft. Radar observations were also made to monitor precipitation development in the cloud.

3.3 Results of the Seeding Experiments

During the period 1982 to 1985, 98 experiment clouds were selected. Ten clouds had to be rejected during analysis due to missing information. Out of the 88 clouds analyzed, 57 had been treated with a seeding agent and 31 were treated with a placebo (control clouds).

Observations with the research aircraft show that the class of cumulus clouds selected for the experiments do not naturally produce high concentrations of ice crystals. Seeding these clouds with either silver iodide or dry ice is effective in producing high ice crystal concentrations and these ice crystals spread through the cloud and grow with time.

None of the test clouds that lasted less than 20 minutes developed precipitation. Twelve of the control clouds lasted for 20 minutes or longer, but none of these developed precipitation. Thirty-six seeded test clouds lasted for 20 minutes or longer after the seeding agent was applied and developed precipitation (i.e. 63 percent of the seeded clouds were observed to have rain fall out of the cloud at cloud base). Twenty of the 36 clouds were suitably located to determine if rain fell to the ground. Out of those 20, seven produced rain on the ground. Thus, it is estimated that 35 percent of the seeded clouds that lasted for 20 minutes or longer produced rain on the ground and 22 percent of all seeded clouds produced rain on the ground. All the test clouds that produced rain on the ground were seeded with silver iodide.

Rainfall estimates calculated from the radar data indicate that the test clouds produced up to 16,000 cubic meters of rainwater when seeded and cover areas up to 140 square kilometers which averages to 0.1 mm of rain. In one case, 0.9 mm of rain was measured at the ground.

3.4 Cloud Climatology Studies

To enable estimates of the potential impact of the results of the seeding experiments on regional rainfall, a cloud frequency study was undertaken. This study showed that on average, during the summer months, 6.6 to 11 percent of the sky in southern Alberta is covered with the type of clouds investigated in the seeding experiments. The study also indicated that clouds of the type used in the experiments are just as prevalent during a drought as they are during a non-drought period. The climatology studies suggest that an additional 10 mm of rain could be realized from seeding isolated cumulus clouds during the summer. With larger cloud systems this could be increased even more.

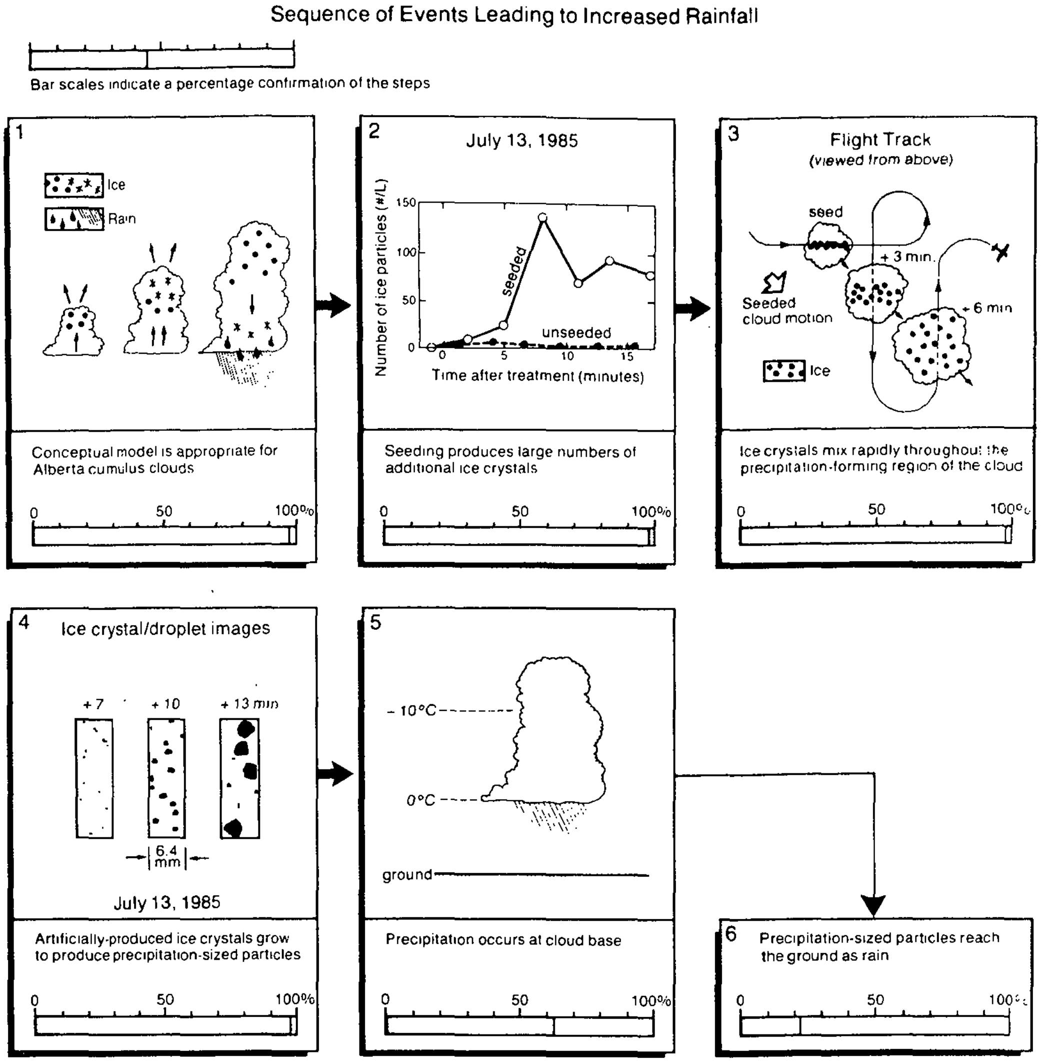

Figure 6 Sample results from rainmaking experiments. The panels indicate steps in the rain augmentation concept and the bars show the degree to which each step has been verified. Panel 1 illustrates the concept of rain formation in an Alberta cumulus cloud. Ice crystals form on ice nuclei in the cloud's updraft and grow as the cloud provides moisture. When the updraft dies, the particles fall, and melt to form rain. Panel 2 shows the number of ice crystals in a seeded and a natural cloud as a function of time. Panel 3 indicates the spreading of ice crystals in the cloud. Panel 4 shows the images recorded when ice particles and water drops intercept the laser beams onboard the research aircraft during several passes after seeding. Panel 5 illustrates that for the clouds which last 20 minutes or longer after seeding (63%), ice particles grew large enough to fall out of the cloud. Panel 6 shows that 22% of the seeded clouds produced rain on the ground.

3.5 Alternate seeding techniques

3.51 Cloud-base seeding

An exploratory study was undertaken during the 1985 field season to test the cloud-base seeding technique for accuracy of delivery. Results from four experiments showed that silver iodide delivered at cloud base was transported into the cloud. Distinct seeding effects were observed similar to those seen with cloud-top seeding. Therefore, although the timing may be more difficult to control, it seems that seeding at cloud base is an alternative to seeding within, or above, a cloud near its top.

3.52 Ground-Based Seeding

An alternate method to both cloud-top and cloud-base seeding with aircraft is seeding from the ground using some form of silver iodide generator. Such devices have the advantange of simplicity, ease of access, no aircraft operating costs and manual operation.

A project to evaluate the efficiency of seeding summer clouds using ground-based silver iodide generators was also conducted as part of the weather modification program. This technique has been used by I.P. Krick and Associates in Alberta and elsewhere for more than 30 years. The test system involved a network of the coke-fueled and arc generators installed at 60 to 70 sites in southern Alberta during the summers 1981 through 1985. The coke generators burn pellets of coke that have been soaked in a solution which contains silver iodide, while the arc generators burn pure silver iodide by means of an electric arc. The operational objective was to increase rainfall in a 15,000 km2 target area south of Calgary.

Mapping and plume-tracking flights conducted in conjunction with the I.P. Krick ground-generator operations in southern Alberta showed that the generators typically produced narrow plumes a few hundred metres wide occupying a few percent of the target volume. Occasionally, plumes were encountered near cloud base.

Laboratory tests of the generators by Colorado State University showed they did produce effective ice forming nuclei albeit at lower rates than other systems. The question that has not been satisfactorily answered is whether the seeding material is sent to the right target at the right time and in the appropriate concentration.

An independent statistical evaluation of the effect of ground-generator cloud seeding in southern Alberta was carried out by the University of Alberta. This study concluded from three different analyses that no evidence of a change in rainfall greater that 12 percent could be found.

3.6 Summary and Conclusions

The cumulus seeding experiments have shown conclusively that some cumulus clouds that would not rain naturally can be made to rain by seeding with an ice nucleating material. Of the clouds seeded in the course of these experiments, 22 percent produced rain on the ground and rainfall was observed at cloud base in 63 percent. While half the test clouds were treated with dry ice, all of the clouds that produced rain on the ground were seeded with silver iodide.

Seeding at cloud base with aircraft seems to be a viable alternative to seeding at cloud top. No conclusions can yet be drawn about the effectiveness of seeding from the ground with ground-based generators.

The experiments conducted to date have dealt with a very specific type of cloud which is equally prevalent in times of drought and of normal rainfall.

These results indicate that cloud seeding for rain augmentation should be considered a tool for water management. However, before the economic potential of this tool can be assessed, further experiments are required to optimize the seeding techniques and to assess the potential of increasing rain from other types of summer clouds. Before appropriate clouds can be seeded routinely, it must be determined if there are any kinds of clouds for which seeding would decrease rainfall. If such clouds exist, the seeding technique must be able to exclude them in routine seeding operations.

Finally, a properly-designed statistical experiment will be required to determine economic benefits. Such an experiment should include considerations of downwind effects (i.e. the possibility that cloud seeding in one area robs some area downwind of its rain).

4 SNOW

4.1 Potential of Snowpack Augmentation

Inadequate rainfall during the growing season can be alleviated in some areas through irrigation. Much of the water currently being used to irrigate crops in southern Alberta comes from spring runoff, and it is estimated that a 10 percent increase in the average cumulative mountain snowpack would result in 250,000 acre-feet of increased runoff in the Oldman River basin alone, adding greatly to irrigation and other water supplies. Municipalities would also benefit from additional snowpack.

Research and development into cloud seeding for snowpack augmentation is underway in the western United States to help alleviate potential water shortages. Projects are currently being conducted in California, Colorado, Montana, Nevada and Utah by various universities, state and federal agencies, including the U.S. Department of the Interior and the National Oceanic and Atmospheric Administration (NOAA). Cloud seeding in the mountains has been identified recently by the United States Secretary of the Interior as "the most cost effective and promising means of meeting the water needs of the Colorado River basin".

U.S. results indicate that cloud seeding may increase the mountain snowpack by about 15 percent. In Colorado, it has been estimated that such increases could augment streamflows by 10 percent.

4.2 Snow Augmentation Concept

Cloud seeding for snow augmentation is also based upon the fact that the atmosphere is not always naturally "efficient" in producing precipitation. In a moderate westerly airflow over a mountain ridge, with clouds one km deep and extending one hundred km along the mountains, about 5000 m3 (one million gallons) of water, pass over the ridge each minute. Because of a scarcity of ice nucleating particles, supercooled water droplets in these clouds often do not freeze even at temperatures much colder than zero. In the absence of ice nuclei, the cloud droplets evaporate in the descending air on the leeward side of the mountain barrier.

In a weather modification program, ice nucleating agents (either silver iodide or dry ice pellets) are delivered to the clouds to initiate snow crystal growth. The seeding principles for converting cloud water to snow are very similar to those for rain augmentation.

4.3 Alberta Investigations

A limited investigation of the feasibility of increasing snowfall over the southern part of the Alberta Rocky Mountains was carried out during the past five years.

A preliminary assessment of the snow climate and clouds of the southern Canadian Rockies was recently completed which investigated the snow climatology of the region and measured the properties of winter clouds over the mountains. The snow climatology showed there are different snowfall patterns on each side of the continental divide. The spring contribution to the total snowpack was noted. The climate studies indicated that meteorological conditions within the region were appropriate for cloud-seeding technology.

Measurements by the research aircraft during four two-week field programs from 1982 to 1984 showed evidence of liquid water in the clouds and an increase in liquid water near barrier peaks. Estimates for three selected cases indicated less than one percent to 16 percent of the moisture was converted to snow. These results suggest that the precipitation process could be made more efficient if artificial ice nuclei were added.

4.4 Summary and Conclusions

Limited observations from snow clouds over the Rocky Mountains in southern Alberta suggest that the potential exists to increase mountain snowpack. Therefore, a project called SNOWATER has been proposed to adapt snow augmentation technology for use in Alberta.

5 TECHNOLOGICAL BENEFITS OF THE PROGRAM

Atmospheric research to study weather modification requires a broad base of expertise in such disciplines as meteorology, statistics, computing and electronics as well as a broad range of supporting technologies. As a result, the Alberta Research Council has developed a team of experts and new technologies that can be applied to other types of research and problem solving.

A major component of the program was the cloud physics research aircraft developed jointly with INTERA Technologies through funding from Alberta Agriculture and the Alberta Research Council.

The meteorological expertise associated with the weather modification program has been contracted to Alberta Environment to support studies of air quality in Fort McMurray and Calgary. The research in Fort McMurray involved using the research aircraft to track effluent plumes from oilsands processing plants.

The Alberta Research Council is working with the University of Dayton, Ohio, to supply aircraft data collected during the program to be used in updating icing standards for commercial aircraft.

The computing expertise used in weather modification research has been very useful in applying many of the technologies to other projects. All aspects of the research and operations now rely on computing to store and analyze data from the research aircraft, the weather radar systems, the weather information from the Atmospheric Environment Service and even the data obtained from telephone surveys of farmers.

Statistical expertise used in weather modification evaluations has also been applied to crop-yield modelling for Alberta Energy and Natural Resources and in oil production studies.

Research on hailstorms has improved the ability to forecast convective weather. A computer program that produces weather forecasts in a manner similar to the human meteorologist (using artificial intelligence techniques) has been developed and may soon be in the private sector. In addition to aiding weather modification research and cloud-seeding operations, improved forecasts of hailstorms provide more accurate and advanced warnings for the public.

Weather radar is needed to detect and track storms for weather modification research. Radar can also be used to estimate rainfall over broad areas, which is useful in predicting stream flow. A facility has been added to the weather radar system in Red Deer that has the capability of transmitting measurements to the Alberta River Forecast Centre in Edmonton as rainfall occurs. In addition, computing technology has been adapted so that radar information from the Atmospheric Environment Service's weather radars can be collected and transmitted to the River Forecast Centre.

The radar data collected as part of the weather modification program has been analyzed for Alberta Disaster Services to assist in assessment of severe weather events and applied to the development of forecasts of damaging lightning for the Canadian Electrical Association. Radar data is also being used by Alberta Government Telephones to study signal fading during heavy rainfall.

6 CONCLUSION

The highlight of the recent program has been the success of the rain augmentation project. This aspect of the weather modification technology has been solidly demonstrated on a limited scale. The hail problem is the most complex and difficult to solve, but substantial progress has been made and hail suppression looks feasible at least for some types of storms. The potential to increase snow through cloud seeding has been demonstrated and the technology looks promising. The potential economic gains from cloud seeding are substantial. Results of the last five-year program lead to optimism about the use of cloud seeding to benefit the province's economy and technological capabilities. It is recommended that weather modification receive continued support.

7 ACKNOWLEDGEMENTS

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