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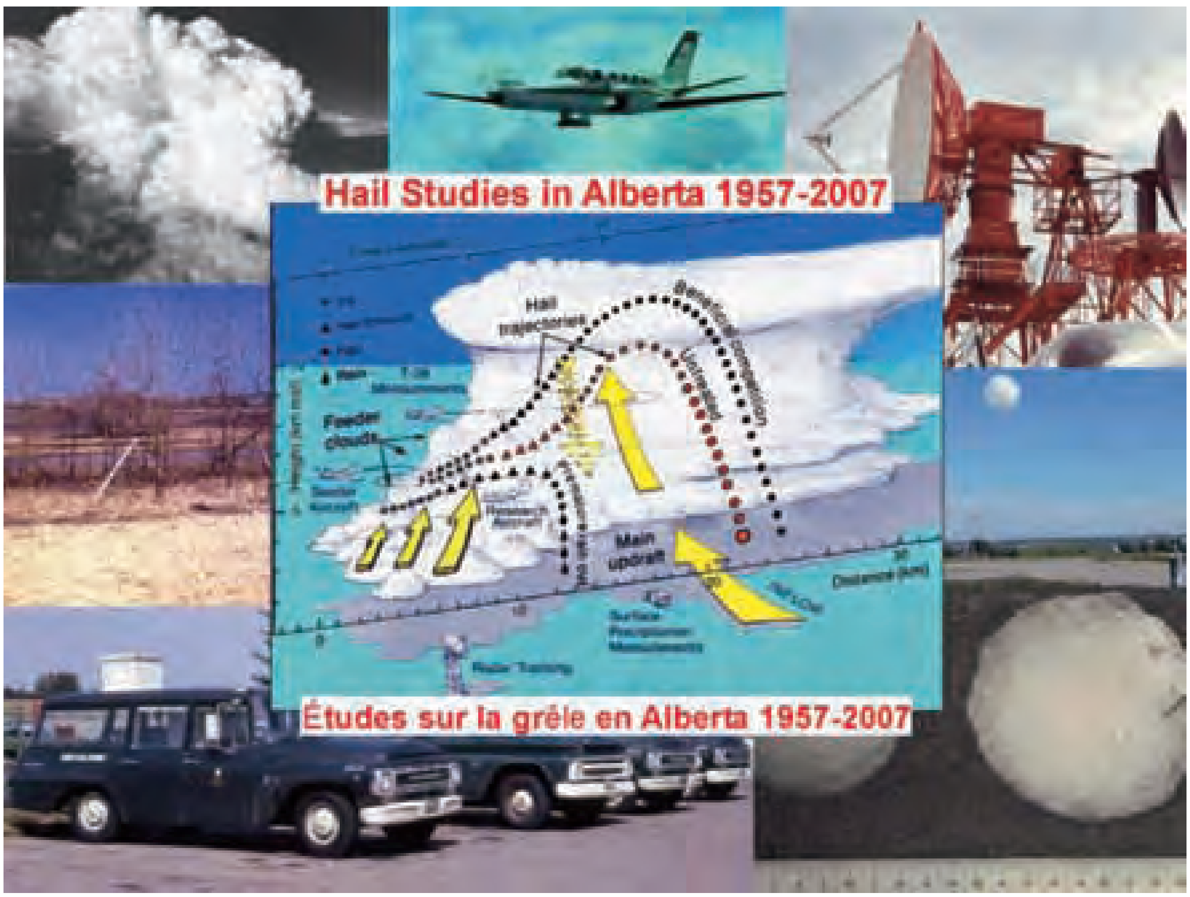

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... from the *CMOS Bulletin SCMO* Editorial Board

Dear readers,

The *CMOS Bulletin SCMO* Editorial Board is pleased to join the scientific team celebrating this year 50 years in studying hail in Alberta. This scientific team, whose members have varied throughout the years, come from different universities, McGill University, University of Alberta, l'Université du Québec à Montréal, University of Wyoming, USA, and University of Essex, UK, and from different government organizations, federal and provincial. The impact of hail storms is catastrophic on this Canadian region and has economic consequences on major crops. The Editorial Board thought that, because of the importance of the study and of its longevity, it deserves a special publication. This special issue of the *CMOS Bulletin SCMO* provides an historical synopsis of this scientific adventure. It also lists its major accomplishments. Furthermore, it looks at the future in presenting a new study, now at an advance stage of planning, the UNSTABLE project.

We hope that you will enjoy reading this special issue and we look forward to reading your comments in a future issue of the *CMOS Bulletin SCMO*.

CMOS Bulletin SCMO Editorial Board

... du comité éditorial du *CMOS Bulletin SCMO*

Chers lecteurs,

L'équipe éditoriale du *CMOS Bulletin SCMO* est fière de se joindre à l'équipe scientifique qui célèbre cette année 50 ans de recherche sur un problème météorologique particulier, la grêle en Alberta. Cette équipe scientifique, dont les membres ont varié au cours des années, provient de milieux universitaires multiples: l'université McGill, l'université de l'Alberta, l'université du Québec à Montréal, l'université du Wyoming, États-Unis et l'université d'Essex au Royaume-Uni, et de différentes organisations gouvernementales, fédérale et provinciales. L'impact de la grêle sur cette région canadienne est catastrophique et a des répercussions économiques sur les principales récoltes. L'équipe éditoriale a donc jugé bon de publier ces textes en un numéro spécial étant donné l'importance du sujet traité et de sa longévité. Ce numéro spécial du *CMOS Bulletin SCMO* relate l'historique de cette brillante aventure scientifique. Il en énumère les accomplissements les plus significatifs. Et il jette un regard sur l'avenir en mettant en vedette une étude qui est présentement à un étape avancée de la planification, le projet UNSTABLE.

Nous souhaitons que vous apprécierez ce numéro spécial et il nous fera plaisir de lire vos commentaires dans un prochain numéro du *CMOS Bulletin SCMO*.

Comité éditorial du CMOS Bulletin SCMO

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Inside / En Bref

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Le but de la SCMO est de stimuler l'intérêt pour la météorologie et l'océanographie au Canada.

CMOS Bulletin SCMO
"at the service of its members / au service de ses membres"

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Cover page : The composite picture on the front cover shows an artistic rendering of the conceptual model of seeding multi-cellular hailstorms (centre). Also shown, clockwise from top left are: the giant hailstorm photo of 11 August 1972 (Goyer 1978); INTERA-ARC research Aircraft; AHP S-, X-, and C-Band radars; radiosonde balloon release; tennis-ball size hailstone from 6 July 1975; *Project Hailstop* storm-chase vehicles; and hail-flattened crop (100% damage with trees 'defoliated' in background). Also appearing is the logo for project UNSTABLE. For more information on hail studies in Alberta, please read the two articles on **pages 3 and 20**.

Page couverture: La composition centrale de la page couverture est une interprétation artistique du modèle conceptuel de l'ensemencement de tempêtes de grêle multi-cellulaires. On voit aussi, dans le sens anti-cyclonique commençant en haut à gauche de la photo, la fameuse tempête de grêle géante du 11 août 1972; l'avion de recherche de INTERA-ARC; les radars en bandes AHP S-, X- et C; un lancement de ballon radiosonde; des grêlons de la taille de balles de tennis du 6 juillet 1975; les véhicules de poursuite de tempête de grêle du *projet Hailstop*; ainsi qu'une récolte abattue par la grêle (100% de dommage avec arbres défoilés en arrière-plan). On montre également le logo du projet UNSTABLE. Pour plus d'information sur ces deux études de grêle en Alberta, prière de lire les articles en **pages 3 et 20**.

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50th Anniversary of Hail Studies in Alberta
Accomplishments and Legacy

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Note: *In the above table, the years in parentheses after each author's location denote their participation on ALHAS, AHP, or AWMB.*

ABSTRACT: This year marks the 50th anniversary of the start of hail studies in Alberta. There were two major projects during this period involving several agencies, the one constant being Alberta Research Council (ARC). The McGill University Stormy Weather Group, with federal funding support, was prominent in the early period, but phased out as weather modification emphasis increased after 1969. The radar facilities were originally provided and operated by the National Research Council. By 1973 the funding was provided mainly by Alberta Agriculture and ARC and continued until the field studies ended in 1985. This article provides a historical synopsis, summarizing the observational methods and many of the scientific accomplishments. Finally, the legacy of the hail studies in terms of research programs since 1985 is discussed. Full details of the scientific results can be found in the large body of published literature.

RÉSUMÉ: Cette année marque le 50ième anniversaire du début des études de grêle en Alberta. Pendant cette période, deux projets importants impliquaient plusieurs agences dont le fidèle Conseil de recherche de l'Alberta (l'ARC). Le groupe universitaire McGill sur la météorologie des tempêtes, avec le soutien financier du fédéral, était proéminent dans la première période, mais s'est désisté peu à peu avec l'accentuation en 1969 sur la modification du temps. À l'origine, l'équipement radar a été fourni et opéré par le Conseil national de recherche. À partir de 1973, le financement a été fourni surtout par le ministère de l'agriculture de l'Alberta et l'ARC et a continué jusqu'à la fin des études sur le terrain en 1985. Cet article présente un exposé historique, en énumérant les méthodes d'observations, et rappelle plusieurs accomplissements scientifiques réussis. Finalement, le legs des études de grêle en tant que programmes de recherche depuis 1985 est discuté. Les détails complets des résultats scientifiques peuvent être trouvés dans la littérature publiée.

1. Introduction

Central Alberta experiences thunderstorms on 55-75% of summer days, hail on 50% of days, and severe hail (bigger than walnut size) on 15% of days (Strong and Smith, 2001). The point frequency of hail over central Alberta varies from 2-6 days per year (Wojtiw, 1975). While these hail frequencies are comparable to those of the High Plains of the U.S. in the lee of the Rockies, tornadoes are not as common in Alberta as over the southern U.S. Alberta thunderstorms form predominantly over the foothills and track generally eastward (Figure 1). They are remarkable because of the high frequency of large hail, which causes widespread damage to economically significant grain crops such as wheat, canola, barley and oats.

Thus, economic losses due to hail have been a long-standing problem in Alberta. However, during the early-1950s a series of severe hailstorms caused more damage than usual in the central Alberta region between Calgary and Red Deer, where hail insurance was very limited or not available at all in many localities. This prompted farmers in central Alberta to approach the provincial government for help, including the possibility of using the newly discovered techniques of cloud seeding to mitigate hailstorm damage. The issue was passed on to the Alberta Research Council (ARC) for guidance, where research chemist Mac Elofson and the Director of Research, Nathaniel Grace, were already predisposed towards taking on the problem (Elofson, 1991). Weather modification science at that time was in its infancy. Consequently, following meetings with interested parties in Alberta, it was recommended that, because of the lack of scientific consensus on the viability of weather modification, a research program should be established to gain a better scientific understanding of hailstorms before any attempts were made at mitigation.

In June 1955, the Meteorological Branch of the Department of Transport convened a meeting with the Alberta Research Council (ARC), the provincial Department of Agriculture, and the University of Alberta to discuss the scientific issues. It was agreed that the Meteorological Branch and ARC should co-operate on a summer pilot program in the main hail belt of central Alberta during the summer of 1956. Elofson and Grace took on this pilot program, working out of Didsbury in central Alberta; they were joined by Dick Douglas from the McGill Stormy Weather Group (SWG). Their goal was to test the feasibility of using farmers as observers to provide valuable information on storms.

Postcard questionnaires were mailed out to some 6500 farmers in an area of 10,000 km^2 around Red Deer with a request to respond when they received hail. More than 500 volunteer reports were mailed in. The most surprising discovery from this was that hail occurred somewhere in the area on 42 days during the summer. This greatly exceeds the climatological point hailfall frequency of 4 days per year recorded at the meteorological stations in the test area. The hail occurrences could be plotted accurately since each farm was precisely located on the Dominion Land Survey grid system. This pilot project was considered a success, but the need for a radar storm-tracking system was immediately recognized. Hence, the McGill SWG was asked to take over scientific leadership of the project for 1957, with funding provided by the Meteorological Branch.

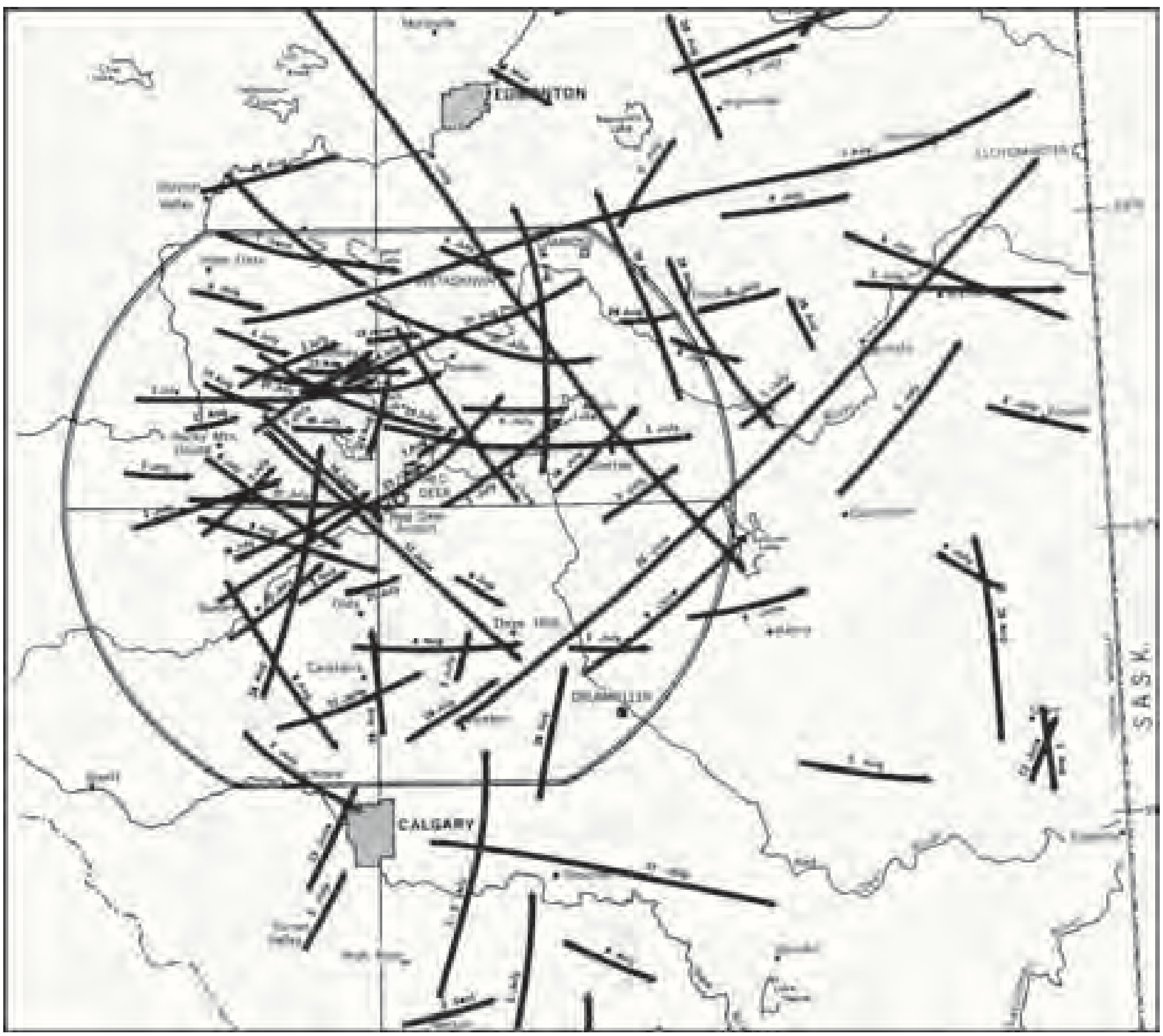

Figure 1: 1975 Hailswath tracks for storms with hail size greater than grape. Outlined area is the AHP (1974-85) research and operations region (after Deibert, ed., 1975).

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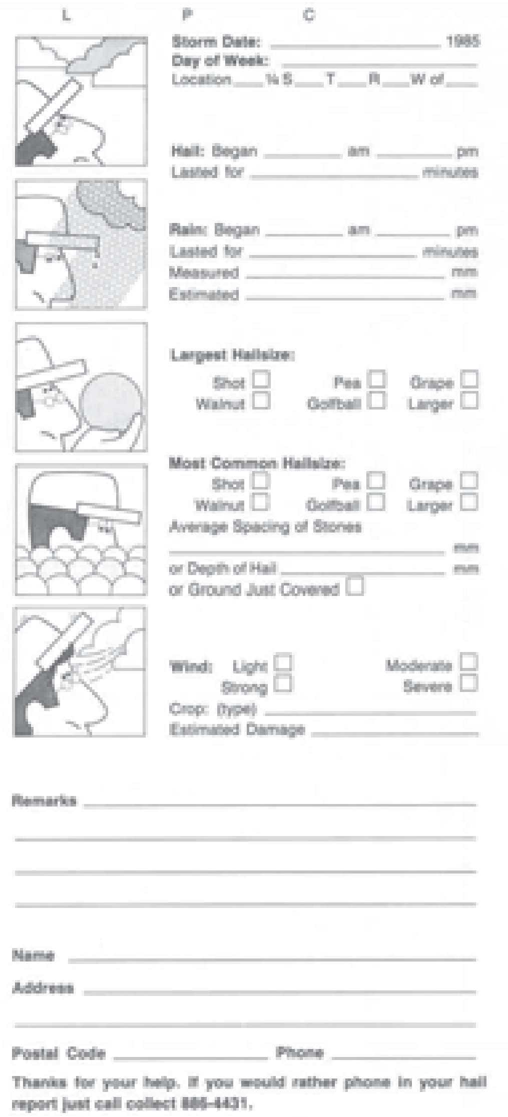
Alberta Hail Studies,
P.O. Box 111,
R.C.A.F. Station Penhold,
Alberta.

Date of storm: July 27th
Exact location of hail occurrence: ¼ N.W. S. 16 T. 37 R. 28 W. 4th
Hail began 5.30 a.m. / p.m. Hail lasted 5 hr minutes
Size of largest stones: Shot; pea; grape; walnut; golfball
(If larger than golfball, estimate diameter ________ inches.)
Hail was accompanied by: Lightning; high winds
Hail began: before rain; after rain; at same time as rain
(Circle appropriate word)
Remarks: Storm moved in from North West with High winds Crop Damage 100%
Name John McDonald Address RR #4 Red Deer
If you have no more cards, check here ☐ Phone ________
Do not write below this line

DAY	MO	YR			S	T	R	W	BGN	DUR	S	BRG	DIST			
27	07	59	00	1	0	16	37	28	4	1730	3	03				0

Figure 2a



L P C

Storm Date: ________ 1985
Day of Week: ________
Location ___ ¼ S ___ T ___ R ___ W of ___

Hail: Began ________ am ________ pm
Lasted for ________ minutes

Rain: Began ________ am ________ pm
Lasted for ________ minutes
Measured ________ mm
Estimated ________ mm

Largest Hailsize:
Shot ☐ Pea ☐ Grape ☐
Walnut ☐ Golfball ☐ Larger ☐

Most Common Hailsize:
Shot ☐ Pea ☐ Grape ☐
Walnut ☐ Golfball ☐ Larger ☐
Average Spacing of Stones
________ mm
or Depth of Hail ________ mm
or Ground Just Covered ☐

Wind: Light ☐ Moderate ☐
Strong ☐ Severe ☐
Crop: (type) ________
Estimated Damage ________

Remarks ________

Name ________
Address ________

Postal Code ________ Phone ________

Thanks for your help. If you would rather phone in your hail report just call collect 886-4431.

Figure 2b

Figure 2: Hail reporting form for (a) 1959 Alberta Hail Studies, and (b) 1985 Alberta Hail Project.

2. Alberta Hail Studies, 1957-73

Hail research began in earnest in the spring of 1957 with the installation of a 3-cm Decca radar at RCAF Station Penhold (later called Red Deer Airport) by the SWG in collaboration with the National Research Council (NRC) and ARC. The Alberta Hail Studies (ALHAS) was thus born in 1957, and so began a program of systematic and continuous summer observations of hailstorms using three main tools: *radar* to study the internal structure of storms; *cloud photography* to study the visual morphology of cloud turrets and their growth rates; and volunteer *hail reports and samples* to study hailfall patterns on the ground. The airport site became the field research and operations base for the next 30 years. The research was initially concentrated in a quasi-rectangular region, roughly 350 km by 150 km, which included Red Deer and Calgary.

Figure 2a is a sample volunteer hail report from 1959, providing valuable information on storm date, location, time and duration of hail, maximum size and relevant storm comments. This type of hail reporting was continued with minor revisions and additions until the hail program ended in 1985 (Figure 2b). It was supplemented by telephone surveys immediately following storms.

The initial focus on precipitation particles established a certain mode of research that continued into the 1970s, based on five key questions:

1. What is the climatology of hail in central Alberta?
2. What are the characteristics of hail-producing storms observed by radar?
3. What are the freezing properties of water from hailstones and rain?
4. Using numerical models of the day, how does hail grow within a storm?
5. What synoptic weather phenomena are associated with hailstorms in Alberta?

		June	July	August	September	TOTAL
No. of hail days:	1957	22	26	19	10	77
	1958	21	19	16	4	60
No. of reports:	1957	1045	1444	585	124	3198
	1958	328	289	232	72	921

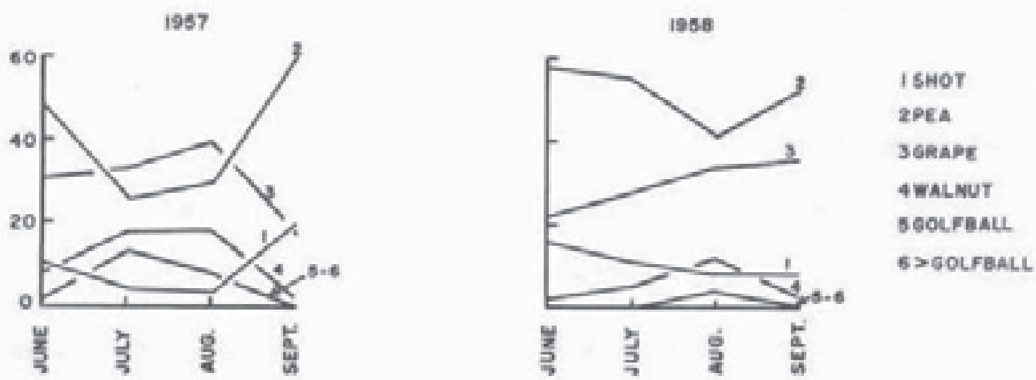


Figure 3: Numbers of hail days and reports and distribution of hail size in central Alberta, 1957-58 (reproduced from Douglas, 1959).

At that time, and up until the late 1970s, there was a general belief within the severe storm research community that while larger-scale (synoptic) processes *prepared the atmosphere* for storms to develop, once initiated, storms formed their own circulation, kinematics and life cycle virtually independent of synoptic processes. We now understand that thunderstorms are not independent entities, and that they, in turn, influence synoptic processes.

2.1 Some Early ALHAS Research Results, 1957-63

The Meteorological Branch continued its support of the program, committing a meteorologist for weather forecasting and related duties, from 1960 through 1975. With continued funding from the Meteorological Branch, McGill scientists conducted most of the research analysis during this early period, establishing the early climatology shown in Figure 3.

This period likely produced the earliest confirmation of organized hailswaths, as depicted in Figure 4 for a severe storm on 26 July 1962. This was an early step in recognizing that hail events were not sporadic outputs from the storm but organized features. In addition to hail reports and microphysical data obtained from actual hail samples (with subsequent laboratory analysis), radar was the major research tool in these early years of ALHAS.

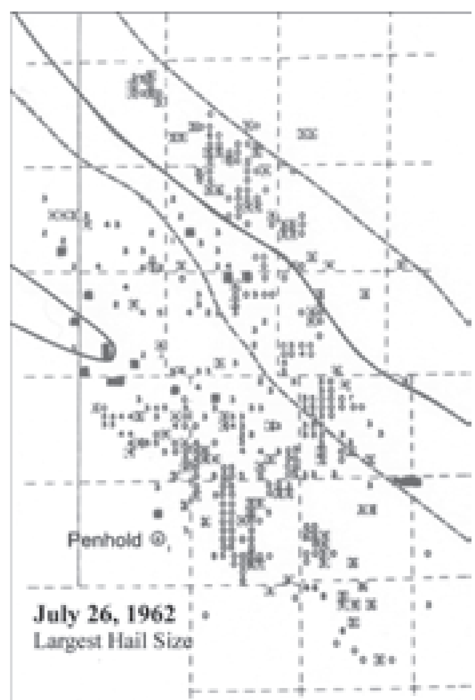


Figure 4: Two hailswaths (denoted by solid/broken lines) inferred from volunteer hail reports for severe hailstorm of 26 July 1962,with hail sizes indicated by plotted numbers: 1-shot; 2-pea; 3-grape; 4-walnut; 5-golfball; 6 >golfball; 0-unknown size (reproduced from Williams & Douglas, 1963).

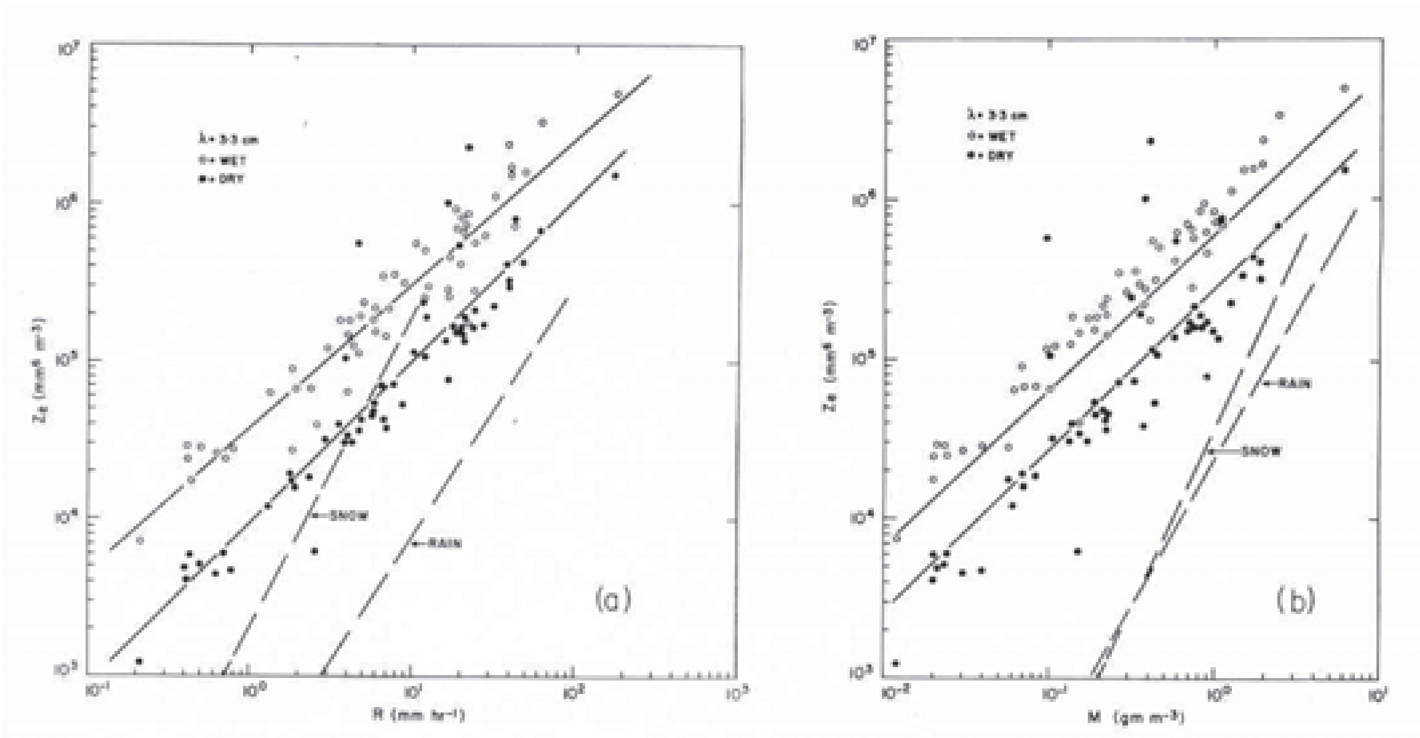


Figure 5: Equivalent reflectivity (3.3 cm) vs. precipitation rate (R) and hail mass concentration (M) (reproduced from Douglas, 1963).

The 3-cm radar was a crude meteorological tool with output consisting of photographs of the PPI scans. Nevertheless, it made it possible to relate the radar storm cells to ground-based hail data. A major improvement in radar analysis was introduced by the SWG in 1959, with the introduction of a ‘grey-scale’ that displayed radar echoes in quantized shades of grey corresponding to values of reflectivity. This allowed the detection and location of the highest intensity echoes. In spite of serious attenuation problems with the 3-cm band radar signal, SWG scientists carried out ground-breaking research, revealing relations between reflectivity and rainfall rate and between reflectivity and hail mass concentration (Figure 5).

Achievements during this period included:

■ distinguishing between single-cell storms that gave a single burst of hail, and multi-cell storms where new cells formed on the southern flank, producing almost continuous hailswaths up to 100 km in length;
■ quantifying the strong correlation between the height of the radar echo top and the probability of hail at the ground;
■ developing an instability index (Slydex) for forecasting hail occurrence (Sly, 1964);
■ developing a theory of accumulation zones of high liquid water content (LWC) to account for rapid hailstone growth;
■ initiating laboratory and theoretical work on the drop freezing and nucleation processes (Vali, 1965).

2.2 Shift in Research Emphasis to Large-Scale Dynamics, 1964-68

The installation of a 10-cm, broad-beam radar in 1963 facilitated studies of storm dynamics. At the same time, an interest in extra-storm dynamics also arose. Several developments contributed to this new interest: having a trained forecaster on-site, early insights into storm and extra-storm dynamics observed with the old 3-cm, ‘grey-scale’ radar and via a continuing cloud photography program, the acquisition of a METOX radiosonde system in Calgary in 1966, to assess atmospheric instability and wind profiles, and the acquisition of a number of pilot balloon theodolites for measuring wind fields. The sounding systems allowed investigation of mesoscale dynamics beyond the storm boundaries. In 1967, the broad beam radar was replaced with a new 10-cm, pencil beam radar. This reduced the attenuation problem considerably and it quickly became apparent that research had to expand well beyond the ‘visible storm’ structure.

These new tools revealed that certain synoptic patterns favoured the formation of thunderstorms, such as a southwest flow at upper levels with an approaching shortwave trough (Longley and Thompson, 1965). The mean upper air charts from the Longley and Thompson study suggest that Alberta storms occur predominantly behind the low-level trough (or cold front), in the cold baroclinic zone, but ahead of the upper trough. This synoptic environment is significantly different, in general, from that of storms forming over the prairies to the east, where a cold front or frontal wave is often involved.

During this period, it also became apparent that the mountains and foothills played an important role in Alberta storms. This discovery resulted in moving the Calgary radiosonde system into the foothills at Rocky Mountain House around 1969. However, apart from the work of Derome (1965), who showed that environmental ascent, especially in the boundary layer, was related to storm formation, the primary research focus remained on storm scale processes, throughout the first 20 years.

Meanwhile, great strides were also being made elsewhere in radar and cloud physics research. As a result, the project gained international interest and participation, including exchange visits between U.S., Russian and Canadian scientists. The new 10-cm radar provided the highest resolution of any research radar in North America. A new signal display technique HARPI (Height-Azimuth-Range Position Indicator) was developed by the SWG (Zawadzki and Ballantyne, 1968). It provided 1-km resolution in echo intensity at a range of 60 km. These detailed measurements gave a whole new insight into storm structure, showing, for the first time, the weak echo region (WER) and high intensity overhang echoes associated with the updraft. The addition of polarization to the radar signal was a major advancement in radar technology that showed promise for identifying precipitation types. By combining echo polarization information with normal reflectivity, Barge (1972) was able to develop real time "hail detector" display. This proved to be invaluable for directing seeding aircraft and mobile precipitation samplers during subsequent seeding operations in 1972 and 1973.

During 1967, an instrumented Cessna turboprop aircraft from Meteorology Research Inc. made turbulence and ice nucleus measurements in and around cumulus clouds in the foothills. Such measurements were a necessary precursor to cloud seeding, providing an indication of the ice nucleus production rates that would be required. During 1968 and 1969, an instrumented C-45H Beechcraft aircraft from the University of Wyoming made extensive measurements of water vapor fluxes in the updraft regions of storms (Marwitz and Berry, 1971), enabling moisture budgets for a storm to be estimated.

Pell (1967) reviewed the concept that steady-state storms produce a near continuous swath of hail along their tracks. His work revealed ‘gaps’ in the hailswaths and he concluded that a much denser network of hail observations was necessary to determine the source of the gaps. Subsequently, Pell (1969) observed an echo-free region within a hailstorm; this observation was subsequently confirmed by Chisholm (1973), who identified these regions as a manifestation of a strong updraft in the storm. This weak echo feature remains an essential ingredient in nowcasting severe storms today, providing alerts for severe hail and potential tornado formation. Thyer (1970) and Ragette (1971) revealed new features of the boundary layer wind field in the pre-storm environment, as well as wind structures in and around storms.

2.3 Parallel Hail Suppression Program, 1956-68

During the first dozen years of ALHAS, weather modification was not part of the research effort. Frustrated by this perceived inaction on the part of government and research agencies, local farm groups, including the Alberta Weather Modification Co-op and the Wheatland Weather Modification Association, canvassed volunteer contributions and raised sufficient funds to contract Irving P. Krick Associates of Canada Ltd. to carry out cloud seeding operations. This program was initiated in July 1956, using a network of farmer-operated, ground-based generators, intended to deliver silver iodide into convective clouds via natural convection. There were claims that this seeding program produced dramatic reductions in hail damage losses. However, a subsequent evaluation of ground-based seeding, carried out by AHP in the 1980s, showed that, while plumes from ground-based generators occasionally reached cloud base, they typically were narrow and filled only a few percent of the target volume.

2.4 Project Hailstop, 1969-72

The first dozen years of hail research had yielded an appreciable scientific understanding of hailstorm behaviour. Meanwhile, the interest and pressure from the farming community was rising. The time seemed right to investigate cloud seeding for hail suppression. Phase 1 of Project Hailstop consisted of a series of cloud seeding experiments, conducted in July 1969, using a B-26 aircraft from the Desert Research Institute in Reno, Nevada (Renick, 1969). The experiments involved seeding in updraft areas below cloud base, using AgI and Indium Hydroxide (an inert tracer). Ground-based mobile units were deployed to collect precipitation samples. Also in 1969, a T-33 jet from the NRC was used to measure the upper-level winds and turbulence structure in the storm environment.

In order to implement the seeding more efficiently and precisely in 1970, a new cloud seeding concept was proposed. The idea was to seed newly developing towers at the appropriate time in their life cycle, in order to induce greater competition for the available water supply, thereby preventing the growth of large hail. To accomplish this, a new cloud seeding delivery system was developed jointly by ARC and NRC using the T-33 (Summers et al., 1972). Droppable pyrotechnic flares were used, fused to fall about 2 km before releasing the AgI in the final 1 km of fall. A unique feature was radar chaff released at flare burn-out, to enable seeding locations to be pinpointed. The required seeding heights were estimated from a real-time cloud model and the aircraft was directed to target cells at the correct altitude, on the basis of radar echoes and pilot visuals. Flares were then dropped at 300-m intervals across the target. These logistics were tested on 40 storms during 1970-72, with assistance from University of Wyoming aircraft. These experiments suggested that storms could be seeded successfully using droppable flares, since the radar recorded lower radar reflectivities and lower precipitation fall speeds from seeded cells than unseeded cells. These results suggested that there were smaller hailstones in the seeded cells and this was confirmed by smaller hail collected at the ground. The results also indicated that a capability existed to detect physical effects of seeding and use them as an evaluation tool, rather than relying solely on statistical analyses.

Renick (1966) developed a stereo, time-lapse cloud photography system that provided detailed information on the visual structure and growth rates of storms. Together with Warner et al. (1972), he associated the cloud towers of a hailstorm with updraft regions in the storm and with individual radar cells that developed every few minutes. This work led to the development of important kinematic models of single-cell, multicell and supercell storms (Chisholm and Renick, 1972). The evolution and wind profile of a typical multicell storm is shown in Figure 6. The identification of multiple, regenerating cells in storms helped to explain the ‘gaps’ in hailswaths noted by Pell (1967).

During this period, work also began on a dynamical hailstorm model (Srivastava, 1964; Takeda, 1969), and ground-based, mobile units were developed to chase storms, measure winds and collect hail and rain samples for laboratory analysis. Chisholm (1973) developed a simple, one-dimensional, steady-state model to estimate the vertical velocity, temperature, and liquid water content in storms, using single soundings. This proved useful both for short-term forecasting and for diagnostic studies of storms. English (1973) used a two-dimensional cloud model to estimate hail growth rates and size; the model also inferred radar reflectivities that were similar to values measured in four severe storms.

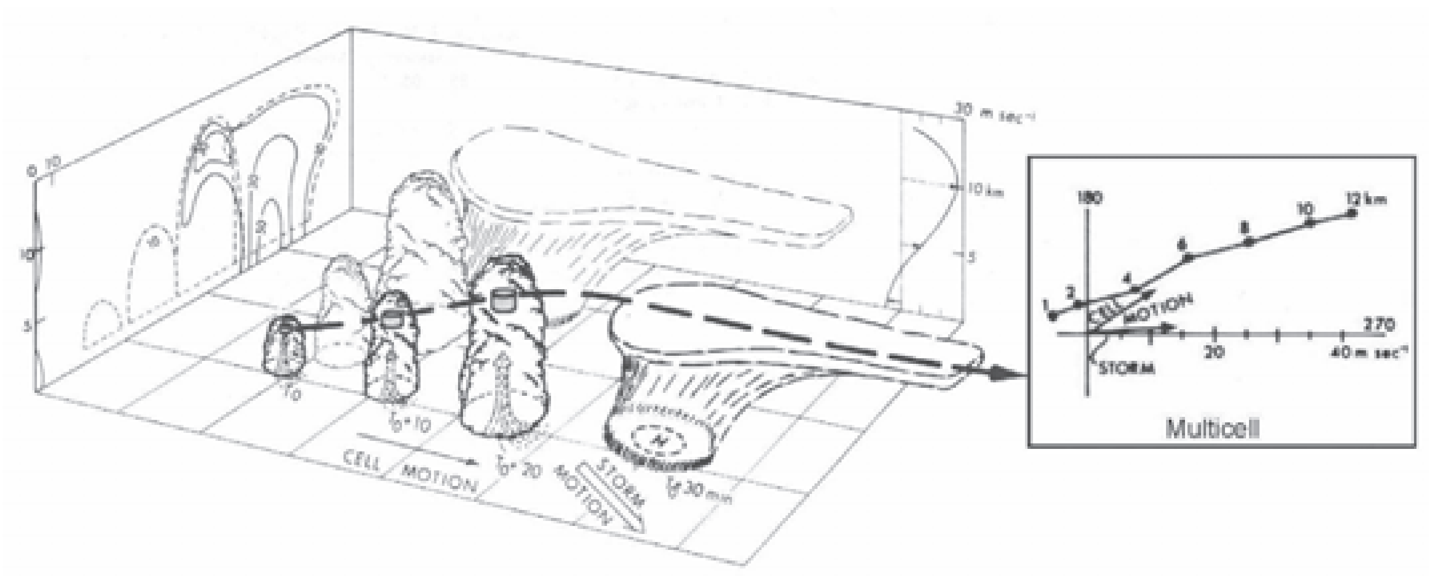


Figure 6: Kinematic model of an Alberta multicell storm and its wind hodograph (reproduced from Chisholm and Renick, 1972).

2.5 1973 - A Transition Year

Responding to increasing concerns expressed by farmers in central Alberta over continuing crop losses and their perceived lack of progress in implementing effective hail suppression techniques, the provincial government established a Special Legislative Committee in 1972, with a mandate to investigate crop insurance and weather modification in Alberta. After a series of hearings around the province, which included presentations from many sectors and from invited experts from outside the province, a report was tabled in the Legislature in November 1972. The main recommendation was that the province should finance a 5-year, active hail suppression program to begin in 1974. However, as plans were already in place for the 1973 ALHAS field program, an Interim Weather Modification Board was appointed to fund and oversee a pilot cloud-seeding project. The IWMB, which became the Alberta Weather Modification Board (AWMB), consisted of a dozen or so individuals, representing the farm community, the University of Alberta, ARC and Alberta Agriculture. INTERA Technologies Ltd. were chartered to seed all potential hail storms in a defined area south of Penhold, using three turbocharged Cessna aircraft. In 1973 seeding was carried out on 15 days.

2.6 Hailfall Analyses

Eighteen years of intensive hail survey data facilitated the formulation of a basic hailfall climatology (Wojtiw, 1975). Figure 7 shows that the highest point frequency of hail occurs over or near the foothills, with maxima near Rocky Mountain House (RM) and Sundre (SU). Wojtiw also demonstrated the important seasonal variation of hailfall, which appears to follow the summer crop emergence, growth and harvesting cycle. An updated version of the seasonal cycle for the full 29-year period (1957-85) of hail studies can be found in ARC (1986).

Figure 7: Annual point frequency of hail over central Alberta, based on 1957-73 ALHAS hail surveys (reproduced from Wojtiw, 1975).

The first attempt to quantify hail size distributions in Alberta using hailpads was carried out in 1973. Alberta hailpads were one foot square pieces of Styrofoam, fixed to the ground and calibrated to estimate the hail size distribution, ice mass, and impact energy density, from recorded hail dent sizes on the pads (Strong, 1974). Detailed objective data on hailswaths and hailstreaks, based on surface measurements, were now available for the first time (see Figure 8, after Strong and Lozowski, 1977). This program was discontinued after 1980 because the pad analysis was very labour-intensive; however, it could now be resurrected as an inexpensive but valuable analysis tool, in view of the advent of digital photography and automated analysis software that can easily be run on today's desktop computers.

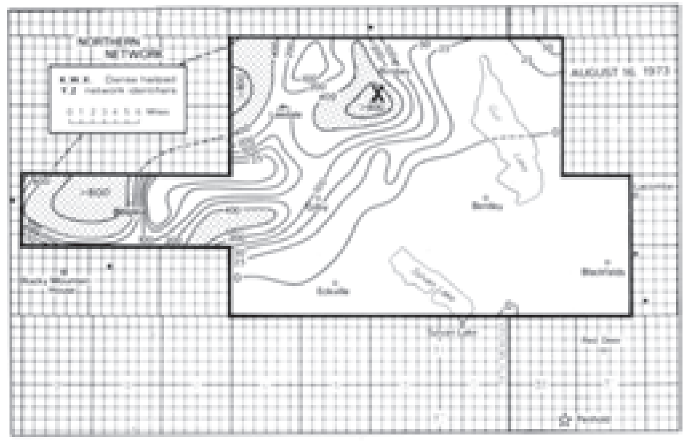


Figure 8a

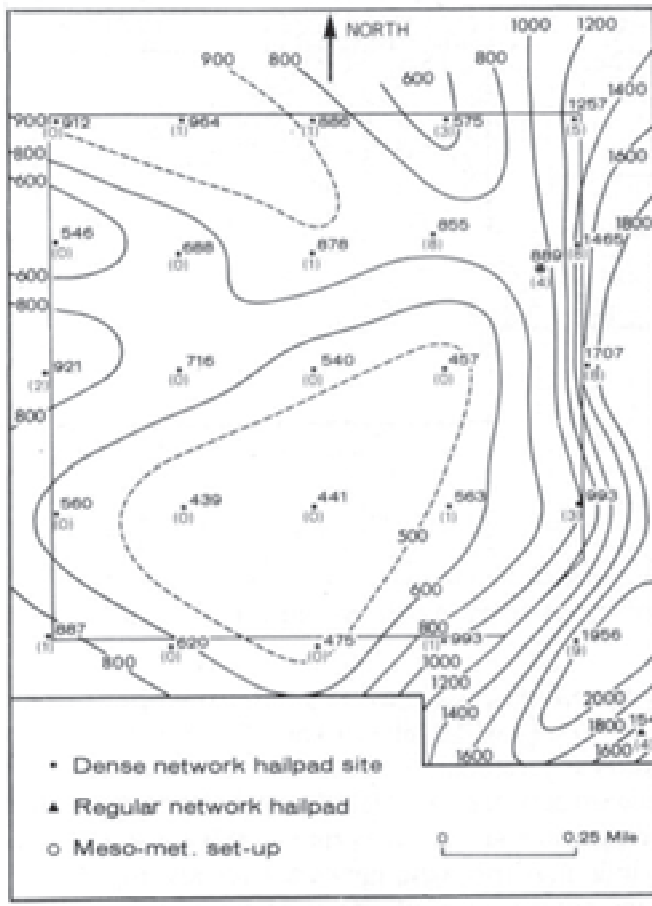


Figure 8b

Figure 8: (a) Mesoscale and (b) Cloud-scale analyses of hailswath impact kinetic energy density (J m-2) on August 16, 1973. Each small square in (a) is one section of land (1 square mile), with the 'X' marking the land section of (b) (reproduced from Strong and Lozowski, 1977).

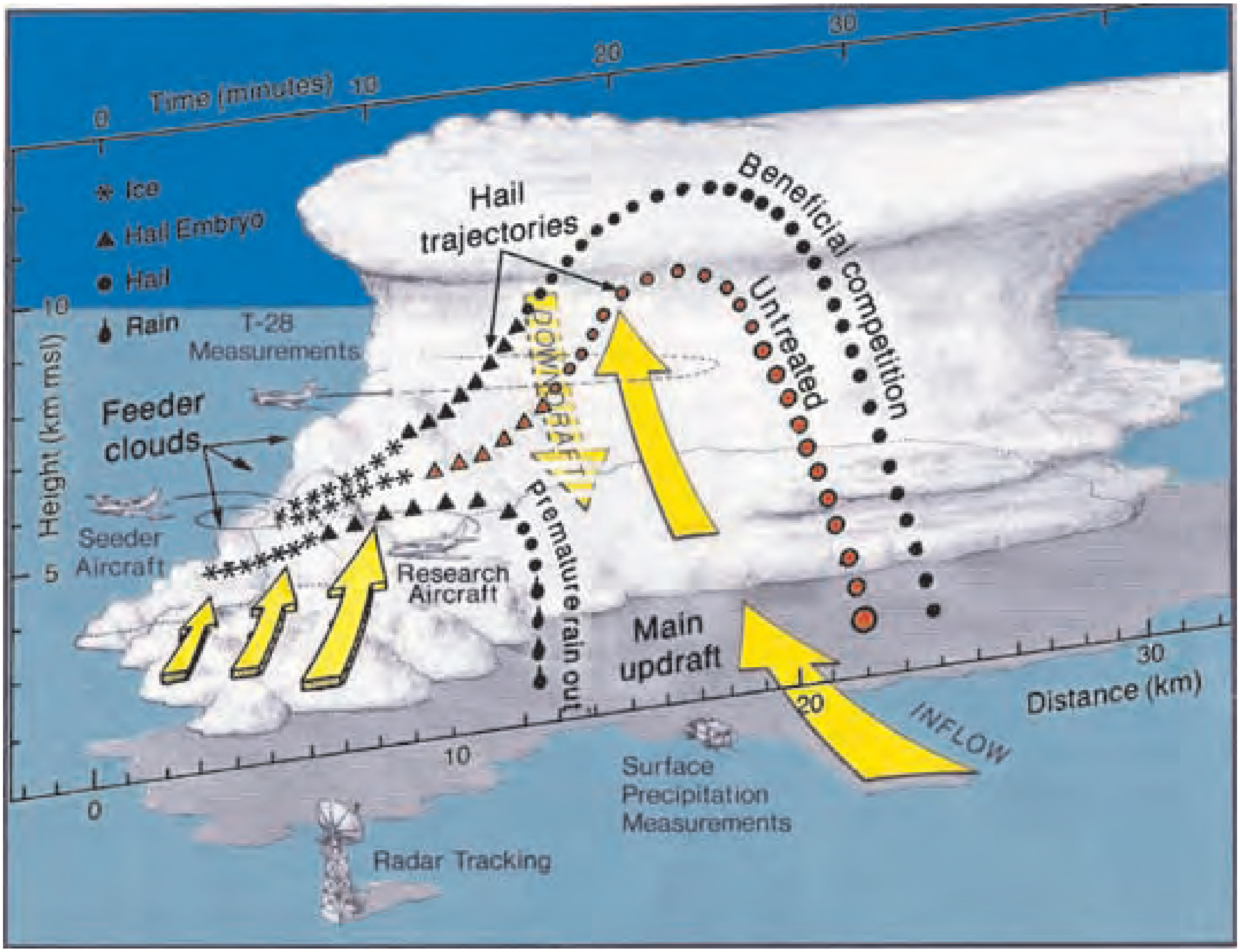


Figure 9: An artistic rendering of the hailstorm conceptual model, including effect of seeding, where "premature rainout" occurs in feeder clouds (lower-left flank), while seeding material (AgI) entering the rapidly-developing new cells leads to "beneficial competition", producing larger numbers of smaller hailstones (adapted from ARC, 1986).

3. Alberta Hail Project (AHP), 1974-85

The final dozen years of large-scale hail studies in Alberta began in 1974, under the rubric Alberta Hail Project (AHP). The AHP was operated by ARC and administered by the Alberta Weather Modification Board (AWMB), which had been established by the Alberta government, with primary funding from Alberta Agriculture. There were two 5-year programs, 1974-78 and 1981-85, with two interim years in 1979 and 1980. The second 5-year program differed slightly from the first in that it included exploratory studies of cloud seeding to increase rain and snow. These were managed by Guy Goyer (1975a,b) of ARC.

3.1 The Alberta Weather Modification Board (AWMB), 1974-85

The AWMB consisted of several farmers (5) and representatives from the University of Alberta (2), Alberta Agriculture (1) and ARC (2). Its mandate was to conduct both a research and an operational hail suppression program and to evaluate each. The 80 mile (~130 km) radar range ring was used to define the project area shown in Figure 1, with northern and southern sectors omitted due to heavy aircraft traffic around the Edmonton and Calgary International Airports. The plan was to conduct full-seed operations over the southern half of the project area and randomized experimental seeding over the northern half. This compromise seeding solution was formulated to satisfy the desire for "crop protection" coming from some farmers in the southern half of the project area (as expressed by their representatives on the AWMB). Like many compromises, it had its drawbacks. In particular, evaluation was confounded, because the AWMB mandated that storms moving northward from the southern half into the northern half should continue to be seeded across the boundary, while any northern storms threatening the southern half had to be seeded prior to crossing the boundary. Despite this additional complication introduced into the evaluation of the randomized seeding program, the AWMB did, nevertheless, provide a solid funding base for hailstorm research.

3.2 Cloud Seeding Operations

The AHP project facilities were located at the Red Deer Industrial Airport and consisted of weather and aircraft tracking radars and a computer system developed and operated under contract by the Alberta Research Council. Project aircraft were equipped with special transponders that enabled controllers at the site to identify, track and direct seeding aircraft to the hailstorms. A computer-generated, real-time radar and aircraft display system was developed for this purpose, and data were recorded for subsequent scientific analysis of storm characteristics. A 5-cm radar system was also added to provide an all-weather monitoring capability (for example, when on-site winds were too high to operate the 10 cm radar antenna).

INTERA Technologies Ltd of Calgary were contracted to conduct the cloud seeding operations, using seven twin-engined aircraft, from1974 to 1985. Two cloud seeding methods were used. Cloud-top seeding was executed with ejectable, short-burn, silver iodide (AgI) flares, dropped into growing convective turrets along the edges of the main storm. Cloud-base seeding was conducted just below cloud base, along the edge of the storm updraft area, using burning flares attached to the aircraft's wings. The seeding program ran from June 20 to September 10 each year, over a target area of 48,000 km^2, centered on Red Deer Airport. All potential hailstorms in the southern half of the area were seeded, while during the first 2 years, the northern half of the area was seeded on a 50-50 randomized basis. A partial analysis of the effect of the seeding operations on hail crop losses was presented by Goyer and Renick, (1979).

3.3 Cloud Microphysics and the Hailstorm Conceptual Model

During Project Hailstop, a conceptual model of the microphysics and multi-cellular structure of Alberta storms (Figure 9) had evolved from radar, aircraft and photogrammetric studies, which showed how the air and moisture flows interacted with precipitation in the storm (Renick, 1971; Summers and Renick, 1971; Renick et al, 1972; Chisholm, 1973). It was hypothesized that hailstorm embryos formed in feeder clouds that are seen, visually, as cloud towers and by radar as individual echo cells. These cells as they developed went on to become the main body of the storm. According to the model, the embryos grew rapidly on the abundant super-cooled liquid water carried aloft by the main updraft.

Later, this conceptual model was refined, based on the work of Barge and Bergwall (1976), who showed that radar storm cells contained fine scale reflectivity patterns (FSRPs). These FSRPs usually evolved more regularly than the larger storm cells. FSRPs were usually identified on the southern edge of storm radar echoes, and could be tracked from their formation through their intensification stages, as they moved through the high reflectivity region of the echo, until they finally became obscured in the echo dissipation zone. FSRPs were considered to be a radar manifestation of the new, rapidly growing cloud towers, visually observed on the southern flank of the storm.

Cumulus clouds forming along the southern edge of the storm (the new growth zone) usually persisted for 10 to 15 minutes before growing rapidly into large cloud turrets. The tops of these 'new-growth zone' cumuli were usually colder than 0°C and were considered to be the major source of hail embryos for the storm. The hail suppression hypothesis suggested that the introduction of ice nuclei into these developing towers would generate larger numbers of embryos that would compete with natural embryos for the available liquid water, resulting in reduced hailstone sizes.

In order to gain an understanding of the physical processes occurring in storms and the effects of cloud seeding on them, the Alberta Research Council and INTERA Technologies Ltd, jointly developed an instrumented cloud physics aircraft. Controlled, glaciogenic seeding experiments on the feeder clouds and growing towers in the new growth zone were conducted. The aim was to assess the impact of seeding treatments upon the growth of potential hailstone embryos within these towers and upon the production of hail by the main storm. In these experiments, feeder clouds meeting pre-specified cloud-top temperature, horizontal cloud dimensions, liquid water concentration, ice concentration and updraft criteria were seeded. The double blind, randomized seeding treatments used either a placebo, Silver Iodide (produced by droppable flares) or dry ice pellets. Following seeding, the treatment effects and the subsequent precipitation growth processes were simultaneously documented, by repeated penetrations of the treated cloud by the heavily instrumented research aircraft and by observation with the S-band radar system. Storm chase vehicles were also deployed to intercept the storm and collect time-resolved hailstone samples.

The results from the randomized hailstorm seeding experiments indicated that seeding increased precipitation within feeder clouds, (Krauss and Marwitz, 1984; Krauss and English, 1984). In some cases, cloud seeding appeared to cause hail embryos to precipitate out of the feeder cloud prematurely. However, limitations in the measuring and observing facilities did not allow conclusive proof that more hail embryos led to smaller hail on the ground, or that premature rain-out of embryos yielded fewer hailstones on the ground. However, some evidence from hailstone samples indicated that cloud seeding altered hailfall at the ground (Cheng et al., 1985).

During 1985 an 'armoured' T-28 aircraft from the South Dakota School of Mines and Technology flew cloud penetrations into the region where hailstone embryos were thought to enter the storm and become hailstones. Flights were coordinated with the Cessna Conquest research aircraft and mobile sampling on the ground.

3.4 Radar Research

Research with weather radar began in 1957, when the National Research Council (NRC) installed a 3.2-cm Decca DC-19 radar at Penhold. This was replaced in 1963 with a 10-cm FPS-502 (S-band) radar. Meanwhile, since NRC had developed a 1.8-cm polarization diversity radar (McCormick, 1964), they designed a dual polarization antenna for the FPS-502, using a feed horn that was scaled up from the 1.8-cm feed horn. The new antenna was installed in the spring of 1967 (Allan et al., 1967). The goal was to detect hail in convective storms by means of the circular depolarization ratio and the cross-correlation of simultaneously received signals of right and left circular polarization.

The Alberta polarization diversity radar was recognized at that time as the best of its kind. Up until the S-band was installed, the Soviets were the leaders in using polarization techniques to study precipitation. However, they were limited by the poor polarization qualities of the antennas used (Shupiatskii and Morgunov, 1963). As noted in previous sections, the S-band radar was used to further knowledge about the development and growth of hailstorms. As a result of polarization studies both in Alberta and in Ottawa it was determined that:

- Raindrops tend to fall with their symmetry axis vertical;
- The degree of correlation between the main and orthogonal components is higher for rain than for hail;
- The circular depolarization ratio (CDR) can help to distinguish rain from hail, but propagation effects cannot be ignored (Barge 1972; Humphries 1974);
- A combination of the CDR, the radar reflectivity factor, and the cross-correlation is sensitive to precipitation type and hence could be useful for identifying the hydrometeors present in the observed volume (Torlaschi et al., 1984, Al-Jumily et al., 1991).

The addition of a 5-cm weather radar in 1974 provided the opportunity to use both polarization and dual-wavelength techniques to study hydrometeors (Humphries and Barge, 1979). Initially, data from the radar systems were in the form of photographs of the radar PPI displays or in the form of tracings from a strip chart recorder. Ultimately systems for digital signal processing and recording were developed as well as methods for the display of the digitally recoded data. A weather research group in Brazil purchased this radar data processing and display technology in 1980. Although the last major field program of the Alberta Hail Project occurred in 1985, data from the polarization radar were used for research well after the radar was decommissioned (Holt et al., 1994, Humphries et al., 1991). The three radars used during AHP research and cloud-seeding operations are depicted in Figure 10.

Figure 10: Radars used in AHP research and cloud-seeding operations, L-R: 10-cm S-Band polarization diversity radar, X-Band aircraft-tracking radar, 5-cm C-Band radar.

3.5 Mesoscale Research and Forecast Operations

One component of the AHP program included mesoscale studies of the storm environment, using atmospheric profile data from fixed and mobile sounding sites. Robitaille et al. (1979) investigated the representativeness of soundings in various storm quadrants and found that the most representative soundings lie within 20-100 km of the front quadrants, especially the right-front quadrant. Soundings in the northwest quadrant of a storm were generally unrepresentative of its convective potential. This finding has important implications for using soundings from Stony Plain, Alberta’s only synoptic site, to estimate convective potential over central Alberta.

A statistical forecast technique called the Synoptic Index of Convection (SC4) was developed, based on two synoptic dynamic variables and two instability indices, which were correlated to the Convective Day Category (CDC). This technique predicted storm intensity over the AHP operations area as reliably as a trained forecaster (Strong, 1979; Strong & Wilson, 1983; Strong & Smith, 2001). It was later incorporated into a prototype artificial intelligence forecast system funded by the MSC, called METEOR (Elio et al., 1987). The forecast SC4 (or CDC) was reliable enough that it was used in the cloud-seeding decision process. The technique was later adapted in several other projects, including the Greek and Argentine hail programs, and the current Alberta hail suppression program.

A series of field experiments on the mesoscale storm environment, called the Limestone Mountain Experiments or LIMEX (Strong, 1989), was carried out from 1980-85. These were designed to test a multi-scale conceptual model of Alberta thunderstorms (Strong, 1986, 2000, 2001), which incorporates synoptic scale and topographic forcing, surface cyclogenesis, the formation of a capping lid from a nocturnal inversion, sensible and latent heat fluxes, and mesoscale convergence over the foothills. Mesoscale aspects of the model appear in Figure 11a. The LIMEX-85 experiment utilized nine radiosonde systems in a network with 50-60 km spacing, along with interspersed automatic weather stations. It focused on the formation and breakdown of the capping lid, prior to storm formation, and the important role that regional daily evapotranspiration plays in storm formation over the central Alberta foothills. One significant result was the revelation of how rapidly the pre-storm boundary layer changes, that this usually occurs over a 2-3 hour period during late morning (demonstrated in Figure 11b), and that it invariably goes undetected by synoptic (1200 and 0000 UTC) soundings. LIMEX also highlighted the importance of soundings in the storm formation region, namely over the foothills.

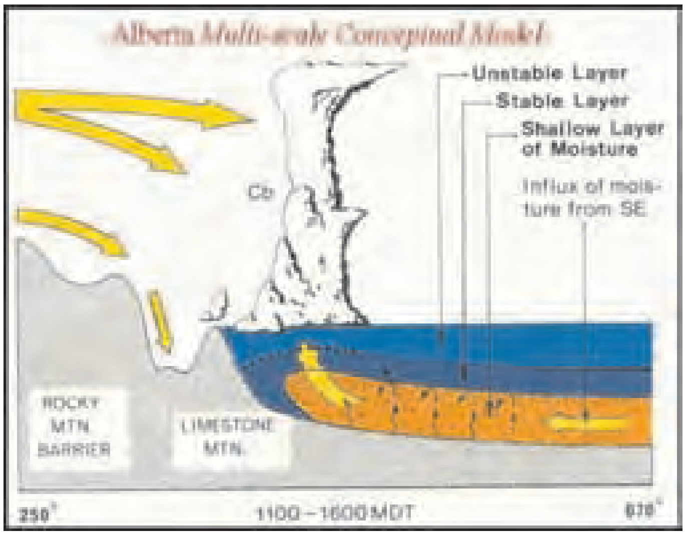


Figure 11a

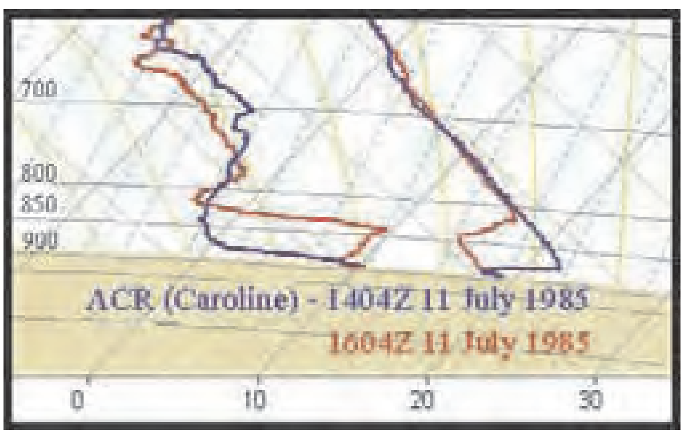


Figure 11b

Figure 11: (a) The multi-scale conceptual model of Alberta thunderstorms (after Strong, 1986, 2000), and (b) LIMEX-85 field test demonstrating typical rapid boundary layer change prior to severe storms on 11 July 1985.

3.6 Other Research

Part of the weather modification research mandate included exploratory field experiments for rain and snow enhancement, and an evaluation of ground-based seeding.

3.6.1 Rain Enhancement Experiments

During the period 1982-85, a series of cumulus seeding experiments was carried out. Treatment methods similar to the controlled, airborne, glaciogenic hail seeding experiments were applied to isolated towering cumulus clouds, in order to determine whether seeding could produce rain. Observations with the research aircraft showed that the class of cumulus clouds selected for the experiments does not naturally produce high concentrations of ice crystals. Seeding these clouds with either Silver Iodide or dry ice was effective in producing high ice crystal concentrations, which spread through the cloud and grew with time. It was demonstrated that some cumulus clouds, that would not rain naturally, could be made to rain by seeding with an ice nucleating material (Kochtubajda, 1986, 1995).

3.6.2 Snow Enhancement Experiments

Limited investigations of the feasibility of increasing snowfall over the southern sections of the Alberta Rocky Mountains, via cloud seeding, were carried out during the 1980-85 research program. Field observations were made over four two-week periods, during the winters of 1982-84, to gather meteorological and in-cloud data, as evidence of the modification potential of wintertime orographic clouds over the southern Rockies. In-cloud data were obtained via research aircraft flights over the mountains in the Pincher Creek to Cranbrook corridor. Rawinsonde observations were made at a valley location upstream of the mountain range.

A preliminary assessment of the snow climatology in the region was carried out. The snow climatology showed that there are different snowfall patterns on each side of the continental divide, with a notable Spring contribution. Meteorological conditions were found to be appropriate for cloud seeding. Measurements of in-cloud properties with an instrumented research aircraft showed evidence of liquid water in the clouds that did not precipitate. There was an increase in liquid water content near the barrier peaks. Estimates from three selected cases indicated that less than 1-16% of the available moisture was converted to snow. These results suggested that the precipitation process could potentially be made more efficient by seeding with additional ice nuclei.

3.6.3 Ground-based Seeding Evaluation

A project to evaluate the efficiency of seeding summer clouds, using ground-based Silver Iodide generators, was conducted by AHP in an area south of Calgary, between 1981 and 1985. Laboratory tests of the generators by Colorado State University showed that effective ice-forming nuclei were produced but at lower rates than with other systems. Mapping and plume-tracking flights over the test area showed that narrow plumes a few hundred metres wide were produced, occupying only a small fraction of the target volume. No evidence of a widespread seeding signature was found (Robitaille et al., 1986).

4. Post ALHAS/AHP Activities

Needless to say, the official end of the provincially-funded hail studies program in 1985 (due to reduced provincial budgets, less-than-outstanding cloud-seeding results, and farmer-scientist politics) did not bring an end to severe storms in Alberta. Nature regularly hits the province with devastating convective storms; notable post-AHP storms include: the Edmonton tornado of 31 July 1987, major Calgary hailstorms in 1991 and 1996, the Pine Lake tornado of 14 July 2000, and the Edmonton hailstorm of 11 July 2004. Each of these storms topped Environment Canada's Top Ten Weather Stories in their year (e.g., see Phillips, 2001). Several notable activities have been conducted and various technological advances have been made since formal termination of the hail studies program.

During the ALHAS/AHP period, an extensive archive of data was collected from several measurement platforms, including the S-band, C-band and X-band radars, an instrumented cloud physics research aircraft, mobile precipitation sampling, rainfall and hailfall telephone survey reports, upper-air soundings and surface precipitation networks. In the early 1990s, a data rescue effort was undertaken to save this unique dataset (Kochtubajda et al., 1996); the archive and related documentation can be found at http://datalib.library.ualberta.ca/AHParchive/.

Huge advances in remote sensing technology have also been made since the AHP was disbanded, including radar, satellite imagery, radiometer profiles of temperature and humidity, wind profilers, GPS moisture, and lightning networks, to mention a few. Figure 12 shows the short-term (1998-2000) climatology of lightning frequency across western Canada, determined using the Canadian Lightning Detection Network (Burrows et al., 2002). It shows that the highest incidence of lightning occurs over the Alberta foothills, closely corresponding to the hail frequency climatology of Figure 7.

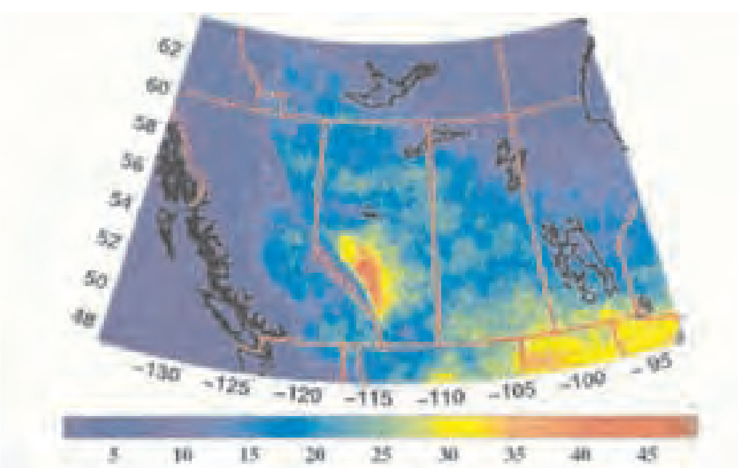


Figure 12: 1998-2002 Lightning frequency across western Canada (reproduced from Burrows et al., 2002).

4.1 The Alberta Hail Suppression Project, 1996-present

The current Alberta Hail Suppression Project was initiated in 1996 in response to the damages associated with the severe hailstorm that struck Calgary on September 7, 1991. Insured losses due to that storm were approximately $400 million (Charlton et al., 1995, Insurance Bureau of Canada, 2004). The Alberta Severe Weather Management Society was created in 1996 by the private insurance companies in Alberta, with the sole objective of conducting a cloud seeding program to reduce the damage to property by hail. It is the first project of its kind in the world to be funded privately, and it focusses on the reduction of damage to property and not agriculture. The current project area is defined by an area of high storm frequency and a rapidly increasing population base (the Calgary - Red Deer corridor). It is based upon the cloud seeding conceptual model, methods, and results of the long-term hail research project conducted by the AHP.

Weather Modification Incorporated (WMI) of Fargo, North Dakota was awarded the first contract to conduct the Alberta Hail Suppression Project in 1996. The project was made an on-going program of the Alberta insurance industry in 2001 because of the decrease in hail damage costs in Alberta, counter to the trend in the hail regions in the USA and the rest of the world. Although the new project does not include a research focus, it has been useful in providing infrastructure and data for scientists working on the project, and for several independent research projects (e.g. AGAME, UNSTABLE), graduate student theses, and publications in the formal scientific literature (Krauss and Santos, 2004; Milbrandt and Yau, 2006; Brimelow et al., 2006; Smith et al., 2007).

4.2 A-GAME, 2003-05

The Alberta GPS Atmospheric Moisture Evaluation (A-GAME) project was initiated in 2003 as an application of the GPS receiver network of the University of Calgary Geomatics Engineering Department (Skone and Hoyle, 2005). The primary objective involved using radiosonde data to evaluate the accuracy of precipitable water estimates retrieved from GPS (Skone and Hoyle, 2005). Sub-objectives included using GPS precipitable water data to study Alberta thunderstorm initiation, and building on the multi-scale conceptual model of Alberta thunderstorms (Strong, 1986, 2000) briefly described in Section 3.5 (and Fig. 11), by investigating the role of *drylines* interacting with the capping lid in storm genesis (Hill, 2006). This was the first ever field research study of drylines in Canada, and significant sharp dryline boundaries were recorded in some severe storm situations where mixing ratios dropped by 3-5 g kg^{-1} over distances as short as 1 km or less.

5. Accomplishments and Legacy

5.1 ALHAS/AHP Accomplishments

The hail studies programs (ALHAS/AHP) yielded an impressive number of results that improved the understanding and prediction of hailstorm and precipitation processes, and contributed to the development of severe weather expertise in Canada. A few important achievements are summarized here:

■ Provision of a *field facility* (unfortunately lost with the demise of AHP), with data systems and techniques for observing hailstorms and making other relevant measurements that were second to none;

■ Development of a sophisticated *polarization diversity weather radar system* for understanding hailstorm structure, behaviour, and detection of hail within storms;

■ Development of a technique that combined *CDR*, radar reflectivity factor, and the cross-correlation to distinguish precipitation type;

■ Development of an understanding of the *role of freezing nuclei* in initiating precipitation formation;

■ Development of one- and two-dimensional *computer simulation models* of storm development and precipitation growth used for operational cloud seeding decisions;

■ *Identification of three distinct storm types* (single-cell, multicell, and supercell) based on storm dynamics, structure, growth rates, precipitation development and hailfall patterns, and from which storm duration, propagation, hail/rain intensities and amounts, and potential storm damage can be estimated qualitatively;

■ Development of a *conceptual model of in-cloud storm processes*;

■ Development of a *practical system for seeding multicell hailstorms* that became the basis of operational hail suppression programs elsewhere in the world;

■ Demonstration of a *methodology for physical* (as opposed to statistical) *evaluation of cloud seeding* effects;

■ Development of a reliable *statistical forecast index* that improved storm forecasting, was incorporated into an AI model, and was adopted by other national and international programs;

■ Development of a *multi-scale conceptual model of Alberta thunderstorms* incorporating synoptic and mesoscale processes, orographic forcing, and surface fluxes and convergence;

■ Collection of a *mesoscale upper air dataset* (LIMEX-85) that continues to be used in mesoscale research more than 20 years later;

■ Compilation of a *comprehensive climatology of hail* for central Alberta (1957-1985) unparalleled by any other program; data were obtained from farmers' reports of hail size, hailfall amounts, hailfall durations, accompanying rain, wind, crop damage and relevant storm comments;

■ Finally, the project provided a unique *training ground for graduate students* who worked closely with Canadian and visiting scientists, observing and collecting data, while new studies using AHP data continue today thanks to the AHP data archive. To date, at least *47 M.Sc and 18 Ph.D theses* have been completed using AHP data at participating universities as listed below:

McGill University	20 M.Sc.	12 Ph.D.
University of Alberta	21 M.Sc.	3 Ph.D.
Université du Québec à Montréal	6 M.Sc.	
University of Wyoming, USA		1 Ph.D.
University of Essex, UK		2 Ph.D.

5.2 ALHAS/AHP Legacy

Hail studies in Alberta evolved over a thirty year period, beginning in 1957, when relatively little was known about hailstorms in Alberta except their destructive capacity. Starting with the most fundamental observations, investigators were able to determine the extent of the hail problem and to develop conceptual models of the hailstorm. Various seeding hypotheses were suggested in an attempt to develop a weather modification technology, and experimental procedures were designed to test the validity of the conceptual model and the seeding hypotheses.

It is difficult to gauge the full impact of the ALHAS/AHP program. It likely ranks as the largest and longest-running meteorological research program in Canada in terms of people and effort. During many summers, there were in excess of 100 scientists, technicians, pilots, students, administrative staff and short-term employees serving on the project. In addition to the many scientific achievements, the project served as a training ground for meteorologists and students, many of whom went on to careers in the Meteorological Service of Canada (MSC) and other organizations. Many ALHAS/AHP participants put their field experience to good use in later research programs, including CCOPE (1981), the Greek (1986-91) and Argentine (1998-2004) hail suppression programs, CASP (1986, 1992), RES (1991), the Mackenzie GEWEX Study (1997-2005), A-GAME (2003-04), and DRI (2005-present). Graduate students continue to use AHP data in their thesis work. AHP technology and knowledge transfer to other projects is also a significant part of the AHP legacy. The operational seeding program provided tremendous experience for dozens of AHP cloud-seeding pilots and controllers, many of whom went on to work in other international weather modification programs, major airlines and related areas of the airline industry.

Statistics Canada lists the Calgary-Edmonton corridor as the fastest-growing region of Canada (http://www.statcan.ca/start.html), suggesting that severe convective storms will likely have even greater economic and human impacts in the future. Environment Canada is reacting to this concern with a planned intensive field study on severe storms in 2008, called UNSTABLE (Understanding Severe Thunderstorms and Alberta Boundary Layers Experiment). Several former AHP participants are involved in the planning and research for this project. It is described in the current issue of the Bulletin (Taylor et al., 2007), and it is based partly on the scientific foundation established by the AHP LIMEX studies. Former ALHAS/AHP scientists can rest assured that many of their findings will be utilized in this and future field research.

6. Acknowledgements

The ALHAS/AHP projects of 1957-85 were initiated and continued for three decades, because of concerns from the farming community of Alberta. They were funded in large part by grants from Alberta Agriculture and the Alberta Research Council, with significant financial participation from McGill University, the Meteorological Service of Canada (under various previous names), the National Research Council and the Natural Sciences and Engineering Research Council of Canada. However, while these agencies provided the economic ingredients for hail studies, it must be acknowledged that little research could have happened without the pioneers at the Stormy Weather Group of McGill University. They started with little or no knowledge of hailstorms, but, in a very methodical way, using innovative field measurements, the meticulous analysis and interpretation of data and the development and testing of hypotheses, they made a major contribution to hail science.

The authors of this article take great pride in having been part of the ALHAS/AHP teams for significant periods of their careers. We dedicate this article to two groups - the many scientists, engineers, technicians, summer students and others, who contributed directly to this program for more than 30 years, and the Alberta farming community, who were the instigators, supporters and beneficiaries of the program. Alberta farmers were not only the original driving force behind both ALHAS and AHP, they also helped provide a tremendous amount of volunteer scientific data, through hail and rain surveys and samples, hailpads, instrumentation sites and more, often in the midst of suffering devastating losses due to hail damage. Finally, this article reminds us of those participants and supporters who are no longer with us. Their dedication and work will not be forgotten.

Finally, we wish to acknowledge the Alberta Research Council (http://www.arc.ab.ca/), Weather Modification Incorporated (http://www.weathermod.com/), and Levelton Engineering Solutions (http://www.levelton.com/) for their financial contributions towards the cost of producing this special issue of the *CMOS Bulletin SCMO*.

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The Understanding Severe Thunderstorms and Alberta Boundary Layers Experiment (UNSTABLE):

A Report Following the First Science Workshop 18-19 April 2007, Edmonton, Alberta

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Résumé (Traduit par la direction): Les chercheurs d'Environnement Canada et d'autres scientifiques intéressés venant du milieu universitaire et du secteur privé sont à concevoir une expérience sur les contreforts de l'Alberta afin d'examiner les processus de la couche limite atmosphérique associés au déclenchement convectif et à l'origine d'orages violents. Le projet “Comprendre les orages violents et l'expérience albertaine sur la couche limite («UNSTABLE»)”, planifiée pour l'été 2008, fera usage d'un réseau à haute résolution d'instruments fixes et mobiles en surface, en altitude et en vol pour échantillonner les processus à la méso-échelle dans la zone de l'origine de ces orages. Des efforts pour rencontrer cet objectif seront faits pour transmettre les résultats aux prévisionnistes d'Environnement Canada dans le but d'accroître le temps d'attente et l'exactitude des avis et des veilles d'orages violents en Alberta et dans le reste du Canada. Faisant suite à des informations générales sur le projet, on présente un sommaire de la première rencontre scientifique d'UNSTABLE.

Introduction

Environment Canada researchers and other interested scientists from academia and the private sector are currently designing a field experiment over the Alberta foothills to investigate Atmospheric Boundary Layer (ABL) processes associated with convective initiation (CI) and severe thunderstorm genesis. The Understanding Severe Thunderstorms and Alberta Boundary Layers Experiment (UNSTABLE), planned for summer 2008 (funding permitting) or possibly 2009 (if funding delayed), will utilize a high-resolution network of fixed and mobile surface, upper air, and airborne instruments to sample mesoscale processes in this thunderstorm genesis zone. Targeted efforts will be made to transfer results to Environment Canada forecasters with the aim of increasing lead time and accuracy of severe thunderstorm watches and warnings in Alberta and the rest of Canada. Following some background information on the project, a summary of the first UNSTABLE science meeting is presented.

Rationale for UNSTABLE

The Canadian prairies are subject to a high frequency of thunderstorms and associated severe weather during the summer months. Based on severe weather reports received by the Prairie and Arctic Storm Prediction Centre (PASPC), the prairies experience an average of 203 severe weather events each summer (McDonald and Dyck 2006). Areas of the prairies experiencing a high frequency of thunderstorms are evident in climatological lightning data from the Canadian Lightning Data Network (CLDN). A map of the mean number of days with at least one cloud-to-ground lightning flash detected between 1999 and 2006 (Burrows 2006, personal communication) shows that the Rocky Mountain foothills region of Alberta experiences, on average, the most days with lightning (Fig. 1). A secondary maximum of lightning activity extends through the far southern portions of Saskatchewan and Manitoba.

> Note: In this paper, severe weather refers to the occurrence of tornadoes, hail with diameter **20 mm** or greater , convective wind gusts of **90 km h^{-1}** or greater and/or convective rainfall amounts of **50 mm** or greater in **1 h**.
>
> **ABL** = Atmospheric Boundary Layer.
> **CI** = Convective Initiation.

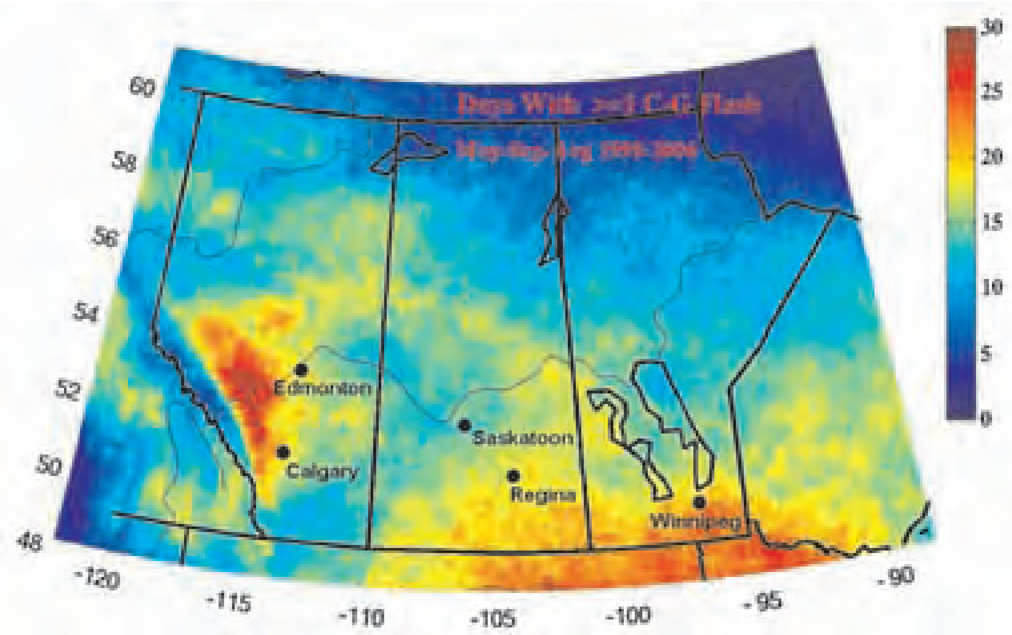

Figure 1: Climatological lightning activity over the Canadian Prairies showing the average number of days with at least one cloud to ground flash from 1999 to 2006 (Burrows 2006, personal communication).

Alberta has proven to be particularly susceptible to costly summer severe weather events. The most devastating event in the last half century is the Edmonton F4 tornado and hailstorm of 31 July 1987 resulting in 27 lives lost and damage estimates in the range of $660 M[1]. Public Safety and Emergency Preparedness Canada estimates that since 1980 more than 40 lives and $2 B have been lost in association with severe thunderstorms. Nearly all of these events occurred within the Edmonton to Calgary corridor which lies just east of the Alberta foothills. Thunderstorms developing on the foothills tend to move eastward with prevailing westerly winds aloft. Alberta contains 2 of Canada's 10 busiest airports (Calgary International 3rd and Edmonton International 6th, Transport Canada 2006) and the Edmonton to Calgary corridor is one of the most densely populated and fastest growing regions in Canada (Statistics Canada 2006, see Fig. 2). Given the above, the potential for further risk to life and property in southern Alberta due to summer severe weather events is clear. Improved understanding of processes associated with the development of severe thunderstorms in the Alberta foothills and application of that knowledge to operational forecast techniques will allow forecasters to maximize their ability to issue accurate and timely severe weather warnings and forecasts.

Meteorologists face numerous challenges with respect to forecasting severe thunderstorms. These include, though may not be limited to:

■ Limited knowledge of the ABL structure and evolution, especially with respect to the stratification of water vapour in the vertical;

■ Inadequate conceptual models to describe processes leading to CI and the development of severe thunderstorms;

■ Difficulty in detecting mesoscale boundaries and circulations in regions of interest and their behaviour in association with CI. In the absence of sufficient observations, appropriate techniques are needed to infer important atmospheric characteristics and their evolution, given available observations.

■ An incomplete understanding of important land-surface interactions with the convective ABL in the region of interest and their role in CI

■ Inconsistent performance of numerical models with respect to the above (e.g., strengths, weaknesses, systematic biases)

The foothills region of Alberta suffers from an inadequate observational network with respect to surface and upper-air measurements. The one radiosonde location in Alberta (Stony Plain, 53.52˚N 114.09˚W, 766m) is ~200 km from favoured CI regions in the foothills and is often not representative of the ABL in the pre-storm environment over the foothills region. Surface observations over the foothills region are sparse. During the summer of 2006 there was an area of ~30,000 km^2 without any real-time surface observations over the foothills west of the Edmonton – Calgary corridor (Fig. 3).

[1] Events prior to 2001 are adjusted to 1999 dollars.

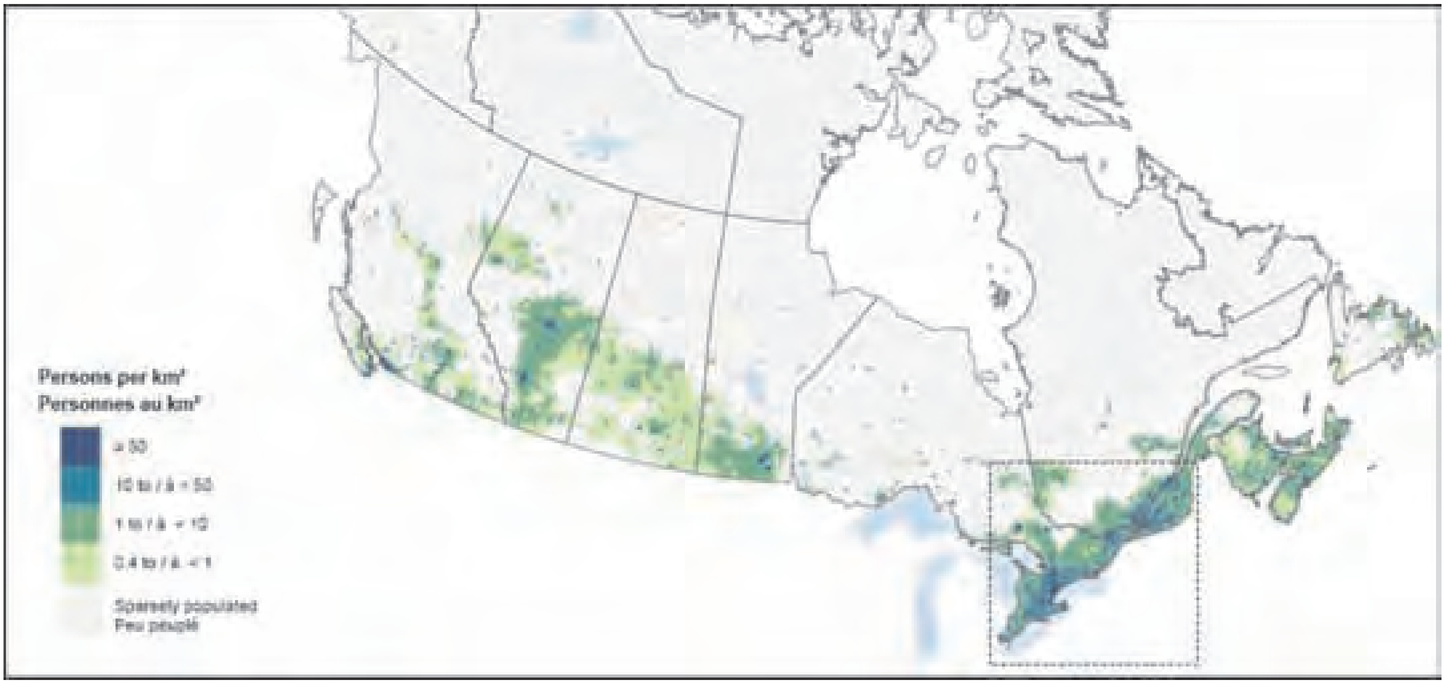

Figure 2a

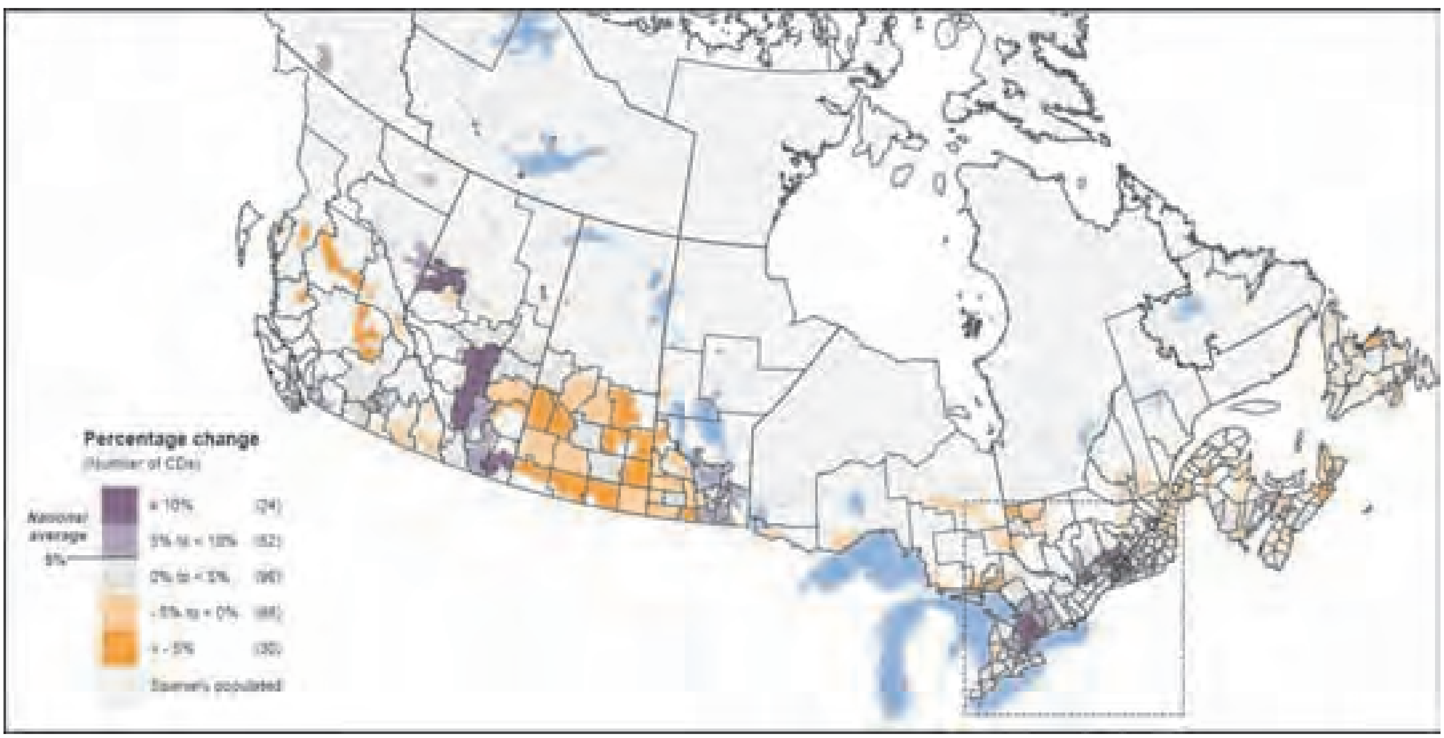

Figure 2b

Figure 2: (a) Population density and (b), change in population from 2001 to 2006 over southern Canada from the Statistics Canada 2006 Census. The Edmonton – Calgary corridor is among the most densely populated and fastest growing regions in Canada.

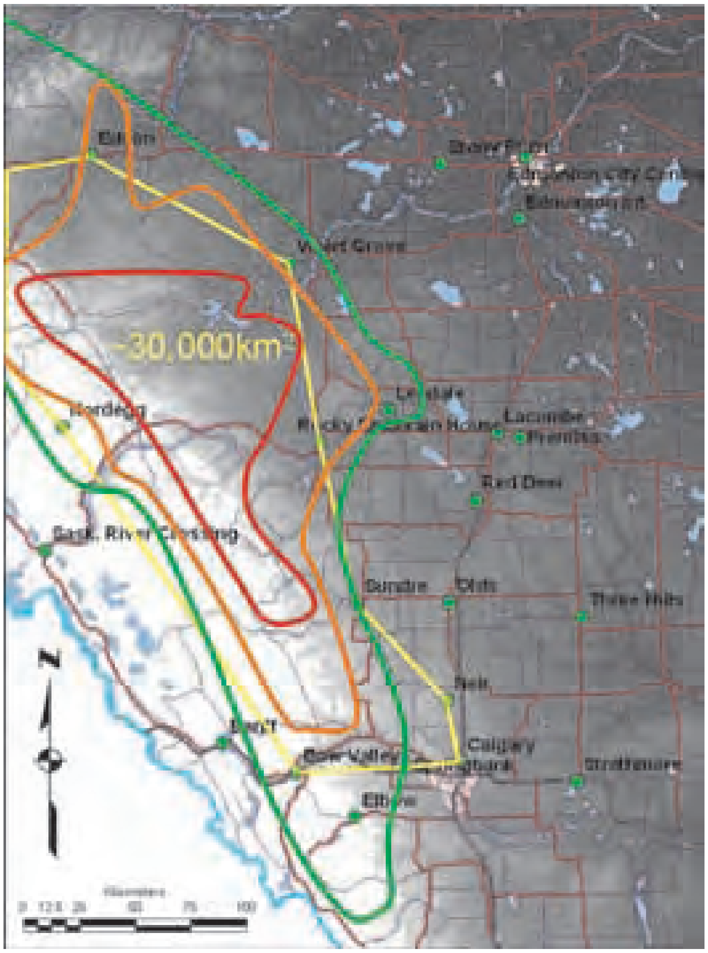

Figure 3: Hourly surface observation sites available to forecasters over the foothills region of Alberta. The yellow polygon denotes an area of just over 30,000 km^2 within which there are no real-time surface observations. Approximate contours of days with at least 1 cloud-ground lightning strike as in Fig. 1 are contoured at 22-26 (green), 27-32 (orange), and > 32 (red). We see that the area with the greatest number of lightning days corresponds to a void in surface observations within the current operational network.

A significant amount of severe thunderstorm research has occurred in Alberta dating back to the Alberta Hail Studies (ALHAS) and Alberta Hail Project (AHP) between 1957 and 1985. Later field experiments include the Limestone Mountain Experiments (LIMEX, Strong 1986, 1989) and the Alberta GPS Atmospheric Moisture Evaluation (A-GAME, Hill 2006). Research from these projects focussed mainly on hail and upper-air processes. More recent research in Canada and the U.S. has focussed on ABL moisture, convergence boundaries, and mesoscale circulations associated with CI and severe storms (e.g., Sills et al. 2002, Sills et al. 2004, Weckwerth et al. 2004, Weckwerth and Parsons 2006, Hill 2006). These findings indicate that more work is required both regionally and abroad to better understand the significance and influence of ABL processes on CI and the development of severe thunderstorms.

UNSTABLE Goals and Science Questions

UNSTABLE seeks to fill in some knowledge gaps with respect to ABL processes and severe thunderstorms. The overall goals of the UNSTABLE project can be summarized as:

- To better understand atmospheric processes leading to thunderstorm development over the Alberta foothills (both prior to and during CI) with an aim to extend results to the rest of Canada;

- To improve the accuracy and lead time for severe thunderstorm watches and warnings;

- To assess the utility of the GEM-LAM model in resolving physical processes over the Alberta foothills and its ability to provide useful numerical guidance for the forecasting of severe convection;

- To refine current existing conceptual models describing CI and the development of severe thunderstorms over Alberta and the western prairies through observational and numerical modeling studies.

A primary goal of UNSTABLE is to improve accuracy and lead time for severe thunderstorm watches and warnings. For this to be achieved, appropriate mechanisms must be in place to ensure knowledge gained from UNSTABLE is transferred to operational forecasters. Collaboration between the National Labs and Storm Prediction Centres within Environment Canada is increasing. Already, laboratory staff are involved in training workshops and seminars and have implemented Research Support Desks (RSDs, Sills 2005, Taylor 2006) directly in forecast operations within two of Canada's Storm Prediction Centres. The PASPC is anticipated to be involved in UNSTABLE during the field campaign and is involved to a lesser extent in the planning of the project. Following a period of data analysis, laboratory staff will work with the PASPC (and other Storm Prediction Centres) to incorporate results into operational conceptual models and forecast techniques. This will be accomplished through traditional means such as those listed above but also through the RSD where researchers can work with forecasters in real-time to apply UNSTABLE results to convective forecast and warning decisions.

To achieve the goals of the project, and for experiment planning purposes, three primary science questions have been formulated to investigate specific areas related to CI and severe thunderstorms. These involve ABL processes, land surface interactions, and numerical weather prediction. Scientific leads have been identified for each question to oversee their respective component of UNSTABLE including instrumentation / measurement strategies and data analysis. Each science question and a brief summary are included below.

1) What are the contributions of ABL processes to the initiation of deep moist convection and the development of severe thunderstorms in the Alberta Foothills region?

This first question deals with processes associated with ABL water vapour and convergence lines as they relate to CI and severe storm development. More specifically, we are interested in characterizing ABL diurnal evolution, water vapour stratification, and the role that mesoscale convergence boundaries and circulations play in CI. The influence of highly varied terrain and mesoscale circulations and boundaries on storm evolution will also be investigated. In recent years the dryline has been identified as an important feature for CI in the region. Four-dimensional characterization of the dryline prior to and during storm development will be a priority of the field campaign. UNSTABLE will result in a dataset of high-resolution observations that will be used to evaluate the utility of current observational networks and to modify existing conceptual models for CI and severe weather outbreaks in southern and central Alberta.

2) What are the contributions of surface processes to the initiation of deep moist convection and the development of severe thunderstorms in the Alberta Foothills region?

This question deals mainly with the effects of latent and sensible heat fluxes associated with varying soil moisture and evapotranspiration. We are interested in investigating effects of adjacent wet and dry soils (as defined by an agrometeorological model) on storm initiation and evolution. Attempts will be made to sample the development and evolution of moisture gradients and mesoscale circulations associated with surface discontinuities (e.g., land-land breezes). Targeted, high-resolution field observations will be compared with existing observations to evaluate the degree to which the current observational network can be used to detect these circulations sometimes associated with thunderstorm development.

3) To what extent can high-resolution numerical weather prediction models contribute to forecasting the initiation and development of severe convective storms that originate in the Alberta foothills?

The last science question relates to the use of high-resolution numerical modeling to forecast CI and severe thunderstorm development in the Alberta foothills. Specific questions address the ability of the Canadian Meteorological Centre's Global Environmental Multi-scale (GEM) Limited Area Model (LAM) at 2.5 km resolution to simulate ABL and surface processes investigated in questions one and two, observed storm structures, and microphysical fields. Also of interest are identifying any deficiencies in current physical parameterizations and the effects of performing nested model runs on higher-resolution grids (e.g., 1 km). Other areas to be investigated using the observational dataset from UNSTABLE include high-resolution ensemble forecasts of CI and the use of a high-resolution analysis to improve prediction of CI and subsequent storm development.

Figure 4: Environment Canada's Automated Transportable Meteorological Observing System (ATMOS).

Experimental Design

UNSTABLE will take place from 1 June to 31 August 2008 with a three-week Intensive Observation Period (IOP) planned from 9 July to 31 July. Fixed mesonet stations will be deployed prior to 1 June with all other supplementary instrumentation deployed during the IOP. The field campaign will utilize targeted, high-resolution fixed and mobile measurements from a variety of observation platforms. Central to the success of the project is a mesonet of surface weather stations, mobile surface observing platforms, multiple profilers, and an upper-air campaign utilizing multiple radiosondes, a tethersonde and, if sufficiently funded, a research aircraft. The surface mesonet is designed using both grid (~ 25 km spacing) and linear (~ 10 km spacing) configurations to resolve surface characteristics spatially and their evolution in time. The mesonet will consist of existing weather stations in cooperation with the Government of Alberta and Canadian universities and 10-15 Automated

Transportable Meteorological Observing Systems (ATMOS, see Fig. 4). Mobile surface measurements will be used to resolve surface convergence and other boundaries in space and time. To do this we will deploy one or more Automated Mobile Meteorological Observing Systems (AMMOS, see Fig. 5) capable of atmospheric state variable measurements (including wind speed and direction) while stationary or in motion.

Figure 5: Environment Canada's Automated Mobile Meteorological Observation System (AMMOS), photo by David Sills.

Upper-air measurements during UNSTABLE will be conducted using up to 5 radiosonde systems (3 mobile and 2 fixed), a recently-purchased Vaisala tethersonde, and a number of profiling and total column water vapour instruments (radiometers and GPS precipitable water measurements) contributed by the University of Manitoba and the University of Calgary. The majority of these instruments will be deployed in fixed locations but the University of Manitoba Centre for Earth Observation Science will be participating with their Mobile Atmospheric Research System (MARS) trailer. The MARS contains a profiling radiometer, Atmospheric Emitted Radiance Interferometer (AERI) and Doppler sodar along with a surface weather station. The MARS will be deployed in conjunction with other mobile surface observations in the vicinity of mesoscale boundaries and favoured areas for CI.

The UNSTABLE study area is designed to take advantage of other existing observing networks. These include existing surface stations, the Stony Plain radiosonde station, the CLDN, Environment Canada radars at Carvel (53.56˚N, 114.14˚W) and Strathmore (51.21˚N, 113.40˚ W), and satellite imagery received by Environment Canada. Additional radar information is anticipated from the Weather Modification Inc. radar at the Olds-Didsbury airport (51.71˚N, 114.11˚W). The study area consists of a primary and a secondary domain. Most of the instrumentation described above will be deployed in the primary domain as indicated in Fig. 6. The secondary domain will allow for mobile measurements to be obtained when features of interest develop away from the foothills but in locations where storms could still impact densely populated areas. Final locations of instrumentation in Fig. 6 are still unconfirmed as mesonet and other equipment siting is under way.

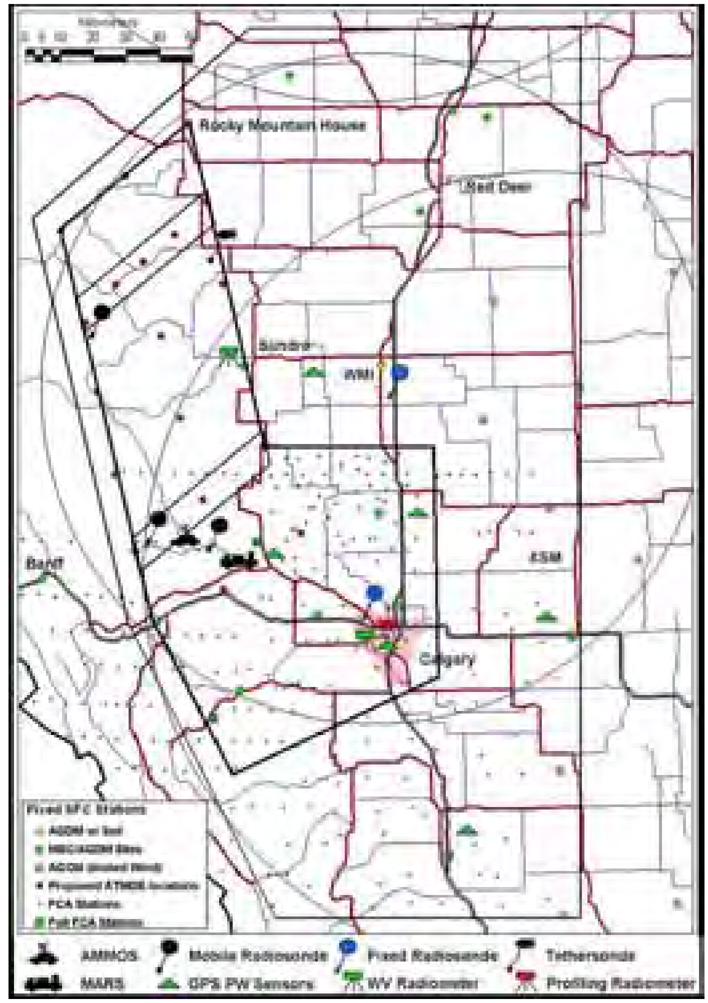

Figure 6: Map showing possible instrumentation locations within the UNSTABLE domain(s). Black circles are 120 km range rings for WHK and XSM radars and the 100 km range ring for the WMI radar. The heavy black line is the primary UNSTABLE domain enclosing the mesonet, the lighter black line is the secondary study domain. Black polygons within the primary domain are proposed locations for higher resolution lines of mesonet stations (the southern one will depend on station availability). Fixed surface mesonet and other stations are as indicated as is other instrumentation to be deployed. Final locations of fixed profiling / other platforms are to be determined. Mobile instrumentation will be deployed on Intensive Observation Days (IODs) within a specified target area. Aircraft (not shown) will be deployed on IODs when mesoscale circulations are expected to develop. Circuits and stepped traverses will be employed to sample the circulation spatially and in the vertical.

The Canadian Meteorological Centre will continue to run the GEM-LAM model in quasi-experimental forecast mode over the western 2.5 km grid during the summer of 2008. In support of UNSTABLE, the eastern boundary of this grid will likely be extended to approximately the Alberta-

Saskatchewan boarder. The full western grid (with the extended boundary) with model terrain is shown in Fig. 7. The real-time runs performed on this grid will be examined in detail during the experiment with close comparisons made to the measurements taken during the IOP period. Case study simulations and sensitivity experiments will be performed in hind-cast mode on this grid as well as finer resolution subdomains.

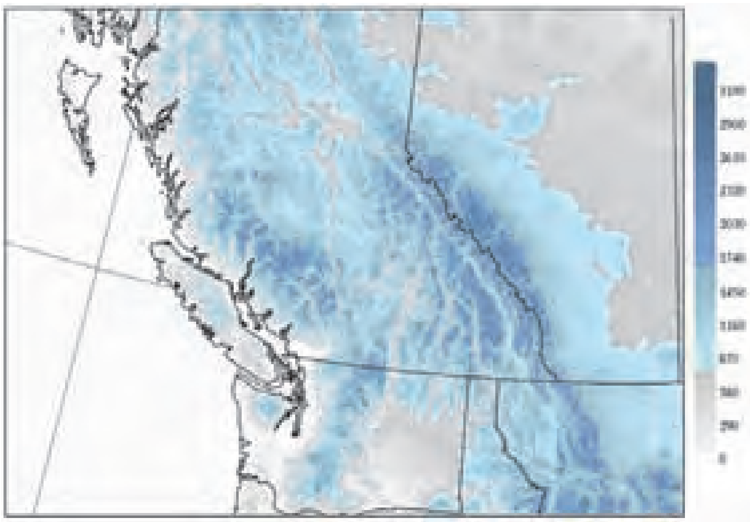

Figure 7: Western 2.5 km grid for the GEM-LAM to be used for the real-time NWP forecasting during the summer of 2008. Shading indicates model terrain elevation (m).

The First UNSTABLE Science Workshop, 18-19 April 2007

The first UNSTABLE science workshop was held in Edmonton, Alberta on 18-19 April 2007. The meeting brought together over thirty Canadian scientists from across the country representing various divisions of federal and provincial government agencies and Canadian universities. This workshop was an opportunity for interested participants in the experiment to share their interests and contributions to the project and to discuss the draft science questions along with strategies for answering them. The meeting allowed the principal investigators to confirm the level of contribution of participants and their involvement in the field campaign. Results of discussions from the meeting are being used to refine both the science questions and the UNSTABLE science plan. Organizations that were represented at the meeting are listed in the table shown below.

Organizations represented at the Science Workshop held in Edmonton, Alberta, 18-19 April, 2007

Hydrometeorology and Arctic Laboratory, Environment Canada
Cloud Physics and Severe Weather Research Section, Environment Canada
Prairie and Arctic Storm Prediction Centre (Edmonton and Winnipeg), Environment Canada
Climate Research Division, Environment Canada
Recherche en Prévision Numérique, Environment Canada
University of Manitoba
University of Alberta
University of Calgary
McGill University
Canadian Forest Service
Alberta Agriculture and Food
Alberta Environment

The workshop began with presentations on UNSTABLE observations. These included descriptions of the Foothills Orographic Precipitation Experiment (FOPEX, Smith 2005, 2007), The Alberta GPS Atmospheric Moisture Evaluation (Hill 2006), The Foothills Climate Array mesonet (M. Adams, University of Calgary), GPS measurements of precipitable water (S. Skone, University of Calgary), and the Province of Alberta surface weather stations. The second session of the meeting included presentations from UNSTABLE collaborators and included representatives from the University of Manitoba, University of Alberta, the Prairie and Arctic Storm Prediction Centre, and McGill University detailing their interest and contributions to the project.

Following the formal presentations, science leads summarized their respective science questions and strategies for answering them. Science leads are (1) Neil Taylor and David Sills (Environment Canada), (2) John Hanesiak (University of Manitoba), and (3) Jason Milbrandt (Environment Canada). These presentations served as an introduction to guided break-out sessions. Participants were asked to select one of the science questions and contribute to discussions on such things as:

■ Refinement of specific science questions as presented in the draft science plan;

■ Who plans to be directly involved in the field campaign and how?

■ Funding strategies and opportunities for in-kind support;

■ Data requirements, instrumentation and deployment strategies necessary to answer the science questions;

■ ‘Champions’ for data analysis and quality control.

Break-out discussion results were presented to the group as a whole on the morning of 19 April followed by open discussion by participants.

The workshop achieved its goals and allowed potential UNSTABLE participants to discuss details of the project for an extended period of time. This workshop was invaluable to help refine the direction of the project with respect both to the science objectives and strategies to fulfill them. It also provided an opportunity for UNSTABLE participants to formalize their involvement and contributions to the project. Results from the discussions included identification of a lead for the upper-air campaign, clarification of instrumentation available from Canadian universities, preliminary agreements with respect to data sharing, and support from the PASPC.

Next Steps

Planning for UNSTABLE continues with many issues remaining to be addressed. The science plan is now being revised for submission to Environment Canada management for funding. Specifically, the science questions themselves will be finalized along with instrument requirements and measurement strategies. Beginning in fall 2007 the UNSTABLE field operations plan will be finalized including a data management strategy. This document will detail all logistics issues to be considered during the field campaign (e.g., people in the field, communications, instrumentation, training, occupational health and safety, etc.). Following the production of a draft operations plan, a small and focussed workshop will take place to refine the details. In early spring 2008 instrumentation land-use agreements for mesonet sites will be finalized leading up to deployment and testing in May 2008. Testing of mobile instrumentation and communications will occur in June prior to the intensive observation period scheduled to begin on 9 July 2008.

Summary

UNSTABLE is a collaborative project bringing together scientists from Environment Canada, Canadian universities, other federal and provincial government agencies, and the private sector to investigate severe thunderstorm development in Alberta. The focus on atmospheric boundary-layer phenomena reflects current knowledge gaps within the meteorological community in understanding how thunderstorms form. With a focussed transfer of results into Environment Canada forecast operations, there is an opportunity to enhance lead time and accuracy of severe weather watches and warnings, both in Alberta and across the country.

The first science meeting of the UNSTABLE project was an important step in developing the project. By bringing together the collective knowledge and experience of scientists working in related areas across the country, we can refine the scientific objectives of UNSTABLE and leverage their contributions to ensure its success.

Figure 8a

Figure 8b

Figure 8: Photos from the First UNSTABLE Science Workshop, (a) Hydrometeorology and Arctic Laboratory manager Gary Burke welcoming participants to the workshop, and (b) participants during one of the coffee breaks. Photos courtesy Jingang Wu.

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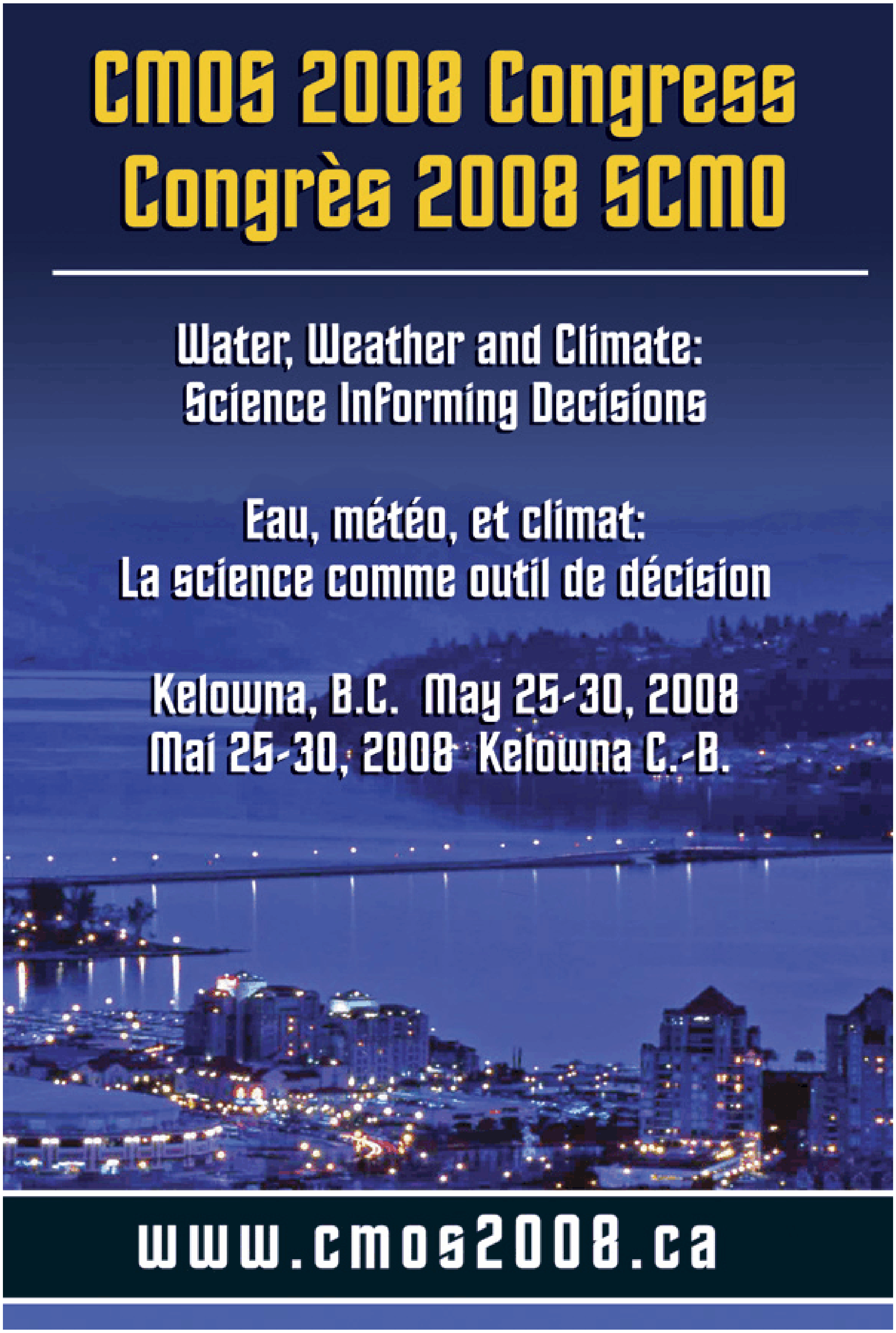
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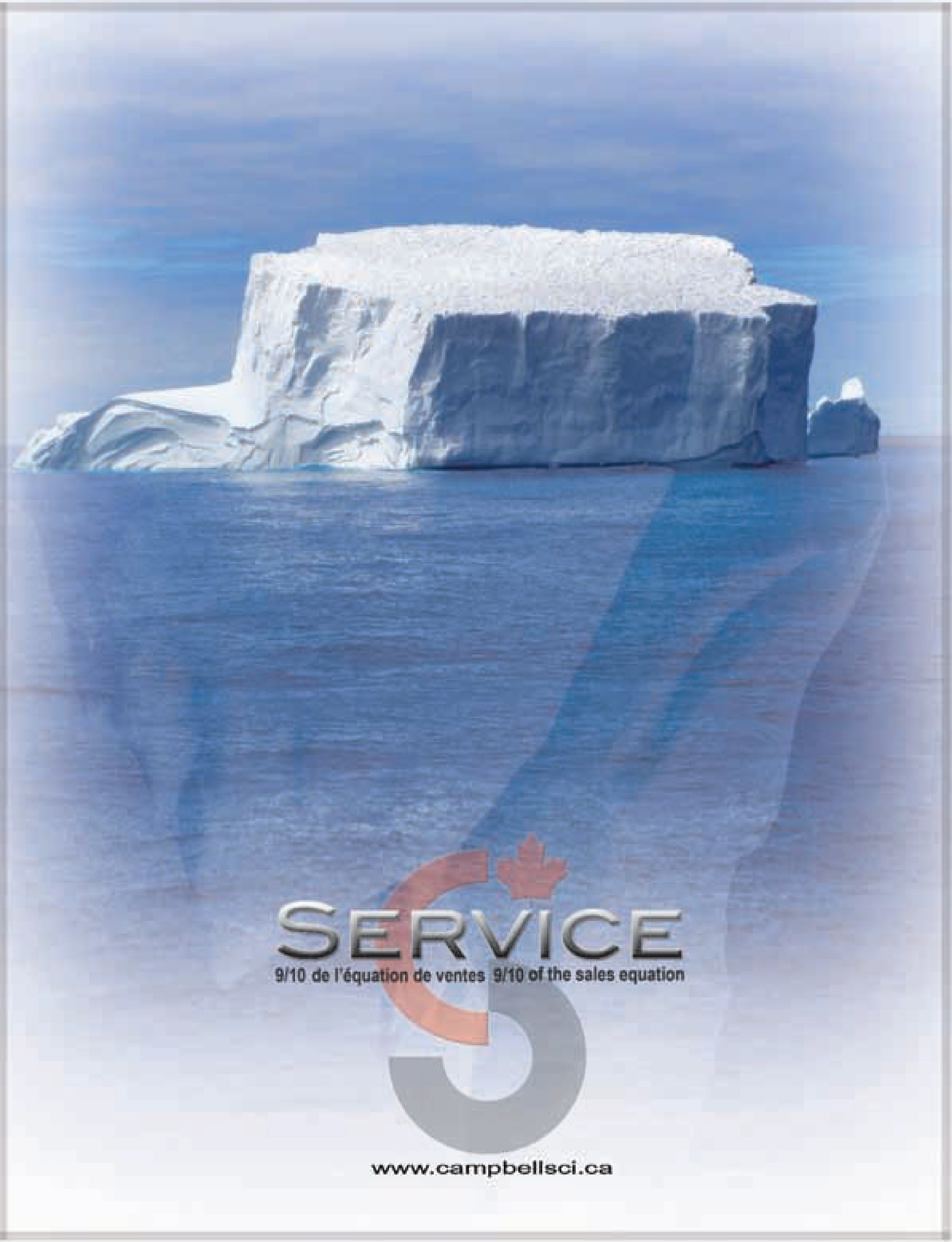
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