AUGMENTING SNOW BY CLOUD SEEDING: A TOOL FOR MANAGING WATER RESOURCES[1]

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Abstract.--A research aircraft has been used to document the microphysical characteristics of winter clouds over the Alberta Rockies. Data shows that the potential exists to stimulate mountain snowfall through cloud seeding. Selective seeding of clouds could provide a mechanism to augment water supplies.

INTRODUCTION

Meltwater from mountain snowpack provides the principal water source (some 75 percent) for most agricultural, urban, industrial and recreational requirements in southern Alberta. This water resource provides the means for significant irrigation agriculture in this region. Its continued supply is central to the maintenance and continued development of irrigation-based agriculture.

In particular, future demands for water in the South Saskatchewan Basin may not be satisfactorily fulfilled. This is due to both the natural variability of the water supply and high rates of water usage, primarily for irrigation. The potential shortage of water is particularly acute for the Oldman River Basin which currently has over 600,000 irrigated acres, with a potential for over 1,300,000 irrigated acres (ECA, 1982).

Considerable quantities of moisture are contained in the atmosphere as it passes over Alberta. Because of the forced lifting of the air as it passes over the mountains, atmospheric moisture condenses to form "orographic" clouds, which can produce snow. However, if the clouds are warm (-10°C) and shallow they often do not produce

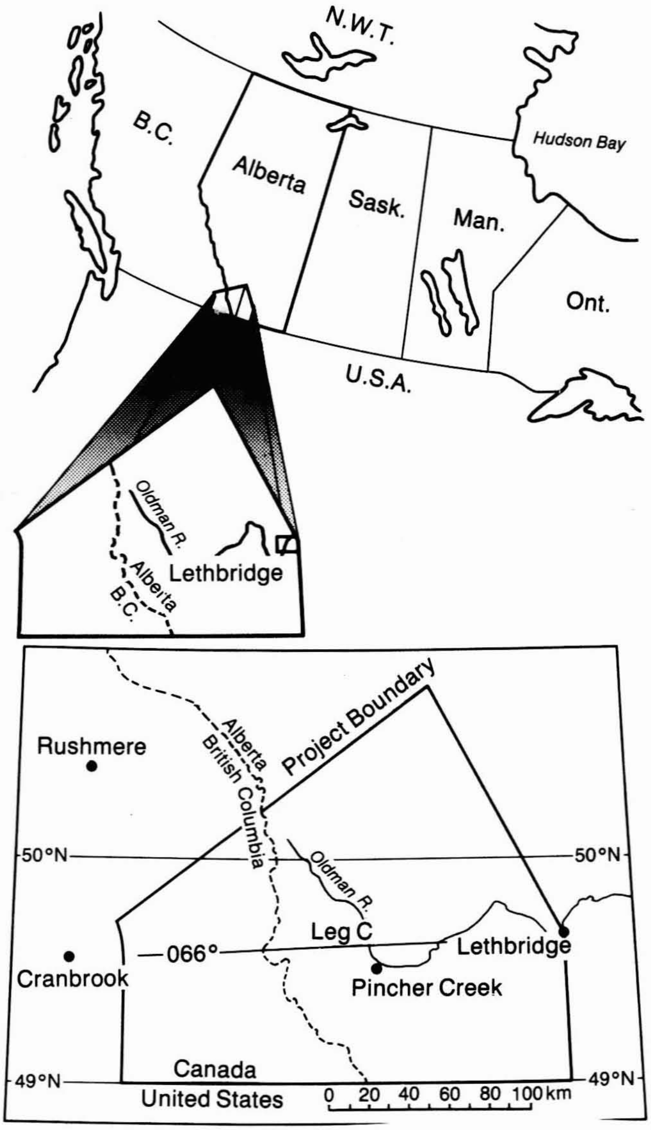

Figure 1. Alberta Research Council Snow Project Area. Leg C is the primary flight leg radial.

[1]Paper presented at the International Snow Science Workshop, Lake Tahoe, California, October 22-25, 1986.

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snow even though they contain adequate quantities of moisture. For example, with a moderate westerly flow in a cloud one kilometer deep extending 100 kilometers (sixty miles) along the mountains and containing one-tenth of a gram of condensed water per cubic meter of cloud, five thousand cubic meters (one million gallons) of water pass over the mountain crests each minute. Cloud seeding attempts to initiate or enhance snowfall from these clouds that may otherwise evaporate on the leeward side of the mountains.

The Alberta Research Council has completed a Snow Project to examine the feasibility of supplementing mountain snowpack through the controlled use of cloud-seeding techniques. This project's aim was to measure and analyze the precipitation processes of snow-producing orographic clouds. The project study area straddled the Alberta-British Columbia border (fig. 1), and included the Oldman River Basin. This paper provides a brief overview of cloud seeding for snowpack augmentation and summarizes results of this project. It presents evidence that cloud seeding can be useful to stimulate mountain snowfall and, hence, augment water supplies where necessary. The ability to control the amount of snow in the mountains through selective cloud seeding provides a mechanism to implement provincial water management policy for southern Alberta.

BASIC PRINCIPALS OF OROGRAPHIC CLOUD SEEDING

Orographic clouds are those whose form and extent is determined by the disturbing effects of orography upon the passing flow of air. Because these clouds are linked with the form of the terrestrial relief, they generally move very slowly, if at all, although the winds at the same level may be very strong (Huschke, 1959).

Such clouds may contain supercooled water droplets that often remain in the liquid state at temperatures much colder than freezing due to a scarcity of ice nucleating materials. When ice particles are present in these supercooled clouds, they grow at the expense of the droplets and may eventually become large enough to reach the surface as snow. In the absence of ice particles, the cloud droplets evaporate in the descending air on the leeward side of the mountain barrier.

When ice particles are relatively few in number and adequate supercooled liquid water is present, cloud seeding can be used to make these clouds snow. This involves the delivery of ice nucleating agents, either silver iodide smoke or dry ice pellets, to the regions of supercooled liquid water within the clouds. These agents then greatly increase the concentration of ice crystals which use the cloud water to grow into precipitation-sized particles that fall as snow to the surface. Thus, more of the cloud water would be converted to snow and not lost to evaporation on the leeward side of the barrier. The increased snowpack would then provide additional streamflow during spring melt.

Cloud seeding for snowpack augmentation has been undergoing research and development in the western United States to help alleviate potential water shortages. Projects are being conducted by various universities, state and federal agencies including the U.S. Department of the Interior and the National Oceanic and Atmospheric Administration (NOAA). These projects are currently being conducted in California, Colorado, Montana, Nevada and Utah.

Cloud seeding in the mountains has been recently identified 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" (CREST, 1983). Recent results from the U.S. indicate that cloud seeding may be able to increase the mountain snowpack by about 15 percent (Super and Heimbach, 1983; Cleveland, 1978). In Colorado, it has been estimated that such increases could augment streamflows by 10 percent, or an additional 2.3 million acre-feet for the Colorado River basin (CREST, 1983).

FEASIBILITY OF OROGRAPHIC CLOUD SEEDING FOR ALBERTA

The Alberta Research council has investigated the feasibility of applying cloud seeding techniques to augment snowpack in the southern Canadian Rockies (fig. 1). This effort focused on providing background information on the snow climate and winter cloud characteristics within the area.

Analyses of the snow climate provided background information on snowfalls in the region (Barlow, et al., 1983: Thyer et al., 1985). Different snowfall regimes were found on each side of the continental divide. The importance of the spring contribution to the total snowpack was noted. The climate studies indicated that meteorological conditions within the region were acceptable for the application of cloud seeding technology.

Microphysical observations were made by flying a pre-selected flight track on radials extending eastwards over the mountain ranges from Cranbrook, British Columbia (fig. 1). Flight levels generally ranged from 11,000 to 13,000 feet MSL, approximately 2,000 to 4,000 feet above the maximum barrier height. Minimum aircraft flight levels were frequently within 500 feet of cloud tops. Most clouds were broken stratiform layers with occasional embedded convective elements.

A summary of microphysical measurements is presented in table 1.

The values in table 1 represent the arithmetic average of all "in-cloud" one-second data averages. Included are the flight date, number of one-second "in-cloud"samples, environmental temperature at measurement level, liquid water contents, ice crystal concentration, ratio of liquid water to ice crystals and mean ice crystal diameter. Also noted are estimates of the cloud base heights and base temperatures representative of the clouds. The liquid water to ice ratio expresses the amount of

Table 1. Summary statistics of "in-cloud" microphysical characteristics for each flight. Included are averages of cloud supercooled liquid water content (LWC), ice crystal concentration (ICC) and mean ice crystal diameter (IC Diam).

Flight	# sec incloud	Temp (deg C)	LWC (g/m^3)	ICC (#/l)	LWC/ICC (g of water per crystal)	IC Diam (mm)	Cloud Base Height (kilofeet)	Cloud Base Temp (deg C)
830315	4127	-19.0	0.17	10.5	111	411	10	-12
830324	2303	-14.4	0.34	1.0	1264	397	9	-8
831209	2805	-19.9	0.01	5.6	13	533	7	-13
831210	3777	-13.6	0.22	3.0	722	295	7 to 10	-6 to -13
840201	919	-19.2	0.05	1.9	199	330	8	-8
840208	1408	- 9.9	0.10	1.1	409	150	11	-7
840209	2903	-13.0	0.11	1.8	470	309	11	-13
840210	2737	-18.2	0.06	1.3	137	394	8	-8
840211	3389	-17.1	0.01	10.1	346	320	6	-6
840212	4451	- 9.9	0.02	11.0	61	323	5 to 11	0 to -10
840213	2222	-12.8	0.09	54.0	52	86	10	-9

water available per ice crystal and has been suggested as an index of "seedability" (Heggli, et al., 1983). Higher ratio values indicate that there may be sufficient supercooled liquid water present for additional ice crystals to grow to precipitation-sized particles.

Cumulative frequency plots of all one-second liquid water and ice crystal values were plotted for the aggregated data sets. These plots have been presented elsewhere (Barlow, et al., 1985) and will only be noted briefly here. The results suggested that cloud liquid water values in excess of 0.1 gm^{-3}, are relatively frequent. These plots indicated that over 50% of the liquid water values recorded during each of the three field seasons exceeded this value. Average ice crystal concentrations are close to or less than 10 per litre for most cases.

As indicated in table 1, the combination of relatively high liquid water values and relatively low ice crystal concentrations yields high "seedability" ratios. Typical values for this ratio are on the order of a few hundred and suggest, according to a minimum benchmark of ten (Heggle, et al., 1983), a "seeding potential".

The results of a more detailed analysis of aircraft data collected on February 9, 1984 have also been examined. A total of 17 cloud penetrations were made during flights on this day. These measurements were made near the upper edge of a stratocumulus deck that extended across the divide and became mostly broken to the east. Cloud bases were approximately eleven thousand feet (-13°C) with tops approaching thirteen thousand feet (-14°C). The relative frequency of occurrence of ten-second averages of "in-cloud" liquid water contents is given in figure 2. Over 55% of the values exceed the 0.1 gm^{-3} minimum for seeding potential cited for the Sierra Mountains (Marwitz and Stewart, 1981). Ice crystal concentrations were all less than ten per litre, commonly around one per litre. This combination of available liquid water and low ice concentrations suggests that many of these clouds met the microphysical criteria for being "seedable".

The possible influence of mountain topography on the distribution of cloud liquid water may have an impact on the design of any future seeding experiments. To examine this, the geographical distribution of liquid water measurements were made for selected cases along the east-west aircraft flight track. Figure 3 illustrates such a distribution for the March 24, 1983 case. A geographical cross-section of the mountain topography from the western to eastern endpoints of the flight line is illustrated, and the locations of Cranbrook (YXC), Sparwood (WSW), Pincher Creek (ZPC) and the Continental Divide are

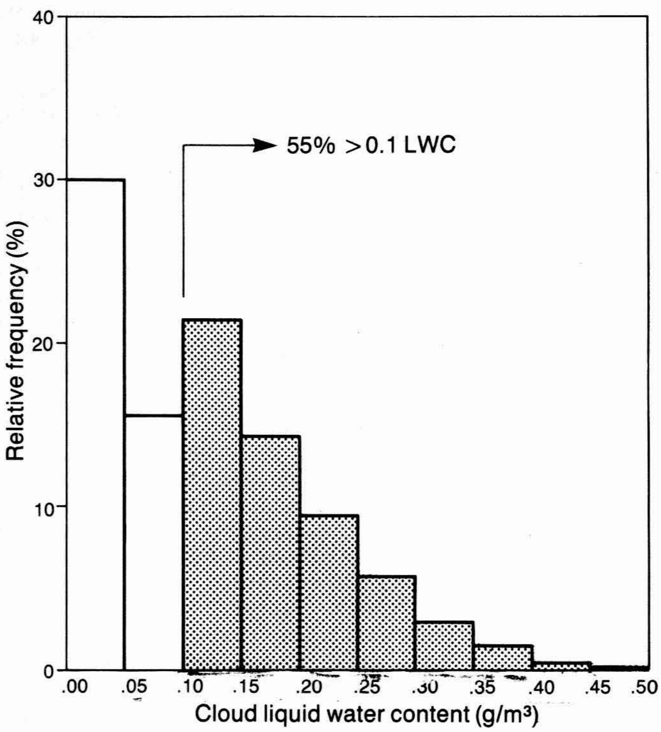

Figure 2. Frequency distribution of "in-cloud" liquid water content for cloud penetrations made on February 9, 1984.

indicated. The cloud liquid water contents for one flight pass and the average for all flights are indicated above the topography where they were made. Liquid water measurements were averaged over every 0.1 degrees of longitude from west to east.

These measurements indicate a cloud mass generally to the west of the divide, with an isolated cloud complex at the eastern project edge. Some evidence of a linkage between increased liquid water amounts and elevated topography is indicated both in the single-pass plot and the averaged data. Peak liquid water values are indicated upwind of the two highest ranges. While these results are limited, they suggest that the local relief may play an important role in the establishment of pockets of supercooled liquid water upwind of barriers. This would be consistent with results recently reported for winter orographic clouds in central Utah (Long, et al., 1985).

IMPLICATIONS FOR WATER RESOURCE MANAGEMENT

Water produced by orographic cloud seeding is indistinguishable from the natural supply: It is generated in the same manner as the natural supply. The net effect of cloud seeding is to increase the water supplies in the natural channels of a basin and this augmented water will have the same quality as the natural supply (Weisbecker, 1974).

The distinguishing characteristic of augmented water in terms of economic application is the added cost. For the Oldman River Basin it is estimated that orographic cloud seeding could increase winter snowpack by about 15% with a concomitant increase in streamflow of 10% or 250,000 acre-feet. This water could be used to significantly reduce shortages in dry years. In years with otherwise normal runoff, it could be

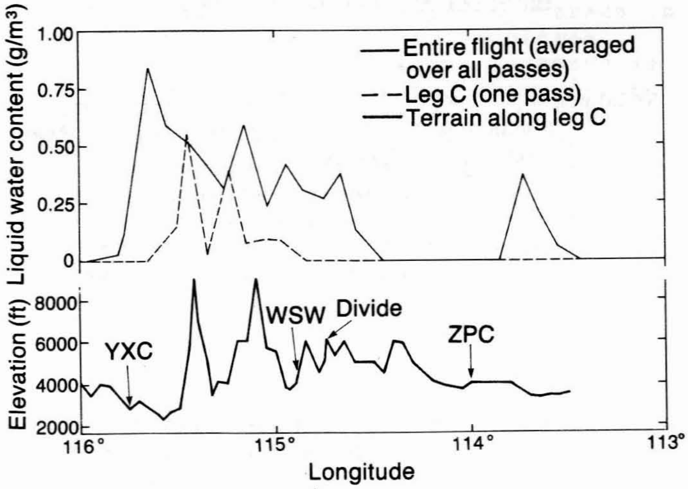

Figure 3. East-west distribution of liquid water for March 24, 1983. Topography between Cranbrook, British Columia (YXC) and Pincher Creed, Alberta (ZPC) is indicated (distance is approximately 150 km).

used to irrigate approximately 100,000 additional acres. Operational costs to produce this additional water are estimated to be five dollars ($5) an acre-foot.

Another characteristic of runoff from augmented snowpack is its impact on the reliability of the total water supply. With adequate storage and regulating facilities, it could be made available when the natural supply falls short of expectations. However, it must be kept in mind that in a naturally dry year the amount of additional water from cloud seeding will also be reduced in a corresponding manner. (Weisbecker, 1974).

Augmented water from orographic cloud seeding can be controlled through select application of the technology. The upper limit is established by the cloud seeding opportunities corresponding to the natural meteorological conditions. However, the cost per acre-foot of water produced will be affected by the scale of the operations. Accordingly, orographic cloud seeding need not produce unusable water. It can be implemented in stages and in locations to match a buildup in demand, or it can be cut back if demand drops off.

These characteristics are in accord with provincial water management policy for southern Alberta which calls for measures to reduce effects of variations in the natural water supply and calls for augmenting water supplies where necessary.

SUMMARY

Evidence has been presented to show that an opportunity exists to augment orographic snowfall in the southern Canadian Rockies through cloud seeding. Cloud seeding technology can be applied in a controlled manner to permit snowpack augmentation in selected regions at selected times (fig. 4). Application in dry years will assist in meeting basic user demands and in normal years will permit additional irrigation.

ACKNOWLEDGEMENTS

The authors acknowledge the support of Alberta Agriculture, the Alberta Water Resources Commission and the Alberta Research Council for portions of this study.

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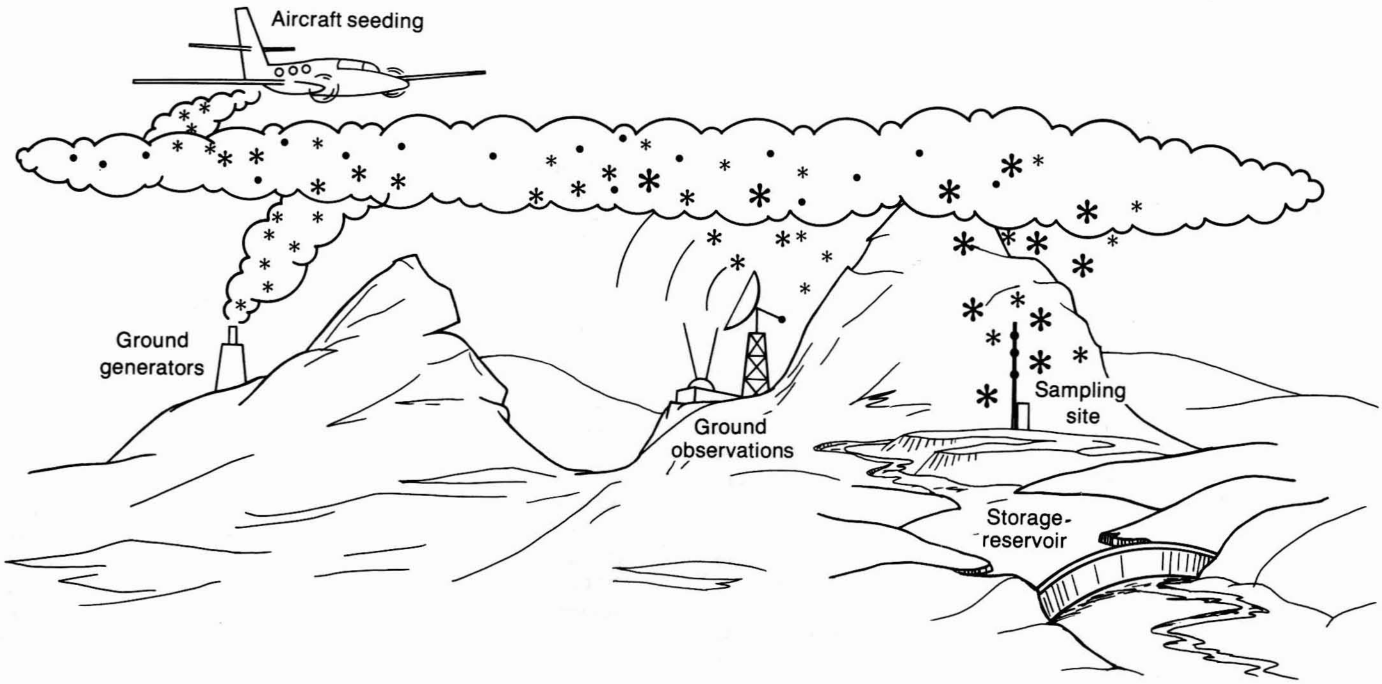

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