STRONG RESPONSES OF CERTAIN CLOUD TYPES TO CLOUD SEEDING FOR SNOWPACK MANAGEMENT

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ABSTRACT

A recent compilation of the reported results of more than 600 precipitation management projects worldwide has led to a summary of those specifically aimed at snowfall enhancement, and among them a differentiation among cloud types and weather conditions. As a result, it appears that strong positive responses are related to clouds with moderate updrafts in the -10 to -20 C region, and strong negative responses to clouds with stronger updrafts and tops colder than about -35 C. Weather systems generating these clouds, and implications for snowpack management are discussed.

1. INTRODUCTION

Nineteen eighty-six is the fortieth anniversary year of the discovery of modern cloud seeding for weather modification. It is just about the same age as the transistor. Why has it not been more widely applied?

A recent compilation of the reported results of precipitation management projects worldwide lists 25 seasons of experimental projects and 127 seasons of practical projects either intended specifically for effect on snowfall or conducted at places and times when snow was the principal precipitation form. These are listed in Table 1. The average of the reported snowfall increase is 11.5 percent, but the variability among projects has been so great that people were naturally skeptical (Todd and Howell, 1985).

Much of the apparent variability came from operations and evaluations that treated all occasions of precipitation nearly alike, as if they were expected to respond similarly. Over the past 15 years, reanalyses of many of these data sets, together with theoretical and laboratory studies of the manner of formation of snow within cloud systems, have led to realization that cloud seeding has markedly different consequences under different weather conditions and, to a lesser extent, in response to different seeding techniques and materials. It is the purpose of this paper to consider how these findings apply to snowpack management.

2. UPDRAFT SPEED AND CLOUD TEMPERATURE

The clearest difference in response has been found between clouds with moderate updrafts and cloud-top temperatures in the range from -10 C to about -20 to -25 C, and clouds with strong updrafts or cloud-top temperature -35 C or colder. This difference has been related to the time required for formation and growth of precipitation-size particles and the time available as the condensate rises through the portion of the cloud where growth is rapid.

TABLE 1.

EXPERIMENTAL AND PRACTICAL PROJECTS AFFECTING SNOWFALL

Location	Years	Mode	Reported Result
Campbell Rvr, Brit Columbia		Practical	+9% runoff
Snowy Mountains, Australia		Experimental	+19% precipitation
St. Maurice Rvr, Quebec	1951	Practical	+29%
" " " "	1952	"	+12%
" " " "	1953	"	+28%
" " " "	1955	"	+13%
Lake St. John, Quebec	1952	Practical	+30%
" " " "	1956	"	-7%
Concepcion, Chile	1983	Practical	+13%
Serena, Chile	1979-80	Practical	+15%
Vallenar, Chile	1979-80	Practical	+10%
San Gabriel Mtns, California	1962-75	Practical	+20%
San Joaquin Rvr, California	1951-84	Practical	+6% runoff
Kings River, California	1955-83	Practical	+6%
Coeur d'Alene, Idaho	1951-74	Practical	+10%
Bear Lake, Idaho	1954-70	Practical	+11%
Southern Utah	1973-83	Practical	+17%
Ukraine, USSR (winter)	1980-84	Experimental	+23%
Climax, Colorado (Note 1)	1960-70	Experimental	+52%
Climax, Colorado (Note 2)	1960-70	Experimental	-55%
Wolf Creek Pass, Colorado	1964,66,68	Experimental	+80%
San Juan Mtns, Colo. (Note 1)	1970-75	Experimental	+14%
San Juan Mtns, Colo. (Note 2)	1970-75	Experimental	-55%
Park Range, Colorado (Note 1)	1960's	Experimental	+100%
Park Range, Colorado (Note 2)	1960's	Experimental	-24%

Note 1. Cloud tops or 500-mb temperature in warmer range (see text)
Note 2. Cloud tops or 500-mb temperature in colder range

2.1 Time Available Greater than Time Required

The maximum cloudwater content available for precipitation, in grams per cubic meter, is fixed primarily by the temperature (hence the saturation vapor density) at the cloud base, and secondarily by the expansion of the air as it ascends to regions of lower pressure. The principal detractor is dilution of the updraft by mixing with drier environmental air.

When the updraft is large and slow, protected by its size from rapid dilution, there is ample time for the initially-formed cloud droplets to grow to precipitation size, either by collision with each other or by activation of ice-forming nuclei which become the seeds of ice crystals. As long as any liquid droplets are present, colliding ice crystals tend to stick together and form snowflakes. In this situation, the time available for precipitation formation is greater than the time required; natural snow formation keeps up with the rate of condensation, and opportunity for increasing it by seeding is absent.

In fact, seeding in some circumstances may interfere with the natural formation of precipitation. When growth to raindrop size by collision among supercooled drizzle drops is important, freezing them up by cloud seeding may cause them to bounce apart instead of coalescing.

2.2 Time Available Less than Time Required

Three situations can greatly shorten the time available for precipitation formation. The first is that of a cloud too small and too quickly diluted with drier air to support any precipitation process. These are the typical small cumulus of fair weather.

A second situation is that of a cloud with the temperature at its base so cold that very little moisture is present to condense into cloud droplets; the growth of precipitation embryos does not proceed to completion before the cloud dissipates or rises past the -40 C isotherm. At -40 C, homogeneous nucleation of ice occurs, and all supercooled water disappears. Significant growth ceases, and collisions no longer lead to coalescence or aggregation, so snowflakes cannot form.

The third situation is when a very strong updraft carries the condensed particles very quickly to the level where extreme cold and expansion of the air, freezing the particles and carrying them farther apart, inhibit further growth, so that precipitation embryos do not have time to attain precipitation size.

In these last two situations, seeding tends to raise the temperature at which complete freeze-up of precipitation growth occurs, hence to decrease the amount and probability of precipitation. It is usually referred to as overseeding.

2.3 Time Available Nearly Equal to Time Required

The effect of seeding is most clearly expressed when, by shortening the time required for precipitation formation, it can cause precipitation to form when otherwise sufficient time would not be available. This occurs most commonly in clouds that pass the smallest stage but still have limited lifetimes due to mixing with drier air aloft. This growth commonly occurs with lifting of convectively unstable air, resulting in cloud towers the tops of cool to temperatures between -10 C and -20 C. In the longer-lived clouds, growth of embryos by aggregation may reach the precipitation stage, and significant populations of ice crystals grown from natural nuclei may appear. Once the precipitation process gets well under way, the resulting release of latent heat tends toward both upward and lateral growth of the cloud, substantially increasing the volume of cloud in which precipitation forms. Natural dissipation of the cloud by mixing with environmental air remains the principal limiting factor.

In this situation, seeding with ice-forming nuclei tends to decrease the time required for precipitation to form and thus to increase the proportion of borderline clouds that reach the precipitation stage. It achieves this by increasing the population of active embryos, which then produce a higher concentration of ice crystals, promoting both collision-collection (riming growth) and aggregation (snowflake growth) as long as some supercooled liquid droplets remain to assure stickiness in crystal-to-crystal collisions.

3. RESPONSES OF SNOWFALL SITUATIONS

In snowstorms, the cloud-base temperature varies widely from about +10 C to perhaps -20 C, a range of nearly eight-fold in saturation vapor density. The higher vapor densities are typical of certain orographic situations such as the Sierra Nevada of central California, where the cloudbase over the foothills may be at an altitude no more than 1 km while the heaviest precipitation falls on ground above 2 km. In the case of warm-front snowfall from a cyclonic storm, the cloud-base height in the warm air mass at the foot of the warm-front wedge is often only a few hundred meters, while most of the snow falls into the frontal inversion and through the cold air mass where it is much higher above the ground.

When the ascending air is stable, the updraft speed is often of the order of centimeters per second in frontal situations and up to tens of centimeters per second in orographic situations, both tending to provide adequate time available for precipitation formation. In the orographic situation, where the airflow at the highest levels reached by the damming effect already begins to descend some distance upwind of the summit, liquid water has been observed near the ground in the Sierra Nevada and at Mt. Washington, NH, signaling an opportunity for some increase of snowfall by local seeding.

Not infrequently, orographic flow behind a cold front in such locations as the Sierra Nevada and the central Rocky Mountains generates a cloud layer with cloud-top temperatures near -20 C that may last for a day or more with wind speeds that do not allow sufficient time for full development of natural precipitation. These situations correspond to "foehn" or "chinook" conditions over the downwind slope. Although the accompanying snowfall rate is usually low, seeding appears to have been effective in approximately doubling it through the sometimes long duration of the chinook.

Clouds that form along the cold front of a cyclonic storm are generated by forced lifting of the warm air ahead of the front, and they vary widely in depth and development. Only when the cloud-top temperature occurs in the favorable range of about -10 C to -25 C have they been reported to yield substantial increases. However, as the cold air deepens behind the front, the clouds that form within it, often in bands oriented across the direction of wind shear, often comprise good seeding targets. Precipitation from them ordinarily reaches the ground as snow whenever the temperature at the ground is colder than about -2 C to -3 C, being more commonly snow when the precipitation rate is greater.

4. IMPLICATIONS FOR SNOWPACK MANAGEMENT

In many parts of the world, melting snowpack is the principal water supply for agricultural irrigation and for industrial and municipal water supply. Developments consist of constructing reservoirs sufficient to retain at least the average season's snowmelt and often large enough to carry over above-normal snowmelts for use in below-normal years. The larger ones are nearly all multiple-use installations, providing hydroelectric power generation as well as water storage and flow regulation. The capital cost of these large constructions is great enough to justify substantial efforts to increase their economic efficiency. This has become the motivation for the greatest number of weather modification operations applied to snowpack management.

Whenever a hydrologic system is processing less water than its maximum design capacity, there is an opportunity for increased efficiency by an increase in snowpack. Only when the snowpack is above the design capacity of the system to handle it is additional snowfall undesirable from this viewpoint, although other uses of the snowshed must be considered and often give rise to specific operating limitations respecting road conditions, wildlife habitat, etc.

Where snow stimulation operations have been subjected to governmental control, a season-end maximum design snowpack is usually specified, within the capacity of the system to utilize it efficiently, typically at a value of about 130 percent of normal. Usually the cut-off limit is higher in the early part of the season and scales down gradually to the season-end limit. In addition, suspensions are commonly called for during unusually severe winter snowfall conditions.

The majority of the snowpack-enhancement operations have been evaluated statistically with the generally favorable results indicated in Table 1. However, the scientific community has not accepted these indications as decisive because randomized control data have usually been missing, or, when present, have been the subject of various doubts. It is only by post-analysis that the results presented earlier in this paper have been derived.

The second most common use of snowfall management has been for winter sports areas, where an early start to the season gives a competitive edge and helps establish skier loyalty. Especially in the eastern U.S., the use of snowmaking machines is so widespread as to be nearly universal, but operating them is expensive and every bit of snow from the sky helps. In much of the Rocky Mountain and Sierra ski regions, mid-season snow is rarely a problem and the ski patronage dwindles before the snow goes. Typically, snow-sports applications have not been evaluated statistically, partly because of the irregularity of operations, partly because the users have accepted the risk/benefit ratio as decisively favorable in view of the high cost of operating snowmaking machines.

Third, and fewest in terms of months of winter operation, come projects that were operated primarily as experiments. Unfortunately, none of their experimental designs provided, in advance of operations, for distinctions among cloud types or for randomization within such groupings, and the scientific community has therefore not accepted them as decisive.

Implications for the future are unclear. Applications in the first two categories are continuing with little change in recent years. Scientific experiments have become progressively more complex and hi-tech, and experiments, partly through the inclusion of advanced instrumentation and complex experimental designs, have become more expensive, while financial support for them has slowed down. Modest expansion of practical applications based on satisfactory benefit/risk performance appears to be the trend likeliest to continue.

REFERENCE

Todd, C. J., and W. E. Howell, 1985: World atlas and catalog of reported results of precipitation management by cloud seeding. ACPM, 34 S Lookout Mtn Cir, Golden CO 80401