ON THE CLOUD SEEDING POTENTIAL OF THE BLACK HILLS

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Four of the past five years have seen below normal precipitation and the decrease of water resources in one of the main reservoirs in the Black Hills. At the same time, recent publications of research results have indicated favorable effects of cloud seeding in winter/spring orographic cloud situations. Although the degree to which these results would apply to the Black Hills is not known, discussion of the potential of cloud seeding to the Black Hills is appropriate, because instrumentation, computer, and modeling developments make the prospects of a definitive research and operational cloud seeding project a definite possibility. This paper summarizes some of the background material needed to plan for cloud seeding in the Black Hills to enhance the water resources of the area.

1. INTRODUCTION

The Black Hills, a dome-shaped mountain range in western South Dakota and eastern Wyoming, provide a livelihood and recreation for a large number of people in the Northern Plains region. As the population increases, the need for water becomes even more important, and is critical for many industries in the region, such as forest products, agricultural interests, hunting, hiking, winter skiing, and summer water sports.

A shortage of water affects many of those industries and impacts on the water supply of various local communities, the largest being Rapid City. The forest fires of 1988 were exacerbated by the dryness of the spring and summer season, when nearly 1% of the Black Hills acreage was covered with forest fires, and several homes near Rapid City were destroyed.

The lack of rainfall and snowpack, combined with above average demands on the Pactola Reservoir water supply, reduced the storage of the reservoir to about 50% of normal as of August 1989 (~28,000 acre-feet instead of the 56,000 acre-feet capacity). Precipitation for 1991 was slightly above normal; this, along with conservation measures and new city deep wells coming on-line has resulted in the reservoir at 43,800 acre-feet of storage (78% of capacity) as of 30 November 1991. Plans are underway by various groups to repair irrigation ditches, continue to improve conservation methods, and study and define more precisely the surface and ground water characteristics of the Hills.

The ultimate source of water in the Black Hills, as elsewhere, is atmospheric water. That source is erratic, but much more dependable than the rains on the plains surrounding the Hills. A recent study by Colorado State University scientists (McKee, personal communication) indicates that the rainfall statistics of the Black Hills stand out in marked contrast to the stations surrounding the Hills. The year-to-year variation of rainfall calculated for Black Hills stations is much smaller than for stations over the plains.

This degree of consistency is caused by the mountains and their effect on snow and rain. The Black Hills create a barrier to the airflow, forcing some of the air up and over the Hills. This increased uplift causes clouds to form and increases precipitation in the area. This effect is particularly pronounced in the northern Hills in the cool seasons where the prevailing northwest winds cause an average snow maximum of more than ~250 cm (100 inches) per year compared to only ~90 cm (35 inches) in Rapid City.

In the warmer portions of the year, airflow may diverge around the higher parts of the Hills and converge downwind to create local rain maxima (*Kuo and Orville*, 1973). The extent to which this occurs in the cold season is not known, although the general precipitation pattern in the Hills points to uplift as the main precipitation factor -- see Fig. 1.

Although the Black Hills extract more precipitation from the atmosphere than the surrounding plains, the efficiency of the process is not optimal. In the cooler seasons, the orographic uplift creates stable, shallow orographic clouds which are typically inefficient producers of precipitation. The clouds may form on the upwind side of the Hills and evaporate on the other, downslope side without releasing much of their water content in the form of precipitation. Present estimates are that 10 to 15% more precipitation can be gained from stable, orographic cloud systems via cloud seeding, although a detailed investigation is needed and no seeding experiments on such systems have been conducted in the Black Hills. The estimates come from other experiments conducted in mountainous regions of the west, which are summarized later.

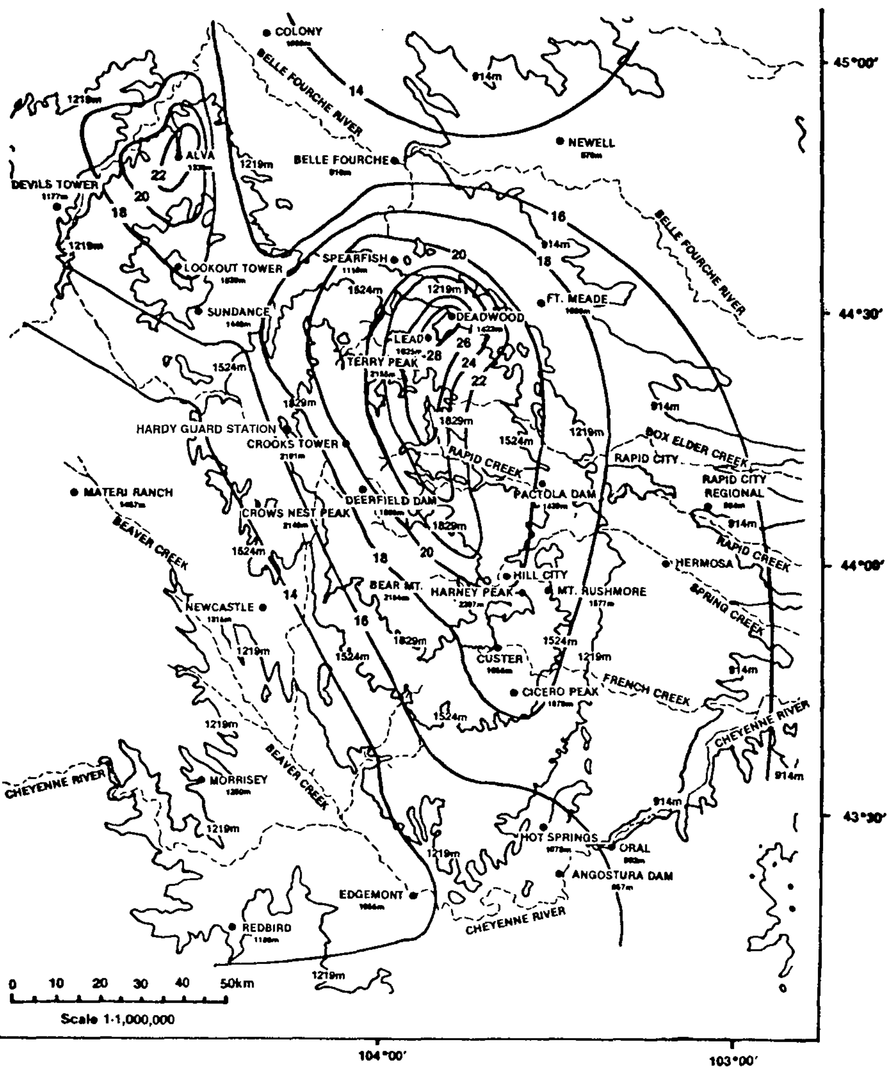

Fig. 1: Isohyetal map of average annual precipitation (inches) in the Black Hills, 1951-1980. Contours are for 1000-ft intervals (305 m).

The primary purpose of this paper is to discuss the cloud seeding potential of the Black Hills so that intelligent planning can be done regarding the atmospheric water resources of the region. The ultimate desire is to gain enough knowledge and operational capability in cloud seeding to insure that the Black Hills region enters a drought situation as late as possible and recovers from one as early as possible in the future.

The remainder of this paper will deal with precipitation climatology, microwave radiometer measurements, experimental strategy, safety, evaluation, uncertainties, resource needs, and economic justification.

2. CLIMATOLOGY OF PRECIPITATION IN THE REGION

A report by *Miller* (1986), the Black Hills Engineer (*Johnson,* 1949), U.S. Forest Service snow course measurements, and various National Oceanic and Atmospheric Administration (NOAA) publications give information about precipitation in the Black Hills region. The current situation is one of low water contents in various communities and reduced water in Pactola Reservoir.

Figure 1 gives the average annual precipitation over the Hills. The average in the higher Hills ranges from ~500-760 mm (20 to 30 inches) per year. Forty to fifty percent of the total comes from January to mid-June, with May and June providing the maximum precipitation. Nearly all of the precipitation will be snow in January to early May and predominantly rain from then on through summer and part of the fall. Snowfall averages from 76 to 280 cm (30 to 110 inches) over the entire snow season, or about 13 to 25 cm (5 to 10 inches) per month.

Table 1 gives representative precipitation amounts at a few locations in the Hills, and Table 2, the snowfall amounts to support the above statements taken from the Black Hills Engineer (*Johnson,* 1949). Table 3 shows snowcourse measurements at O'Neil Pass for the past few years. Table 4 gives seasonal precipitation amounts at several stations.

TABLE 1: Mean Monthly and Annual Precipitation and Selected Stations In and Around the Black Hills (to Jan 1, 1949)

Stations	Yrs.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	An'l
Ardmore, S. D.	34	0.38	0.40	0.86	2.04	3.03	2.88	1.91	1.56	1.13	1.11	0.45	0.42	16.17
Belle Fourche, S. D.	40	0.36	0.27	0.75	1.28	2.13	3.04	1.69	1.29	1.34	0.88	0.52	0.37	13.92
Custer, S. D.	37	0.43	0.45	0.90	2.02	2.98	3.02	2.82	2.52	1.26	1.22	0.46	0.39	18.47
Deadwood, S. D.	20	1.32	1.09	2.22	3.46	4.73	4.72	3.26	2.11	2.29	2.03	1.64	1.28	30.15
Deerfield, S. D.	38	0.58	0.40	0.83	1.84	2.66	3.48	2.86	2.22	1.42	1.14	0.54	0.36	18.33
Dumont, S D.	40	1.41	1.06	1.62	2.48	2.87	3.57	2.68	1.88	1.57	1.31	1.03	1.04	22.52
Hardy Rang. Sta., S. D.	39	1.66	1.02	1.46	2.24	2.54	3.20	2.13	2.10	1.63	1.48	1.00	1.07	21.53
Harvey's Ranch, S. D.	38	1.48	1.18	1.87	2.96	3.73	4.28	3.07	1.98	1.51	1.41	1.10	1.02	25.57
Hermosa, S. D.	40	0.38	0.31	0.95	1.83	3.52	2.91	2.42	1.96	1.23	0.98	0.41	0.36	17.26
Hot Springs, S. D.	52	0.63	0.49	1.04	2.00	3.06	3.10	2.32	1.92	1.32	1.28	0.59	0.53	18.28
Lead, S. D.	40	1.06	0.87	1.64	2.96	3.78	4.01	2.58	1.84	1.78	1.60	1.15	0.93	24.20
Oelrichs, S. D.	58	0.70	0.68	1.23	2.16	3.11	3.31	2.29	1.39	1.20	1.20	0.77	0.63	18.62
Rapid City, S. D.	61	0.42	0.42	1.04	1.99	3.31	3.39	2.28	1.58	1.20	1.02	0.47	0.37	17.49
Spearfish, S. D.	59	0.71	0.74	1.52	2.43	3.43	3.97	2.12	1.58	1.66	1.39	0.98	0.84	21.37
Newcastle, Wyo.	39	0.58	0.45	0.80	1.41	2.48	2.68	2.11	1.64	1.30	1.07	0.59	0.50	15.61
Sundance, Wyo.	39	1.02	0.82	1.46	1.82	2.64	3.32	2.05	1.06	1.52	1.42	0.97	1.02	19.19
Means		0.82	0.66	1.26	2.19	3.13	3.43	2.41	1.79	1.46	1.28	0.79	0.70	19.92

TABLE 2: Average Snowfall (to Jan 1, 1949)

Station	Yrs.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	An'l.
Ardmore, S. D.	37	5.8	6.3	8.2	4.9	0.7	0	0	0	0.2	2.3	4.4	6.7	39.5
Belle Fourche, S. D.	40	5.3	4.1	7.3	2.6	0.9	0	0	0	0.1	1.4	4.3	5.4	31.4
Custer, S. D.	18	6.1	6.0	10.2	6.0	2.0	0.3	0	0	0.8	2.7	4.9	5.7	44.7
Deadwood, S. D.	20	13.6	11.8	18.5	16.7	4.5	0.1	T	T	0.6	6.5	12.8	14.0	99.1
Deerfield, S. D.	18	8.9	5.6	12.5	8.8	3.4	0.5	0	0	1.0	3.6	6.6	5.0	55.9
Dumont, S. D.	18	20.2	13.2	19.4	12.7	4.6	1.7	0	0	1.3	6.6	12.8	12.7	105.2
Hardy Rang. Sta., S. D.	18	16.2	11.8	18.1	16.1	4.7	1.9	0	0	2.3	7.3	12.4	12.2	103.0
Harvey's Ranch, S. D.	17	16.7	11.4	20.7	18.7	7.1	1.7	0	0	2.1	8.2	12.0	12.0	110.6
Hermosa, S. D.	6	7.3	1.8	5.3	2.4	0.9	0	0	0	0	1.6	2.3	1.3	22.9
Hot Springs, S. D.	39	4.1	5.6	5.1	3.9	0.3	0	0	0	0.3	1.9	4.0	5.3	30.5
Lead, S. D.	40	11.6	10.8	16.7	15.5	5.3	0.2	0	0.2	0.6	6.1	9.9	10.8	87.7
Oelrichs, S. D.	50	6.1	5.3	8.3	5.7	0.2	0	0	0	0.2	2.5	4.0	5.7	38.0
Rapid City, S. D.	61	4.6	4.3	7.8	5.2	0.9	T	0	0	0.2	1.9	3.7	3.9	32.5
Spearfish, S. D.	51	8.7	7.2	12.6	9.2	2.3	T	0	0	0.6	4.4	8.4	8.1	61.5
Newcastle, Wyo.	39	6.8	5.2	7.0	4.2	0.7	T	0	0	0.3	2.9	5.2	5.8	38.1
Sundance, Wyo.	37	12.9	11.6	11.9	9.2	2.6	0.4	T	0	1.0	2.9	10.6	13.4	76.5

An interesting figure (Fig. 2) shows the mean annual precipitation (3-year running averages) at Rapid City for the past 100 years. Twenty-year cycles show up for dry periods -- mid-1890's, 1911-14, 1931-39, early 50's, and early 70's. This bodes ill for the region if the 1990's continue the cycle. There are certain climate models which also predict a warming and summer drying for the Northern Plains, but results are very dependent on the way clouds are simulated. Nevertheless, most climatologists think the data on increasing greenhouse gases are persuasive enough to suggest a warming trend in the near future.

Table 5 from *Johnson* (1949) shows the number of days with 0.01 inch or more of precipitation by month. The higher Hills (Lead) have 5 months with more than 11 days per month of precipitation, while stations on the periphery of the Hills have only 6 to 7 days of precipitation in the best months. (e.g., Newcastle, Wyo.).

The mean temperatures at 850 mb and 700 mb (Figs. 3 and 4) for Rapid City give a good indication of the times that ground generators would be effective over the Black Hills. These two figures indicate the -5°C level would be within a few thousand feet of the mountains from October through May (*Dennis et al.*, 1966).

Figure 5 shows an 850 mb wind rose for Rapid City, giving the mean wind direction and speed for the four seasons. Northwest flow predominates, with southeast and south flows becoming more important in the spring and summer.

TABLE 3

Snow Course Data

	Year	February 1 Snow Depth	February 1 Water Content	March 1 Snow Depth	March 1 Water Content	April 1 Snow Depth	April 1 Water Content
	1985						
Current Reading		18.41	3.60	19.82	3.45	23.09	5.45
Accum. Total		406.77	184.38	1053.59	239.73	1132.28	296.63
42-year Average		21.59	4.39	25.09	5.71	26.96	7.06
	1986						
Current Reading		23.27	6.18	23.5	6.63	20.0	6.36
Accum. Total		930.04	190.56	1077.09	246.36	1152.28	302.99
43-year Average		21.63	4.43	25.05	5.73	26.79	7.04
	1987						
Current Reading		14.9	2.8	20.7	4.0	23.4	5.5
Accum. Total		944.94	193.36	1097.79	250.36	1175.68	308.49
44-year Average		21.48	4.7	24.95	5.69	26.72	7.01
	1988						
Current Reading		14.7	3.4	25.5	4.3	24.7	7.2
Accum. Total		959.64	196.76	1123.29	254.66	1200.38	315.69
45-year Average		21.33	4.4	24.96	5.66	26.68	7.02
	1989						
Current Reading		15.7	2.7	20.9	3.5	8.5	2.3
Accum. Total		975.34	199.46	1143.59	258.16	1208.63	317.99
46-year Average		21.20	4.3	24.9	5.6	26.27	6.9
	1990						
Current Reading		20.1	4.2	23.8	5.5	23.0	6.8
Accum. Total		995.44	203.66	1167.39	263.66	1231.63	324.79
47-year Average		21.18	4.3	24.8	5.6	26.2	6.9
	1991						
Current Reading		18.0	2.5	24.8	4.7	19.4	4.9
Accum. Total		1013.44	206.16	1192.19	268.36	1251.03	329.69
48-year Average		21.1	4.3	24.8	5.6	26.1	6.9

TABLE 4

1951-1980 Precipitation Data (inches)

	Side	Elevation (meters)	Winter (Dec,Jan,Feb)	Spring (Mar,Apr,May)	Summer (Jun,Jul,Aug)	Fall (Sep,Oct,Nov)	Annual
Wasta	E	707.60	1.19	5.36	6.64	2.47	15.67
Scenic	E	856.55	1.07	5.52	6.52	2.48	15.60
Newell	E	875.35	1.05	4.60	6.36	2.36	14.37
Belle Fourche	E	920.49	1.17	4.82	6.29	2.59	14.87
Rapid City	E	965.33	1.50	5.62	6.82	2.35	16.29
Buffalo Gap	E	982.10	1.44	5.43	7.67	2.73	17.27
Hermosa		991.25	1.13	5.82	7.68	2.28	16.91
Fort Meade	E	1006.50	1.75	6.74	7.76	2.93	19.18
Oelrichs	E	1021.75	1.37	5.92	6.57	2.54	16.40
Hot Springs	E	1078.18	1.13	4.84	6.69	2.43	15.08
Ardmore		1082.15	1.28	5.34	6.19	2.38	15.18
Colony (Wyo)		1088.85	1.16	4.57	6.01	2.61	14.35
Spearfish		1111.73	2.10	7.09	8.03	3.65	20.87
Devils Tower 2 (Wyo)	W	1177.91	2.10	5.30	6.22	3.13	16.75
Redbird (Wyo)	W	1186.45	1.00	4.66	5.93	2.14	13.73
Morrisey (Wyo)	W	1250.50	1.07	4.49	4.84	2.05	12.44
Newcastle (Wyo)	W	1316.08	1.46	4.39	6.04	2.00	13.87
Alva 5 SE (Wyo)		1338.95	2.71	8.13	7.87	4.14	22.85
Deadwood	E	1424.35	4.09	10.40	9.10	4.90	28.48
Pactola Dam	E	1439.60	1.13	6.96	9.62	2.58	20.29
Sundance (Wyo)	W	1448.75	1.88	5.40	6.77	2.88	16.93
Upton 13 SW (Wyo)	W	1457.90	.98	4.43	5.34	1.84	12.58
Hill City		1520.43	1.28	6.33	9.47	2.45	19.55
Lead 1 E	E	1625.65	4.37	10.36	9.05	4.86	28.64
Custer	W	1656.15	1.37	5.68	8.51	2.39	17.94
Budkala Ranch		1863.55	2.64	7.24	9.25	3.37	22.50
Deerfield Dam 4 NW	W	1897.10	3.06	7.23	9.57	3.49	23.35

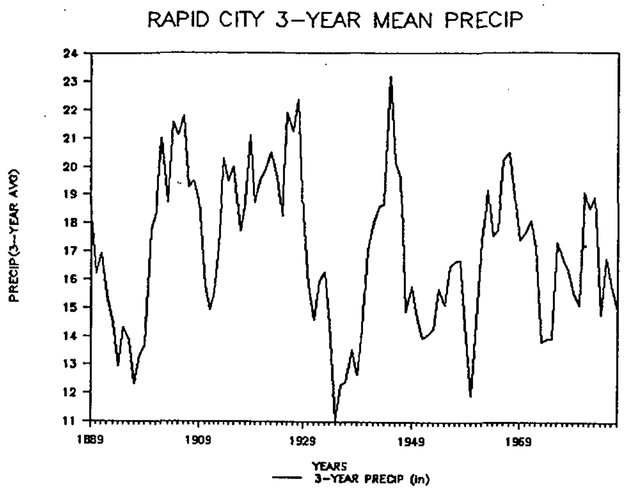

Fig. 2: Mean annual precipitation (inches), (3-year running averages), at Rapid City for the period 1889-1988.

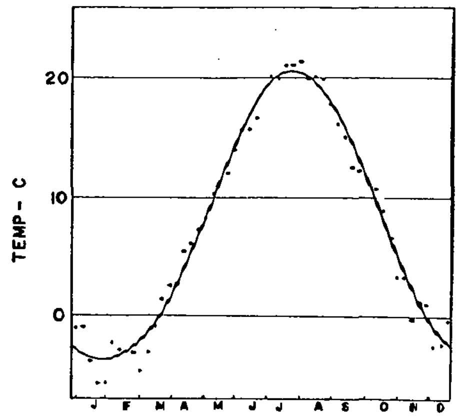

Fig. 3: Weekly means of 850-mb temperature and annual trend at Rapid City, SD. [Dennis et al., 1966]

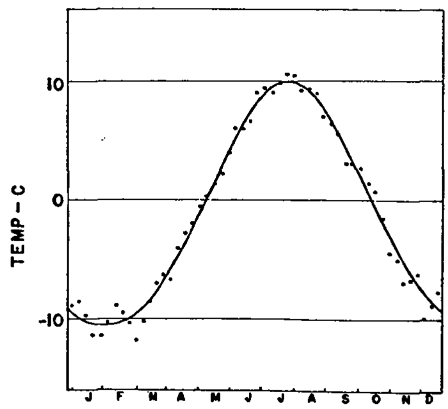

Fig. 4: Weekly means of 700-mb temperature and annual trend at Rapid City, SD. [Dennis et al., 1966]

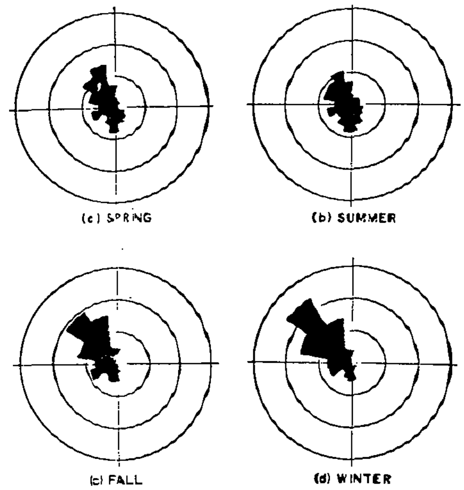

Fig. 5: Wind roses by season for 850-mb level at Rapid City, SD. [Dennis et al., 1966]

TABLE 5: Average Number of Days With 0.01 Inch or More of Precipitation (to Jan 1, 1949)

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	An'l.
Ardmore, S. D.	4	5	7	5	10	10	8	6	6	5	4	4	74
Belle Fourche, S. D.	4	3	6	7	8	9	6	5	5	4	4	4	65
Custer, S. D.	7	5	7	9	10	11	7	6	5	5	5	6	83
Deerfield, S. D.	5	4	8	8	10	10	8	6	4	4	4	4	75
Dumont, S. D.	8	7	9	10	11	11	8	7	6	6	6	7	96
Hardy Rang. Sta., S. D.	9	8	13	11	11	12	7	7	6	7	8	8	107
Harvey's Ranch, S. D.	5	5	9	9	11	11	8	6	5	5	5	6	85
Hermosa, S. D.	4	2	5	6	9	11	9	7	6	4	3	3	69
Hot Springs, S. D.	3	4	5	7	9	9	8	6	5	4	2	3	65
Lead, S. D.	11	8	11	11	12	13	9	8	6	7	8	9	113
Oelrichs, S. D.	3	3	5	6	7	7	6	4	3	4	3	3	54
Rapid City, S. D.	6	6	9	9	12	13	10	8	6	6	5	6	96
Spearfish, S. D.	7	6	9	10	11	12	9	8	6	5	6	6	95
Newcastle, Wyo.	6	4	6	7	7	7	5	6	6	5	4	5	68
Sundance, Wyo.	6	6	5	5	10	10	5	5	6	6	6	6	76

3. BLACK HILLS MICROWAVE RADIOMETER STUDY

3.1 Introduction

A microwave radiometer and acoustic sounder were installed in an open area at the Hardy Guard Station (Fig. 1) in February 1990 to measure liquid water and the horizontal wind in a vertical column above the site. Along with some knowledge of the temperature at the surface and aloft, this would give information on the amount and flux of supercooled water in this region of the Black Hills. This site is located in high plateau near the NNW-SSE crestline of the Black Hills. Supercooled water is the basic ingredient for the growth of precipitation, primarily snow, in this area, in this time period. The presence of supercooled water indicates the potential for cloud seeding to increase the snowpack over and above that which would occur from natural snowfall alone. An increased snowpack is favorable for maximum runoff in the spring.

The instrumentation was left in place until the end of April 1990 so that nearly three months of data were obtained. Liquid water was detected for 370 hours during this period, of which 322 hours involved supercooled liquid. Some hours of data were lost due to non-operation of the equipment, but probably not more than 10% of the time. Consequently, the data represent the distribution of supercooled liquid water (SLW) during this period.

The data can be used, with certain assumptions, to calculate the maximum potential snowfall. The methods used to analyze the data for supercooled liquid water, its flux, and the potential snowfall are explained in *Boe and Super* (1986). In addition, standard meteorological data were examined to see when precipitation was occurring in the northern Black Hills and compared with the frequency of the occurrence of SLW.

3.1.1 Example of data

Figure 6 shows an example of the graphs made from the data obtained by the microwave radiometer (*Orville,* 1992). The abscissa is hours from midnight and the ordinate is either water vapor (on the left) or supercooled liquid water (on the right) in units of centimeters. The graph shows data for 15 March. The vapor is generally an order of magnitude greater than the SLW and more continuous. Times of higher vapor content are more favorable for precipitation. The SLW can be either high or low during precipitation. In this instance, there was some snowfall measured at the site.

Graphs like this were used to determine the total number of hours with SLW. An overlay with every hour and with every tenth of a millimeter marked off was used to classify each hour of SLW by the appropriate tenth of a millimeter.

For perspective, the value "one millimeter of liquid water" represents the amount of water in a vertical column 1 cm^2 by 1 km in depth which equals 1 gram of water per cubic meter of air. Consequently, the SLW values indicate that the water contents in these clouds seldom exceeded a few tenths of a gram of water per cubic meter of air, typical of other mountain regions in the West.

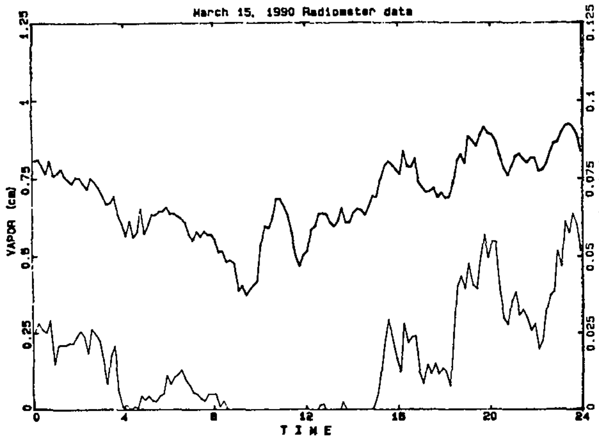

Fig. 6: Example graph of microwave radiometer data for a 24-hr period, 15 Mar 1990. The vertical axis is water vapor on the left, supercooled liquid water (SLW) on the right. The horizontal axis shows time of day (MST). The upper curve is vapor; the lower curve is SLW.

3.1.2 Results

The analysis shows that the vast majority of the hours of data give SLW values between 0.05 and 0.25 mm (the midpoint values of the categories). The maximum value is in the 0.8 to 0.9 mm category. Note that these are one-hour averages so that the values shown are less than the actual maxima. A few peaks greater than 1.0 mm occurred during the project.

Figure 7 shows graphically the results of the analysis. Fifty-nine percent of the values fall in the 0 to 0.1 mm category; about 20% in the 0.1 to 0.2 mm category. Only 1% of the values occur in the categories larger than 0.7 mm.

These results are quite similar to those obtained in the Grand Mesa region of Colorado. Figure 8 shows data from 958 hours of measurements in the cold season using the same kind of equipment as in the Hills (*Boe and Super,* 1986). The similarity of the

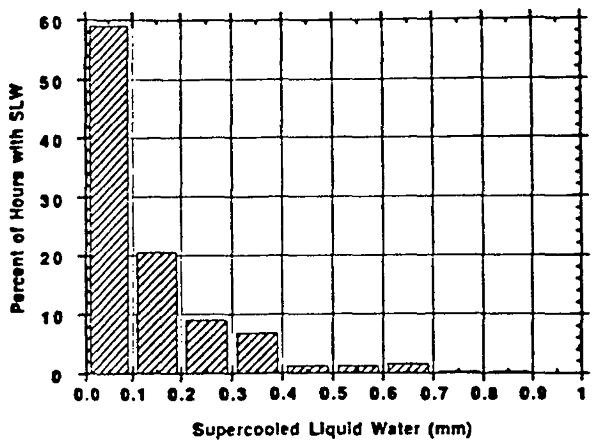

Fig. 7: Distribution of 1 h averages of supercooled liquid water (SLW) recorded by microwave radiometer for 322 h during Feb through Apr 1990 for the Hardy Guard Station.

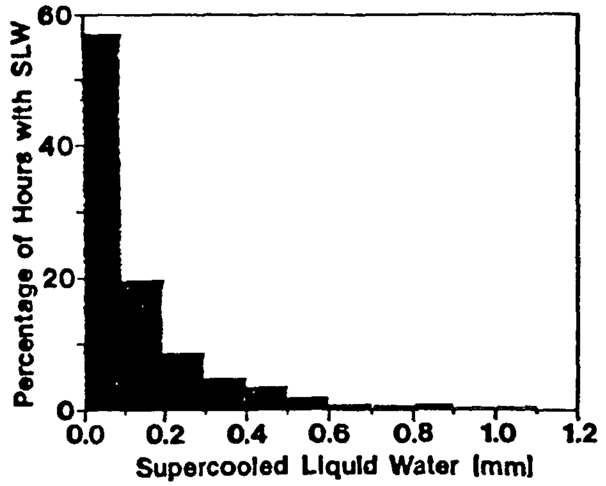

Fig. 8: Same as Fig. 7 but for 958 h during Nov and Dec 1983 and Jan through Mar 1985, for Grand Mesa, CO. [From Boe and Super, 1986]

figures is striking. Data from the Mogollon Rim of Arizona (*Super and Holroyd,* 1989) show similar trends.

Calculations were also made of the maximum snow that could be produced by the flux of supercooled water. The flux is obtained by assuming an 8 m s^{-1} horizontal wind (the 850 mb mean wind speed for Rapid City in the winter). The snowfall is calculated by assuming a 1 m wide column and a 10 km long strip. (Compare *Thompson and Super,* 1987.) The two smallest categories have the potential to produce significant snow, because of the large number of hours involved. The total potential of 124 mm (equivalent water) would represent about ~1.2 m (4 feet) of snow. Actual snow at Lead during this time was more than ~1.2 m (4 feet), a fortuitously good comparison. Snow at Rochford was less, but the record is incomplete.

3.1.3 Summary of microwave radiometer study

These microwave radiometer results indicate that cold cloud conditions over the northern Black Hills produce many hours of supercooled liquid water that might be useful in producing snow. Over 300 hours were sampled with some SLW. The majority of the observations revealed only small amounts of SLW and not many hours of supercooled liquid water in a three-month period. However, significant potential additional snowfall was indicated. These results are very much in line with results from other mountainous regions in the West.

4. CLOUD SEEDING CONSIDERATIONS, STRATEGY AND EXPERIMENT

Several regions in the Black Hills appear to be suitable for cloud seeding operations. The shortage of water in Pactola reservoir makes that watershed a natural one to focus upon at first, but other regions in the Black Hills should also be considered.

4.1 Pactola/Deerfield Watershed

The Pactola/Deerfield watershed looks like an appropriate target area for a winter/spring orographic cloud seeding project. Topographical charts indicate that the watershed occupies approximately 800 km^2 (309 mi^2), much of it in the high country at elevations of 1,829 m (6000 feet) or more (see Fig. 9). The figure shows that there will be forced lifting 300-900 m (1000 to 3000 feet) of air with any wind flow into the Hills. Winds from the southwest to west or from the east would appear to give the best lift because of their nearly perpendicular flow against the main mountain mass.

The climatology of the region suggests that snowpack and runoff could be increased from October or November through May. The most beneficial time for runoff would probably be the February to June period, if rain increase was also an objective. An average of 4 or 5 days per month produce precipitation at Deerfield in the fall and winter months, increasing to 8-10 days in May and June. More days of precipitation occur in the northern part of the watershed. More days might produce precipitation, if the cloud seeding works as advertised, causing snow to fall from clouds which might not snow naturally.

The mean temperature charts in section 4 (data for Rapid City) indicate that the -5°C temperature level would be intersecting the higher elevations of the watershed only during the winter months, and would be above the highest elevation in other months. Consequently, ground generator seeding with AgI would be useful in the colder months, but aircraft seeding would likely be needed as the seasons progressed.

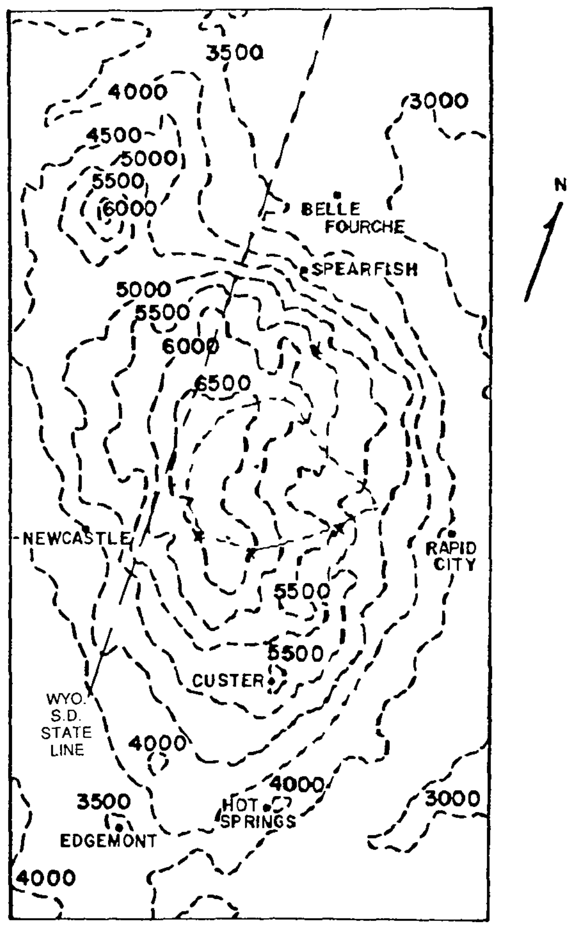

Fig. 9: Smoothed Black Hills topography (height in feet). Pactola watershed is outlined west of Rapid City.

We estimate that 50 to 70 suitable seeding days would occur in the 7-month period (November-May), with several hours per day appropriate for seeding.

These estimates are made using climatological data. Studies of past satellite data and National Weather Service daily weather data would give a better picture of possible seeding opportunities. Also, additional measurements of supercooled liquid water using a microwave radiometer, and aircraft sampling of clouds over the Black Hills would add valuable information to the project.

4.2 Other Regions in the Hills

Seeding for snowpack enhancement in the northern Black Hills could aid the skiing and mining industry. As shown in Fig. 1, the maximum precipitation occurs in the northern Hills, with more than ~250 cm (100 inches) of snowfall per winter/spring seasons. The predominantly northwest airflow yields many cases of upslope flow in the winter/spring season.

The watershed for this region is just north of the Pactola/Deerfield watershed. Runoff occurs primarily into the Belle Fourche River and reservoir system.

In the central Hills, south of the Pactola/Deerfield watershed, the main watersheds feed Spring Creek and French Creek and the cities of Hill City, Keystone, and Custer.

In the southern Hills, Angostura is the primary reservoir. The Cheyenne River (fed by Beaver Creek) is the main source for the reservoir. Custer and Hot Springs and several small lakes would be the primary beneficiaries of added water in the central and southern Hills, in addition to Angostura.

The annual rainfall is only about ~400 mm (16 inches) in this portion of the Hills, and the number of days with detectable precipitation is relatively low [65 days in the south vs. 113 days in the north (Table 5)]. Consequently, seeding opportunities could be expected to be fewer. Nevertheless, the various watersheds in the Black Hills offer a variety of opportunities to enhance the water resources of the region.

An experiment involving the Black Hills should extend for a period of several years -- to establish what the seeding potential actually is, and then to see if the technology could be improved.

5. SAFETY CONSIDERATIONS

Most current weather modification experiments and operations employ safety criteria. Flash floods and avalanches are the primary dangers of a winter/spring orographic cloud seeding project, although avalanches are of little concern in the Black Hills. Additional snow on roads and springtime rains may create minor weather related hazards. However, the additional 13 to 25 cm (5 to 10 inches) of snow caused by the cloud seeding should be well within the driving experiences of the Black Hills residents. Also recall that the snow increases involve relatively small rates which occur over extended periods of time. This should have minimum impact on wildlife, also.

As the project extends further into spring, then soil moisture and runoff should be considered. The soil moisture can be monitored, and runoff studies are currently being proposed by the U. S. Geological Survey and the South Dakota School of Mines and Technology. Whenever severe weather or heavy rains are forecast by the National Weather Service, operations can be suspended to avoid any possibility of cloud seeding contributing to a dangerous weather situation.

The NWS has conducted studies on flash floods and has produced guidelines on items to watch for in such situations (*Maddox et al.,* 1980). Satellite and radar data are helpful in predicting flood conditions and should be available to operations personnel. The radar data would be helpful in showing the rain rate, growth rate of cells, and the area over which the precipitation is falling. The satellite data would add further information as to the degree of convection, the growth rate of convective cells, and the depth of the clouds.

As a part of the standard operating procedures, safety criteria would be specified and suspension rules decided upon by a combined citizen/scientist advisory board.

Examples of such rules on other projects are:

1) Seeding will be suspended if snowpack is a certain percentage of normal at a certain time of the year -- values can be worked out for any particular area of the country.

2) No seeding will be done on traveling storms with flood potential (depends on area of storm and rain rate).

3) Seeding will cease in any region under an NWS flash flood watch or warning.

4) Seeding will cease upon request of the local weather modification authority, as relayed through the Project Director.

5) Seeding will cease whenever the field meteorologists determine that a potential flash flood situation exists.

6. METHODS OF EVALUATION

6.1 Statistical

Some sort of evaluation is needed to determine the effectiveness of weather modification projects and to show where improvements can be made. Statistical, physical, and numerical simulation methods can now be used to estimate the effects of cloud seeding. *Dennis* (1980) discusses the need for statistical evaluation and describes several methods -- target/control, historical regression, and randomized experiments. Much of the following comes from his work.

Target/control ratios are used often in operational projects. Comparisons are made of precipitation events in the target area, and in one or more control areas, which are assumed to be unaffected by the seeding. Often percentage-of-normals are determined for the target area and the control areas, where "normal" is the mean average precipitation during some predetermined historical period. The ratio of the percentages-of-normal in the target to control area over a period of time is calculated and ratios greater than one assumed to indicate a positive effect of seeding. However, as *Dennis* (1980) points out, because there is a lower limit of zero for the target/control ratio and no upper limit, the expected value of the ratio is generally greater than one. Usually certain transformations of the normally highly skewed precipitation data are needed to fully analyze the results.

Historical regression methods are more sophisticated than the target/control ratios. Precipitation gages with long term records prior to seeding are selected in the target and control areas and the average precipitation computed. The data are used to develop a mathematical expression relating an estimate of the rainfall in the target area to that in the control area. Once this expression is calculated, then the success of a cloud seeding attempt is estimated by computing the difference between the actual target precipitation and the estimated target precipitation. The percentage change due to seeding is estimated to be this difference divided by the estimated target precipitation (times 100). These results depend heavily on the correlation between the precipitation in the target and control areas. Also to be noted is that great care is needed in selecting suitable control areas so that they are close enough to the target area to maximize the correlation coefficient but far enough away, or judiciously selected upwind or crosswind, to avoid contamination by the seeding.

Randomization is considered by statisticians and many meteorologists to be the only way to conclusively demonstrate seeding effects. *Dennis* (1980) categorizes these experiments as single area, target/ control, or crossover designs. The key point to randomization is that a decision to seed is made by random choice and that observed differences between seeded and non-seeded cases can then be ascribed to the seeding.

In all of these techniques, precipitation gages are required to estimate the amount of precipitation, and measurements on a regular routine are also required. For some of the statistical designs, more gages are required than the few normally existing in any area. Considerable expense can occur to fully instrument an area and obtain the measurements on a regular and timely basis.

6.2 Physical Studies

Improved aircraft cloud physics instrumentation has made it possible to measure the physical effects of seeding and to obtain convincing evidence of positive cloud seeding results. Figure 10 shows an example of such results. This makes cloud seeding effects in these winter types of clouds as evident as the visual effects obtained in the seeding supercooled fog or stratus. Instruments can also be deployed on the ground, and seeding effects detected there. In addition, the use of chemical tracers appears very helpful in revealing seeding effects (*Warburton et al.*, 1986; *Stith et al.*, 1989). Aircraft and ground measurements can add plausibility and a physical basis to statistically oriented field experiments.

6.3 Numerical Simulations

Mesoscale and cloud scale numerical models could strongly support the physical and statistical studies. The development of the models and the availability of supercomputers to run the models has added greatly to the understanding of clouds and cloud seeding concepts. The potential to apply these models to help design, conduct, and evaluate the field experiments can only now be realized.

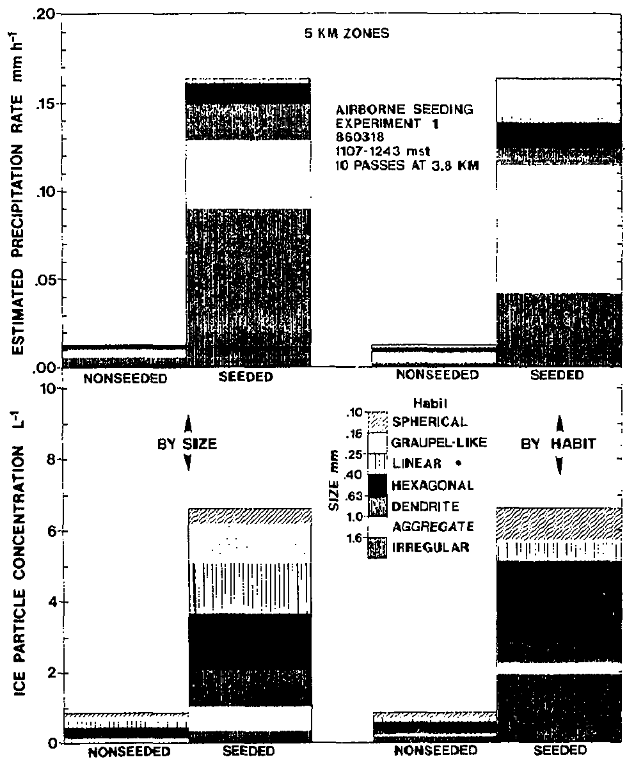

Fig. 10: Mean IPCs and estimated precipitation rates within 5 km upwind of the Snow Lab by crystal habit and size for seeded and non-seeded periods during the first airborne seeding experiment. [From Super and Boe, 1988]

A mesoscale model developed by Terry Clark and associates at the National Center for Atmospheric Research is being adapted to the Black Hills (*Hjelmfelt*, 1989). Richard D. Farley of the South Dakota School of Mines and Technology (SDSM&T) has helped in the model development (*Clark and Farley*, 1984). Much of the cloud physics in this model, particularly the ice-phase microphysics and cloud seeding simulations (yet to be added), has been developed by SDSM&T scientists (notably, R. D. Farley, F. J. Kopp, and H. D. Orville).

This mesoscale model has been applied with much success to airflow about the island of Hawaii and the Sierra Nevada in California (*Smolarkiewicz et al.*, 1988). We anticipate that when applied to the Black Hills, it will show the areas of forced uplift, convergence, blocked flow, and the natural precipitation patterns over the Black Hills. Cloud seeding numerical simulations should show the kinds of changes to be expected due to seeding, as well as the proper location of ground generators and appropriate aircraft seeding tracks. The understanding of precipitation processes and their interactions with the mountain induced airflow will increase markedly with the application of this model to the Black Hills, and will offer great insight into the seeding operations. Together with physical studies used to validate the model and to show seeding effects, the evaluation of cloud seeding results using these methods has a chance of reaching new, more precise standards.

A meeting of meteorologists, statisticians, and others should be held to consider the most appropriate way of evaluating a cloud seeding experiment in this region.

7. MAJOR SCIENTIFIC UNCERTAINTIES

Field experimentation in cloud seeding over the Black Hills (and other regions of the State) involves several uncertainties at this time. The climatology of seedable cloud situations is not well known here. Ground-based radiometer measurements, aircraft sampling, ground observations of snowfall, and more extensive satellite studies of clouds over the Hills would all serve to better distinguish those situations when supercooled liquid water is present and what the ice crystal concentrations are. A characterization of the various storm types which affect the region would probably be very revealing concerning seeding possibilities. A general cloud climatology is needed and is recommended for any cloud seeding project (*Orville et al.,* 1986). That has not been accomplished yet for the Black Hills or other portions of the State.

The degree to which embedded convection is present in the orographic clouds is not known. Such convection would lead to more SLW and help in dispersing the seeding material in the clouds. The effects of the ice-phase seeding may enhance the embedded convection as shown in *Orville et al.* (1984). How much this will lead to a redistribution of the precipitation as well as an increase is unknown.

Downwind effects are another uncertainty, but the indications from other orographic projects are that they will be positive (*Brown et al.,* 1978). The analysis of downwind effects is difficult, but important, to forestall criticism from downwind populations. Often "downwind" is difficult to define because low-level flow frequently comes from one direction, often the south or east, and upper-level flow from another direction, normally the west. The clouds that form over the Hills sometimes develop in this type of flow. In fact, such clouds are more a manifestation of a "circulation process" than an "entity-in-themselves". The orographic clouds show where updrafts are. The mountains tend to strengthen mesoscale updrafts and enhance clouds as they pass through the Black Hills region. As the clouds move off the Hills, the clouds encounter mesoscale downdrafts and weaken, leading to the well known "rain shadow" effect downwind of mountains. During their passage over the Hills and downwind in the upper-level west winds, the clouds have been fed by moist low-level southerly winds, but the amount of vapor that is processed to cloud and precipitation depends critically on the larger scale dynamics set up by the mountains. In regions of enhanced updrafts, more precipitation falls. So for the ranchers to the east of the Black Hills, they are often not downwind, but their precipitation is mightily affected by the Black Hills to the west.

Even those times when the lower and upper winds are all from the west, the effects of the cloud seeding are minimal in taking water out of the atmospheric flow. Relatively basic calculations show that the water vapor flowing from the west over the Hills or across the southern boundaries of the State is measured in <u>millions</u> of acre-feet per day. Cloud seeding attempts to produce 100's to 1,000's of additional acre-feet from the cloud systems. Hence, one vapor molecule in 1,000 is being captured in the precipitation process and 999 remain for continued cloud and precipitation development "downwind" of the Black Hills, which again, to reemphasize, is very dependent on the dynamics of the atmosphere.

The extent to which seeding results in other parts of the mountainous west are applicable to the Black Hills is somewhat vague, but the hope is that results from other orographic projects are, to some extent, transferable. The Black Hills are not as tall as the Rockies, but they do provide some uplift, and precipitation patterns indicate a strong orographic effect. In addition, the similarity of radiometer SLW results (as shown in Figs. 7 and 8) with other regions suggests that seeding results may be transferable.

Potential seeding effects in above average and below average years are not well established. Optimum precipitation changes need to be studied.

8. RESOURCES NEEDED -- POSSIBLE SOURCES

An extensive, effective cloud seeding experiment will require talented people and sophisticated equipment. The operational portion of the experiment will require ground generators, precipitation gages, wind and thermodynamic soundings, liquid water detectors, forecasting facilities, seeding material, seeding aircraft, radar, computers, and communication equipment.

The evaluation and physical studies portion will require specially instrumented aircraft, silver analysis and other chemical equipment, supercomputer access, other computer services, satellite and radar data, snow and rainfall data, runoff measurements, etc.

Personnel of many different talents are required -- cloud physicists, climatologists, forecasters, mesoscale analysts, numerical modelers, chemists, statisticians, pilots, technicians, and others.

A 5- to 10-year operation and evaluation will require on the order of $200,000 to $250,000 per season for the aircraft and ground generator seeding operations, and at least a like amount for the evaluation of the experiment.* Periodic intensive field studies should be conducted to gain additional information about specific aspects of the problem, with added costs of perhaps $500,000 to $1,000,000 during those seasons. Consequently, $5,000,000 to $10,000,000 may be required over a 10-year period in which the seeding effects would be quantified and the technology advanced to improve the results.

*Actual expenses of research and operations depend on many factors. The numbers presented here are highly speculative and need further discussion.

Fortunately, many of the necessary scientific personnel are available at nearby universities such as the South Dakota School of Mines and Technology (SDSM&T), University of Wyoming, Colorado State University (CSU), and the University of North Dakota (UND). SDSM&T has a long history of cloud seeding research and evaluation. CSU has been a leader in winter orographic cloud seeding. University of Wyoming personnel participated in the World Meteorological Organization (WMO) sponsored Precipitation Enhancement Project (PEP) in Spain, and were instrumental in determining the cloud climatology of the PEP clouds. UND has come on the scene more recently, but has developed expertise in aircraft observations of clouds and tracer techniques.

We look upon the NOAA Federal/State Cooperative Program as one possible source of funds for such a project. This program is designed to help states develop their cloud seeding capabilities and evaluate the effects of cloud seeding. Support has been given to Arizona, Utah, and Nevada for winter cloud seeding studies, and North Dakota and Illinois for summer cloud seeding work. South Dakota would fit in well for studies of seeding in the transition from winter to summer conditions. The precipitation maximum in the spring months makes seeding in the Black Hills appropriate for the program.

The Bureau of Reclamation also has a program designed to help states manage their water resources. Fifty-fifty matching of funds (can be "in-kind") is required. Their scientific personnel in Denver have conducted much of the research and analysis in winter cloud seeding in the past. In addition, the Bureau is responsible for water allocations from the Black Hills reservoirs and should be concerned with water recharge, conservation, and water resource management.

The Forest Service and other agencies might also be interested in the general problem of water management in the Hills. Thinning of trees is well known to increase runoff and could be used in conjunction with the cloud seeding to increase water in the reservoirs. The U. S. Geological Survey has begun studies of the surface and ground waters in the Hills. These studies will be important for determining the runoff as a function of season and should help in selecting the most opportune time for cloud seeding.

Private industry and the various municipal governments in the region should have an interest in the conduct and outcome of any such long-term study. The City of Rapid City, private industry, the Pennington County commissioners, and the West Dakota Water Development District have shown their interest by funding a short-term cloud seeding pilot project in the spring of 1989. Important lessons were learned from that project that should improve any future projects, and are mentioned below.

9. ECONOMIC JUSTIFICATION

The awareness of the economic value of Black Hills water has been heightened in the region. Improved water resource reliability for skiing, mining, agricultural and water recreation uses, as well as reduction of forest fire danger are all logical results of a successful cloud seeding program. Of course, storm systems have to occur for the cloud seeding to be effective.

The cost of water to irrigators is currently $1.25 per acre-foot; to the City, something more than $10 per acre-foot. Water for ski slopes and mining can be at least as expensive.

Estimates of cloud seeding operations have been $200,000 to $250,000 for a combined ground generator/aircraft operation -- the smaller number for the Pactola watershed, the larger for an entire Black Hills project. The potential additional water in the Pactola/Deerfield watershed due to cloud seeding is in the range of 20,000 to 40,000 acre-feet. Only a small fraction of this can be expected to run off, perhaps 15 to 30%, depending on ground conditions, and the time of the year. Consequently, each acre-foot added to the reservoir is potentially quite expensive. Note that the additional precipitation will tend to increase the runoff of the natural precipitation also. A rough estimate of this effect can be made by assuming that runoff increases as the square of the precipitation (*Sellers,* 1965, p. 89) or in some other nonlinear fashion. *Rahn et al.* (1990) give an exponential increase for runoff from their analysis of data in the Black Hills. Using their value results in <u>a doubling of the runoff attributable to the cloud seeding.</u> Thus, a precise number for the total added runoff is difficult to specify.

If the entire Black Hills is seeded, or at least the primary watersheds and reservoirs, then the amount of water added to the land could be considerably more, increased by as much as a factor of 5. The additional costs are not that great (~$50,000), so that there is economy in increasing the scale of the project. In addition, more seedable conditions occur if larger areas are covered.

However, it should be noted that successful conduct of a cloud seeding project to maximize the economic benefit to a region requires highly efficient operations and the proper weather conditions. A short pilot project in the spring of 1989 over the Pactola watershed provided examples of missed seeding opportunities due to inadequate aircraft deicing equipment, inadequate ground snowplow equipment at the home airport, excess ferry time to the target area, blockage of seeding altitudes for Air Force exercises, and delays due to legal action. On the positive side, several seedable opportunities did occur during the 6- to 8-week period of the project in an abnormally very dry period.

10. SUMMARY

The dome shaped Black Hills present a favorable region for the testing and development of cloud seeding capabilities. Normal precipitation amounts range from 380 - 760 mm (15 to 30 inches) per year -- the smaller amount in the southern Hills, the larger amount in the north. Recent years have seen a decrease in precipitation and a rapid lowering of Pactola reservoir, the primary water source for Rapid City and downstream irrigators. In addition, dry forests have burned, and ski and water recreationists have suffered.

The Black Hills produce orographic cloud systems throughout the year, but more frequently in the winter/spring seasons. Supercooled liquid water is produced, but is not optimally processed into precipitation.

Results in other mountainous regions of the West indicate 10 to 15% increases in seasonal precipitation using ground generators and aircraft cloud seeding methods. (Isolated ski slopes received greater increases.) Some form of silver iodide solution is the most common seeding agent.

The physical characteristics of the clouds over the Black Hills need more careful study, both as to their natural precipitation processes and to their response to cloud seeding. Preliminary indications and analogue situations indicate that the clouds would be susceptible to increases in precipitation by cloud seeding. Review of the literature indicates that adverse downwind effects would not occur.

Modern technology, such as sophisticated cloud physics instrumented aircraft, radar, satellites, and ground radiometers offer the chance of detecting cloud seeding effects in near real time and of predicting good seeding opportunities. Airflow and cloud models run on supercomputers make it possible to simulate the airflow over the Black Hills and predict the cloud seeding effects.

The time appears right to mount a properly designed cloud seeding operations and research project to enhance the water resources of the Black Hills.

APPENDIX A

Status of Summertime Cloud Seeding Appropriate for the Black Hills

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The seeding of summer convective clouds also holds promise of yielding more rain, given the proper conditions, but is not as well accepted as winter *orographic cloud seeding*.

In the early 1950's, ground generator seeding was conducted in late spring and summer months of 1951 through 1954 for portions of the Black Hills region under the direction of the Western South Dakota Rain Increase Corporation. Some limited ground-based experimental seeding was conducted in 1958 under the direction of the South Dakota Weather Control Commission. Beginning in 1961, aircraft seeding operations were conducted under the sponsorship of School of Mines Research and Development Association and Grazing, Inc. Such operations continued primarily in the southern Hills area throughout the 1960's, with major research projects beginning as early as 1965 (*Schock,* 1977).

The earliest major research project applicable to the Black Hills region was the Rapid Project, conducted from 1966-68. This was a randomized crossover design experiment using aircraft and silver iodide as a seeding agent. The results of this experiment were that moderate size clouds (cloud tops less than about 10 km height) would produce more rain if seeded than their unseeded counterparts. These clouds occurred on days that were called shower days. If the clouds were too vigorous, and associated with traveling squall lines, there were indications of rain decreases from the seeded clouds. These clouds occurred on days that were called storm days, and were objectively selected.

The size of the target and control areas used in these experiments was about 1800 km^2 (700 mi^2). The additional rain produced was about 30,000 acre-feet over the three summers, an increase of nearly threefold over the unseeded rains.

The results of this work were further supported by a seeding experiment in North Dakota in which aircraft AgI seeding at a rate of 300 to 600 g hr^{-1} on days with "dynamic seedability" (as predicted by a one-dimensional, steady-state model) yielded substantial rain increases, more than doubling the rain output. Some of these analyses were decided upon after the project was completed, so no conclusive statistical evidence is available. Further experiments set up to test the apparently favorable results are warranted.

More recent pertinent work has involved cloud seeding in the HIPLEX** program (1979-80, *Smith et al.,* 1984) and in Alberta, Canada (*Kochtubajda,* 1986). The HIPLEX work gave definite evidence of starting the ice process in cumulus congestus clouds, but the trail to more precipitation on the ground was not completed due to entrainment of dry air into the clouds and the small size of the clouds. The Canadian work showed shower development in all of the clouds treated with dry ice or silver iodide, and small amounts of additional rain on the ground.

Numerical simulations of the clouds on all of the HIPLEX test case days gave results that indicated the seeded clouds should produce nearly 50% more rain than the unseeded model clouds. However, the total rain from all of the clouds (about 20 cases) was only a few hundred to a thousand acre-feet, and the average change on the order of a few 100 acre-feet (*Wu,* 1985).

Seeding summer convective clouds in the Black Hills has a special concern. The Black Hills flood of June 9-10, 1972, affected many who still live in the Hills, and some blame the flood on salt seeding of clouds, an activity that had been going on the afternoon preceding the flood (the flood occurred between 9 and 12 at night).

A thorough study has been made of the conditions leading to the flood, and no connection has ever been established between the salt seeding and the flood. Instead, a very vigorous, anomalously strong weather system moving into the Black Hills region was found to be responsible for the tragedy. A very similar weather system caused the Big Thompson flood in Colorado four years later, in which no cloud seeding was being done. Nevertheless, the connection of seeding and the flood is still in some persons' minds and needs to be understood when contemplating summer cloud seeding in the region.

In summary, the most favorable clouds for seeding in the summertime are those with cloud tops from -10°C to -30°C and in an active growth stage (*Dennis,* 1980; *Smith et al.,* 1986). Seeding with AgI and CO_2 from aircraft is probably the most efficient method for these clouds. Release rates of several hundred grams per hour for the AgI and 100 to a few hundred grams of CO_2 per km flight track are needed. Both updraft seeding, from below cloud base (AgI only) or on-top seeding can be effective. Safety considerations should be followed and seeding suspended in severe weather conditions.

**High Plains Experiment conducted by the Bureau of Reclamation in the late 1970's.

Whether this type of cloud seeding would help the reservoirs around the Black Hills is speculative. Evaporation rates are high and runoff is low in the summertime. Direct rain onto the reservoirs is not significant, because the area of the reservoirs is so small. The value of the water for other uses such as dry land farming, forests, and some municipal water supplies would presumable still be significant.

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