THE AFTERMATH OF THE 1972 RAPID CITY FLOOD

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Abstract. The aftermath of the 1972 Rapid City flood included a controversy over the propriety of cloud seeding on the day of the flood and a lawsuit against the U. S. Government. Preparation of the defense against the suit involved analyses of hourly rainfall accumulations, radar data from the seeded clouds, and possible microphysical and dynamic effects of seeding clouds with powdered sodium chloride (salt). Recent developments in numerical modeling offer some hope of improved understanding of the storm. However, mesoscale systems remain somewhat unpredictable, and realization of this fact has inhibited research dealing with the deliberate modification of large convective clouds.

1. ORIGIN OF THE CONTROVERSY

The Institute of Atmospheric Sciences (IAS) of the South Dakota School of Mines and Technology (School of Mines) conducted two cloud seeding flights at the eastern edge of the Black Hills on Friday, 9 June 1972. Late that evening, a flash flood swept down Rapid Creek and devastated Rapid City. On the following day, the IAS Director, Dr. Richard Schleusener, organized a telephone "tree," which produced the gratifying news that all IAS staff members and their immediate families had survived the flood.

On Monday morning (12 June), Schleusener left Rapid City to keep a previously arranged appointment. That afternoon the IAS Assistant Director asked me to take a telephone call from a reporter for the *Omaha World-Herald.* The reporter asked if there had been any cloud seeding in the vicinity of Rapid City on 9 June and, if so, could it have caused the flood? I told the reporter that experimental cloud seeding had taken place but that, in my opinion, the flood was due to natural causes. Soon there were calls from other reporters anxious to pursue a possible connection between cloud seeding and a major flood.

On the following morning, 13 June, I briefed Schleusener on the media contacts and recommended that, in view of the unfavorable publicity being generated, some accounting should be given to the appropriate South Dakota authorities. On the same day, he sent a memorandum through channels addressed jointly to Mayor Don Barnett of Rapid City and Governor Richard Kneip. His memorandum stated that, "The storm in the vicinity of Pactola Reservoir that caused the flood did not develop until about 6:00 p.m. This storm was immediately recognized by our meteorologists as dangerous and was never seeded by our group." The Governor's office accepted Schleusener's report and issued a statement asking the public to refrain from spreading rumors. An investigative team sent to Rapid City by the Bureau of Reclamation (Reclamation) of the U. S. Department of the Interior (Interior), which sponsored the IAS cloud seeding experiments, also reported in an internal memorandum dated 21 June that cloud seeding did not cause the flood.

Other authorities expressed contrary views. Mr. Ferdie Deering, editor of the *Oklahoma Farmer-Stockman* sought the opinion of Dr. Irving Krick, whose firm was conducting a project in Oklahoma at the time. Krick wrote to him on 16 June that, "We have come to the conclusion on the basis of our studies that cloud seeding in this situation quite possibly triggered the chain of events that led to this tragic disaster." He stated that his views were preliminary and requested that they not be published "until a full assessment ... can be made." However, the opinions he expressed at the 1972 fall meeting of the Weather Modification Association in Ft. Collins, Colorado, were indistinguishable from those in his letter to Mr. Deering.

As the Schleusener memorandum of 13 June could be construed as self-serving, an independent assessment was needed. Responding to the wishes of Gov. Kneip, the Director of the South Dakota Division of Weather Modification appointed Dr. Pierre St. Amand, Prof. Ray J. Davis, and Robert D. Elliott as a Board of Inquiry to investigate the affair and issue an impartial report. Following a week of very hard work by the board members, St. Amand presented a preliminary report at the conclusion of the Third National Conference on Weather Modification, which took place in Rapid City, 26-29 June. He pointed out that similar floods had occurred several times in the 90 years that Rapid City had existed, and said that an unusual confluence of meteorological events had caused the flood. The final Board of Inquiry report was submitted to the South Dakota Weather Control Commission later that year (Board of Inquiry, 1972). An abbreviated version that appeared in the *Journal of Weather Modification* (St. Amand *et al.,* 1973) stated that "... in the absence of cloud seeding, the result would have been the same."

The controversy still refused to die. A TV network reporter attending the Third National Conference on Weather Modification had drawn my attention to two fairly broad maxima in a map showing total rainfall of 9 June in the Black Hills, one to the north and the other to the south of Rapid Creek. He challenged me to prove that the two maxima, each exceeding 300 mm, were not due to the two cloud seeding flights. A free-lance science writer raised the same point in a column in the 24 September issue of the *Denver Post* (Metzger, 1972).

IAS staff members were not at liberty to rebut views such as Metzger's because of the possibility of lawsuits related to the flood. A discussion of precipitation mechanisms was deleted from the final version of an IAS report on the 9 June meteorological situation (Dennis *et al.,* 1973). Although the School of Mines had an insurance policy in the amount of $2,000,000 covering the effects of cloud seeding, which named the U. S. Government as an additional insured, it was obvious that suits could be filed for much larger amounts.

2. THE LAWSUIT

Davis (1988) has provided a lawyer's perspective on the legal proceedings that followed the flood.

The heirs of several persons who died in the flood filed six administrative claims with Interior in 1974 seeking a total of almost $4,000,000 in damages. The claims erroneously identified the 9 June cloud seeders as Reclamation employees. After the claims were denied, the heirs of five of the victims named in the claims filed a lawsuit (Lunsford vs. United States) in Federal court in June 1975 seeking $1,625,000 in damages. The suit also asked for $100,000 in compensation for property damages suffered by another party. The suit alleged that cloud seeding by a Government contractor on 9 June 1972 had been conducted in a careless and reckless manner and had contributed to the flooding of Rapid Creek. The Federal Tort Claims Act allows suits against the Government for negligence on the part of its employees, but not for negligence by contractor personnel. Recognizing that fact, the plaintiffs alleged that Reclamation's employees had been negligent in that they failed to supervise the experiments properly. The plaintiffs sought to have the suit declared a class action, a move of critical importance (Davis, 1988).

Some scientists opined at the time that the mere appearance of a connection between cloud seeding and the Rapid City flood was so damaging to the field of weather modification that it did not matter whether there was an actual connection or not. This escape was not available to IAS staff members, who spent considerable time in the late 1970's helping the U. S. Attorney for South Dakota and lawyers representing the insurance company prepare a case for the defense.

Although the Government claimed sovereign immunity in Lunsford vs. United States, work began on several additional lines of defense, including rebuttal of the allegation that cloud seeding had contributed to the losses suffered by the plaintiffs. The plaintiffs in a civil suit are supposed to prove their case beyond a reasonable doubt, so the uncertainty that attends the results of all cloud seeding projects tended to favor the defendant. On the other hand, the fact that the defendant was the United States, with supposedly limitless resources, increased the risk that a sympathetic jury might relax the standard of proof in order to remedy a perceived injustice. The results of a public opinion poll taken in South Dakota in late 1972 were not reassuring. About 30 percent of the persons interviewed thought there was some relationship between cloud seeding and the flood, with 4 percent seeing cloud seeding as the sole or primary cause (Farhar, 1974).

For a number of reasons, the plaintiffs in Lunsford vs. United States were not successful. Two professors of meteorology have told me they were asked to testify that cloud seeding could have caused the flood, but had declined to do so. As it turned out, the issue of causation never was argued formally in court.

The class claim was dismissed in 1976, and this decision was affirmed by the U. S. Court of Appeals for the Eighth Circuit in late 1977. One reason for dismissal was that the unspecified members of the class had not filed administrative claims first, as required by the Federal Tort Claims Act. The claim for $100,000 in property damages was dismissed for the same reason.

After several years of additional legal proceedings, some of which dealt with the question of Government liability vs. Government immunity for negligent acts by contractor personnel, and some with the issue of Government immunity in flood-control projects, "... federal immunity won the day," (Davis, 1988). The suit was dismissed with prejudice in 1982, and it does not appear that the heirs of the flood victims have any further legal recourse.

3. REVIEW OF EVENTS OF 9 JUNE 1972

The issue of causation was not carried to the stage of discovery proceedings. Therefore the defense team did not know what approach the plaintiffs would take to link cloud seeding to the flood. Obviously, the lines of reasoning offered by Krick and Metzger had to be countered. We also tried to anticipate other arguments that might be brought up by expert witnesses for the plaintiffs.

Although the 9 June storm flooded several streams in the eastern Black Hills, the suit involved only events in the Rapid Creek Basin. The operators of Pactola Dam, which was a Reclamation facility, closed the gates at the time the heavy rain began, and there never was any threat that inflow into Pactola Reservoir would fill it (Thompson, 1972). Nearly all of the rainwater which flooded Rapid Creek fell in an area of only 130 km^2 between Pactola Dam and Canyon Lake Dam, a small recreational facility in west Rapid City (Fig. 1). One obvious step was to examine again the events of 9 June to check again the statement in Schleusener's *memorandum* of 13 June that the storms that affected that particular area were not seeded. The examination had the added benefit of familiarizing the defense lawyers with some basic concepts of meteorology, cloud seeding, and experimental design.

The IAS seeded two test cases with powdered sodium chloride (salt) on 9 June as part of its Project Cloud Catcher and also released some salt in an area-seed mode. Cloud Catcher was a randomized experiment using a floating-target design and directed from a radar site about 10 km east of Rapid City (Dennis *et al.,* 1974). Boardman and Smith (1974) describe the computerized radar system used for logging the Cloud Catcher data. Thompson (1972), the Board of Inquiry (1972), St. Amand *et al.* (1973), Dennis *et al.* (1973), and Maddox *et al.* (1978) have described the weather situation of 9 June 1972 from different perspectives.

The seeding flights of 9 June are summarized in Table 1, while the "footprints" of the two test cases are indicated on Fig. 1. The Board of Inquiry report and St. Amand *et al.* (1973) provide detailed information on the time, location, and quantity of each salt release.

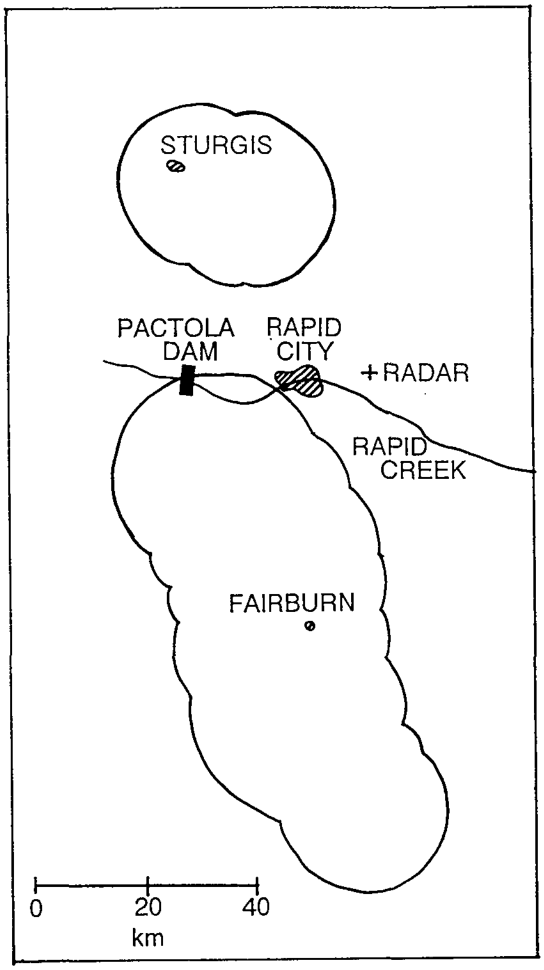

Fig. 1: Map of operational area. First test case of 9 June 1972 formed at edge of the Black Hills northwest of Rapid City and showed little movement, even though individual convective cells moved northwestward. As cells dissipated, new cells continued to form in the same general area. Second test case formed over the plains to the southeast and moved northwestward at 25 m s^{-1} through a combination of rapid cell motion and convective development ahead of existing cells.

Because of its rapid movement, the circle defining the second test case extended into the Rapid Creek basin from the south during the last few minutes of its official existence (Fig. 1), even though the last seeding had been done 30 minutes earlier near Fairburn, some 50 km south-southeast of Pactola Dam. Another troublesome fact was that about 20 kg of salt had been released in an area-seed mode just after the aircraft took off from Rapid City Regional Airport at 1638* for its second flight of the day (Table 1). Some of that salt might have

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*All times MDT.

TABLE 1

Key Times in Cloud Seeding Flights
of 9 June 1972*

	First Flight	Second Flight
Takeoff	1454	1638
Test case declared	1504	1658
Begin seeding	1505	1639+
Official beginning of case	1514	1708
End of seeding	1543	1737
Landing	1549	1753
Official end of case	1614	1808

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*All times MDT.

+Area-seed mode, seeding on test case began 1658.

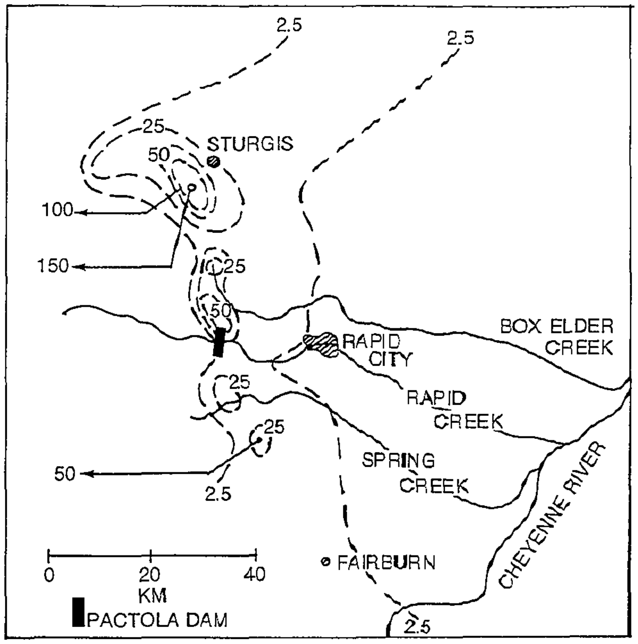

Fig. 2: Rainfall accumulations of 9 June 1972 up to 1800 in millimeters. [Adapted from Halligan and Longsdorf, 1976]

drifted northwestward across the northern part of the Rapid Creek basin. Therefore it was necessary to examine rainfall accumulations below Pactola Dam up to 1800.

The National Weather Service (NWS) conducted a bucket survey after the flood and produced hourly and cumulative rainfall maps from the resultant data (Halligan and Longsdorf, 1976). A review of those maps and others plotted by IAS staff using NWS data confirmed that most of the Rapid Creek drainage below Pactola Dam received only light rain before 1800 (Fig. 2). The exception was a small area just north of Pactola Dam, where over 50 mm of rain fell before 1800 (Fig. 2). The NWS maps also showed that the heavy showers from the second test case fell, as would be expected, near the center line of its track, on watersheds to the south of Rapid Creek. Cumulative rainfall plots showed that heavy rain began southwest of Sturgis between 1500 and 1600 and continued into the evening. At Pactola Dam the heavy rain set in about 1800, but a downstream station 8 km (5 miles) west of Rapid City received no rain at all until after 1900 (Fig. 3). On the basis of the rainfall maps up to 1800, cumulative rainfall plots, and the radar data, Schleusener's statement that the storms that flooded Rapid City were not seeded appeared defensible.

Examination of the hourly rainfall maps also showed that Metzger's hypothesis linking the 9 June rainfall maxima north and south of Rapid Creek to the two cloud seeding flights was highly improbable. Linking the cloud seeding flights to the maxima in total daily rainfall, which were mostly due to rain that fell during the evening, would imply that the effects of the first flight propagated southwestward at an average speed of 2 m s^{-1}, while the effects of the second flight propagated northwestward at 5 m s^{-1}. Cell motions from the southeast at 10 to 15 m s^{-1} and southeasterly winds at all levels up to 5 km above sea level ranging from 15 to 25 m s^{-1} argued strongly against his interpretation of the observed rainfall distribution.

4. STATISTICAL APPROACHES

Various people have appealed to statistics in discussing the 1972 Rapid City flood. Occasionally someone will describe it as a 100-year flood or as exceeding a 100-year flood. Although the Schleusener memorandum of June 13 and the Board of Inquiry (1972) noted that similar floods had struck Rapid City in the past, it is not known how bad the previous floods would have been if Pactola Dam had existed when they occurred.

At a hearing on the lawsuit in Rapid City on 16 June 1976, the judge asked the plaintiffs' lawyers for their opinion of serious flooding that had occurred in the northern Black Hills on 14 June 1976 in the absence of any known cloud seeding. One of them answered, after a time-out for consultation, that the rainfall on 9 June 1972 was more "concentrated" in time and therefore unlikely to have been due to natural processes.

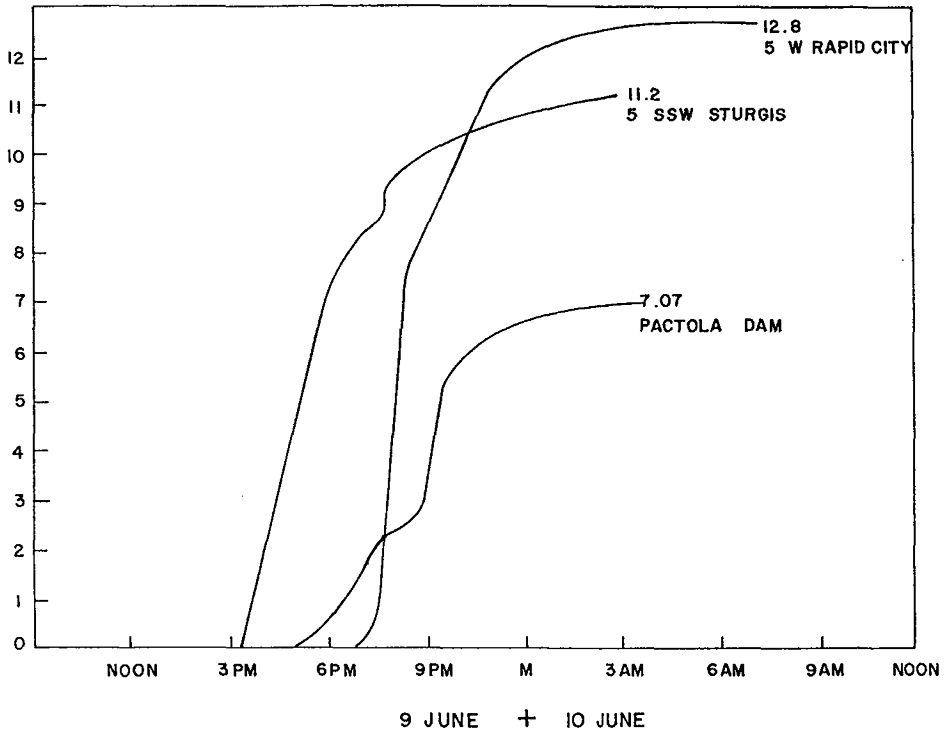

Fig. 3: Cumulative rainfall totals (in inches) as a function of time at three representative stations. [From Dennis *et al.,* 1973]

A few weeks later, Nature provided an unexpected and tragic confirmation of its ability to wreak flood havoc without any obvious human assistance. The Big Thompson flood in Colorado of 31 July 1976 arose from a weather situation very similar to that of 9 June 1972, except that it was displaced southward a few hundred kilometers (Maddox *et al.,* 1978). Once again, a quasi-stationary mesoscale convective complex (MCC) hovered over an eastward-facing slope for several hours and rainfall totals exceeded 250 mm over a considerable area.

Immediately after the flood, the IAS staff studied the 9 June test cases to see if their behavior was so abnormal as to suggest a radical, artificial modification. The principal Cloud Catcher evaluation was based on a regression analysis, in which the cube root of the rainfall from each test case, as estimated from radar data, was compared to that expected on the basis of the cloud depth, defined as the difference in height between the maximum observed radar echo top and the height of cloud base as observed from the seeding aircraft. There was a break in the project at the beginning of the 1971 season, when a 10-cm radar set replaced the 3.2-cm radar set which had been used for data logging in 1969 and 1970. The results of various regression analyses (Dennis *et al.,* 1974, 1975) are summarized in Table 2. In plain language, the 1971-72 data had to be analyzed separately from those of 1969-70, and showed no evidence of an overall seeding effect.

In 1972, the IAS was still pooling the Cloud Catcher data for all years. Therefore the statistical results presented to the investigative team from Reclamation shortly after the flood differed a little from those presented below, but the conclusions were essentially the same.

The data on maximum cloud depth (CDP) and radar-estimated rainfall (RER) for all 1971 and 1972 Cloud Catcher cases as given in Table A.3 of Dennis *et al.* (1974) can be fitted by

$$(\mathrm{RER})^{1/3} = 1.20 + 1.15(\mathrm{CDP}) \qquad (1)$$

with a correlation coefficient of 0.73. For the first case of 9 June, cloud base was at 1.9 km and maximum radar echo height was 14.5 km, for a CDP of

TABLE 2

Results of Linear Regression Studies in Cloud Catcher after Dennis *et al.* (1974)

No-seed 69-70 vs. No-seed 71-72	Need different regression lines ($p = 0.01$)
Salt seed 69-70 vs. No-seed 69-70	Adjusted means different ($p = 0.06$); may need separate regression lines ($p = 0.17$)
Seed 71-72 vs. No-seed 71-72	One regression line fits both

12.6 km. For this case, Eq. (1) predicts a rainfall total of roughly 3800 kT. The observed RER was much less at 1600 kT. For the second case, cloud base was at 2.1 km and maximum radar echo height was 16.0 km, giving 13.9 km for CDP. For this case, Eq. (1) predicts a rainfall total of roughly 5000 kT. The observed RER was 5500 kT, the largest for any Cloud Catcher case.

One possible interpretation of the numbers just quoted is that cloud seeding decreased the rainfall from the first Cloud Catcher case of 9 June by about 2200 kT and increased the rainfall from the second case by roughly 500 kT, but this interpretation is simplistic. Statistics detect only trends, rather than the effects of seeding on individual cases. Furthermore, the 9 June cases were not representative of the Cloud Catcher cases of 1971-72. They were the two tallest, so confidence in a purely statistical result is diminished. It should be noted, too, that RER for a single convective storm is itself subject to uncertainty of the order of 25 to 50%. One can only say that the 9 June cases behaved about as expected on the basis of observations of the other Cloud Catcher cases.

Each official Cloud Catcher case lasted one hour. This limitation seemed reasonable, as the lifetime of a typical convective cell is 20 or 30 minutes and the seeding aircraft, a light twin, could seed only a few cloud towers with salt on each mission. However, Reed (1973) presented a risk analysis based on the assumption that all the rainfall, property damage, and drownings that occurred in the Black Hills on 9 June were due to cloud seeding. A variety of criticisms and alternative suggestions were offered in invited responses to Reed's letter, which were published with it. In our response, Schleusener and I noted that Reed had not identified any physical mechanism to link cloud seeding to the flood-producing storms. After the suit was filed, it appeared prudent to anticipate linkages that might be proposed by expert witnesses for the plaintiffs and to prepare responses.

5. MICROPHYSICAL EFFECTS OF SALT SEEDING

The salt seeding in Cloud Catcher was an example of hygroscopic seeding, which is sometimes called "warm-cloud seeding." It was hypothesized that the salt particles released in updrafts would take on water and grow into artificial raindrop embryos by the time they reached cloud base, hasten the onset of rain by coalescence of liquid droplets, and thereby increase the precipitation efficiency of the target clouds. Seeding of clouds that had started to rain was limited to updrafts outside of the rain shafts, as it was not considered useful to add raindrop embryos to cloud-filled air that already contained raindrops.

Seeding rates were limited by the capacity of the seeding aircraft, which was 160 kg. Seeding 10 km^3 of air with one salt particle per liter, a reasonable objective for all but the small test cases, would require a total of 10^{13} particles. For reasons of economy and efficiency, the IAS staff thought that it would be desirable to use a salt grind with mass-median diameter around 10 or 20 μm. The best available commercial grind was examined and found to have a mass-median diameter near 25 μm. Providing 10^{13} such particles implied a need for 180 kg of salt for each test case. In addition to using an anti-caking agent, the IAS seeders had to mix the fine salt with a coarser grind to avoid clogging of their dispenser. The coarse salt yielded so few particles per unit mass that it was essentially dead weight, so the 160 kg carried by the seeding aircraft was inadequate for the larger test cases.

Metzger (1972) and some lay critics of the 9 June operation have noted the large quantity of salt, about 320 kg in all, "dumped" into the clouds. As calculations presented above have shown, the quantity released on each flight was the minimum required to produce a detectable effect in a convective cloud cluster of moderate size.

The Board of Inquiry (1972) and St. Amand *et al.* (1973) addressed the question of whether or not cloud seeding could have contributed to the flood by estimating the amount of water that condensed around the salt particles released. Their answer was 1.4 metric tons, which they estimated at one billionth of the rain that fell. The result of this calculation has been quoted in official documents as proof that cloud seeding did not augment the flood, and in the popular press to prove the absurdity of the IAS attempts to increase rainfall. In reality, the calculation is irrelevant. It is also meaningless to compare the number of salt particles released to the number of natural droplets formed in a seeded cloud, as is done on page 334 of St. Amand *et al.* (1973). **The purpose of the salt seeding was not to increase the number of cloud droplets or the amount of condensate; the purpose was to increase the precipitation efficiency of target clouds by introducing artificial raindrop embryos near cloud base.** The Board of Inquiry (1972) noted that fact and moved on to a discussion of the Langmuir chain reaction, in which raindrops formed around salt particles might break up to yield a new generation of raindrop embryos. Without some such process operative, salt seeding could never be economically feasible.

In a cumulus cloud with a warm base, liquid water concentrations (LWC) are high, and cloud droplets tend to be large. Droplets coalesce into raindrops in favored locations in 10 or 15 minutes after cloud formation, regardless of whether the cloud is seeded or not, and the raindrops thus formed can set off the Langmuir chain reaction. The Cloud Catcher results for 1969-70 indicated that apparent rainfall increases due to hygroscopic seeding, expressed as a percentage of the expected natural rainfall, decreased with cloud size (Dennis *et al.,* 1975). In view of the warm cloud bases, the great cloud depths eventually attained, and the abundance of natural giant nuclei, as evidenced by dense haze below cloud base, the 9 June clouds were not promising candidates for salt seeding.

6. PHYSICAL CONTAMINATION OF NON-TARGET CLOUDS

Although the Board of Inquiry report and St. Amand *et al.* (1973) stated that cloud seeding did not contribute to the Rapid City flood, they contained several statements that made them two-edged swords as far as preparing a defense against the lawsuit was concerned. Metzger (1972) quoted the Board of Inquiry (1972) report to support his contention that cloud seeding had contributed to the deluge. The troublesome statements included, "The cells seeded during the first sortee [*sic*] probably moved northwestward and joined the main cloud mass to the north of the hills .... The cells seeded on the second sortee [*sic*] marched into the main cloud mass." Figure 7 of the report shows a vertical section through a huge cumulonimbus cloud centered on the Black Hills, with feeder clouds moving in from both east and west to merge with it. [This figure does not appear in St. Amand *et al.* (1973), although reference is made to it in the text.] The seeded test cases are identified as feeder clouds moving in from the east. "It can be asserted with confidence that they were, however, outlying members of the main system," (Board of Inquiry, 1972, p. 24).

The expressions "main cloud mass" and "main system" are not completely defined in the Board of Inquiry report or in St. Amand *et al.* (1973). The expressions probably make the most sense if they are equated to Schleusener's "Pactola storm," the MCC that formed near Pactola Dam about 1800 and that progressed very slowly downstream over the next several hours. Figure 7 of the Board of Inquiry (1972) report is confusing on two counts. First, it suggests a single giant storm centered squarely on the Black Hills. In reality, the highest parts of the Hills received only light to moderate rain on 9 June; flooding rains were limited to a narrow north-south band on the east side of the Hills. Second, it depicts the situation that existed during the evening, after the Pactola Storm had become organized as a quasi-stationary MCC dominating the eastern side of the Black Hills.

At the time the 9 June seeding was carried out, convective activity over the Black Hills consisted of a number of complexes, some of them moving with surprising speed and others, especially those in the northern Hills, showing signs of being anchored to the topography. The test cases were not feeder clouds, but convective complexes separated by several kilometers from their nearest precipitating neighbors in order to avoid confusion in the collection of data for evaluation purposes. It is unlikely that any detectable amount of salt was entrained into cumulus clouds outside the test cases while the test cases were in progress. However, salt released in an area-seed mode on the first flight might well have penetrated the northeastern Black Hills near Sturgis before being entrained into clouds forming in that area.

On first being entrained into clouds, the salt particles would go into solution. Regardless of whether or not they initiated formation of raindrops, most of the salt would be washed out in the ensuing showers. However, it is quite likely that debris from dissipating convective cells, including raindrop fragments containing several kilograms of seeded salt, were entrained into new convective cells forming further downwind (northwestward) in the prevailing southeasterly flow.

A salt particle of 25 μm diameter weighs about 0.02 μg. A raindrop formed around such an embryo through the collection of 1,000,000 cloud droplets, each formed around a natural cloud condensation nucleus (CCN) 0.2 μm in diameter, would also contain about 0.005 μg of natural salts, mostly ammonium sulphate. If it evaporated, it could yield, in theory, a salt particle weighing several times as much as one resulting from evaporation of a purely natural raindrop. However, raindrops are constantly breaking up and reforming during their fall, with the time constant for the process being only 3 to 5 minutes. Salt from any original particle could be redistributed over and over again before the raindrop fragments were entrained into other clouds. Therefore, in considering the contamination of successor clouds, the crucial issue appears to be the total mass of salt involved, rather than the original size distribution.

Dennis *et al.* (1973) have estimated the total influx of moist air to the storm system over a 6-hour period at 4×10^{13} m^3. Unfortunately, no aerosol samples were collected on 9 June. Figure 8-8 of Pruppacher and Klett (1978) shows that hazy, maritime air like that flowing into the Black Hills on 9 June typically contains from 1 to 5 μg m^{-3} of chlorides in the form of giant particles over 2 μm in diameter, and around 1 μg m^{-3} of sulphates, mostly in the form of large particles (between 0.2 and 2 μm diameter.) The large sulphate particles would function as CCN, but produce ordinary cloud droplets rather than the large droplets likely to become raindrop embryos. Leaving them aside and assuming a conservative value of 1 μg m^{-3} for chlorides in the form of giant particles, one can estimate that the storm had at its disposal over 40,000 kg of natural salt, much of it sodium chloride from the sea surface, in the form of giant particles. Therefore contamination by, at most, some tens of kilograms of fugitive salt dissolved in cloud and rain water could not have impacted any significant fraction of the total storm system.

St. Amand *et al.* (1973) also considered the fate of raindrops formed around salt seeds, swiftly carried aloft by updrafts, frozen, and ejected to the anvil clouds as ice particles. Those would remain intact, and each would contain more salt than its purely natural counterparts. Falling from the spreading anvil clouds, they could have contaminated new cloud towers. However, the extra salt would not affect their ability to collect cloud droplets by collision and freezing, nor would it make them especially active as freezing centers in whatever new clouds they might enter.

7. POSSIBILITY OF DYNAMIC EFFECTS

The possibility of producing dynamic effects in individual convective clouds by glaciogenic seeding to release latent heat of fusion is widely recognized. The existence of dynamic effects related to hygroscopic seeding is harder to document.

In his 16 June 1972 letter to Deering, Krick noted that the latent heat of condensation per unit mass of water is several times greater than the latent heat of fusion, and reasoned that the dynamic effects of hygroscopic seeding would therefore be greater than those associated with glaciogenic seeding, say with silver iodide. He has cautioned against releases of seeding agents from aircraft in moist, tropical air masses, saying that the resultant heat releases near cloud base could result in severe weather. However, as the hygroscopic seeding in Cloud Catcher did not change the total amount of condensate, it could not have affected the total release of latent heat of condensation.

Before the flood, Dr. Harold Orville of the IAS was investigating possible dynamic effects of hygroscopic seeding with the aid of a two-dimensional numerical cloud model. Salt seeds released in updrafts grow into solution droplets before they reach cloud base, thereby leading to a premature release of some latent heat that otherwise would be released just above the visible cloud base. Someone proposed modeling this effect by arbitrarily increasing the temperature just below cloud base by some amount, say one-third of a degree Celsius.

Orville left for a temporary assignment in Washington, D.C., in 1972, and his associates were carrying on these studies in the weeks following the flood. I wrote to him on 17 July as follows: "Assume for the sake of argument that we have 10 particles per liter or 10^4 m^{-3}. If each of these particles has grown to become a droplet of 100 μm radius at cloud base (a generous estimate), the amount of water condensed at cloud base would be only 0.04 gm m^{-3}. This would not produce a temperature excess of one-third of a degree ...."

The temperature excess produced under the assumptions listed above is about 0.1°C. In reality, a salt concentration of 10 particles per liter was not attainable for all of the updraft of a large cloud, and the particles released from aircraft near cloud base did not have time to grow to equilibrium size before reaching cloud base. The temperature excess due to seeding was zero at the level of the salt release, say 300 m below cloud base, and could have increased to a few hundredths of a degree Celsius at cloud base. It had to disappear immediately above cloud base, as the water vapor that condensed prematurely to produce it was not available for condensation again within the cloud, and the salt could not drive the ambient relative humidity below 100 percent once it was diluted in large cloud droplets. By way of contrast, the observed temperature excess (over ambient) in several convective updrafts penetrated by the seeding aircraft on 9 June was near 1°C.

Subsequent work with the two-dimensional model has confirmed that dynamic effects of hygroscopic seeding are small compared to those produced by glaciogenic seeding (Orville and Chen, 1982). They are due to changes in precipitation loading and to subtle second-order effects related to the probability of drop freezing as a function of drop-size distribution. As natural precipitation mechanisms were very efficient in the clouds of 9 June (Board of Inquiry, 1972; St. Amand *et al.*, 1973), changes in precipitation loading and the resultant dynamic effects must have been very small.

8. CHAOS AND WEATHER

Fritsch (1986) has reported on numerical modeling experiments that show that dynamic effects of glaciogenic seeding theoretically can extend to the mesoscale and persist for several hours. Despite the fact that dynamic effects of hygroscopic seeding are an order of magnitude smaller, one cannot prove that some subtle dynamic effect of the 9 June seeding, such as the premature initiation of a downdraft in one cloud tower, did not influence subsequent convective cells passing over the Black Hills.

Numerous authors have postulated divergent behavior of the atmosphere. In his novel *Storm*, copyrighted in 1941, Stewart (1943, p. 44) put the following sentence in the mouth of a fictional professor of meteorology: "A Chinaman sneezing in Shen-si may set men to shoveling snow in New York City."

The idea of a cause-and-effect relationship between a sneezing Chinaman and a snowstorm in New York City is fascinating. It could never be proven or disproven using actual data, but can be subjected to a thought experiment. Presumably, the sneeze would affect local weather in China and its impact would propagate eastward around the globe, reaching New York City several days later. Surely, however, the exact impact of the sneeze would depend upon numerous other events, such as a minor escape of volcanic gas in Hawaii happening (or not happening) in the interim. As these future developments could not be known at the time of the sneeze, what is the justification for picking out one trivial event among the myriad factors affecting the future weather and identifying it as **the cause** of a storm happening several days later?

Professor Edward Lorenz found that infinitesimal differences in initial conditions could lead to very different outcomes of a numerical simulation of atmospheric processes, thereby lending credence to the concept that atmospheric processes are divergent and, in a sense, chaotic. Over the past decade or so, the development of the theory of chaos has altered considerably the way in which scientists view the weather (Dutton, 1992). Weather events do not have neatly identifiable causes stretching indefinitely back in time. They emerge, following physical laws, from a set of antecedent conditions too complex for complete specification, and are therefore inherently unpredictable. Useful predictions (actually statements of probability) can usually be made for a few days in advance, but errors eventually overwhelm the forecaster.

Because the atmosphere is chaotic, one can postulate a link between cloud seeding and any subsequent weather event, secure in the knowledge that the suggested connection can never be disproven. For example, Krick (1973) has speculated about a possible connection between the seeding of Hurricane Debbie in the mid-Atlantic in 1969 and subsequent floods in Tunisia. Because small impulses need time to amplify into obvious differences in the subsequent state of the atmosphere, it is probably as reasonable to link the Rapid City flood to seeding somewhere else in the western United States several days earlier as to the 9 June seeding at the eastern edge of the Black Hills. One could make a case for canceling any cloud-seeding mission anywhere on the grounds that it might cause harmful weather somewhere else several days later. I am not proposing this seriously, because carrying the same line of reasoning to its ultimate conclusion would shut down not just cloud seeding, but nearly all petrochemical plants, airline flights, and farming around the world.

9. FORECASTING FLASH FLOODS

The theory of chaos allows us to reframe the question of whether or not cloud seeding on 9 June caused the flood as follows: "Was the flood 'locked in' before the cloud seeding flights took place, or did the seeding somehow provide the final impetus?" Putting the question this way shows how closely it is tied to the problem of flash flood forecasting, which is also related to the allegation that the 9 June cloud seeders acted in a careless and reckless manner.

The shut-down procedures for Cloud Catcher were handled as an administrative matter and were not incorporated in the work plans. There had been days when experiments were suspended because of wet conditions in the Black Hills. On 9 June, as usual, a qualified meteorologist stayed on duty in the forecast office on the School of Mines campus to monitor teletype traffic and notify the operations director at the radar site of any warnings or unusual hourly observations that might indicate a problem.

During a visit to the radar site in the afternoon, I raised with the operations director the possibility of cancelling the second seeding mission because of a forecast of possible heavy rain in the Black Hills during the night. As no flood watches or warnings had appeared, we opted merely to do no seeding over the Black Hills. However, the unexpectedly rapid movement of the second test case carried it into the Hills anyway. Lawyers on the defense team told me later that we would have been on firmer legal ground if the issue had never come up. A complete lack of precautions against an unforeseen "act of God" is less of a legal embarrassment than inadequate measures against a dimly perceived hazard.

Radar data from the second Cloud Catcher case of 9 June were among the first pieces of information that alerted the local NWS forecasters to unusually vigorous convective activity near the eastern edge of the Black Hills. If the hourly data collected by the IAS pilot balloon network had been reduced in real time by the operators, as could be done today on hand-held computers, another hour or so of lead time might have been made available.

Progress in flash-flood forecasting since 1972 has been slow. The flood warnings for the Big Thompson flood of 1976 were less timely than those for the Rapid City flood. According to the *Denver Post* of December 3, 1990, a flash flood in Shadyside, Ohio, in June of that year killed 26 people without any warning ever being issued.

Improved flash-flood warnings appear to depend on three-dimensional, mesoscale numerical models, which are being developed at several institutions, with new atmospheric sounding systems to provide the input. The U. S. Weather Research Program plans to put mesoscale modeling on an operational basis before the year 2000 to improve local and regional weather forecasts (Dutton, 1992). Hjelmfelt and Farley (1992) have adapted a mesoscale model to the Black Hills topography. Eventually, it may be possible to run the model using data from the morning of 9 June to estimate initial conditions. If major storms develop in the model over a range of initial conditions approximating that fateful morning, the model results would be solid evidence that the flood-producing storm was not due to the cloud seeding flights conducted during the afternoon. More importantly, such an outcome would justify hope that the next major flood in the Black Hills will be identified before the rain starts to fall.

10. IMPACTS ON SUBSEQUENT CLOUD SEEDING PROJECTS

Davis (1988) has pointed out that the Rapid City flood had an inhibiting effect on subsequent weather modification projects. The work plans for most current projects have objective shutdown criteria designed to avoid even the appearance of contributing to floods, avalanches, or other weather-related disasters. Because of forecast uncertainties, persons setting the criteria are caught in a dilemma, as they try to balance safety requirements against the need to maximize economic benefits.

Although local residents were very understanding in their contacts with IAS personnel in the weeks following the flood, the flood eroded their support for weather modification experiments and operations in South Dakota (Farhar, 1974). Attempts in the late 1980's to kindle interest in a program to increase snowpack in the Black Hills stirred up latent opposition, some of which could be traced back to the flood. On the national level, confidence in the ability of cloud seeders to modify weather in an intelligent, predictable fashion was destroyed by the extreme range of reactions within the scientific community to suggestions that cloud seeding had contributed to the deluge.

The Rapid City flood suit had a chilling effect on United States Government agencies sponsoring cloud seeding research. Until 1974, the Government apparently assumed that it could not be held responsible for the negligence of its contractors. That is what the Federal Tort Claims Act says. The fact that the Rapid City flood suit was filed against the United States and not the School of Mines, which was the contractor, raised the possibility that the independent-contractor defense might be breached. As noted earlier, the suit alleged that Reclamation employees were negligent in that they failed to supervise properly the contractor's operations.

The IAS finished its 1972 field projects, but after that year it never seeded another cloud under Reclamation sponsorship. It is true that Reclamation's entire atmospheric research program was cut back in 1973 as the Nixon administration sought to reverse its free-spending policies of the 1972 election year, but the elimination of the IAS field projects fitted in with a change towards closer Reclamation control of field experiments. The next major Reclamation study of convective clouds, the High Plains Cooperative Program (HIPLEX), began with data collection in Montana, Kansas, and Texas. HIPLEX-1, a randomized cloud seeding experiment, was operated in southeastern Montana in 1979 and 1980. According to some Reclamation employees, the decision to seed clouds there rather than in western Kansas was due in part to the greater likelihood of severe weather, especially tornados, in Kansas. The IAS participated in the evolving design and evaluation of HIPLEX-1 (Smith *et al.,* 1984), but only after the site had been selected. The operations director was a Reclamation employee.

HIPLEX-1 was a back-to-basics experiment on the initiation of precipitation in small to medium-sized cumulus clouds by dropping dry ice (solid carbon dioxide) into their tops. It mimicked the technique used by Schaefer in 1946 in the first successful cloud seeding flight in the United States. The HIPLEX-1 results confirmed statistically that dry ice initiates ice-phase precipitation in supercooled cumulus clouds (Mielke *et al.,* 1984) and refined our knowledge of the growth rates and crystal habits of solid precipitation particles in cumulus clouds (Cooper and Lawson, 1984). However, none of the clouds treated were big enough to produce more than sprinkles at the ground. Considering the economic irrelevance of HIPLEX-1 and the risks attendant on the modification of large convective clouds, it is understandable that the U. S. Government's largest effort at convective cloud modification so far in the 1990's has been its contribution through its Agency for International Development to the national weather modification program of Thailand.

11. CONCLUSIONS

The Rapid City flood of 1972 revealed the inability of weather forecasters to predict major flash floods and dealt a crippling blow to weather modification research programs dealing with convective clouds capable of producing heavy rain. The issues raised by it remain unresolved. Resumption of experiments dealing with large convective clouds over hilly terrain appears unwise pending the development of more advanced methods for flash-flood forecasting. Future programs likely will be preceded by stringent benefit-risk analyses and environmental assessments, and will have to incorporate more sophisticated shutdown procedures than the inadequate ones used in Project Cloud Catcher.

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