CALIFORNIA CLOUD SEEDING AND IDAHO PRECIPITATION

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Abstract. Long-standing concerns over the effects of cloud seeding projects in California generated this review article. The ability to determine the downwind (or extended area) effect of cloud seeding is limited. Court cases have been inconclusive because it is currently impossible to demonstrate cause and effect due to cloud seeding. The idea that successful seeding results in less precipitation downwind seems logical at first glance, but is not supported by theory, the characteristics of atmospheric water, the physics of cloud dynamics and the precipitation process, the efficacy of the seeding agents, or the limited data available. Generally, the extended area effects of seeding are the same as the effects in the target area, and the maximum extent documented for a downwind effect is 180 miles. Southern Idaho is more than 400 miles from the target areas of California cloud seeding projects. In addition, the most common situation when seeding winter orographic clouds as practiced in California, is an increase in precipitation due to the seeding agent being carried beyond the target area. The available information does not seem to support the proposition that cloud seeding in California affects precipitation in Idaho; downwind precipitation could tend to increase rather than decrease. Because of the lack of definitive information, the subject is still open to debate.

1. INTRODUCTION

In February 1994, state Senator John Peavey of Idaho requested that the Idaho Forest, Wildlife, and Range Policy Analysis Group (PAG) consider a study based on his proposition that cloud seeding projects in California might be reducing precipitation in southern Idaho. The Senator's concerns focused on what are generally called the downwind, extra-area, or extended area effects of cloud seeding, and can be characterized by the "robbing Peter to pay Paul" analogy (National Academy of Sciences, 1966, 1973; Dennis, 1980).

Senator Peavey suggested that precipitation might have declined recently because of the influence of California cloud seeding projects when compared to preceding years. Preliminary data analysis (Table 1) indicated that precipitation has increased in southern Idaho since 1970 ($t=2.20$, $P=0.03$ for annual totals). However, these data were not sufficient to address the subject and we subsequently prepared this report based on the published literature (see 9. REFERENCES) and expert opinion (see 8. ACKNOWLEDGE-MENTS).

2. BRIEF HISTORY OF CLOUD SEEDING

The first cloud seeding experiment in the United States was conducted in 1946 in Massachusetts. Dry ice was dropped from an aircraft, producing snow that evaporated before it hit the ground (Dennis, 1980). Scientists soon determined that the most efficient and cost-effective seeding agent was silver iodide (Vonnegut, 1947).

Numerous cloud seeding operations were subsequently undertaken, and practical applications outpaced scientific inquiry (U.S. Senate, 1978; Dennis, 1980). Meteorologists attempted to extract useful information from these projects, with results that were sometimes contradictory and generally inconclusive. The efficacy of cloud seeding was open to debate. However, these projects were useful in identifying the research problems and scientists were able to design and conduct seeding experiments to generate more reliable information (Schickedanz and Huff, 1971; National Academy of Sciences, 1973; Dennis, 1980). Most cloud seeding research occurred from 1950 to the late 1970s. Relatively little information on this subject has been published since 1980 (but see Grant et al., 1992) and all research by the Bureau of Reclamation has been eliminated in 1994 (J. Golden, pers.

Table 1. Mean (standard error) precipitation in inches, from five weather stations* in southern Idaho for pre- and post-1970, summarized by annual total, summer (May-October), and winter (November-April)†.

	1917-1969	1970-1991	t-test
Annual total	17.4 (2.7)	19.5 (2.9)	t=2.20, P=0.02
May-October	3.1 (0.8)	3.2 (0.6)	t=0.38, P=0.70
November-April	12.7 (2.1)	13.8 (2.4)	t=1.52, P=0.12

* Located at Cambridge, Emmett, Idaho City, Island Park, and Pocatello, Idaho.
† Most cloud seeding operations in California occur during this period.

comm.). Knowledge of downwind dynamics is incomplete because cloud seeding projects do not have the budget, inclination, or time to explore the research aspects of cloud-seeding science (J. James, pers. comm.). There are currently six state-based cooperative research programs overseen by the National Oceanic and Atmospheric Administration (Golden, 1994).

3. GENERAL RESEARCH FINDINGS

The following six generalizations were derived from analysis of the published research.

3.1 Cloud Seeding Effectiveness

Cloud seeding may be effective in attaining several goals, including:

- increasing precipitation,
- hail suppression,
- fog dissipation, and
- reducing storm intensity. (National Academy of Sciences 1966, 1973; Dennis, 1980).

However, there is a relatively narrow set of conditions in which seeding will result in the desired effect (Elliot, 1986).

3.2 Conflicting Research Results

Early research produced conflicting results, indicating precipitation increases, decreases, or no effect due to cloud seeding (National Academy of Sciences, 1966, 1973; Dennis, 1980).

3.3 Research Difficulties

Proof of the influence of cloud seeding was difficult to obtain for several reasons:

- the large amount of natural variation in storm systems,
- logistical and technological difficulties in data collection,
- the difficulty of designating and sampling control and treatment clouds (areas) and replicating the experiments, and
- the lack of a theoretical base describing the physical processes of seeding (Ludlam, 1955; American Meteorological Society, 1967).

The lack of theory and supporting observations impeded the identification of optimum cloud conditions and seeding applications (Rangno, 1986; Reynolds, 1988). Computer modeling was suggested as necessary for any meaningful advancement (RAND Corp., 1969).

3.4 Knowledge for Efficiency Improvement

The efficiency and effectiveness of cloud seeding has been improved by increased understanding of:

- complex cloud dynamics (Hobbs, 1975),
- the precipitation process (Marwitz, 1987), and
- technological advancements in the application of seeding agents, techniques, and measuring instrumentation (Super, 1989).

3.5 Effectiveness

Shallow, winter orographic (mountain) clouds were the best candidates for seeding, resulting in 10% to 20% increases in precipitation under favorable conditions (American Meteorological Society, 1992). The seeding of summer convective clouds was less effective and the results less predictable (Dennis, 1980; Silverman, 1986; Orville, 1986). Thus, a majority of cloud seeding projects in California as well as the other western states have focused on increasing mountain snowpacks or winter rains.

3.6 Downwind Effects

Downwind (or extended-area, or extra-area) effects of cloud seeding from research findings were weak, contradictory, and inconclusive:

- relatively little information was available,
- most observations were anecdotal, and
- most data collection was opportunistic rather than planned, resulting in inadequate sampling (National Academy of Sciences, 1966, 1973; Dennis, 1980).

4. CALIFORNIA CLOUD SEEDING TRENDS

Much of the available information about cloud seeding has resulted from applied research projects conducted in California (National Academy of Sciences, 1973; U.S. Senate, 1978; Reynolds and Dennis, 1986). However, record keeping associated with activities in California has been sporadic (M. Roos, pers. comm., Figure 1). In general, many projects were conducted in the 1950s, with the number of projects peaking in the mid- to late-1950s. In the 1960s, an average of 7 or 8 projects per year were conducted. This activity doubled in the 1970s. The number of projects declined during the 1980s. Over the past twenty years, the number of cloud seeding projects in California has been roughly ten to twenty per year, with more projects conducted in drought years (M. Roos, pers. comm.). Trends for California are similar ($r>0.70$, Figure 1) to those for the entire United States (Davis, 1991).

The California projects occurred primarily in the central and southern portions of the state. Target areas for seeding winter orographic clouds were in the coastal ranges or Sierra Nevada mountains. Some electric utility companies have maintained three or four consistent, long-term cloud seeding projects for about 30 years to augment mountain snowpack, increase subsequent runoff, and generate more electricity (M. Roos, pers. comm.).

5. EVIDENCE FOR EXTENDED AREA EFFECTS

Unwanted and unanticipated effects from cloud seeding have been a cause of concern since such activities began in the 1940s (National Academy of Sciences 1966, 1973; American Meteorological Society, 1967; Dennis, 1980). However, not very much definitive information is available on this subject. For example, a panel convened by the National Academy of Sciences noted some statistical evidence indicating that cloud seeding may have influenced precipitation 60-120 miles downwind. The panel said, "There is a pressing need for further analyses of the areal extent of seeding effects" (National Academy of Sciences, 1973, p. 8). Nearly 20 years later, the American Meteorological Society said "There are indications that precipitation changes, either increases or decreases, can also occur at some distance beyond intended target areas. Improved quantification of these extended (extra-area) effects is needed" (American Meteorological Society, 1992, p. 334).

In 1978 the U.S. Senate Committee on Commerce, Science, and Transportation held hearings on proposed legislation dealing with weather modification. Extended area effects were defined as unplanned changes to weather phenomena that occur outside a target area due to activities intended to modify the weather in the target area. In addition, a distinction was made between extended area and extended time effects. As part of the hearings, and in the hearings report, all the available information on extended area/time effects from seeding projects was compiled (see U.S. Senate, 1978). The two main conclusions, based on that data, were:

- the best evidence of an extended area/time effect was from projects that seeded winter orographic clouds, and
- the most common effect was an increase in precipitation of 10% to 50%, which could occur over an area of several hundred square miles.

Very few of the studies cited in the U.S. Senate (1978) committee report provided strong evidence. In general, most of the conclusions about extended area effects from those studies were merely suggestive and speculative. The only study the committee report identified as having good evidence was from a California project based in Santa Barbara. These data indicated an extended time effect, i.e., the seeding agent did not act as fast as anticipated. Using ratios of seeded and unseeded cloud bands, it was estimated that this experiment

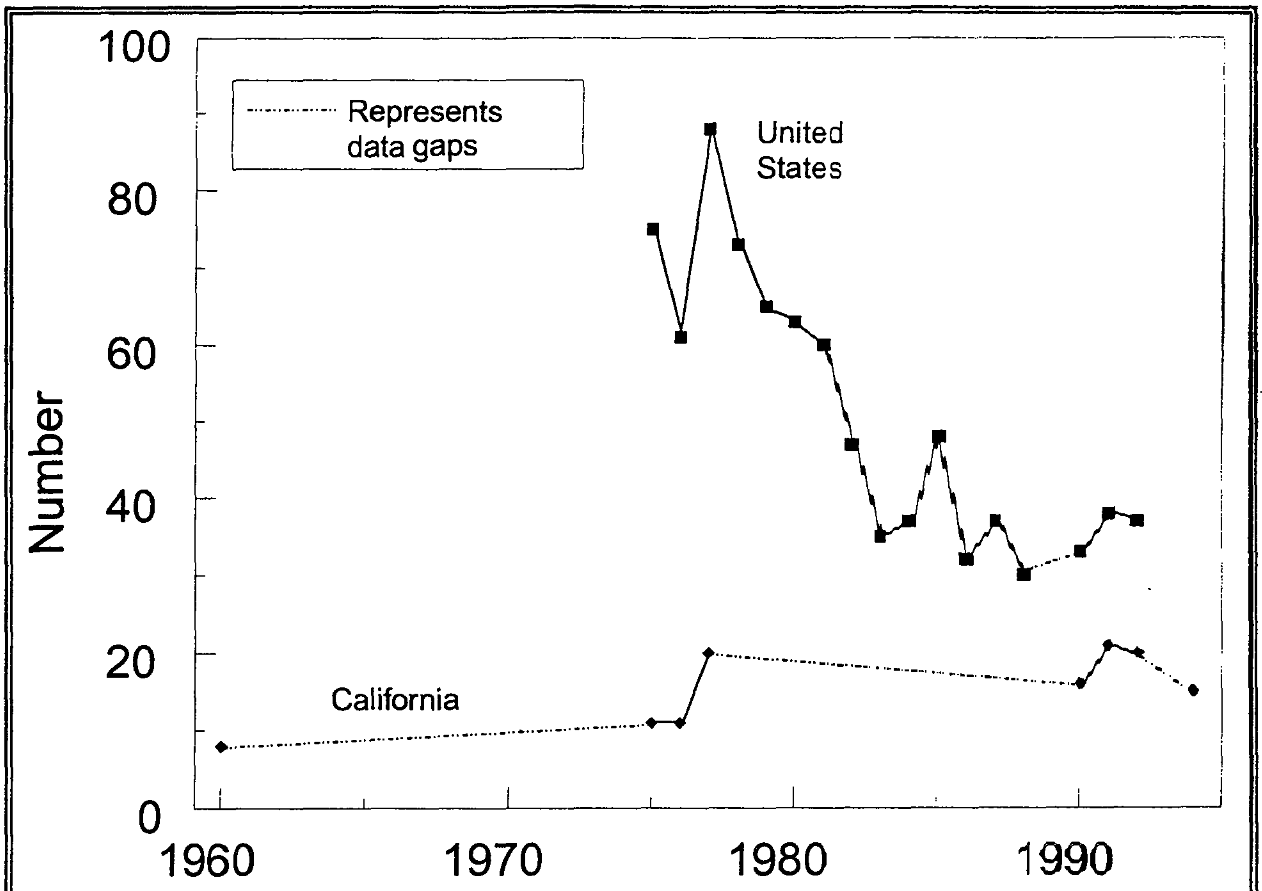

Figure 1. Trends in the number of cloud seeding projects in California and the United States.

Sources: Bennett, 1989; Blackmore, 1991, 1992, 1994; U.S. Senate, 1978; M. Roos, pers. comm.

resulted in as much as a 50% increase in precipitation across an area of 1800 sq uare miles. However, there was no indication of the extent of the effect in a downwind direction

In one of the most statistically rigorous studies conducted, Grant *et al.* (1992) documented significant increases ($p<0.05$) in snowpack and precipitation in target areas of Utah and Wyoming. They also sampled a number of extra-area sites and found small, but insignificant increases in precipitation in those areas associated with the cloud seeding projects.

Can precipitation increases in the target area due to seeding result in precipitation decreases downwind? The U.S. Senate (1978) committee report concluded that of all the extended time/area scenarios proposed, the data provide the least support to this hypothesis. The "robbing Peter to pay Paul" analogy did not seem to hold. This analogy describes the underlying reason why we were asked to prepare this report, and based on available data in the literature, we conclude that it is not likely that cloud seeding in California has any negative effect on precipitation in Idaho due to this scenario. The distance is too great, as results from several studies indicate.

Another potential scenario is that overseeding of clouds in California resulted in decreased precipitation downwind. Two Arizona experiments provide some of the best evidence of extended area effects due to cloud seeding. Neyman and Osborn (1971), and Neyman et al. (1973), documented an apparent 40-45% decrease in rainfall 65-180 miles downwind of the target area in Arizona. However, these results were confounded by a 173% increase in rain at one station (Neyman et al., 1973), and also by decreases in precipitation in the target areas. These experiments were conducted on summer convective cloud systems, for which cloud seeding is less predictable (National Academy of Sciences, 1973; Dennis, 1980). Neyman et al. (1973) suggested that overseeding may have produced the results they documented. Overseeding results in the available water being retained in a cloud because too many ice crystals are created and the production of precipitation impeded (Dennis, 1980). Overseeding is deliberately, but rarely, conducted to suppress hail and reduce storm intensity (Dennis, 1980). However, this is not applicable to the California projects because they are seeding winter storms with the goal of increasing precipitation.

In a more recent paper, Deshler and Reynolds (1990) tracked the persistence of ice crystals formed by seeding a winter orographic cloud over the central Sierra Nevada mountains. Such ice particles were detected as late as 90 minutes after seeding, by which time the storm system had traveled about 60 miles. The authors suggested that these observations lent credence to the idea of extra-area or downwind effects from seeding with silver iodide, which had been postulated by Brown et al. (1978).

5.1 Summary

The best available scientific information on the downwind effects of seeding winter orographic clouds, as practiced in California, is an increase in precipitation up to 180 miles from the target area (National Academy of Sciences, 1973; Thomas, 1977; Dennis, 1980; Grant et al., 1992). This may be the result of the silver iodide not being applied at the right time, in the necessary concentration, or to the appropriate part of the cloud. Thus, the seeding agent may not be activated until carried downwind where it may encounter the proper precipitation-inducing combinations of temperature and moisture.

It is approximately 130 miles from the northeastern corner of California to the southwestern corner of Idaho. However, most cloud seeding projects in California have targeted the coastal mountains or the Sierra Nevadas, adding many additional miles. In general, the projects have occurred in central and southern California. It is about 410 miles from the crest of the Sierra Nevada range east of Santa Barbara to Boise, Idaho.

At least four distance-related reasons explain why California cloud seeding may not have any effect on Idaho precipitation. First, it would be unlikely that the seeding agent would persist in a great enough concentration to have an effect for that distance. Dennis (1980, p. 94) suggested that the active life of silver iodide was only several hours, and only then if released at night because the agent is deactivated by sunlight. This would limit the possibility that overseeding in California could tie up precipitation otherwise destined to fall in Idaho. In addition, any increases in precipitation would be realized before the storm reached Idaho. However, if seeding in California causes rain there or somewhere else on the way to Idaho, then that amount of moisture has obviously been lost from the atmosphere. The question is for how long and how far, and how might that affect an area several hundred miles away. The other three reasons that follow reveal the "robbing Peter to pay Paul" analogy to be unrealistic, too.

The second distance-related explanation is that storm systems and the atmosphere are complex entities. The idea that the total amount of water in the atmosphere is fixed and that artificial precipitation upwind results in less precipitation downwind is a gross simplification that confuses total water in the atmosphere with potential losses from precipitation events (Dennis, 1980, p. 171). Cloud dynamics and precipitation processes are complex-phenomena and conditions in a cloud necessary for precipitation vary throughout the life of a cloud. Only a small fraction of the water in the atmosphere exists as clouds at any one time. Individual clouds can form, precipitate, and dissipate in less than an hour. In addition, the precipitation process is inefficient, leaving most of the water retained in the atmosphere (Dennis, 1980, p. 171). Even after seeding in California, storms headed for Idaho are constantly gaining and losing atmospheric water as well as the conditions necessary for precipitation to occur. Professor Molnau (pers. comm.) suggested there is little connection between Idaho and California precipitation, because the distance was just too great. Furthermore, Professor Jensen (pers. comm.) noted that the atmosphere does not function as if it were an irrigation canal. Unlike diverting upstream water, diverting water upwind is not a realistic proposition.

Third, modification of individual clouds in large storm systems with interstate movements is unlikely to have the large effects hypothesized for southern Idaho. The largest area effect from cloud seeding, estimated with relatively reliable data, was 3,600 square miles

(U.S. Senate, 1978, p. 126). By comparison, the Snake River Plain of southern Idaho is about 40,000 square miles. Additionally, recent droughts in Idaho were not localized events. They occurred statewide and are associated with weather patterns affecting most of the western United States. The overriding effect of regional weather patterns is illustrated by the data presented in Table 1 and Figure 1. These data trends for southern Idaho are the same as those for most of the western United States (M. Molnau, pers. comm.).

Fourth, precipitation increases from cloud seeding are typically small (10-20%) even under the most favorable conditions (Dennis, 1980), but have been reported to be as high as 50% (U.S. Senate, 1978). Precipitation in southern Idaho is highly variable from year to year, so much so that in order to reveal trends, the data must be "smoothed" to reduce the variability, as we have done in Figure 2. These data also indicate increases in precipitation in both north and south Idaho since 1970 and agree with the analysis presented in Table 1. In general, the natural variation in precipitation is about 10 times as great as the effects of seeding (Dennis, 1980). Detecting such a small effect is not possible without well designed sampling of seeded treatment areas, and control areas with no seeding. It is not quite like looking for a needle in a haystack, but "the search for seeding effects is a search for a weak signal in the presence of random noise" (Dennis, 1980, p. 136).

6. LEGAL QUESTIONS

At least three legal questions are associated with the possible extended area effects of cloud seeding (Pierce, 1967; Howe, 1971; Jones, 1991): 1) Who owns or has rights to atmospheric water? 2) Can potential downwind users be harmed from activities upwind? 3) If so, who is liable for damages?

The first question is difficult to answer. There are at least six legal theories under which rights to water in the clouds could be determined (Pierce, 1967; Corbridge and Moses, 1968). However, none appear adequate (Jones, 1991). After reviewing 22 cases from both state and federal courts, Britton and Ford (1994) concluded that current trends in legal interpretations suggested that rights to atmospheric water were most applicable to those that owned the land directly below the clouds.

The American Society of Civil Engineers is attempting to develop a generic, state-based water rights code that deals with the hydrologic cycle as a whole, including the ramifications of cloud seeding (Davis, 1994). Under this proposed code, cloud seeders or their sponsors would apparently be able to apply for a water right based on the results of their seeding activities once the water entered a stream. Those conducting the project would be obligated to quantify the amount and timing of the claimed water right. In other words, no right to water in the clouds would be available until it is "captured" through seeding and reliably quantified. This is similar to western riparian water law under the provision of prior appropriations for a beneficial use (Davis, 1994).

As noted from the available scientific evidence, reliably and accurately quantifying increased precipitation due to seeding would be a difficult and expensive undertaking. Many legal scholars noted that the inability to quantify precipitation from seeding projects was a major stumbling block in the process of determining rights and liability (Pierce, 1967; Corbridge and Moses, 1968; Howe, 1971; Jones 1991). The American Society of Civil Engineers appears to be making assumptions about the efficacy, precision, and measuring of cloud seeding effects (Davis, 1994, p. 321) that are questionable, given the results of research as reviewed herein. In addition, the problems of quantifying precipitation due to seeding will likely preclude a cloud seeding "free-for-all" that one might envision under the model legislation proposed by the American Society of Civil Engineers.

Based on the current state of knowledge and the scientific evidence already presented herein, the answer to the second question would be a conditional no, depending on the distances involved. In addition, Davis (1994) noted that because plaintiffs were not able to conclusively prove any cause and effect relationship, no court had ever awarded payment of damages by the sponsors or operators of cloud seeding projects to those with claims against them.

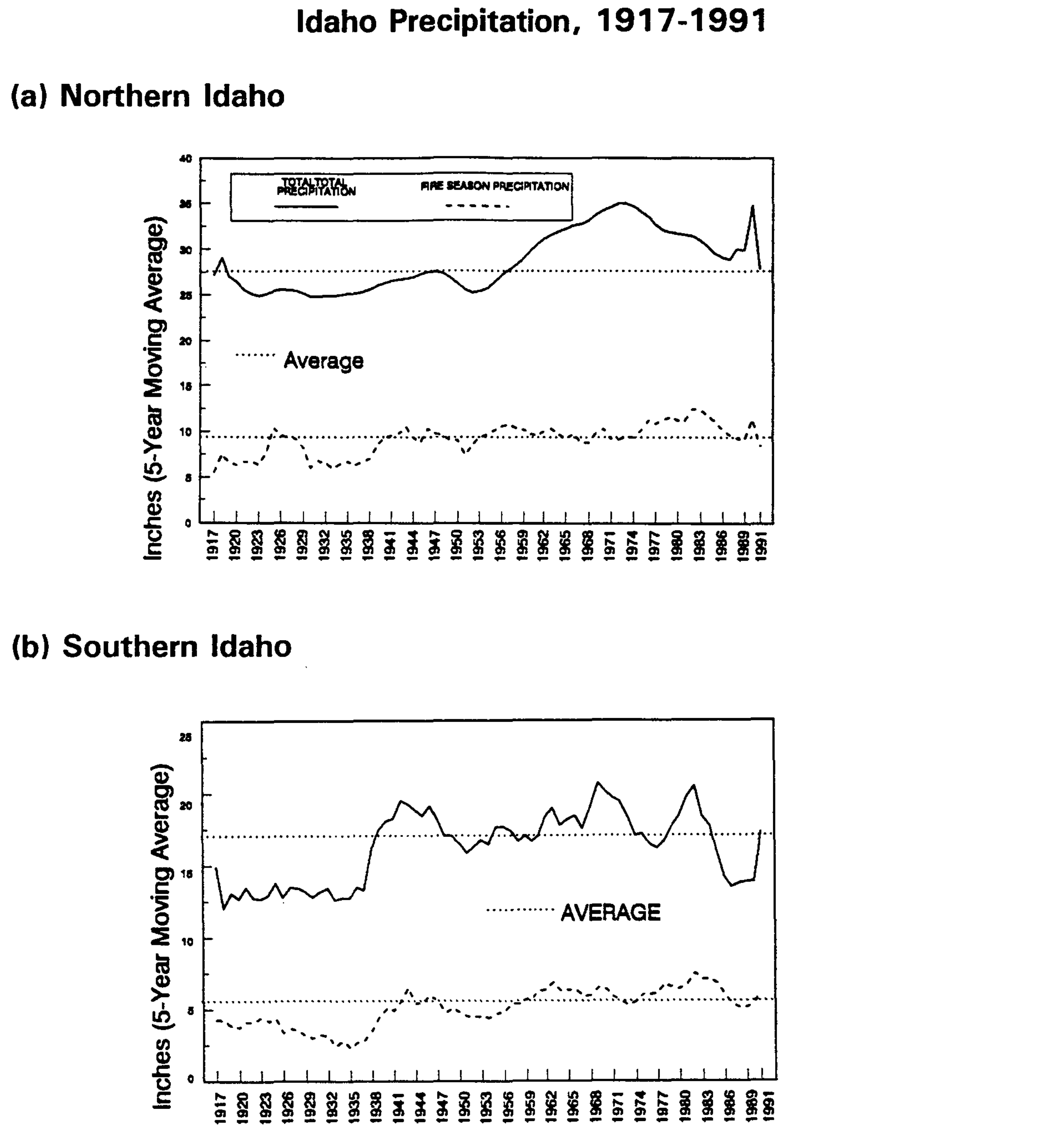

Figure 2. Idaho precipitation trends, 1917-1991; smoothed and averaged from (a) 10 weather stations in northern Idaho and (b) 11 weather stations in southern Idaho.

Source: O'Laughlin, et al., 1993.

The third question on liability from cloud seeding operations is based on a number of legal theories (Pierce, 1967; Jones, 1991). However, to evaluate if a downwind entity had been harmed due to upwind seeding projects requires a determination of a right to atmospheric water and proof of harm as described above. Again, the current inability to reliably measure the effects of cloud seeding is a major problem. Proving that upwind seeding activities resulted in a loss of precipitation downwind is the most difficult scenario to accomplish and, as the data indicate, the least likely to occur (U.S. Senate, 1978).

Cases where increased precipitation due to seeding caused flooding or other damage would most likely be the area of legal action (Pierce, 1967). Six of eight cases reviewed by Jones (1991) concerned complaints of damages due to flooding as a result of cloud seeding. In such cases, the legal doctrine of nuisance may be most applicable to liability judgements (Howe, 1971).

In two of the eight cases examined by Jones (1991), the plaintiffs alleged a loss of precipitation. The court decisions in those two cases contradicted each other. However, it is noteworthy that in one case (Southwest Weather Research, Inc., vs. Duncan, 9 S.W. 2d 940 [Tex. Cir. App. 1958]), an injunction was issued to temporarily suspend cloud seeding operations, but only over the plaintiffs land (Pierce, 1967, p. 281; Jones, 1991, p. 1169).

A number of other legal questions also lack answers. For example, can atmospheric water rights be sold? If so, what quantity can be sold and how far can it be transferred? Are downwind users guaranteed a quantity of water? Disputes within states could be handled by state law and the available information suggests that most extended-area effects due to cloud seeding would be relatively localized. However, projects operating near state, or international borders may have inter-jurisdictional consequences (Davis, 1991). Solutions to these problems are less clear, but could use interstate compacts for riparian water rights as models, or perhaps cooperative legislation, federal arrangements (Howe, 1971), or the recommendations of the World Meteorological Organization of the United Nations (Davis, 1991).

6.1 Summary

Many observers feel that the science of weather modification is too immature for the creation of any legal norms at local, state, national, or international levels (Davis, 1991). Most legal scholars are not satisfied that existing doctrines or theories can adequately handle the potential legal complexities of weather modification activities. They have suggested that new, innovative approaches are needed (Stark, 1957; Pierce, 1967; Corbridge and Moses, 1968; Howe, 1971), and to date these approaches have not surfaced. Due to the complexity of the issue and the flexibility required to handle case-by-case distinctions, state-based administrative solutions have been adopted (Jones, 1991). By 1971, half the states had passed laws regulating weather modification activities by requiring licenses, permits, and notification of the proper authorities that the project will occur. Although a number of bills have been introduced at the federal level, only one has been passed (Public Law 92-205, 1971) and again, it only requires the reporting of state and private weather modification activities (Davis, 1991).

7. CONCLUSIONS

The subject of cloud seeding raises many questions in both the scientific and legal arenas (Howe, 1971; Thomas, 1977; Dennis, 1980; Jones, 1991). One of the greatest uncertainties involves the extended-area or downwind effects of cloud seeding. Most research efforts and data collection have focused on documenting whether or not cloud seeding is effective, the magnitude of the effects, and determining the physical mechanisms by which it could be more effective (Dennis, 1980; but see Grant et al., 1992).

The downwind effects of seeding clouds, if they do occur, are often the same as the effects in the target area; i.e., if precipitation in the target area increases, precipitation downwind is also likely to increase and vice-versa. Most studies of seeding winter orographic (mountain) clouds as practiced in California have documented precipitation increases due to the seeding agent being carried beyond the target area. The data indicate that 180 miles is probably the maximum extent of the effects of cloud seeding (National Academy of Sciences, 1973; Thomas, 1977; Dennis, 1980; Grant et al., 1992). In addition to the distances of more than 400 miles involved between the California target areas and southern Idaho, there are a number of other reasons not to expect much of an effect. Overseeding of clouds may trap water in the atmosphere, but this has only been documented to occur in summer convective storms. Seeding of summer convective storms does not occur in California.

Although still inexact, the science of cloud seeding has advanced to the point that operators can take steps to effectively avoid unwanted outcomes and it is in their best interest to do so. Seeding produces relatively small increases in precipitation and thus any possible shortfalls downwind will be correspondingly small. In addition, cloud dynamics and the inefficiency of the precipitation process would likely result in the "recharging" of the storm system.

Interest in cloud seeding and practical applications vary from state to state. California still has a few long-term projects being conducted by electric utility companies, with increases in activities during periods of drought. Oregon and Washington have not had any cloud seeding projects since the late 1970s (C. Craig and D. McCheznie, pers. comm.) However, cloud seeding as a means to augment stream flows for the recovery of imperiled salmon is a future possibility (C. Craig, pers. comm.). Indeed, in the Intermountain West there is as much or more activity now than there ever has been, although research activity peaked in the early 1980s. One commercial firm operates several projects in the region and has worked in central America, Taiwan, and the middle east (D. Griffith and E. Thomlinson, pers. comm.).

The legal rights to atmospheric water and the consequences of capturing that water are undecided. Attorneys and policy makers addressing this problem appear to be either assuming a greater degree of efficacy and precision in cloud seeding than currently exists, or are recommending that legal doctrines be deferred until those conditions are realized. Difficulties in proving harm or benefit from cloud seeding projects makes legal questions a moot point at this time.

It does not appear from our review of available research and discussions with experts that cloud seeding in California has any effect, negative or positive, on precipitation in Idaho.

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