A Critical Review of the Australian Experience in Cloud Seeding

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ABSTRACT

From 1947 to 1994 a number of cloud-seeding experiments were done in Australia based on the static cloud-seeding hypothesis. A critical analysis of these successive cloud-seeding experiments, coupled with microphysical observations of the clouds, showed that the static cloud-seeding hypothesis is not effective in enhancing winter rainfall in the plains area of Australia. However, there is evidence to suggest that cloud seeding is effective for limited meteorological conditions in stratiform clouds undergoing orographic uplift. In particular, two successive experiments in Tasmania show strong statistical evidence for rainfall enhancement when cloud-top temperatures are between –10° and –12°C in a southwesterly stream. The evidence for similar effects on the Australian mainland is more controversial. In the summer rainfall regions of northern Australia, the extreme rainfall variability makes it impossible to design a statistical experiment that can to be evaluated in a reasonable time using currently available techniques. Rainfall enhancement in these regions remains inconclusive.

1. Background

In many regions of the world, traditional sources and supplies of surface water, rivers, and dams are either inadequate or under threat from the ever-expanding land use and growing populations. In these regions the possibility of precipitation enhancement is both politically and economically attractive. Therefore, it is not surprising that following the classic experiments of Schaefer (1946) in the United States, which showed that pellets of dry ice could rapidly glaciate a laboratory cloud, the scientific community was excited by the potential for cloud seeding to augment precipitation. These early experiments led to the static cloud-seeding hypothesis that the introduction of an optimum concentration of ice crystals would enhance the precipitation efficiency of a cloud by converting the reservoir of supercooled water droplets into precipitation-sized particles.

As the science of weather modification developed, two new techniques were evolved based on the dynamical cloud-seeding hypothesis and the hydroscopic cloud-seeding hypothesis. The concept behind the dynamical cloud-seeding hypothesis is that the sudden release of the latent heat of fusion when a supercooled cloud is rapidly glaciated through seeding increases the buoyancy of the cloud and this in turn generates a deeper and more vigorous cloud that produces more rain. The hydroscopic cloud-seeding technique is to seed warm-based cumulus clouds with hygroscopic nuclei. The assumption in this technique is that large droplets will form on the seeded giant cloud condensation nuclei, thereby increasing the precipitation efficiency in the updraft of the cumulus cloud. It will be argued that almost all of the cloud-seeding experiments in Australia were based on the static cloud-seeding hypothesis, and therefore the general discussion of cloud-seeding experiments in the paper is confined to those based on this hypothesis. Similarly, this paper does not deal with the many cloud-seeding operations (i.e., the applications of seeding material to clouds without an associated measurement program) that have been conducted in Australia and elsewhere.

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In final form 12 August 1996.

Reynolds (1988) separated cloud-seeding field programs into two types. He defined statistical programs as projects designed to determine increased precipitation within a predefined target area using randomized seeding methods and physical programs as those projects whose main objective is to determine the natural precipitation processes taking place over a region and to understand how these processes might be augmented through seeding.

Over the years both physical and statistical programs have demonstrated that cloud seeding is, at best, successful in comparatively limited circumstances, and controversy still remains even in those regions where cloud seeding is claimed to be successful. There are three comparable series of regional statistical cloud-seeding experiments, predicated on the "static cloud-seeding hypothesis," that attempted to demonstrate scientifically the positive effects of cloud seeding. These are the Climax cloud-seeding experiments in the United States, the Israeli cloud-seeding experiments, and a series of cloud-seeding experiments in Australia.

The Climax I and II randomized cloud-seeding experiments were carried out in the Colorado Rockies over portions of winter seasons from 1960 to 1970 (see, e.g., Grant and Mielke 1967; Mielke et al. 1971; and Chappell et al. 1971). In Israel between 1961 and 1975 two randomized cloud-seeding experiments were carried out (Gagin and Neumann 1974, 1981; Rosenfeld and Farbstein 1992). The Climax experimenters concluded that artificial seeding increased precipitation significantly when the 700-hPa winds were from the southwest and when the 500-hPa temperatures were higher than –20°C. Statistical analyses from the Israel I experiment showed a 15% increase in rainfall and the Israeli II experiment (north target area) showed a 13% increase. The results from the Israeli II experiment (southern target area) showed a rainfall decrease. However, when "desert dust" days were excluded from the sample, there was an increase in rainfall on seeded days. The interpretation of the results of both these "successful" cloud-seeding experiments has been challenged by Rangno and Hobbs. Rangno and Hobbs (1993) argue that the cloud seeding had no effect in the Climax experiments and assert that Israeli experiments also failed to establish the efficacy of cloud seeding (Rangno and Hobbs 1995).

There are many examples of physical cloud-seeding programs in the United States. Programs to study winter clouds include the Colorado Orographic Cloud Seeding Experiment (COSE), and the Sierra Cooperative Pilot Project (SCPP) in California (see Reynolds 1988), while the HIPLEX-I program was an example of a program to test the static seeding hypothesis on summertime cumulus clouds (Silverman 1986). Cotton and Pielke (1992) argue that there is evidence that orographic clouds can cause significant increases in snowpack and that this evidence is far more compelling than for the more continental and cold-based orographic clouds. They further contend that currently it is still not possible to produce statistically significant increases in surface precipitation from all supercooled cumuli or orographic clouds. Recent examples of physical experiments outside the United States include the "Al Ghait" program in Morocco (Baddour et al. 1994) and the WMO Precipitation Enhancement Project (PEP) in Spain (Vali et al. 1988). These types of physical studies provide plausibility to any statistical inference that seeding increases precipitation. PEP in Spain is an example of a project that did not proceed to the statistical evaluation stage because of the precipitation potential of the clouds prevailing over the experimental region was found to be small (Vali et al. 1988).

In more recent times, new programs have commenced both in southern Europe [Italy (Del'Angelo et al. 1994) and Greece (Brown and Tomlinson 1994)] and the Middle East [Syria (Abbas and Suzan 1994) and Jordan (Tahboub and Kafawin 1995)]. It is clear that in both of these regions cloud seeding is seen as an important tool for water augmentation. These new initiatives emphasize a need to critically analyze past cloud-seeding experiments so as to avoid similar mistakes being made in the design and analysis of new projects.

Between 1947 and 1994 a number of cloud-seeding experiments were done in Australia (see Table 1 and Fig. 1). Most of these experiments were designed by and conducted in conjunction with the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The aim of this paper is to review the cloud-seeding experiments in Australia as a contribution to the general debate on the efficacy of cloud seeding. The early Australian experiments can be described as "black boxes" whereby the clouds are seeded in some way and the only output analyzed and measured is rainfall on the ground (Cotton 1986). Over time, these experiments evolved into "gray boxes," whereby seeding windows were established based on direct physical observations. The later experiments were all designed to include both a statistical evaluation and a physical understanding of the processes.

TABLE 1. Cloud-seeding experiments in Australia (1947–94).

CSIRO single cloud experiments	(1947–56)
Early CSIRO experiments	(1955–63)
• Snowy Mountains	
• New England	
• Warragamba	
• South Australia	
Seeding by state governments	(1965–71)
Experiments in Tasmania	(1964–94)
• Tasmania I	(1964–71)
• Tasmania II	(1979–83)
• Tasmania III	(1992–94)
CSIRO Emerald experiment	(1972–75)
CSIRO western Victoria experiment	(1979–80)
Western Australian northern wheatbelt cloud study	(1980–82)
Melbourne Water/CSIRO experiment	(1988–92)

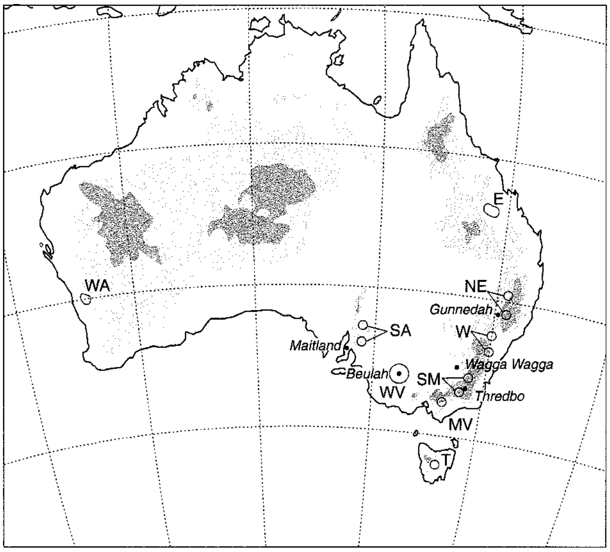

FIG. 1. Location of cloud-seeding experiments in Australia. Emerald experiment (E), New England experiment (NE), Waragamba Dam experiment (W), Snowy Mountains experiment (SM), Melbourne Water experiment (MW), Western Victorian cloud-seeding experiment (WV), South Australian experiment (SA), Western Australian northern wheatbelt cloud study (WA), and Tasmania (T). Also shown are the towns of Gunnedah, (NSW), Wagga Wagga (NSW), Thredbo (NSW), Beulah (Vic), and Maitland (SA). The light shading shows orography greater than 250 m and the dark shading orography greater than 500 m.

2. Historical review of past cloud-seeding activities in Australia

a. CSIRO single cloud experiments

Cloud-seeding experiments began in Australia in 1947, shortly after the classic experiments of Schaefer (1946). The first cloud-seeding trials were carried out by Kraus and Squires (1947) near Sydney. In these and subsequent experiments from 1947 to 1952, scientists in the CSIRO Division of Radiophysics used Royal Australian Air Force aircraft (mostly Liberators, Beaufighters, and DC3s) to drop dry ice into the tops of cumulus clouds. Radar observations showed that seeded clouds rapidly developed precipitation and this led to the conclusion that the method worked reliably and initiated rain that would not have occurred otherwise. However, the success of the rainmaking was determined by the temperature of the cloud top. Below −7°C there was a 100% chance that the clouds would produce precipitation, but at temperatures of −15°C and lower, the results lost their significance because of the high probability of naturally occurring rain (Bowen 1952).

Similar trials using silver iodide smoke as the seeding agent were made from 1953 to 1956 in clouds located anywhere from South Australia to Queensland (Smith 1974). Experiments were carried out using both ground-based and airborne silver iodide generators. The use of ground-based generators was abandoned in this period because of concerns that the silver iodide from the generators failing to reach cloud base. Further, the nucleating properties of the silver iodide decayed during daylight hours. Efforts instead focused on the dispersal of silver iodide from burners mounted on an aircraft. Warner and Twomey (1956) analyzed 35 cumulus and layer clouds and concluded that silver iodide was an effective agent in clouds, the upper levels of which had temperatures lower than −5°C. Precipitation was induced within 20–25 min after seeding in cumulus clouds and somewhat later in stratiform clouds. Subsequently, a fully randomized series of trials was undertaken whereby a cumulus cloud was seeded with silver iodide and the subsequent history of the cloud observed. Any rain that fell from the cloud was measured by an impactor mounted on an aircraft. Analysis was made of the rainfall from clouds whose tops were colder than −10°C and where no appreciable rain developed from near by clouds in 30 min. It was concluded that more rain fell from the seeded than from the unseeded clouds at a significance level of 2%. The mean rainfall from seeded clouds exceeded that from unseeded clouds by 2×10^5 m^3, and it was estimated that if this result could be achieved 500 times per year in an area of 1000 km^2 it would represent an increase of 10 cm in annual rainfall. It was on the basis of these results that CSIRO embarked on a program of area experiments (Smith 1967).

b. Early CSIRO area experiments 1955–63

During the period 1955–63 four experiments were carried out in Australia in the locations shown in Fig. 1 (Smith 1974). In these and most other cloud-seeding experiments conducted in Australia, the seeding material was dispensed into the cloud as smoke from burners using a solution of silver iodide and ammonium iodide dissolved in acetone. These experimental regions were the Snowy Mountains in southern New South Wales, South Australia, the New England district of New South Wales, and the Warragamba catchment area west of Sydney. The purpose in each case was to find out if rain over a specified area could be increased by seeding clouds with silver iodide released from aircraft.

In the Snowy Mountains, New England, and South Australian cloud-seeding experiments, the duration for a seeded period was determined by a meteorological criterion and was typically 10–15 days; in the Warragamba area it was 1 day. Two areas in the Snowy Mountains experiment were used: one as target and one as control, and during any one period a random process determined whether clouds over the target area should or should not be seeded. In the other experiments, a crossover design was chosen; that is, a random process was used to determine which area would be target and which area would be the control for each period. In other aspects the experiments were similar. Of these four experiments, only that conducted in the Snowy Mountains produced statistically significant evidence for rainfall increases over the duration of the entire experiment, with a 19% increase significant at the 5% level. South Australia showed a 5% decrease at 70% significance level, New England showed a 4% increase at the 10% significance level, and Warragamba showed a 3% decrease at the 60% significance level. Therefore, it was concluded that, in general, the results were unconvincing and could not justify any definite statement as to whether or not these experiments had increased or decreased the rainfall.

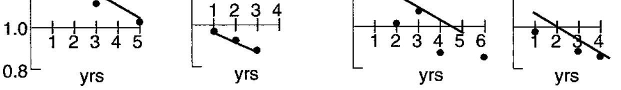

FIG. 2. Variation of rainfall increase factor associated with seeding years in each experiment (from Smith 1974).

The experiments did, however, have one feature in common, namely that all recorded an apparent decrease in results with time. Figure 2 shows a least squares fit to the double ratios from the four experiments as a function of the year of the experiment. The least squares fit suggest that the initial measured increase in rainfall in the Snowy Mountains and New England experiments reduced with time, while the poorer showings of the other projects became steadily worse (Smith 1974). This was puzzling. Bowen (1966) postulated that the apparent decrease in effectiveness of the Australian cloud-seeding operations with time was the result of the persistent and cumulative effects of silver iodide. More recently, Bigg and Turton (1986, 1988) argued that there is indeed evidence of prolonged increases in ice nuclei released from vegetation following the application of silver iodide and it is these secondary ice nuclei generated from the silver iodide that are involved in the persistent effects of seeding. The hypothesis is that increased levels of silver on the ground enhance the multiplication of bacteria, which themselves later act as ice nuclei when ingested into clouds. This suggests that persistent effects associated with silver iodide seeding result in rainfall enhancement that is not detected in the analysis and, more importantly, invalidates statistical treatments that rely on a comparison of the ratio of the target to the control on seeded and unseeded days. The problem with this explanation is that as yet there is no evidence of a physical mechanism to transport the bacteria into the clouds and therefore the hypothesis must be considered speculative.

In summary, these area cloud-seeding experiments showed that cloud seeding was not a simple technique and that it was not fully understood. CSIRO consequently embarked on a new set of area cloud-seeding experiments designed to take into account the apparent deterioration of results with time, and the variability of results with seeding conditions and with rainfall gradients.

c. Seeding by state governments

In the years from 1965 to 1971 state governments in Australia were active in operational cloud seeding and in the continuing debate concerning its effectiveness (McBoyle 1980). In 1964–66 there was extreme drought in Australia, and there was enormous pressure on politicians to support cloud seeding. CSIRO set up "Courses of Instruction" in cloud-seeding techniques, both to inform state government departments and other interested parties as to what cloud seeding had to offer and to train people to undertake cloud-seeding operations. CSIRO acted in an advisory capacity to the states but did not participate in operational cloud seeding.

Operations or investigations of cloud-seeding potential were undertaken in Victoria, New South Wales, Queensland, South Australia, and Western Australia (McBoyle 1980). In all cases where the analysis of the seeding operations was possible, the results were either inconclusive or, worse, controversial. For example, there was considerable debate over the interpretation of the results from a seeding project in the Wimmera–Mallee region of Victoria carried out in 1966. O'Mahony (1967) argued that (a) the rankings of the rainfall in the target and control areas were not significantly different from one another; (b) in the ranking of the ratios of target to control rainfall, the ratio for the seeded period was found to occur at the middle point of the 42-yr sample; and (c) the extent of the departure from normality of the target/control ratio for 1966 was not significant. Adderly (1968) replied on behalf of the CSIRO claiming that O'Mahony applied his tests to data not truly representative of the area over which the seeding operation was carried out. The debate between O'Mahony and Adderly continued for some time. As pointed out by McBoyle, this debate did not increase the credibility of rainmaking in the scientific community.

d. Experiments in Tasmania

1) TASMANIA I 1964–71

The design of the first Tasmanian cloud-seeding experiment attempted to address the problems raised by the results of the early area experiments (Smith 1974). The location of the experiment is illustrated in Fig. 3. The target was a Hydro-Electricity Commission (HEC) catchment area located on the Central Plateau; three designated control areas were unseeded on occasions when the target area was seeded. This made it possible to allow for the effect of rainfall gradients in all directions. The time was divided into pairs of periods of about 12-day duration; clouds were seeded during half of the periods selected on a random basis. The seeding schedule was carried out in alternate years only. During the intervening years no seeding was done but rainfall measurements were continued.

The experiment was carried out in alternate years until 1971 and the results suggested that rainfall increases as high as 30% were achieved in autumn at a significance level of 3%. For the other seasons, the results were not nearly so conclusive, but the results for autumn and winter were sufficiently encouraging for the HEC to carry out further experiments to test the possibility of using cloud seeding as a water resources management tool. The HEC adopted the practice, from 1972 onward, of examining the dam levels in the major catchment areas and deciding, in the light of expected water requirements, whether or not to implement cloud seeding in the following fall. The rationale for the strategy adopted by the HEC was that hydropower has a high benefit/cost ratio compared to the oil-powered generators that are used when water supplies are low.

2) TASMANIA II 1979–83

Tasmania II was conducted by the Tasmanian HEC in the months of April to September from 1979 to 1983. The experiment was analyzed by CSIRO (Shaw et al. 1984). The aims of the experiment were to increase the inflow into the storage lakes, to demonstrate that any increase in rainfall had not occurred by

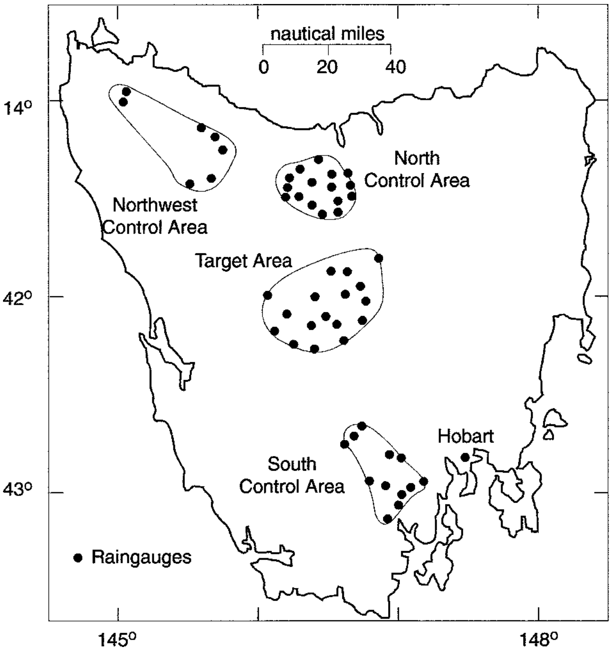

FIG. 3. Experimental areas in Tasmania (from Smith 1974).

chance, and to check whether areas downwind of the target area were affected. The seeding period was based on the concept of a "suitable seeding day," which was defined before the experiment, and a randomization scheme based on an overall seed/no seed ratio of 2:1. The suitable day was defined for both stratiform and cumulus cloud conditions and was determined by aircraft measurements and flight-crew observations made a predetermined distance upstream of the target area. The distance corresponded to 1-h wind drift for stratiform clouds and 30-min wind drift for cumulus clouds.

A stratiform cloud suitable day was declared under the following conditions:

- cloud top −5°C or colder;
- depth 1/3 terrain clearance of base;
- supercooled water at the seeding level (a few hundred meters below cloud top or at −15°C level if the cloud extended above that height) was > 0.1 g m^{-3}, failing that, 2 mm of ice accreted in 5 min on an icing rod of 2-mm diameter;
- the horizontal extent of the clouds was such that, in the crew's opinion, they were likely to be seedable for half-an-hour or more; and
- wind at the seeding level was < 130 km h^{-1}.

A cumulus cloud suitable day was declared under the following conditions:

- cloud top colder than −12°C;
- depth was greater than height of base;
- supercooled water at the −10°C level was > 0.5 g m^{-3}; alternatively, 1 mm of ice accreted on an icing rod 2 mm in diameter during one pass.
- diameter at freezing level was > 2 km;
- bases were firm and flat, with tops extending vertically above them; and
- wind speed at cloud base was < 100 km h^{-1}.

Over the 5-yr experiment there were 89 suitable days and of these the first 12 were excluded from the analysis because of misapplication of the rules of the randomization scheme, 6 were removed because they were declared cumulus days, and 4 were excluded because of excessive wind, leaving a sample of 66 days. The analyzed experiment showed that rainfall increased following seeding and that these increases were associated with stratiform cloud in southwesterly air streams. In Tasmania II there was a 37% increase in rainfall on suitable days. The total calculated increases in rainfall were about one-half those calculated from the previous seeding experiment, but were accomplished using one-tenth of the seeding time. Tasmania II represent a shift from a black box experiment to a gray box experiment where physical criteria were used to define a seeding window.

The authors found no convincing evidence of effects of seeding downwind of the target area. However, they note that this may have been because the analyses were not sufficiently sensitive to detect any such effects (Shaw et al. 1984).

3) TASMANIA III 1992–94

The design of the Tasmania III experiment was similar to that of Tasmania II, the main difference being that the seeding agent was dry ice and not silver iodide. The 3-yr experiment (1992–94) conducted and analyzed by the Tasmanian HEC was run from May to October. The meteorological and flight data are currently being prepared for detailed statistical analysis. In addition to the Tasmania III cloud-seeding experiment, drought-relief projects were undertaken over the Central Plateau catchments from 1988 to 1991 and over the east coast and midlands of Tasmania in 1994. The drought-relief operations were not randomized and so any evaluation of these activities was confined to historical analyses.

e. CSIRO Emerald experiment 1972–75

Studies of large cumulus clouds were made in the area around Emerald, Queensland, from 1972 to 1975. The clouds were considered to be suitable for seeding in a region where the increased rainfall would have been valuable for irrigation and mining. In a series of experiments, isolated cumulus clouds were seeded using both silver iodide and dry ice. When dry ice was used, the seeding produced an almost immediate conversion of the cloud tops from water to ice, and precipitation echoes were observed on the 3-cm aircraft radar. The same effect was not observed when silver iodide was the seeding agent. However, the problem of detecting extra rain on the ground was complicated by the extreme spatial and temporal variability of the rainfall in the area studied. Intense, widely separated showers fell from the isolated cumulus clouds or cloud masses, making it difficult to measure the mean area rainfall and necessary to use large numbers of rain gauges. From these preliminary experiments it was concluded that while opportunities for cloud seeding undoubtedly existed in the area, a controlled experiment would need many years if it were to yield a reliable answer. Consequently the experiment was abandoned because of the lack of resources. The premature termination of the experiment left many fundamental questions about the effect of the seeding on the clouds unanswered. For example, it was not clear whether the changes in the clouds following seeding by dry ice were dynamic or static processes.

f. CSIRO experiment in western Victoria 1979–80

The western Victorian cloud-seeding experiment was carried out in a major wheat-growing area where extra rain during the growing season would be of economic benefit. Planning for the experiment involved a new degree of sophistication in cloud-seeding experiments in Australia. The philosophy behind the western Victorian experiment closely mirrored that developed for the WMO Precipitation Enhancement Project and reflects the leadership given to both experiments by Chief of the Division, J. Warner.

The following three preconditions were associated with the site selection.

1) Clouds suitable for seeding had to occur reasonably frequently in an area and be identified with a particular synoptic-scale weather pattern.
2) The frequency of occurrence of these suitable clouds, and the amount of extra rain expected to be derived from them, had to be such that there was a reasonable chance of detecting the seeding effects within 5 yr.
3) The cost of mounting the experiment had to be considerably less than the economic benefits from the extra rain.

Cloud observations, statistical analysis of past historical weather records, and economic analysis of wheat yield as a function of rainfall were undertaken from 1975 to 1978, and in 1978 a prospectus giving full details of the experiment was circulated internationally to interested scientists (King et al. 1979).

The analyses and in situ observations showed that suitable cloud was associated with rain depressions or “closed lows” and that approximately five “closed lows” were expected each season. Although five a season was considered to be a low number of seeding opportunities, the rainfall from these systems was uniform, producing good correlations between target- and control-area rainfalls.

Seeding on a declared suitable day was undertaken by either one or two aircraft fitted with two burners containing a solution of silver iodide and ammonium iodide in acetone. The suitable day was defined using criteria similar to that used in Tasmania, and a seeding strategy based on the calculation of particle trajectories was used to optimize rainfall in the target area. In addition to the seeding program there was a separate extensive program of physical measurement that included aircraft and ground observation.

Despite this very careful planning, it was found that during the first 2 yr of the experiment (1979 and 1980), only 7 days satisfied synoptic conditions defined by the experiment, and of those 7 days when optimal seeding conditions were expected, none was found. This was due almost entirely to the abundance of natural ice crystals in the cloud system (King 1982).

In retrospect, it is apparent from the 1979 and 1980 field data that the number of seeding opportunities was substantially overestimated in the preexperiment studies based on the analysis of synoptic charts. A reanalysis of historical data showed that 60% of the closed lows with deep stratiform clouds had cloud-top temperatures lower than −25°C. Contrary to the 1975–78 observations, the in-cloud observations suggested that these clouds invariably contained more than enough ice crystals for precipitation to form. The reanalysis showed that realistically the number of closed lows is less than 1.5 a season compared with the initial estimate of five, thereby giving no prospect of obtaining answers on the effects of seeding in the originally planned 5-yr experiment (King 1982).

At the same time as the seeding project was being reevaluated, a revised economic analysis showed that aircraft costs were increasing relative to wheat prices. The analyses suggested that by 1983 the cost–benefit ratio for the experiment would have been entirely eroded (King 1982). It was therefore clear that continuing the western Victorian cloud-seeding experiment could not be justified.

All subsequent cloud-seeding experiments conducted or supervised by CSIRO since 1980 have been modeled on the western Victorian experiment in that they have all been randomized experiments incorporating a physical measuring program, a statistical analysis and an economic evaluation.

g. Western Australian northern wheatbelt cloud study 1980–82

The northern wheatbelt cloud study was undertaken in Western Australia by the Western Australian Weather Research Association (WAWRA) and the Western Australian Government (Bailey 1982). The operational seeding and research program was managed primarily by the School of Physics and Geosciences at the Western Australian Institute of Technology (now Curtin University). CSIRO advised Curtin University during the project. The study ran from 1980 to 1982 during the months from May to October.

The cloud physics study showed that, in general, cloud tops were relatively warm (−5° to −15°C). Large numbers of ice crystals were more frequent in May and June, the first two months of the observations when the rainfall was greatest. When liquid water was present in the clouds it frequently exceeded 1 g m^{-3}. However, on the best seedable days the rainfall was usually light and, at best, represented 29% of the total rainfall in the season.

The 3-yr study showed that while there were many clouds each year that had a reasonable potential for seeding, simulations using the techniques developed by Twomey and Robertson (1973) showed that a 30% rainfall increase was needed to have a reasonable chance of detecting rainfall in a 5-yr experiment. To detect a 10% increase in rainfall would need 20 years.

An economic analysis of a seeding experiment suggested that the cost would be $3.31 per hectare of land under cultivation with an initial $0.89 per hectare in the first year to cover capital costs. If a 10% increase in rainfall were achieved on all the best seedable days in 1981 and 1982, the extra yield per hectare would be worth between $5 and $17 per hectare.

It was concluded that the northern wheatbelt region of Western Australia is probably suitable for cloud seeding conducted on an operational basis. However, unless there was a commitment for resources on a 20-yr timescale, it was unlikely to be suitable for a cloud-seeding experiment.

h. Melbourne Water Corporation/CSIRO experiment 1988–92

The Melbourne Water Corporation conducted a 5-yr cloud-seeding experiment (1988–92 inclusive) from 1 May to 31 October over the 487 km^2 Thomson Reservoir catchment in the Great Dividing Range about 120 km east of Melbourne. Melbourne Water contracted CSIRO to oversee the design and conduct of the experiment and to measure the physical properties of clouds in the area.

Two kinds of clouds were seeded in the experiment: stratiform clouds with and without embedded cumulus. They were seeded a distance upstream calculated on the basis of particle trajectories. Cumulus clouds were seeded a fixed 30-min travel time upwind of the target area.

Suitable clouds for seeding were selected according to criteria based on cloud-top temperature, cloud depth and appearance; cloud supercooled liquid water; wind velocity; and the likelihood that clouds would live long enough to be seeded during two passes along the seeding track.

Stratiform or cumulus clouds upwind of the target area were seeded with silver iodide in acetone solution, while dry ice pellets were dropped into orographic cap clouds and cumulus clouds with tops warmer than −5°C. The choice to seed or not to seed clouds with silver iodide was made randomly with a 2:1 balance in favor of seeded experimental units. For dry ice the balance was 1:1.

Two major airborne field studies were conducted in 1988 and 1990 as an adjunct to the cloud-seeding experiment. The field studies showed that the postfrontal and interfrontal clouds offered the best seeding opportunities (Long 1993).

Observations during the experiment confirmed the hypothesis that substantial quantities of liquid water could at times be generated by orographic uplift when the cloud systems were relatively shallow (cloud-top temperatures higher than −10°C). However, while the results of analyses of the rain gauge network showed that any increase in rainfall was not statistically significant, other tests for the buffer area between the target and the control areas showed a statistically significant increase. When all analyses were considered, Melbourne Water concluded that there was insufficient evidence to justify continuing with cloud seeding as an operational tool.

3. Critical assessment of past cloud-seeding activities in Australia

In Australia, hydroelectric authorities and water boards have looked to cloud seeding to supplement reservoirs for hydroelectric power and for water supply for public and industrial consumption. Many utilities are either negative or doubtful about the effectiveness of cloud seeding. In a survey in 1979, McBoyle (1980) reported a negative response from the State Rivers and Water Supply Commission of Victoria, the Electricity Commission of New South Wales, and the Queensland Water Resources Commission. Earlier, B. Sadler and R. McCullogh [see McBoyle (1980) and references therein] reported that Western Australia's initial attempts at rain making were not successful. The more recent cloud-seeding experiment by Melbourne Water was also deemed to be statistically inconclusive and seeding operations have not been pursued.

The current view of water managers in Australia is that cloud seeding is a marginal water-management tool. It is recognized that rainfall enhancement can be expected to have measurable success only in limited climate regimes and that many regions may be totally unsuitable for cloud seeding. It is also recognized that cloud-seeding operations need to be based on objective water management and scientific goals that have real cost–benefit justification (Sadler 1995). In 1994 the Water Resources Management Committee of the Australian Water Forum decided to sponsor a review of the Australian experience in rainfall enhancement and to set down some principles and guidelines to help with more effective deployment of this experience (Ryan and Sadler 1995).

The only mainland study to show a statistically significant increase in rainfall was the Snowy Mountains experiment (1955–59). However, a dispute arose between CSIRO and the Snowy Mountains Hydro-Electricity Authority (SMHEA) over the weight to be placed on the results of subsidiary analyses. To the SMHEA they suggested that the increase resulting from seeding was substantially less than the 19% analyzed by CSIRO, while to CSIRO the limitations of the subsidiary analyses appeared such as to prevent drawing meaningful conclusions (Smith et al. 1963). At the insistence of SMHEA, Smith et al. interpreted the significance levels of the results to be "marginal" and the overall results of the experiment as "encouraging" but "inconclusive." The reasons the experiment was seen as unconvincing are that 1) changes were made after the first year, 2) the discovery that the precipitation values for the experimental units were calculated by people who were aware of the randomized seeding sequence, and 3) the conflicting interpretation of the subsidiary analyses by CSIRO and the SMHEA.

The lesson to be drawn from the Snowy Mountains experiment is that extreme care needs to be taken in the statistical design and conduct of cloud-seeding experiments. In Australia, these lessons were well learned. The basic statistical rules required to design and evaluate a cloud-seeding experiment developed for the Tasmanian experiments have been applied in all subsequent cloud-seeding experiments in Australia. Further advances were made in the design and evaluation of the western Victorian experiment and applied to the Melbourne Water experiment.

The Tasmanian Hydro-Electric Commission is convinced of the economic success of the Tasmanian experiments. This is perhaps best illustrated by the decision of the HEC to undertake Tasmania II with analytical assistance from CSIRO and Tasmania III without any assistance at all. However, the HEC has retained a very pragmatic approach to cloud seeding. McBoyle (1980), quoting from Watson (1976), states that "cloud-seeding has emerged as a feasible and economic proposition in Tasmania when the increase in precipitation can be utilized for power generation." However, it is still viewed as a marginal benefit and its inclusion in the power-generating system presents a number of managerial, design, and operational problems. Currently, Searle (1994) estimates that each HEC cloud-seeding operation costs $645,000 to run and returns an average 55 mm of extra rain each 6-month experimental season. When the extra water in storage is priced against the energy generated by the only HEC thermal station the real profit from the silver iodide seeding averages out at about $14.5 million per annum (I. Searle 1995, personal communication).

In Tasmania II Shaw et al. (1984) required clouds at the seeding level to have supercooled water contents > 0.1 gm^{-3} with a 5-min time constant. The maximum opportunities and the highest liquid water content (~0.3 gm^{-3}) occurred at around –8°C (Fig. 4). Furthermore, the analyses showed evidence to support the case that the seeding was more effective on days when the clouds had high liquid water contents of between 0.2 and 0.5 gm^{-3} (Fig. 5). The major weakness in the Tasmanian experiments from the microphysical point of view was the inability to measure ice crystal concentrations.

In times of severe drought, affected communities have called for operational drought-relief seeding. CSIRO's role in cloud seeding has been determined by the federal government as one of applied scientific

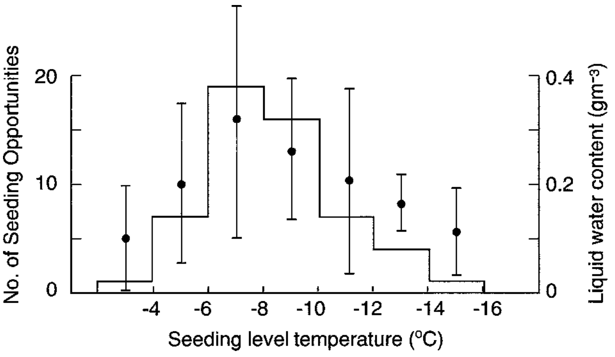

FIG. 4. Distribution of number of seeding opportunities and liquid-water content plotted against seeding temperature (from Shaw et al. 1984).

research. In response, some state authorities have undertaken short-term seeding programs. For example, in November 1994 the NSW state government funded cloud seeding in northern New South Wales for drought relief. Other state government departments sought advice from CSIRO on the viability of cloud seeding as a drought-relief option. Within this framework, CSIRO could not become directly involved in operational cloud seeding simply because no scientific research was associated with such exercises. The role of CSIRO has rather been a consultative one in providing the expertise required to do the seeding most efficiently while at the same time warning that no quantitative results could be determined by either statistical or other known methods.

In recent times, the major criticism of the design of cloud-seeding experiments has come not from statisticians but from a former member of the CSIRO Division of Cloud Physics, Dr. E. Bigg. He has questioned the fundamental design of past cloud-seeding experiments in Australia. Based on the arguments proposed in Bigg and Turton (1986, 1988), Bigg considers that all of the Australian area cloud-seeding experiments were contaminated by the persistent effect of silver iodide, thereby underestimating the effect of seeding (E. Bigg 1995, personal communication). The mechanism hypothesized is that the seeding increases the levels of silver iodide on the ground, which in turn enhance the multiplication of bacteria released by the vegetation, which then act as cloud nuclei when ingested into clouds. If the claims are true, new statistical techniques will need to be developed for the design of cloud-seeding experiments. However, the hypothesis requires an elaborate process based on very little evidence other than Bigg's persistence analysis. Until microbiological observations show that there are ice-activating nuclei entering the cloud systems, Bigg's hypothesis must remain speculative.

4. Circumstances where rain enhancement experiments are not favorable in Australia

King (1982) examined the relevance of the western Victorian cloud-seeding experiment to other areas of Australia.

a. *Winter and spring rainfall over the inland plains in southern and eastern Australia*

The western Victorian site was chosen for a cloud-seeding experiment because its meteorology and agriculture are representative of a large fraction of southeastern Australia. The conclusion from the western Victorian experiment is that the following synoptic systems are generally unsuitable for seeding: 1) frontal systems (including pre- and postfrontal), 2) southwesterly airstreams, 3) closed lows and deep cloud systems (King 1982). Table 2 shows the percentage of the daily rainfall associated with each synoptic system for the months of July to November for 10 yr from 1960 to 1970 together with the total rainfall for Beulah, a rainfall station in the target area for the western Victorian experiment. The systems not examined during the western Victorian experiment were troughs, northeasterly airstreams, and unclassified systems. These unexamined systems represent only 10.8% of the synoptic climatology of southeastern Australia. While they could be assumed to be potentially seedable until proven otherwise they produce only 9.5% of the season's rainfall.

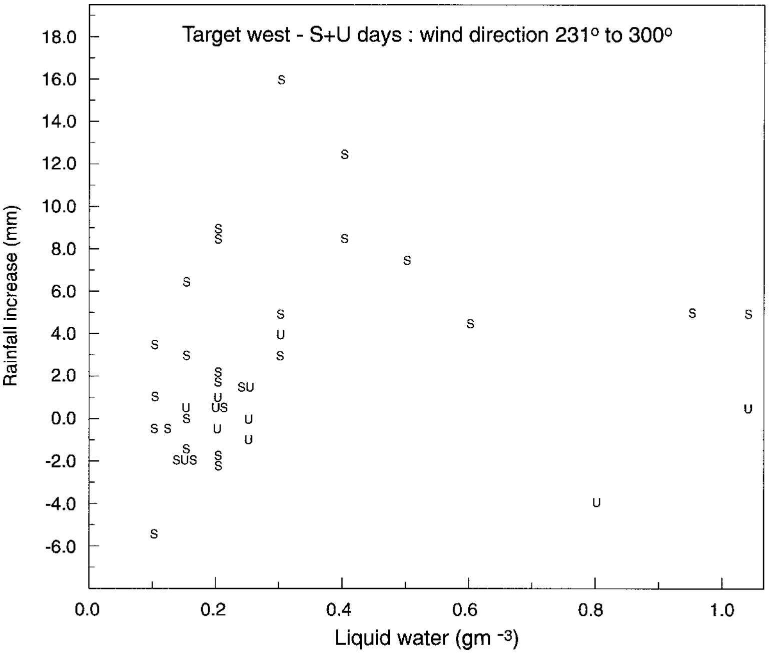

FIG. 5. Estimated rainfall change in the west target area of Tasmania II plotted against liquid-water content (from Shaw et al. 1984). The estimated rainfall change is defined as the observed rainfall (seeded, s, or unseeded, u) over the west target area minus the rainfall (unseeded) calculated from a regression model.

King (1982) extrapolated the results of the western Victorian experiment to other inland plain regions in Australia by undertaking a similar analysis of the synoptic rainfall patterns for stations located at Maitland in Yorke Peninsula (SA), Wagga Wagga (NSW), and Gunnedah (NSW). The locations of these sites are shown in Fig. 1. Table 2 shows the occurrence of different synoptic weather events as a percentage, together with the seeding potential and a rainfall analysis for each location, the daily rainfall associated with one of six synoptic weather patterns, and the fraction of the total season's rainfall. The table shows that for Maitland there is virtually no opportunity for rainfall enhancement, and this is consistent with the earlier seeding experiments by CSIRO from 1953 to 1963 in this region. Near Wagga Wagga on the western plain of NSW only 11% of the season's rainfall comes from potentially suitable synoptic systems. At Gunnedah the seedable opportunities increase to 37.8% and these account for some 36% of the rain. As one proceeds farther north, the summer tropical weather patterns (troughs and northeasterly streams) dominate more and more, and the higher-latitude systems (fronts and closed lows) become less important. Gunnedah has an even balance between summer and winter rainfall and is at the northern limit of the area for which the meteorological conclusions derived from the western Victorian experiment can be extrapolated.

The analysis of King (1982) shows that the inland plains of South Australia, Victoria, and New South Wales are not particularly suitable for seeding. On the economic side, King examined the price movements of beef, wool, and cereals. With all of these commodities the rises in aircraft operating costs outstripped the returns to farmers by a factor of 2 from 1972 to 1980, and indeed it was impossible to find any measure of agricultural return appropriate to the inland plains that had not declined in relation to aircraft costs.

b. *Winter and spring rainfall over the northern wheatbelt region of Western Australia*

In the northern wheatbelt of Western Australia there is a prima facie case for seeding clouds with rainfall enhancement potential and, furthermore, from an agricultural viewpoint seeding these clouds would be economic. From a water management viewpoint the potential targets are not in catchment regions. The disappointing aspect of the northern wheatbelt study is that any increase in rainfall is unlikely to be detected in a 5-yr cloud-seeding experiment. These results are entirely consistent with the lack of conclusive evidence from an earlier seeding operation over the catchments to the south of the Darling Scarp [see McBoyle (1980) and references therein].

TABLE 2. Rainfall data from various weather systems for selected stations in southeastern Australia for the months July–November of 1960–70.

Site	Frontal (%)	Closed low (%)	Deep systems (%)	Southwest stream (%)	Trough (%)	Northeast stream (%)	Other (%)	Potential seeding days per season	Rainfall on potential days (mm)	% of season's rain	Total season's rain (mm)
Maitland (SA)	50.7	26.8		22.0	0.02						272
Beulah (VIC)	51.0	26.5		11.9	4.20		6.6	2.4	15.7	9.5	184
Wagga (NSW)	46.0	21.7	10.8	9.4	7.80		3.8	5.1	30.2	11.1	287
Gunnedah (NSW)	33.0	11.2	18.0		18.50	6.3	13.4	8.6	77.9	36.0	218
Thredbo (NSW)	51.0	8.3	15.2	11.1	4.40		7.1	14.0	121.7	13.0	934

c. The summer rainfall regions of northern Australia

Although the incursion of a tropical cyclone into the area can dominate the whole rainfall season, these are comparatively rare and on average very little of the season's rainfall comes from large-scale synoptic systems with widespread stratiform rain. In regions where the monsoon rains are not active, a large fraction of the rainfall events in these regions involves cumulonimbus clouds giving rise to extreme spatial and temporal variability in the rainfall. In terms of detecting seeding effects, the spatial variability of the rainfall imposes a requirement in the design of any experiment of either many hundreds of automatic rain gauges or a sophisticated radar that can fill gaps in the rain gauge network. Simulations using the technique developed by Twomey and Robertson (1973) show that in northern Queensland the increased rainfall variability requires four times as many opportunities as western Victoria to detect a seeding increase of the same magnitude. This means that an experiment that would produce a statistically significant result in southeastern Australia in 5 yr would take 20 yr in northern Queensland. Consequently, planning a cloud-seeding experiment in the summer rainfall regions of northern Australia requires a commitment of massive resources to an extremely long experiment and this is very difficult to justify on economic grounds. In regions where the monsoon is active cloud seeding has not been seriously considered.

5. Circumstances where rain-enhancement experiments might be utilized in Australia

The region where cloud seeding seems to be effective is in orographic regions where the flow over the mountains substantially enhances the rainfall. However, Australian cloud-seeding experiments in regions of rapid orographic uplift have met with mixed success.

In Tasmania three cloud-seeding experiments have been undertaken. The Tasmania I and Tasmania II experiments indicate increases in rainfall in autumn and winter. The Tasmania II experiment shows that the most of seeding opportunities occurred with cloud-top temperatures between −10° and −12°C. At temperatures lower than −15°C there were very few opportunities for seeding (Shaw et al. 1984). The most suitable clouds are associated with stratiform cloud in a maritime southwesterly airstream. Seeding these cloud systems resulted in a 37% increase in rainfall. Suitable days occurred 18 times a year during the experiment and this resulted in an estimated total increase of 197 mm for seeded days.

Cost/benefit analyses carried out by the Tasmanian HEC for the Tasmanian I experiment suggest that the increased rainfall from seeding represents a gain of 13:1. More recently Searle (1994) argues that the three separate cloud-seeding projects sponsored by the Tasmania HEC spanning 14 yr have confirmed that cloud seeding can routinely enhance runoff into Tasmanian storages by 10%–20%. Searle estimates that the energy gained by the cloud-seeding operations costs less than 0.2 cents kW h^{-1}.

In contrast to the Tasmanian cloud-seeding experiments, the Melbourne Water experiment showed no statistical increase in rainfall over the catchment area. The reasons for the rainfall increase in the buffer area on seeded days are not understood and it is not clear if this can be attributed to the effects of seeding.

The effectiveness of cloud seeding in the Snowy Mountains of Australia remains unproven. The early experiments by the CSIRO, while statistically significant, were inconclusive because of controversy over the analysis of the experiment. However, the analysis by King (1982) showing that for the Snowy Mountains only 100 mm or 11% of the season's rainfall occurs in the shallow southwesterly stream with cloud-top temperatures higher than −15°C suggests that there may be only limited opportunities for cloud seeding.

The effectiveness of cloud seeding in the New England District of NSW, like that in the Snowy Mountains, is still controversial. A reanalysis of the earlier New England experiment using daily periods rather than the initial 14-day seeding period suggests a substantial increase in rainfall over all years (E. Bigg 1995, personal communication). However, this unpublished reanalysis is not consistent with the published design for the experiment and therefore will remain controversial. More recently, Chambers and Long (1992) completed a precipitation enhancement feasibility study in the region of the Copeton Dam in the New England District of NSW. They concluded that there is a good potential for cloud seeding in the Copeton Dam region, with one chance in four of detecting a 30% increase in rainfall in a 5–6-yr experiment and one chance in two of detecting a 20% increase.

A major difference between the meteorology in the New England region and the regions farther to the south is that the clouds with seeding potential in the New England region are cumulus and not stratiform clouds. Visual observations of a lack of aircraft icing made during a recent drought-relief project suggest that the deep rain-bearing stratiform cloud systems are unsuitable for cloud seeding (I. Searle 1995, personal communication).

6. New developments in cloud-seeding technique

Since CSIRO ceased active research into cloud seeding, there have been several significant developments that have not yet been applied in Australia. These technologies are reflected in two fields that have undergone rapid development in the last 10 yr, namely, new instrumentations and the application of numerical modeling techniques to cloud seeding.

Radars with Doppler and polarizing capability are being used to track both the in-cloud properties and air motions in seeded and unseeded clouds. Satellite imagery is being used to distinguish between clouds containing ice and those containing water. Microwave radiometers are being used remotely to measure the liquid-water content of clouds. The synoptic and mesoscale networks needed to analyze the cloud systems being seeded are being enhanced by wind profilers, automatic mesoscale surface networks, and automatic rain gauge networks. The telemetering of these data to a central control office and to the aircraft enhances the seeding operation.

While these new measuring systems undoubtedly enhance the physical interpretation of the cloud-seeding experiment, they are expensive to install and require expert technical support to maintain. In Australia currently there is only one research aircraft and one liquid-water radiometer suitable for cloud-seeding studies and no airborne or mobile Doppler radars. Consequently, in new Australian cloud-seeding studies any options for applying these new technologies will need comparatively large budgets not only to fund the instruments but also to support the scientific expertise required to operate them and analyze the results.

Numerical modeling techniques have advanced to the stage where high-resolution numerical cloud models are able to simulate the generation of rain from cloud systems. They are extremely useful for testing cloud-seeding hypotheses, for calculating the trajectories of ice crystals to devise aiming strategies, to ensure that any seeded rain falls into the target area, and finally to calculate whether or not the seeding material will enter the cloud as hypothesized.

The greatest drawback in the use of numerical models for cloud-seeding studies is that the theoretical basis for ice generation in clouds is still incomplete. Until this knowledge gap is completely filled, model simulations will not be able to verify the increased rainfall from a seeding experiment.

7. Comparison with other cloud-seeding experiments

It is not the place of this paper to critically analyze cloud-seeding projects in other regions of the world. However, it is appropriate to compare the general conclusions concerning cloud seeding in Australia with critical analyses made of experiments in other countries.

In Australia, the physical and statistical elements of a cloud-seeding experiments never developed separately. However, prior to the western Victorian experiment, the physical and statistical studies were not well integrated. With the exception of the WMO PEP it is difficult to make a direct comparison between the Australian physical programs and those in other countries. By and large, they were generally modestly resourced compared to the U.S. physical experiments.

From the statistical point of view, the most successful experiments in Australia have been in Tasmania. The Tasmanian experiments are extremely important benchmark experiments. With both the CLIMAX experiments in the United States and the Israeli experiments being challenged by Rangno and Hobbs (1993) and Rangno and Hobbs (1995), respectively, it is important to find out whether the Tasmanian experiments are subject to any of the same criticisms.

A comparison of the physical characteristic of the clouds in the Israeli and Tasmanian experiments is instructive. Gagin and Neuman (1981) argued that in Israel the highest seeding effects occur when the cloud-top temperature is between −12° and −21°C. In Tasmania the major seeding opportunities occur when the cloud tops are between −10° and −12°C. The Israeli clouds are continental cumulus clouds, whereas the Tasmanian clouds are maritime stratiform clouds. Recent observations by Levin (1994) suggest that ice multiplication is taking place in the Israeli clouds. Observations by Mossop et al. (1970) show that small maritime clouds in southeastern Australia are subject to the ice-multiplication process, while the ice-multiplication process is less important in shallow maritime stratocumulus clouds with similar cloud-top temperatures. While no observations of ice crystal numbers in the seeded stratiform clouds have yet been made, it seems likely that they contain regions of embedded convection and that the ice-multiplication processes are operative in these clouds. Rangno and Hobbs (1995) argue that clouds with a significant ice-crystal multiplication process are not suitable for cloud seeding and there are strong physical arguments to support this thesis. Consequently, there is a need to investigate further the glaciation process in both the Australian and Israeli clouds. If ice multiplication is a dominant process and the statistical validation of the experiments is accepted, then precipitation cannot be explained by a simple "static seeding" hypothesis.

The statistical analyses of both of the Tasmanian experiments adopted the best techniques at the time of the experiment and are not complicated by the dust problems identified with the Israeli experiment. At present there is no prima facie case that the Tasmanian experiments are subject to the errors Rangno and Hobbs (1995) suggest occur in the analysis of the Israeli experiments.

There is a very strong synergy between the WMO PEP and the western Victorian cloud-seeding experiment. While both experiments failed to proceed to a completed statistical evaluation stage, they adopted the same methodologies and planning principles. These principles were that 1) the areas must be of a size such that natural rainfall is reasonably uniform throughout and closely similar in target and control areas; 2) the primary method of analysis is statistical and a period of 5 yr is the minimum that can be contemplated; and 3) even with a good statistical result, there must be good physical evidence before the result can be accepted (Warner 1995).

Changnon and Lambright (1990), in an analysis of controversies associated with science and technology, examined four U.S. weather modification experiment, (the National Hail Research Experiment, the Florida Area Cumulus Experiment, the Sierra Cooperative Pilot Project, and the Precipitation Augmentation for Crops Experiment). They concluded that there were six factors at the root of most controversies. These were (a) inadequate scientific knowledge, (b) a flawed planning processes, (c) scientific issues ignored by funding agencies, (d) a lack of commitment of project management agencies, (e) changes in the project director, and (f) a poor performance by project scientists. It is interesting to make a similar analysis of the controversies associated with the Australian cloud-seeding experience. All of the Australian cloud-seeding experiments suffered from inadequate scientific knowledge, and this lack of knowledge led to controversy. A recent example is the argument in Australia over persistence. Currently there is insufficient knowledge to either reject totally or accept completely the persistence arguments proposed by E. Bigg. So persistence remains a source of speculation and controversy. Undoubtedly the Australian experiments had flawed planning processes and the result of the flawed planning process was a source of disagreements between the scientists in CSIRO, statisticians, and water managers outside CSIRO. This problem is recognized in Australia by both scientists and water managers and has been addressed by developing guidelines based on the experience gained from the history of cloud seeding in Australia. The aim of these guidelines is to develop and aid planning and decision-making for water managers in effective partnership with atmospheric scientists and commercial operators (Ryan and Sadler 1995). The guidelines are developed as principles that recommend the disciplines to be followed in the planning and implementation of a cloud-seeding experiment.

While CSIRO was responsible for both the management and the funding of the seeding experiments in Australia, controversies tended not to arise from scientific issues ignored by funding agencies and a lack of commitment by the project management agencies. Changes in the project director were not a problem at CSIRO. Generally the scientists in the Division of Radiophysics and later the Division of Cloud Physics worked as a team so that while the science was at times vigorously debated, the scientific controversies arising from differing philosophies on the part of participating scientists were minimized.

Generally, the Australian experience would support the conclusion reached by Changnon and Lambright that controversies over the conduct of a cloud-seeding program will be minimized if procedures are put in place that define institutional responsibilities in the project as well as the intrinsic science.

8. Conclusions

Over the last 47 yr, successive cloud-seeding experiments and microphysical investigations of the clouds have shown that the static cloud-seeding hypothesis is not effective in enhancing winter rainfall over the plains area in Australia. However, there is evidence to suggest that cloud seeding is effective for limited meteorological conditions in stratiform clouds undergoing orographic uplift. In Tasmania, there is strong statistical evidence for rainfall enhancement for clouds with cloud-top temperatures between −10° and −12°C in a southwesterly airstream. The evidence for similar effects on the mainland in the vicinity of Melbourne, the Snowy Mountains, and the New England District of New South Wales is less convincing.

In the summer-rainfall regions of northern Australia, the extreme rainfall variability makes it impossible to design a statistical experiment that can be evaluated in a reasonable time period using the currently available techniques. Rainfall enhancement experiments in these regions remain inconclusive. Over the inland plains of Western Australia, the seeding opportunities are too infrequent to permit a realistically funded cloud-seeding experiment. This is not to say that cloud seeding would not produce extra rain in these regions, but rather to recognize that currently there is no acceptable technique to demonstrate the effectiveness of seeding and that any extra rain, and monetary benefits from the operation, are not measurable.

Apart from Tasmania, the prospect of cloud seeding based on the simple static hypothesis seems to be very limited. This is particularly so when the requirements of a statistically significant result in 5–7 yr with demonstrable economic returns are demanded in the experimental design.

Economic analyses based on the Tasmanian experiments and Melbourne Water experiments suggest that for water management purposes, increases of the order of 5%–10% in the rainfall makes a cloud-seeding operation economically viable. However, the analyses by King (1982) suggest this is not the case for the agricultural sector that includes wool, wheat, beef, and sugar. Contrary to the western Victorian results, Bailey (1982) suggests that cloud seeding is economic for cereal crops in Western Australia.

Given the current priorities for atmospheric research in the CSIRO, the study of cloud-seeding techniques must compete with funds for research into climate change, climate variability, and air pollution. It is likely that any substantial research into cloud seeding in the future will be initiated by the water industry and will require substantial support from that body. However, CSIRO will retain its expertise in fundamental cloud physics to evaluate any studies undertaken by the power or water industries.

Acknowledgments. This section of the paper could not have been written without the support and input from former members of the CSIRO Division of Cloud Physics. In particular, we are grateful to Jack Warner, Keith Bigg, Alex Long, Mike Manton, and Doug Shaw.

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