Review of Persistence Effects of Silver Iodide Cloud Seeding

by

Alexis B. Long

P.O. Box 41, 144 Jasper Road
Bentleigh, Victoria, Australia 3204

Abstract. This paper is concerned with persistence effects of cloud seeding for precipitation enhancement. Effects may last for hours or days. Persistence of cloud seeding effects means that this environmental technology may affect the microphysical structure of clouds and the development of precipitation for a significant amount of time after the seeding has been completed.

According to Rottner, Brown, and Foehner (1975) persistence may complicate the evaluation of a cloud seeding experiment and reduce the perceived net effect of the seeding. The sensitivity of the experiment to the actual net effect may be reduced. Their work in Colorado and New Mexico demonstrated a smaller cloud seeding effect because of persistence. When no account was taken that cloud seeding material was incorrectly present in the control period part of the time, the seed:no-seed contrast in precipitation and the effect of seeding were smaller. When the incorrectly seeded parts of the control period were reassigned to the target period, the contrast and the effect of seeding were greater.

There has been considerable post-analysis of precipitation data associated with cloud seeding experiments in Australia by Bigg and colleagues in a search for persistence effects. Unfortunately, there appears to be a flaw in some (but not all) of the analysis which exaggerates the time span (said to be up to two weeks) of the effects.

Artificial ice nuclei are generated by the cloud seeding apparatus and are injected in various ways into a cloud to increase precipitation. The surmised connection between higher nucleus concentrations and increased precipitation suggests that measuring and examining ice nucleus concentrations for a period of perhaps a few days after seeding may be worthwhile in a search for persistence.

Bigg and others have suggested that some silver iodide ice nuclei released in cloud seeding may be carried, presumably with precipitation, to the surface. There the nuclei are believed to stimulate chemical reactions, possibly on plants, that create products that are emitted into the atmosphere to function as persistent ice nuclei. An alternative scenario is that the deposited silver iodide modifies or otherwise causes bacteria on the plants to loft into the atmosphere and also act as persistent ice nuclei.

1. INTRODUCTION

Persistence effects of cloud seeding with silver iodide mean that, while seeding may have immediate effects -- occurring perhaps 0.5 - 1 hr after the seeding -- on the microphysical structure of clouds and the development of precipitation, there may also be other effects extending into the future some hours, days, weeks or months. These persistence effects complicate the evaluation of a cloud seeding operation or experiment. The evaluation normally assumes cloud seeding effects essentially are turned on and off, except for a short 0.5 -1 hr transport lag time, by executing the seeding or terminating it. The complication may be such that the net effect of cloud seeding is apparently reduced and the perceived benefit is diminished.

The U.S. National Academy of Sciences (1973) reviewed the work of several investigators of persistence effects. Although it was fairly well accepted that persistence, if present, could have important effects on the evaluation of cloud seeding effects the evidence for persistence itself as of the NAS report date was ambiguous. Since that date, there has been further research. Both the early research and the later research are examined here.

2. EARLY RESEARCH

Cloud seeding is usually characterized by the dispersal into the atmosphere near a cloud or into a cloud itself of a smoke of ice nuclei composed of the chemical silver iodide. These nuclei lead to the development of small ice crystals in clouds which, through a chain of physical events, produce precipitation at the ground. In addition to any silver iodide ice nuclei produced by cloud seeding there are natural ice nuclei occurring in relatively low concentrations throughout the atmosphere. Low measured ice nucleus concentrations suggest the nuclei are naturally induced, whereas high concentrations may indicate an artificial source such as cloud seeding. If the high concentrations occur for some time (hours, days, weeks, or months) after seeding then these elevated concentrations may reflect a persistence of the cloud seeding nuclei.

Early reports of such persistence came from Boucher (1956) and Grant (1963) who both observed elevated "freezing" ice nucleus counts for days, weeks, or months after seeding was discontinued. This evidence would be more strongly supported if good climatological information on ice nucleus concentrations existed which could establish the natural background levels, and variations from those levels, against which measured artificial cloud seeding ice nucleus concentrations can be compared.

Emerging from this work was a recommendation that an ice nucleus concentration measuring network should be incorporated into any cloud seeding experiment using silver iodide. The network should cover the target area since that is where silver iodide nuclei are to be present in greatest concentrations and where seeding effects are to be most pronounced. The network should also extend downwind of the target area since this may demonstrate where persistence is occurring and why downwind effects (treated in detail in a companion review paper (Long, 2001)) are observed. If the ice nuclei may be entrained in local circulations around and about the target area, the network should also extend laterally and upwind of the target area and control areas. This may demonstrate seeding effects in these outlying areas occurring despite confinement of any seeding to favorable wind regimes.The network should operate throughout a cloud seeding experiment, during off-seasons, and for perhaps one year after the experiment has concluded. The network should operate throughout any pre-determined quiescent, not-seeded periods inserted within the experiment to check for short-term persistent effects of the seeding.

3. BOWEN RESEARCH

Bowen (1966) showed that in a number of cloud seeding experiments the increase in precipitation calculated to be due to the seeding decreased with time. According to Bowen (1966) these experiments (Smith, 1974) included those in the Snowy Mtns, the New England region of New South Wales, the Warragamba catchment, and the South Australia areas of Australia. Effects were also observed in Israel and Arizona. Either the seeding effect actually decreased with time or else some factor was masking the seeding effect which in fact remained approximately constant with time. Bowen's (1966) mathematical analysis suggested a persistence model such that the seeding effect extended into successive subsequent periods of time

"REVIEWED"

when the clouds were not to be seeded as required by the statistical controls applied to the experiment.

Bowen's analysis implies that if some fraction *a* of a percentage seeding effect *s* (increase in precipitation) in a given seeded period extends into the subsequent no-seed period, then the net effect over the lifetime of a cloud seeding experiment is for there to be a seeding effect in the final no-seeded period that is *a* times as large as the seeding effect in the final seeded period. As a result, the perceived seeding effect overall is degraded from about *s* to about *s*-*a* x *s*, say from 30 percent to 9 percent if *a* is 0.7 . This degradation means there is, inadvertently and misleadingly, an apparent decrease in the result of the experiment with time.

From the cumulative properties of the analysis this apparent decrease is greater for shorter, more frequent seeded and no-seeded periods of time and for longer experiment lifetimes. There is a build-up of the degrading effect with time on all seeded and not-seeded precipitation , and it becomes difficult to distinguish the actual seeding effect. The effect of persistence, devolving from the non-zero factor *a*, will decay with time if seeding is terminated and restarted after some extended gap in time. In other words it is possible to avoid the effects of persistence by careful design of an experiment.

Persistence may be less if there is photodeactivation of the silver iodide with time which would have occurred prior to the early 1970's when sodium iodide was combined with silver iodide in the seeding solution from which the smoke was made. After the early 1970's (Dennis, 1980) the solution contained ammonium iodide instead. There was then less photodeactivation and presumably more persistence.

It should be noted that the Bowen persistence model does not imply a decrease in the effectiveness of post-1970's seeding with time in an experiment (the seeding effectiveness remains as good as initially provided photodeactivation is negligible), but rather the model implies a progressive decrease in the sensitivity of the experiment to the seeding effect with time. The sensitivity is an issue because nominally not-seeded data are contaminated by seeding effects overlapping from seeded periods which cause a reduced seed/no-seed difference or ratio of precipitation amounts in the target area. An example of this reduced sensitivity appears in Bowen's analysis of the double ratio. This ratio is commonly used to measure cloud seeding effects in an experiment. It reflects the relative magnitudes of the seeded and not-seeded precipitation amounts in a target area. In Bowen's specific example the double ratio is shown to decrease from 1.2 (20 percent increase in precipitation) to a perceived 1.1 with accumulated seed and no-seed data sets even though the actual seeding effect of 20 percent remains constant.

It should be noted that use of a single area or cross-over cloud seeding experimental design instead of the target-control-design considered by Bowen (1966) will tend to exacerbate the effects of persistence. In these two cases there is either no not-seeded control area or one of the two control areas is always seeded. Both circumstances work against retaining part of the experiment in continual no-seed state and thus permit persistence effects to invade the experiment.

Bowen (1966) recommended measures be taken to negate the effects of persistence. First, good historical precipitation records should be assembled prior to the experiment to form a base against which to judge the experimental precipitation amounts before persistence effects occur. Second, the randomization should not be on the precipitation storm or day, but rather a longer period such as the week, to counter the otherwise geometric increase of persistence effects. Third, there should be a control area which should never be seeded in order that its precipitation not be influenced by persistence. Fourth, the experiment should be alternately opened and closed for long time periods such as a month or a year so that estimates can be made of the build-up and decay of persistence.

Importantly, Bowen (1968) advanced one possible explanation for the persistence of cloud seeding effects. He believed that persistence is not due to a prolonged high concentration of silver iodide ice nuclei. He believed persistence is related to the presence of elevated rain amounts in seeded areas. Bowen notes, first, that precipitation augmented by seeding leads to greater re-evaporation into the atmosphere and a moister environment for cloud development. Second, it appears (Twomey, 1960) that cloud condensation nuclei (CCN) are fewer over moist ground. Accordingly,there is a conversion of clouds from continental to maritime character with a corresponding increase in propensity to rain naturally. This conclusion is supported by the findings of Warner (1968) indicating that increased CCN produced by sugar cane fires leads to less convective showery rain and conversely reduced CCN concentrations lead to more rain. The combined effect of greater water vapor and fewer CCN then would lead to increased precipitation on a no-seed day following a seed day.

In response to Bowen (1965, 1966) Gabriel, Avichai, and Steinberg (1967) studied the precipitation data in the crossover Israeli experiment in a search for persistence effects. The analysis considers progressively shorter periods of time starting with season-to-season then turning to within-season persistence and finally treating day-to-day persistence. The statistical analyses demonstrated no persistence effect in any case. The authors believed the analyses could be adapted to other rainfall stimulation experiments to check for persistence. It should be noted that Gabriel, Avichai, and Steinberg (1967) do not comment on Bowen's (1966) Figure 4 which showed a reduced effect of seeding with time in Israel. The persistence shown by Bowen (1966) is not consistent with their findings.

4. EARLY - MIDDLE 1970'S RESEARCH

In contrast to the persistence studies based on precipitation variables of Bowen (1965, 1966, and 1968) and Gabriel , Avichai, and Steinberg (1967) was the work of Reinking (1972). It was similar to the studies of Boucher (1956) and Grant (1963) and is now summarized herein. The horizontal and vertical air motions present when silver iodide ice nuclei are released are such that a fraction of the released nuclei do not immediately reach the cloud and are not used. These residual nuclei may be transported out of the seeded area although some of them can be expected to remain. A fraction of the residual nuclei may add on to the existing population of natural nuclei and , if eventually ingested into clouds, may affect the precipitation in a way that persists beyond the initial precipitation pulse augmented by the initial seeding. This additional precipitation may occur in a nominally not-seeded period of time and reduce the seeded/not-seeded contrast in precipitation and thus any perceived seeding effect. The sensitivity of the experiment is thereby reduced. Whereas a fraction (#1) of the residual nuclei would act in approximately the above way it should be recognized that there is another fraction (#2) of the residual unused silver iodide ice nuclei which deposits from the atmosphere onto ground surfaces, vegetation, and possibly in snowpacks. These long-term nuclei (#2) may be released later into the atmosphere with effects on precipitation which can be erratic and diluted. Reinking's work did not deal with them but rather with the fraction (#1) of undeposited residual ice nuclei which would be expected to have an effect within cloud seeding seasons.

The data examined in Reinking's study were collected with the Bigg-Warner rapid expansion ice nucleus counter at two sites in the Colorado Rockies namely the High Altitude Observatory (HAO) and Rabbit Ears Pass (REP) . (Note that the Bigg attributed to the Bigg-Warner counter is the same individual whose extensive later work on persistence is reported below.) The nuclei measurements were for silver iodide seeding with 20 g per hour ground generators. A total of 10 years of IIAO and 4 years of REP measurements were obtained. The measurements were assigned to a succession of time periods with S denoting the time period of the seeding itself, D denoting the remainder of that day, and D+i denoting the ith day after D. The data extended out to i=8 or 8 days after seeding, in response to the view that seeding effects may last up to about a week. Examination of the data focussed on the median count since the mean of the counts is influenced by large data outliers , and the mode of the counts is near the detection limit of the counter. The data show that for days D+1 and D+2 the ice nucleus concentrations were significantly above background but that this did not persist beyond two days. Still, many ostensibly not-seeded control storm situations were subjected to this two calendar day persistence of (#1) residual silver iodide cloud seeding nuclei. It should be noted that a residual ice nucleus concentration such as observed was about five times as high as the background concentration and is equivalent to the cloud top being about 2 C colder than normal based on the Fletcher (1962) curves. The effect of a colder cloud on precipitation was not determined.

In Hess' (1974) review of weather modification, Brier(1974) in Chapter 5 on the Design and Evaluation of Weather Modification Experiments and Simpson and Dennis (1974) in Chapter 6 on Cumulus Clouds and Their Modification concerned themselves with the subject of persistence of cloud seeding effects. The following material summarizes their findings.

Brier (1974) notes Grant's (1963) finding that freezing nuclei may 1) remain high for many days after seeding, 2) alter the no-seed character of a target area, and 3) reduce the adequacy of the controls to establish a seed/no-seed contrast for the experiment. Brier (1974) also noted that silver iodide nuclei may be trapped on vegetation in a target area and be blown into the air with nucleating effect at a later time. Finally, Brier (1974) noted that Smith (1967) made several suggestions related to detecting and investigating the persistence effect in seeding experiments of crossover design.

Simpson and Dennis (1974) included a list of tentative causes for extended temporal effects of seeding. These causes were said to be complex, widespread, and subtle. They included

a. physical transport of the seeding agent
b. physical transport of ice crystals produced by a seeding agent
c. changes in radiation and thermal balance, as for example, from cloud shadows or wetting of the ground
d. evaporation of water produced by seeding
e. changes in the air-earth boundary such as vegetation changes over land
f. advection or propagation of intensified cloud systems which subsequently interact with orography or natural circulation
g. cold thunderstorm downdrafts setting off new convection cells elsewhere.

Rottner, Brown, and Foehner (1975) summarized a study of persistence based on data from the Colorado River Basin Pilot Project (CRBPP) and the Jemez Atmospheric Water Resources Research Project (JAWRRP). Silver iodide cloud seeding material was released from ground generators in both project areas. In the CRBPP the concentration of silver iodide ice nuclei was measured with an NCAR acoustic ice nucleus counter. Concentrations were found to be factors of 100 to 1000 higher than background some hours after seeding had ceased. A similarly high concentration was assumed in the JAWRRP. This persistence of artificial seeding ice nuclei influenced the statistical results of the analysis of seeding effects on precipitation amounts. When the defined seed and no-seed periods were considered there was no seeding effect. When a 6 hr period of time was eliminated from the start of the no-seed period because it may have been contaminated with persistent ice nuclei the statistical test showed more precipitation in the seeded period. When the eliminated 6 hr periods were reassigned to the seeding period, there was an even greater seeding effect. These three sequentially different statistical analyses suggested that a seeding effect was occurring during the first 6 hr of the no-seed day because of contamination of that period with ice nuclei remaining from the previous seeded day. This work is a particularly graphic demonstration of a) how ice nuclei can remain in a seeding project area after seeding has ceased, of b) how seeding effects can be masked if seeding occurs even in parts of no-seed control periods, and of c) how seeding effects become clearer if there is a clear assignment of precipitation data to the seeded-category if warranted.

5. BIGG RESEARCH

Bigg (1985a, 1985b, 1985c, 1988, 1995), Bigg and Turton (1986, 1987, 1988) and Mather, Bigg, and Renton (1990) addressed the question of persistence seeding effects. The papers are largely concerned with rainfall and ice nuclei data from precipitation enhancement projects in Australia. The data are incorporated in several different kinds of analysis aimed at demonstrating a persistence effect if one is present.The material that follows critically examines this potentially important body of work.

a) Precipitation effects

The Tasmanian I experiment (Smith , Adderley, Veitch, and Turton, 1971) was specifically designed to reduce accumulating, persistence effects of cloud seeding by alternating entirely not-seeded (odd-numbered) years between randomly seeded (even numbered) years . Seeding was conducted one-half of the time throughout the latter years on a randomized basis. The primary controls were areas to the north and south of the target , the overall control rainfall C being the average rainfall of the two. The first year of the experiment was 1964 and the last year 1970. (Additionally, more intense seeding was conducted in 1971.) A subsidiary area to the east of the target was used for studies of downwind effects, discussed in Long (2001).

An important feature of the 1964-70 experiment was the inclusion of rainfall on days that were suitable for seeding but were not seeded. These SU days were compared with the main sequence of days (SS) that were suitable for seeding and were seeded. Altogether, there were 211 SU days and 202 SS days.

Bigg (1985a) applied a "superposition" method of analysis to the precipitation data.. To apply this method all seeded days (SS) are counted as day zero (0). Bigg states that all target-area rainfalls on those days are summed to give a total $\Sigma\ T(0)$ and the mean of north and south control rainfalls is $\Sigma\ C(0)$. Similarly, target and control rainfalls are summed for each day n to give $\Sigma\ T(n)$ and $\Sigma\ C(n)$. The ratio

$$(\Sigma\ T(n)/\ \Sigma\ C(n))SS$$

is calculated.

The rainfall sequence subsequent to a particular seeded day was terminated at the next seeded day. This is a particularly important point since it ensures that the precipitation nominally on an n-th day is actually on the n-th day after a seeded day and not the rainfall on some smaller-n day after an intermediate seed day. This termination of the rainfall sequence prevents confusion of the day and mixing up of data from different n-value days. The purpose of emphasizing these considerations is to reflect in advance on the fact that later analyses by Bigg did not so terminate the rainfall sequence at the next seeded day and hence used confused data. In my view, this seriously compromised Bigg's later work.

Note that changes in the ratio

$$(\Sigma\ T(n)/\ \Sigma\ C(n))SS$$

from n to n+1 and so on are an indication of systematic changes in precipitation that follow seeding. It should be noted that this ratio is not an ideal measure of persistent effects of seeding, for three reasons according to Bigg (1985a):

1) seeded days form a meteorologically biased selection, so that changes with time may be reflecting natural changes

in meteorology rather than any effect of seeding,

2) the probability of encountering another seeded day within n days diminishes in summer, so that there is the possibility of seasonal bias in changes in the ratio as n increases,

3) the level of

$(\Sigma\ T(n)/\ \Sigma\ C(n))SS$

when undisturbed by cloud seeding can only be determined historically, but climatic shifts may occur that cause historical data to be an unreliable guide. The biases above may be removed by making use of the SU days mentioned above which should have a range of meteorological conditions very similar to the SS group. One then calculates

$(\Sigma\ T(n)/\ \Sigma\ C(n))SU$

to go along with

$(\Sigma\ T(n)/\ \Sigma\ C(n))SS$

and forms the double ratio

$(\Sigma\ T(n)/\ \Sigma\ C(n))SS/(\Sigma\ T(n)/\ \Sigma\ C(n))SU$

The double ratio decreases from values greater than unity for $n \le 5$ as expected but then rises to values of perhaps 1.2 for $n > 19$. This suggests seeding effects may persist much longer than the usually accepted limit of 24 hours. But still, for large n, there are less data and they are no longer scattered throughout the experiment. Thus, the results for $n > 19$ may be questionable.

A subsequent paper by Bigg and Turton (1986) also examined the persistence effects in Tasmania. The physical layout of the target and control areas was as noted above but with a northwest control (NWC) area beyond the north area (N). The superposition method described in Bigg (1985a) and (1985b) was again employed in Bigg and Turton (1986) but the sequence of

$(\Sigma\ T(n)/\ \Sigma\ NWC(n))SS$

ratios were not terminated at the next seeded day but instead carried out forward for $n = 24$ days and backward for $n = -12$ days. It was argued that by going beyond the next seeded day one uses more of the data, but it is equally clear that one is confusing the data by calling some datum the n-th datum when in fact it may be for the zeroth or first day past the next seeded day. Thus, any composite effect such as greater precipitation ratio

$(\Sigma\ T(n)/\ \Sigma\ NWC(n))SS$

attributed to the n-th day may, in fact, simply exist because it is near, within a few days of, a seed day. Bigg and Turton (1986) also argue that additivity of seeding effects means that one can consider ratios at negative times, although the physical meaning of seeding effects before seeding has occurred is questionable.

Whereas Bigg and Turton (1986) start by considering single ratios

$(\Sigma\ T(n)/\ \Sigma\ NWC(n))SS$

they recognize there can be biases in using them and choose to use the double ratio instead. This is consistent with the double ratio choice in Bigg (1985a) and Bigg (1985b). From Bigg and Turton (1986), the double ratio varies with number of days after a seeded day, and is high (1.41) on day zero . This was likely not due to chance. A rerandomization is used to gauge the statistical significance of the double ratios . Bigg and Turton (1986) claim from the double ratio values versus day curve a 41 percent positive seeding effect on day zero and double that for day nine. There is no discussion on how the basic procedure of calculating the ratio beyond the next seeded day affects the ratio. This is a major worry and potential flaw in this procedure.

In a later study of persistence, Bigg and Turton (1988) considered a combination of the data from seven different Australian precipitation enhancement experiments. Three of the experiments were of the target-control design, and the other four were crossover. For these latter experiments it was necessary to create new control data sets. A double ratio of seeded to not-seeded precipitation in target and control areas n days after a seed or no-seed day appeared to imply a prolonged after effect of seeding peaking at perhaps 10-15 days after seeding. The study was repeated just for the winter season and a similar effect was found. As before, the superposition function was not well-defined and represents a confusion of the number of the day for which a precipitation amount is being allocated. Also of concern is how the superposition function for no-seed days takes into account data on the farside of an intervening seed-day. Overall, Bigg and Turton (1988) consider the precipitation for all Australian precipitation enhancement experiments through 1983.

Although Bigg and Turton (1988) lay out the reasons for preferring the double ratio analysis they still resort to the single ratio analysis. Reference in this review is also made to Mather, Bigg, and Renton (1990) and Bigg (1995). The first paper compares the single ratio from Bigg and Turton (1988) with that found in South Africa where a hail suppression project apparently resulted in more rain. The ratios show what appears to be a persistence of seeding effect occurring in both South African and Australian data sets 10-15 days after a seeded day. Bigg (1995) is concerned with single ratio precipitation superposition series for the Melbourne Water target and control areas for both seeded and not-seeded days. The seeded series is found to correlate reasonably well with the single ratio series of the 7 experiments through 1983 considered in Bigg and Turton (1988). Bigg (1995) concluded there was an apparent persistence effect in the Melbourne Water experiment. That this was not coincidence was supported by a very low correlation between the MW not-seeded series and the 7-experiment seeded series. It is not clear why the Melbourne Water or the 7-experiment results of their respective series did not involve the the relatively unbiased double ratio series.Bigg (1985a) and Bigg and Turton (1986) both noted this feature of the double ratio series. Bigg (1985a, 1985c) discussed several double ratio formulations that may be used when a cross-over experiment is being evaluated.

b) Ice nucleus effects

Whereas the Bigg work presented so far has been concerned with precipitation amounts which are the bottom line of a precipitation enhancement experiment, additional understanding of the persistence effect can be gained from consideration of ice nucleus information. Bigg (1985b) presents a time-series of the ice nucleus concentration northwest of the northwest control area. The time-series shows a maximum in the concentration some ten days after seeding, suggesting some persistence of the seeding effect. Yet, these concentrations are measured upwind of the seeding area , and it is therefore difficult to understand how silver iodide reached the sampling site. These results are for up to 2 weeks after seeding. Longer term ice nucleus effects will now be considered.

In both the New England and Warragamba experiments and in an operation in a wheat-growing area of western Victoria a decrease in the ice nucleus concentration by a factor of 2 or 3 was observed after the cessation of cloud seeding activity with the decrease occurring over a period of perhaps 6-12 months. Both decreases are toward a background ice nucleus concentration thereby implying that the higher initial concentration was due to persistence of seeding effects.

Bigg (1985b) derived a cumulative seeding index which appears to have some value in predicting seeding effects from seeding material amounts . It is assumed that the concentration N of ice nuclei from seeding at time $t= t(n)$, namely $N(t(n))$, is related to the initial seeding concentration $N(t(0))$ at time $t=t(0)$ and to the amount of seeding material S dispensed at time $t(n)$ by the equation

$$N(t(n)) = N(t(0)) + \sum_{t=t(0)}^{t=t(n)}$$

$$S(t(n)-t(0))\exp(-\alpha(t(n)-t(0)))$$

S is an accumulating seeding material factor while the exponential is a decay term with a time constant alpha. Bigg related the target to control precipitation ratio in the Tasmania I and New England projects separately to the summation term (the cumulative seeding index) and found a reasonably linear relation in each case. The time constant alpha was 1/75 day for Tasmania and 1/36 day for New England. This finding indicates a connection between ice nucleus concentration and the precipitation seeding effect. What is particularly interesting is that if the nucleus concentration only slowly decays with time after some seeding there will be a corresponding slow decay in seeding effect - hence, a persistence effect.

c) Chemical and biological effects

Bigg and Turton (1987) are concerned with mechanisms whereby silver iodide can interact with the environment and lead to persistent cloud seeding effects. The mechanisms fall into two categories: chemical or biological. Rosinski and Parungo (1966) and Rosinski (1987) have been concerned with the chemical mechanism while Bigg (1985b, 1988) and Bigg and Turton (1986, 1987) have discussed possible biological mechanisms. Both mechanisms are treated here.

Rosinski and Parungo (1966) proposed that persistence could occur if the iodine in silver iodide reacted with terpenes in the plants on which it was deposited after release. A possible example was a seeded pine forest in which ice nuclei were found for some months subsequent to silver iodide release.

Bigg (1985b) was dubious about the above mechanism since the amounts of silver iodide (1 microgram per square meter) deposited annually were so small. In his view the silver iodide would terminate in the soil, be bound there chemically, and not be reemitted from the surface as a secondary ice nucleus. The iodine naturally present in soil would be much more abundant than that from seeding such that the iodine in silver iodide would not be relatively active to any extent. The deactivation of silver iodide in sunlight would work against it acting as a secondary ice nucleus. Bigg's point of view was also published in Bigg (1988) and eventually elicited a response from Rosinski (1987).

Rosinski (1987) argued that the iodine present naturally in the environment is not present in compounds which nucleate ice at warm (but subzero) temperatures and that it is present in any case in quantities lower than produced by plants on which silver iodide is deposited. The iodine from silver iodide takes part in a photochemically activated reaction with terpenes with the solid or liquid reaction product (ice nucleus) reaching the atmosphere by simple evaporation from the plant surface.

Bigg's (1985b) discussion of the biological origin of ice nuclei centers on the ice-nucleating abilities of two plant or soil-dwelling bacteria found in leaf litter known as pseudomonas syringae and erwinia herbicola. (Note: The former bacterium is used to nucleate water in ski snow-making. It is marketed as Snomax by Genencor, Inc.) These two bacteria possess ice-nucleating abilities which vary amongst members of the same bacteria. It has been shown that the emission of ice nuclei occurs mainly from the plant canopy. Bigg speculates that the nuclei are the bacteria themselves. The ice-nucleating ability may originate in the outer-layer of the bacterium in ice-nucleating sites mimicking those on silver iodide deposited on plant material and present in the vicinity of the bacterium. It is further speculated that ice-nucleating bacteria , compared to non-ice-nucleating bacteria, have a propensity to multiply and disperse and propagate. If this is true persistence of seeding effects may be conducive to further persistence.

Bigg and Turton (1986) conducted a

field experiment, involving the application of silver iodide to plant life on the ground, in order to discover what ice nuclei developed and whether they might be suitable for promoting the persistence of seeding effects. Two complete plastic enclosures surrounding growing grass were prepared. Silver iodide solution was added to the grass in one of the enclosures and the ice nucleus concentrations in both enclosures were measured simultaneously and daily over a succeeding 220 day period. About 2-3 times as many ice nuclei were found in the atmosphere in the seeded enclosure. This result is believed to demonstrate that application of silver iodide leads to a persistent enhanced concentration of ice nuclei. The nature of the nuclei was studied by culturing. Approximately five times as many bacterial ice nuclei were measured in the seeded enclosure as in the not-treated one. From these results it is hypothesized that a delayed effect of cloud seeding is an enhanced concentration of airborne ice-nucleating bacteria induced by silver iodide added to vegetation. Bigg (1985b) concludes that a cloud seeding experiment should be accompanied by an extensive ice-nucleus measuring network. Lengthy not-seeded periods in the experiment as in Tasmania I may aid in detection of persistent cloud seeding effects.

Bigg's (1988) second field experiment involved deposition of a silver iodide solution on a field of newly growing wheat, and subsequent measurement of the concentration of ice nuclei at various downwind or other directions from the treated field. One of the filter sites was largely upwind of the treated field and displayed a lower nucleus concentration. Overall, the directions of the high nucleus concentrations were consistent with a nucleus source in the sprayed field and travel of the nucleus with the surface winds. The highest concentrations in the sprayed area occurred within 24 hr of the treatment but peaks in the concentrations were also observed at 10, 20, and 40 days afterward as well. The observation of high concentrations was consistent with terpene-iodine reactions of Rosinski (1987) and with bacterial stimulation by silver iodide and transport, but still there is the possibility that the measured nuclei were being (re)emitted by primary silver iodide particles lodged on the ground.

6. GENETIC ENGINEERING

Levin , Yankofsky, Pardes, and Magal (1987) have explored the question of bacterial ice nucleation. They do not consider it to occur after silver iodide is dispensed into clouds. Rather, they treat ice nucleation as an inherent property of some bacteria. Their discussion begins with a recitation of bacteria which may promote condensation- followed -by - freezing. A selection of the bacteria are genetically-engineered to increase the proportion of bacteria which may promote these processes. The first process is condensation and the bacteria are highly effective in promoting it. Freezing process activity appears rarer involving perhaps 0.1 percent of all bacteria. Efforts are made to increase this percentage to 100 percent such that every particle contains a freezing nucleus.

A cloud model was used to investigate quantitative particle growth by condensation and freezing. Simulated not-seeded clouds as well as clouds seeded with silver iodide or bacteria were considered. More rain was found to fall from the bacteria-seeded cloud than from either of the other clouds. In the bacteria-seeded cloud an ice-process had developed at temperatures as warm as -5C whereas in the silver iodide seeded cloud temperatures colder than -10 C were required.

7. RELATED WORK

Ryan and Sadler (1995) argued that allowance in the past for persistence effects would have implicitly increased seeding effects though there is still a need for development of new statistical tests that explicitly take into account the possibility of persistence. Since persistence appears associated with the use of silver iodide as the particular ice nucleant efforts may be required to identify an alternative material such as

"REVIEWED"

bacterial nuclei. Ryan and King (1997) have also commented on the question of persistence.

Warburton (1973) described the Pyramid Pilot Cloud-Seeding Project. Radar data in the Sierra Nevada showed that in some locations radar echoes may persist while in other locations echoes are transient. If echoes persist several days after seeding then greater precipitation may occur over those days. If this persistence also occurs in a reasonable fraction of a project target area then higher amounts of precipitation may be found in the target during some time period after seeding. It should be noted that persistence of echoes may be connected with a combination of wind flow and topographic features in the target area. Hence, the kind of persistence proposed by Bigg may originate in wind flow interacting with topography and producing radar echoes in a part or parts of a target area for a lengthy period of time over which there is a persistent accumulation of precipitation.

Lund (1973) made a study of the persistence of cloudy and cloud-free lines- of -sight at a location in Missouri, U.S.A. It was found that if cloudy or cloud-free conditions of some degree prevail at some starting time then those conditions tend to continue during daylight hours. The implications are that if cloudy conditions are present when seeding is accomplished there is likely to be cloud later and, therefore, precipitation later with a persistence effect occurring. The whole sky camera, if used in numbers in a network, could be the basis of a study of cloud probability of occurrence as a function of spatial location in target and control areas. This would indicate whether cloud amount is greater during or after seeding, where seeding ought to occur, and where seeding effects would likely occur.

Lund and Grantham (1977) considered persistence, runs, and recurrence of precipitation. Although they focussed on time spans of 12 hr or less, the probabilistic methods they employed should be applicable to daily sequences of precipitation measured at a number of stations . The methods should establish the places and seasons where precipitation may persist after a seeded day. It will be important to understand the way in which a maximum of precipitation develops from the data and the kind of data that are conducive to development of the maximum. It would be important to understand what may be unique in a set of precipitation data that implies such a maximum in the precipitation when data elsewhere may not demonstrate it. There should be provision for using both Lund and Grantham's approach and methods more current with existing probabilistic and statistical methodology.

Super, McPartland, and Heimbach (1975) measured the deactivation of activity of silver iodide released from a ground generator . (The generator solution included the silver iodide as well as ammonium iodide, water, and acetone.) The plume from the generator was tracked downwind with an aircraft carrying an ice nucleus counter.Nucleus concentrations were converted to downwind fluxes in the plume, and changes in fluxes with downwind distance indicated the persistence of the nuclei. Persistences were calculated amounting to a factor of two deactivation of nuclei and possibly none at all per hour of evolution of the nuclei . (This deactivation is to be compared with that of a factor of 10-100 when generator solution includes sodium iodide instead of ammonium iodide.) The minimal deactivation of the silver iodide solution in the current tests suggests the silver iodide may be active for some time after generation and thus persist.

Persistence was treated by Vali, Koenig, and Yoksas (1988) in a study of regions of cloud seeding potential in a broad variety of clouds in the Duero Basin of Spain in three winter and three spring seasons. Such regions contained for 10 min or more, a supercooled liquid water content above 0.1 g per cubic meter over distances exceeding 10 km or above 0.3 grams per cubic meter over smaller distances. The view taken was that if such liquid water content was observed then a region of cloud seeding potential was persistently present. Whereas Bigg believes that the presence of secondary ice nuclei is necessary for large amounts of precipitation 10-15 days after a seeding day there may be other necessary conditions for this precipitation to develop. Other necessary conditions are a) the existence of updrafts to lift moist air until it has cooled sufficiently for supercooled liquid water to form, b) a minimum supercooled liquid water content, c) an upper bound on the number concentration of natural ice particles (say less than 10 particles per liter), d) microphysical colloidal stability of the clouds simultaneously with little or no precipitation, e) a liquid water content in excess of ice water content , and f) the above conditions prevailing over an economically significant target area.

Deshler and Reynolds (1990) have described a field experiment in the Sierra Nevada in which airborne generated silver iodide ice nuclei and microphysical effects on hydrometeors persisted 90 min downwind and 100 km away from the original seedline.

8. CONCLUSIONS

Persistence of cloud seeding effects means the microphysical structure of clouds and the development of precipitation may be affected for a significant amount of time (say days) after the seeding has been completed. Persistence may complicate the evaluation of a cloud seeding experiment and reduce the perceived net effect of the seeding. The sensitivity of the experiment to the actual net effect may be reduced. Studies of persistence have been ongoing by various investigators for about 40 years with mixed results as to how long it occurs in any given situation.

Ice nuclei and precipitation have been the primary focus of persistence studies. Elevated concentrations of ice nuclei introduced into the atmosphere by cloud seeding may persist and be responsible for effects on precipitation in turn. Ice nucleus concentration measurements in at least one experiment were about five times background values for two days after seeding (Reinking, 1972).

Possible persistent effects on precipitation data were found in Colorado and New Mexico. These studies demonstrated a) how ice nuclei can remain in a seeding project area after seeding has ceased, b) how seeding effects can be masked if remanent seeding occurs in parts of no-seed control periods, and c) how seeding effects become clearer if there is a clear assignment of precipitation data to the correct seed or no-seed category if warranted.

The Bigg research showed an apparent peak in the precipitation two weeks after a seeded day. A superposition method was used to extract the mean precipitation n days after a seed day. In early analyses the number n was limited by the next seed day but later analyses considered n larger than that of the next seed day. This later choice is viewed in the present paper as confusing the analysis and is not desirable.

Bigg and others have addressed chemical and biological origins of ice nuclei. The general opinion is that silver iodide being deposited on plants leads to chemical reactions or biological developments that result in the release of chemical reaction products or microorganisms into the atmosphere with ice nucleating capability. Rosinski, Levin and coworkers have made contributions to these topics.

A range of probabilistic and statistical methods may be applied to a precipitation data set or cloud cover data set (the clouds controlling the precipitation) to search for maxima in the precipitation and clouds so many days after a seeded or not-seeded day.

It should be noted that since the early 1970's photodeactivation of silver iodide no longer appears to be a factor reducing persistence given the ammonium iodide now being used in place of sodium iodide in the seeding solution. Hence, the silver iodide may now more readily persist.

Although persisting ice nucleus concentrations are viewed as being important for persistent cloud seeding effects it is known that there are other necessary conditions which must prevail if clouds with significant potential precipitation are to exist. These conditions are related to cloud formation dynamics, minimum supercooled liquid water, excess liquid water over ice water, and minimum cloud depth and area.

9. RECOMMENDATIONS

a. Incorporate design and analysis features into a cloud seeding precipitation enhancement project experiment which permit testing for and estimating persistence effects in addition to, and insofar as they influence, the traditional cloud seeding effects.

b. As part of the design develop a comprehensive long-term precipitation climatology for the experimental areas including the target, control, and surrounding areas to support a range of historical tests for experimental results.. Include in the design appropriately long, closed non-experimental periods during the experimental seasons to allow persistence to decay, to reduce persistence accumulation, and to reduce persistence influences on experimental results. Include a control area in the design but never seed it (i.e., do not use single area or cross-over designs).

c. Evaluate the persistence fraction *a* (see Bowen (1966)) and develop measures of the persistence-modified sensitivity of the main experimental tests.

d. Make a clear exposition of all data and analyses used in the persistence, main, and subsidiary experimental studies so other investigators can repeat the analyses or better understand how to make similar analyses of their own data.

e. Evaluate the precipitation superposition method of Bigg (1985a, 1985b, 1985c) and Bigg and Turton (1986, 1988) focusing on i) the double ratio versus the single ratio variable, and ii) the number of days after a seed day for which the method is valid. Develop the probabilistic-statistical method of Lund and Grantham (1977) and others for this work. Also, consider current methods for extracting delayed seeding effects due to persistence drawn from the discipline of time-series analysis.

f. In addition to ice nucleus concentration as an experimental covariate for precipitation incorporate as other experimental covariates cloud updrafts, boundary layer vapor content, supercooled cloud liquid water content, natural ice particle concentration, cloud colloidal stability, satellite cloud top temperature, cloud top area, cloud volume, and cloud form

g. Evaluate ice nucleus measurement technology (including networks) and its suitability for measuring persistence with respect to natural, silver iodide, chemical, and biological ice nuclei . Develop a network of whole sky cameras and associated data processing and analysis hardware and software for assessment of cloud persistence. Apply meteorological radar for measurement of precipitation persistence in target, control, and surrounding areas.

h. Devise further laboratory and field experiments focusing on the surface deposition of silver iodide on plants, the ground, and snowpacks and its nucleation, chemical and microbiological effects. Consider inherent bacterial ice nucleators as well. Investigate current knowledge in aerochemistry and aerobiology. Explore genetic engineering of cloud seeding bacteria and large quantity releases into the atmosphere.

ACKNOWLEDGEMENTS

Mr. Ian Searle and the Hydro-Electric Corporation supported this work.

REFERENCES

Bigg, E.K., 1985a: Persistent effects of cloud seeding. Search, 16, 40-42.
Bigg, E.K., 1985b: Unexpected effects of cloud seeding with silver iodide. J. Wea. Mod., 17, 7-17.
Bigg, E.K., 1985c: Estimating cloud-seeding

success in the presence of persistent effects of seeding. Fourth WMO Scientific Conference on Weather Modification,Honolulu. Publication WMO/TD- No.53. World Meteorological Organization, Geneva, 467-471.

Bigg, E.K., 1988: Secondary ice nucleus generation by silver iodide applied to the ground. J. Appl. Meteor., 27, 453-457.

Bigg, E.K., 1995: Tests for persistent effects of cloud seeding in a recent Australian experiment. J. Appl. Meteor., 34, 2406-2411.

Bigg. E.K., and E. Turton, 1986: Delayed effects of cloud seeding with silver iodide.J. Clim. Appl. Meteor., 25, 1382-1386.

Bigg, E.K., and E. Turton, 1987: Reply. J. Appl. Meteor., 26, 1466.

Bigg, E.K., and E. Turton, 1988: Persistent effects of cloud seeding with silver iodide. J. Appl. Meteor., 27, 505-514.

Boucher, R.J., 1956: Operation Overseed. Final Report to the Advisory Committee on Weather Control, Vol. II. December 1955 - January 1956, Mount Washington Observatory. U.S. Government Printing Office, 88 pp.

Bowen, E.G., 1965: Lessons learned from long-term cloud-seeding experiments. Proceedings of International Conference on Cloud Physics, Tokyo and Sapporo, 429-433.

Bowen, E.G., 1966: The effect of persistence in cloud seeding experiments. J. Appl. Meteor., 5, 156-159.

Bowen, E.G., 1968: Review of current Australian cloud-seeding activities. Proceedings of the First National Conference on Weather Modification, Albany. American Meteorological Society, Boston, 1-7.

Brier, G.W., 1974: Design and evaluation of weather modification experiments. Chapter 5 in Hess, W.N., Weather and Climate Modification. John Wiley and Sons, 206-225.

Dennis, A.S., 1980: Weather modification by cloud seeding. Academic Press, New York, 267 pp.

Deshler, T., and D.W. Reynolds, 1990: The persistence of seeding effects in a winter orographic cloud seeded with silver iodide burned in acetone. J. Appl. Meteor., 29, 477-488

Fletcher, N.H., 1962: The physics of rainclouds. Cambridge University Press, London, 309 pp.

Gabriel, K.R., Y. Avichai, and R.Steinberg, 1967: A statistical investigation of persistence in the Israeli artificial rainfall stimulation experiment. J. Appl. Meteor., 6, 323-325..

Grant, L.O., 1963: Indication of residual effects from silver iodide released into the atmosphere. Proceedings of Western Snow Conference 1963, 109-115.

Hess, W.N., 1974: Weather and Climate Modification. John Wiley and Sons, 842 pp.

Levin, Z., S.A. Yankofsky, D. Pardes, and N. Magal, 1987: Possible applications of bacterial condensation freezing to artificial rainfall enhancement. J. Clim. Appl. Meteor., 26, 1188-1197.

Long, A.B., 2001: Review of downwind extra-area effects of precipitation enhancement. J. Wea. Mod., 33, in press.

Lund, I.A., 1973: Persistence and recurrence probabilities of cloud-free and cloudy lines-of-sight through the atmosphere. J. Appl. Meteor., 12, 1222-1228.

Lund, I.A., and D.D. Grantham, 1977: Persistence, runs and recurrence of precipitation. J. Appl. Meteor., 16, 346-358.

Mather, G.K., E.K. Bigg, and S. Renton, 1990:Apparent persistent effects in the Nelspruit area from silver iodide seeding for hail suppression. J. Appl. Meteor., 29, 806-811.

National Academy of Sciences, 1973: Weather and Climate Modification - Problems and Progress. Committee on Atmospheric Sciences, National Research Council. National Academy of Sciences, Washington, D.C.,258 pp.

Reinking, R.F., 1972: Target area persistence of cloud seeding material. Preprints, Third Conference on Weather Modification, Rapid City. American Meteorological Society, Boston, 109-112.

Rosinski, J., 1987: Comments on "Delayed effects of cloud seeding with silver iodide." J. Clim. Appl. Meteor., 26, 1464-1465.

Rosinski, J., and F. Parungo, 1966: Terpene-iodine compounds as ice nuclei.J. Appl. Meteor., 5, 119-123.

Rottner, D., S.R.Brown, and O.H. Foehner, 1975: The effect of persistence of AgI on randomized weather modification experiments. J. Appl. Meteor., 14, 939-945.

Ryan, B.F., and W.D. King, 1997: A critical review of the Australian experience in cloud seeding. Bull. Amer. Meteor. Soc., 78, 239-254.

Ryan, B.F., and B.S. Sadler, 1995: Guidelines for the utilisation of cloud seeding as a tool for water management in Australia. Sustainable Land and Water Resources Management Committee, Subcommittee on Water Resources Occasional Paper SWR No. 2. Agriculture and Resource Management Council of Australia and New Zealand, 28 pp.

Simpson, J., and A.S. Dennis, 1974: Cumulus clouds and their modification. Chapter 6 in Hess, W.N., Weather and Climate Modification. John Wiley and Sons, 229-281.

Smith, E.J., 1967: Cloud seeding experiments in Australia. Proceedings of Fifth Berkeley Symposium on Mathematical Statistics (Weather Modification Experiments, Vol. 5) University of California Press, Berkeley, 161-176.

Smith, E.J., 1974: Cloud seeding in Australia. In Weather and Climate Modification (ed. W.N. Hess) pp. 432-453 (J. Wiley and Sons)

Smith, E.J., E.E. Adderley, L. Veitch, and E. Turton, 1971: A cloud seeding experiment in Tasmania. Proceedings of International Conference on Weather Modification, Canberra. Australian Academy of Science, 91-96.

Super, A.B., J.T. McPartland, and J.A. Heimbach, Jr., 1975: Field observations of the persistence of AgI-NH4I-acetone ice nuclei in daylight. J. Appl.. Meteor., 14, 1572-1577.

Twomey, S., 1960: On the nature and origin of natural cloud nuclei. Bull. Obs. Puy de Dome, 1, 1-19.

Vali, G., L.R.Koenig, and T.C. Yoksas, 1988: Estimate of precipitation enhancement potential for the Duero basin of Spain. J. Appl. Meteor., 27, 829-850.

Warburton, J.A., 1973: The Pyramid pilot cloud-seeding project. Proceedings of WMO/IAMAP Scientific Conference on Weather Modification, Tashkent.. Publication WMO - No. 399. World Meteorological Organization, Geneva, 179-186.

Warner, J., 1968: A reduction in rainfall associated with smoke from sugar cane fires - an inadvertent weather modification. J. Appl. Meteor., 7, 247-251.