The Effect of Persistence in Cloud Seeding Experiments

E. G. BOWEN
Radiophysics Laboratory, CSIRO, Sydney, Australia

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ABSTRACT

A basic assumption made in the design of most cloud seeding experiments is that each seeded period is independent of those which preceded it, i.e., that no cumulative effects are present. It now appears that this assumption is not entirely valid.

An investigation is made of the effect of persistence in a typical cloud seeding experiment and it is shown that one consequence is an apparent reduction in the result of seeding with time. There is reason to believe that this has actually occurred in many cloud seeding experiments.

A modified design of experiment is suggested which will indicate whether cumulative effects have occurred and will allow a more accurate assessment of the overall result of cloud seeding.

1. Introduction

A basic assumption made in the design of many cloud seeding experiments is that no cumulative effects occur as a result of seeding. However, evidence is now growing that persistence may have occurred in several types of experiment. In an analysis of silver iodide seeding near Mount Washington, Boucher (1956) has described occasions on which high freezing nucleus counts were found several days after a seeding operation. Similarly, in a mountain experiment in Colorado, Grant (1963) has obtained evidence that the freezing nucleus count remained high for several weeks or months after seeding was discontinued.

It does not follow that the same kind of persistence exists in experiments in other geographical locations, but the fact that cumulative effects might be present can no longer be discounted. There are, of course, several physical processes which might give rise to a cumulative effect. Persistence of the seeding material from one day to the next, changes in the thermodynamics of a situation due to the fact that rain or snow has fallen, and the influence on the condensation nucleus count of moisture lying on the ground, have all been suggested from time to time. The purpose of this paper is to explore the consequence of such effects in cloud seeding experiments. For this purpose we do not need to define the exact physical process; only that when seeding is carried out, the effect on rainfall persists or builds up at a certain rate, and that when seeding stops the effect does not stop instantaneously but decays at some finite rate.

Several designs of cloud seeding experiments have been used in recent years and in general they fall into three broad classes:

1) Experiments in which a single area is either seeded or not seeded according to a random sequence.
2) Two-area experiments in which one of the areas is seeded or not seeded in a random sequence.
3) Two-area experiments in which one or the other area is seeded in a random sequence.

In the analysis of the results of most, if not all, of these experiments, it has been assumed implicitly that each seeding period is completely independent of those that have gone before.

Let us consider an experiment of the second kind in which there are two areas A and B, the rainfall of A being equal to that of B in the absence of seeding. During the experiment A is seeded on a random basis, while B is never seeded.

Consider such an experiment performed for n periods, half of which are seeded. Assume that the result of seeding is to increase the precipitation in A by a percentage s. If there were no persistence, the result of the experiment would be as shown in idealized form in Fig. 1. In practice, of course, the seeding sequence would be randomized, but for convenience in presentation we

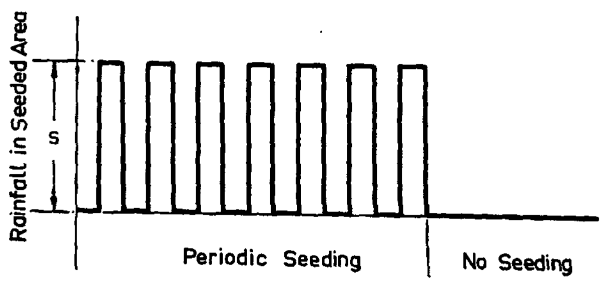

FIG. 1. Idealized result of a two-area cloud seeding experiment with no persistence.

shall regard the periods as alternately seeded and unseeded. Also, this simple pattern would be obscured by the large "noise" fluctuations of rainfall and it would require the superposition of several years of data to provide a meaningful answer.

In the circumstance described in Fig. 1, either the difference in rainfall between successive seeded and unseeded periods or the ratio of these two quantities, gives a real measure of the increase s. When seeding stops, the rainfall reverts immediately to its original value.

2. Effects of persistence

Let us now consider the changes which take place in this simple picture when cumulative effects are present. As before the first period will be considered as unseeded, and the second which is seeded will show the same percentage increase s. Assume now that some fraction a of this carries over into the next period. During the third period, which is unseeded, the increase would therefore be as. During the fourth period (seeded), the increase would be $s+a^2s$, during the fifth period (unseeded), it would be $as+a^3s$, and so on.

During unseeded periods the increase in rainfall in A during the $(n-1)^{th}$ period would therefore be

$$\begin{aligned} S_{A\ \text{unseeded}} &= 0+as+a^3s+a^5s+\cdots a^{n-2}s \\ &= as[1+a^2+a^4+\cdots a^{n-3}] \\ &= as\left[\frac{1-a^{(n-1)}}{1-a^2}\right], \end{aligned} \tag{1}$$

and *during seeded periods* the increase during the n^{th} period would be

$$\begin{aligned} S_{A\ \text{seeded}} &= s+a^2s+a^4s+\cdots a^{n-2}s \\ &= s[1+a^2+a^4+\cdots a^{n-2}] \\ &= s\left[\frac{1-a^n}{1-a^2}\right]. \end{aligned} \tag{2}$$

In practice a would always be less than unity and in the limit these would become

$$\underset{n\to\infty}{\mathrm{L}}: \quad S_{A\ \text{unseeded}} = \frac{as}{1-a^2}$$

$$\underset{n\to\infty}{\mathrm{L}}: \quad S_{A\ \text{seeded}} = \frac{s}{1-a^2}.$$

When *seeding finally ceased*, the increased rainfall in A in subsequent periods would decrease according to the simple geometric progression

$$\frac{as}{1-a^2}, \quad \frac{a^2s}{1-a^2}, \quad \cdots, \quad \frac{a^ms}{1-a^2}.$$

The overall result of such an experiment would then be as shown in Figs. 2(a) and (b) for two widely different values of a and s.

In both cases the ultimate value of the increase during seeded periods is $s/1-a^2$, and this will always exceed the increase during a single period.

However, the test variate often employed in cloud seeding experiments, i.e., the ratio of the total precipitation in successive seeded and unseeded periods, would be

$$\frac{\left(\frac{A}{B}\right)_{A\ \text{seeded}}}{\left(\frac{A}{B}\right)_{A\ \text{unseeded}}} = \frac{1+s\left[\frac{1-a^n}{1-a^2}\right]}{1+as\left[\frac{1-a^{(n-1)}}{1-a^2}\right]}. \tag{3}$$

This ratio will always decrease with increasing n as shown in Fig. 3 for the two cases illustrated in Fig. 2. Commencing with a value $(1+s)$ for the first pair of periods, the double ratio will steadily decrease to a value $(1-a^2+s)/(1-a^2+as)$ when n is large.

Similar considerations apply when the difference in rainfall between A and B is used as the test variate instead of the ratio.

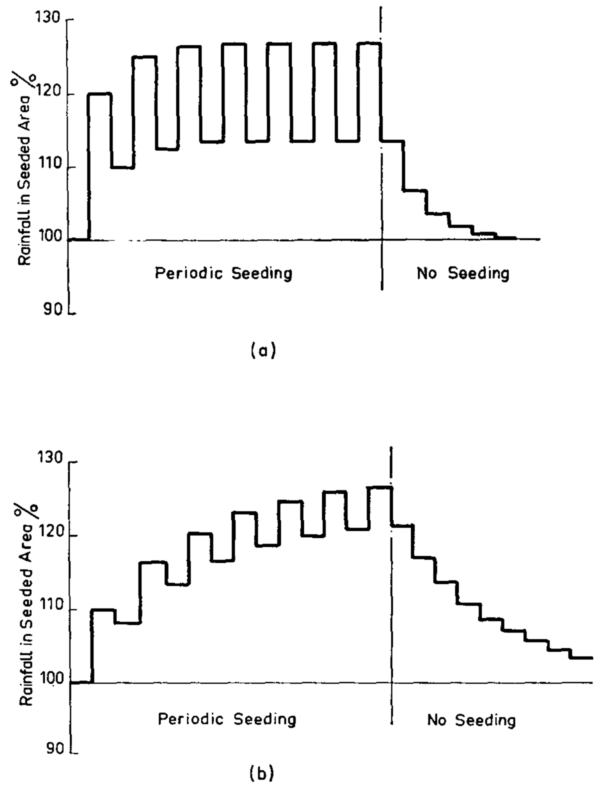

Fig. 2. Growth and decay of the results of a cloud seeding experiment in which there is an increase in precipitation (a), of 20 per cent per seeded period and a persistence of 0.5, and (b), 10 per cent per seeded period and a persistence of 0.8.

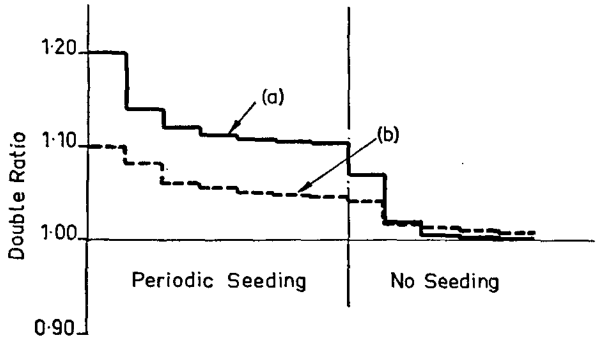

FIG. 3. The apparent result of the experiment if the ratio of successive seeded and unseeded periods is used as the test variate, for the two cases illustrated in Figs. 2(a) and (b).

3. Discussion

It appears, therefore, that if cumulative effects occur in cloud seeding experiments, the comparison of rainfall in consecutive seeded and unseeded periods could give a misleading indication of the results which have actually taken place. As we have seen, it would show an apparent decrease in the result of the experiment with increasing time.

This is precisely the result which has been observed in many recent cloud seeding experiments. In an analysis of six experiments which have taken place in different parts of the world, Smith, Adderley and Bethwaite (manuscript in preparation) have shown that in every case there has been a decrease in the apparent result as the experiment progressed (Fig. 4). This provides strong presumptive evidence that cumulative effects have occurred in all these experiments.

It is important to note that what is observed in such cases is not a decrease in the effectiveness of seeding; more correctly, it is a progressive decrease in the sensitivity of the experiment with time.

A second deduction is that if, as we have assumed, the cumulative and decay effects follow a geometric progression, a seeding schedule which is changed on a daily basis would be more damaging to the end result than if the change had been made on a longer term, for example, by storm periods. Bowen (1965) has shown that this also appears to have been the case in the six experiments referred to above, the double ratio for those experiments scheduled on a daily basis showing a smaller result than those in which the change-over was by storm periods.

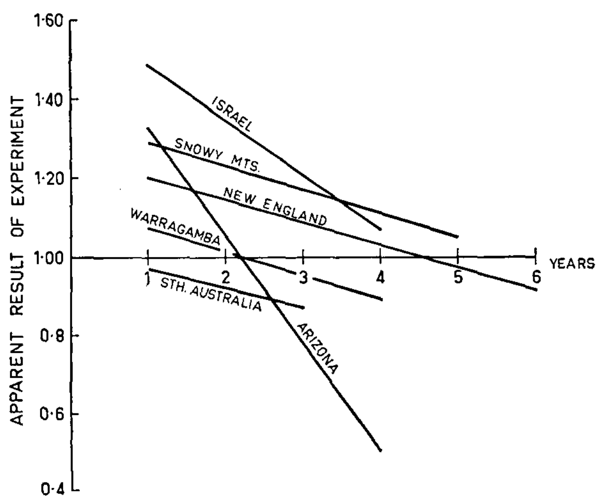

FIG. 4. The reduction in apparent result of six cloud seeding experiments in different parts of the world.

It appears, therefore, that both the gradual decrease in the result of these experiments, and the difference between those scheduled on a daily basis and those by storm periods, support the view that cumulative effects have occurred.

The present discussion is based on the case of a two-area experiment in which one area is either seeded or not seeded on a random basis. Similar considerations apply to the other classes of experiment mentioned in Section 1 of this paper, with two important qualifications.

In an experiment of the first class in which a single area is randomly seeded, no separate control region being available, the only result which can be obtained is one similar to Fig. 3. That is, from the rainfall data alone, it will not be possible to establish whether cumulative effects have taken place or not.

Similarly in an experiment of the third class involving a two area cross-over, it is again not possible to arrive at unambiguous values of the cumulative and decay characteristics as both areas are seeded in the course of the experiment. Moran (1959) has shown that, assuming no persistence occurs, a cross-over experiment has greater power than one in which only a single area is seeded. However, if persistence does occur, it suffers more severely and the sensitivity falls off more rapidly than when only one area is seeded. Moreover, when seeding finally stops, the rainfall will presumably recover at approximately the same rate in the two areas and it will not be possible from the rainfall measurements alone to determine whether cumulative effects have taken place.

4. Design and assessment of future experiments

This analysis brings out a serious failing in the design of many cloud seeding experiments. It emphasizes the importance of designing future experiments in such a way that a clear indication is obtained when cumulative effects have occurred and at the same time allows a realistic assessment to be made of the change in precipitation which actually takes place due to seeding.

Several requirements stand out. In the first place, it is important that under no circumstances should the control area be seeded. Secondly, as in any other experiment, it is preferable that good historical rainfall records be available for the target and control regions so that a proper base level can be established. Thirdly, for the reasons given above, the seeding schedule should preferably be by storm period, not on a daily basis. Finally, in addition to randomizing by storm periods, the whole experiment should be switched on and off on a long-term basis so that estimates of both the build-up and the decay can be made.

A new design along these lines was put into operation in Tasmania in 1964. In this experiment three areas C_1, C_2, and T are used. T is the target region which is seeded or not seeded in a random sequence. C_1 and C_2 are control regions on either side of the target area. Disposed in this way, they have the advantage of reducing the adverse effects of a rainfall gradient across the test area. The seeding schedule is by storm periods which are of approximately 10 to 18 days' duration and the test variate is $T/\frac{1}{2}(C_1+C_2)$. Seeding is performed only in alternate years. However, the rainfall measurements in all areas are continued during the years which are not seeded so that a measure is obtained of the decay in the effects of seeding.

Analysis will be carried out according to Eqs. (1) and (2) in which the principal quantity to be determined is the end effect due to repetitive seeding. A full account of the experiment will be published in due course.

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