

**Comments on the paper by Alexis B. Long entitled
"Review of Persistence Effects of Silver Iodide Cloud Seeding"**

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Statistical analyses of cloud seeding using fixed target and control areas usually contain several hidden assumptions, thought to be so obviously true that they are never stated. They are:

1. The effects of seeding are confined to the day of seeding.
2. There are no cumulative effects of seeding.
3. Unseeded control areas that are crosswind or upwind from the target on the day of seeding are never affected by seeding in the target area.

In the case of crossover experiments, where one of a pair of areas is selected for seeding on a random basis, assumptions 1 and 2 above are made.

Evidence that these assumptions may not be universally true has been comprehensively summarized in review papers by Long (2001a,b).

Most cloud-seeding experiments have attempted to estimate the effects of seeding by comparing the mean ratio (T/C) of precipitation in the target area, (T), to control area, (C), during seeded periods with the same ratio during unseeded periods. The decision as to whether a period is to be seeded or unseeded is made on a random (often limited) basis.

Suppose a mean T/C is calculated for each of n days (n is an integer) before a seeded day, each of which is called day 0, and also for each of n days following a seeded day. The ratios for negative n can have no physical meaning but will illustrate the range of random fluctuations. If the ratios for positive n have similar standard deviations it is unlikely that there were any after-effects of seeding.

Bigg and Turton (1986,1988) tested the first of the above assumptions using this

method on the results of the "Tasmania I" experiment described by Smith et al. (1979). In the first of these papers, n was allowed to range from -15 to 25 , while in the second it was made symmetrical about 0 with $-31 < n < 31$. The latter paper embraced results from 11 separate seeded areas, involving a total of 1245 days and showed a difference between T/C for positive and negative values of n that could not possibly have been due to chance. It was concluded that an increase of up to 20% in T/C occurred, about 2 weeks after a seeded day. Long (2001a) has criticized the work because the individual series contained seeded days other than the one on day 0. He considered that this seriously compromised the work and claimed that each series should have been terminated at the next seeded day before the overall ratio of T/C for day n was calculated. Because after-effects of seeding comparable to those on the seeded day, if they exist, would invalidate the most common methods of statistical analysis used in assessing the results of cloud seeding, it is important that Long's criticism should be closely examined.

Modulation of precipitation by seeding has been found to produce a very small signal obscured by a great deal of random variation ("noise"), mainly due to an imperfect correlation between T and C . Even after the superposition of many seeded days, it has been rare to obtain a highly significant determination of the effect of seeding. The signal-to-noise ratio in such a case can be expected to increase in proportion to the square root of the number of superimposed observations so that the longer an experiment runs the more likely it should be to detect any real result. Unless the after-effects of seeding are considerably greater than the immediate effect of

seeding they will be just as difficult to detect. Intuitively it seems unlikely that we would need to look for persistent effects that last longer than a few days, so that termination of the series at the next seeded day would not seriously affect the ability to detect them. However that is not the conclusion that would be reached by the available data on changes in concentration of ice forming nuclei (summarized by Long), which have often shown a time constant for the decay of a seeding effect longer than a month. For this reason Bigg and Turton decided that sufficient signal might be present for one month after seeding for it to be detected if all available data were used.

It is a signal-to-noise-ratio problem entirely analogous to that of detecting a small transient positive electrical signal resulting, after a time delay, from a repetitive irregularly spaced pulse in the presence of a great deal of electrical noise. Using a detector synchronized to the pulses, we have the choice of terminating the output at each subsequent pulse (method(a)) or continuing it, (method (b)). If the mean spacing of pulses is shorter than the time delay, very little information about the transient will be obtained from the first option unless very large numbers of pulses are included. This is because the number of superimposed signals decreases with time from the pulse, lowering the signal-to-noise ratio. On the other hand, if the outputs continue to be added beyond the next pulse, the base level of the output will no longer be zero during the time delay period and the deduced transient waveform will differ from that of the actual signal. This is precisely the basis of Long's criticism.

The questions that we have to answer in applying a "synchronous detector" to a T/C series in a particular cloud-seeding experiment are: (1) whether terminating the series at the next seeded day will prevent the detection of the effect that is sought through a reduction of the signal-to-noise ratio and (2) if the series is not terminated at the next seeding day, how serious is the distortion of the effect that is sought.

In the Tasmania I experiment (including phase 2, 1971) using method (a), only 25% of the 256 series started on a seeded day continued after day 5 and 5% after day 30. We need to know whether it would have been better to have used method (b).

The Tasmania I experiment declared a set of days "suitable for seeding but unseeded" in the unseeded periods, which will be called "key days". They were specified on exactly the same basis as the seeded days. This set of days had slightly longer average spacings between key days than the seeded day series due to the use of fewer unseeded periods in 1971. It should therefore be more favorable for detecting a signal than the seeded series, using method (a). It can be used to test the relative merits of methods (a) and (b) by modulating the target precipitation as follows: T on key days and the 14th day after a key day was multiplied by 1.3. T on a day that was both a key day and a 14th day after a key day was multiplied by 1.69. This provides the known signal that has to be detected. The control precipitation used was that of the "northwest control" used by Bigg and Turton.

Figure 1 shows the difference between the modulated and unmodulated sequence of precipitation ratios for the 30 days following a key day, for series: (a) terminated at the next seeded day (unbroken curve) or (b) at 30 days from a key day (dashed curve). From (a) it would be concluded that there was no significant modulation either on day 0 or on day 14. However these are the two largest peaks in the 60 day series of (b). **In my opinion, it is not constructive in testing assumption 1 to use a method incapable of detecting a 30% increase in target precipitation on day n .**

A further criticism of the Bigg and Turton (1988) work on persistence offered by Long was that the T/C series were extended to negative values of n , (-30) which were physically meaningless. As stated above, this was precisely why they were included and were also included in figure 1. The point was made in the last paragraph on p.509 of the cited paper but was apparently overlooked by Long.

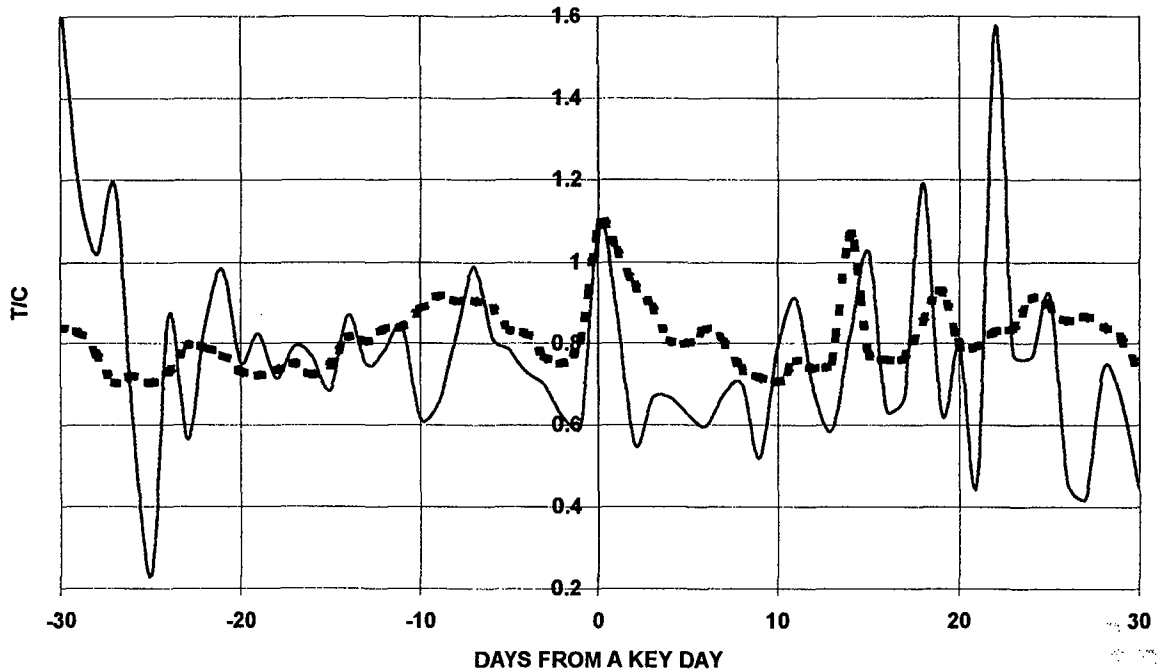


Figure 1:

Response of T/C to an impressed 30% increase in T on key days and the 14th day after a key day. Unbroken curve: series terminated at the next key day. Dashed curve: series terminated at 30 days after each key day. The key days are those classed as "suitable for seeding but unseeded" in the Tasmania I experiment. The mean target (T) and northwest control area (C) precipitations were used.

Another complaint made by Long was that Bigg and Turton (1988) did not use the superior double ratio method for the composite results from Australian experiments prior to 1986. In the 1988 paper we did in fact use a double ratio method and the way in which it was used is described in detail on p.509 of that paper. Days classed as "suitable for seeding but unseeded" were available for only the two Tasmanian experiments. Eight of the 9 other seeded areas used a crossover design and had no unseeded controls. We therefore selected control areas and days classed as suitable for seeding but unseeded after the experiments had concluded. This would be an unacceptable procedure from a statistical point of view for detecting the effect of seeding on a seeded day because of possible bias in the choice of controls. Differences in T/C between positive and negative

values of n would not be affected by such a bias in the absence of persistent effects of seeding. Bigg and Turton (1988) found that persistence effects were indicated for all 11 of the examined cases and produced a composite result to show the mean magnitude of the effect. The remarkably similar result found by Mather et al. (1990) in South Africa suggests that such effects are not confined to Australia and may even be larger elsewhere.

In 1987 I proposed a test for persistence before the start of a new 5-year cloud-seeding experiment in southeast Australia, the "Melbourne Water" experiment. I specified that it would rely on the correlation coefficient between T/C and the single ratio of Figure 4a in Bigg and Turton (1988). The reason for doing this was that a comparison of the double ratio of their figures 3 and 4a, shows that it doesn't really matter which is used. Long has again

criticized the failure to use the double ratio procedure and the use of method (b). The project's statisticians adopted his advice to use method (a), in spite of my objections. Not surprisingly in view of the above discussion, they found that there were no real after-effects of seeding. However Bigg (1995) using method (b), found a highly significant correlation with Figure 4a, in spite of the fact that no significant effect of seeding on day 0 has been claimed. Note that the correlation was not "very low" as described by Long – it was high and significant at better than the 0.1% level.

The conclusion concerning Long's criticisms is that they were based on an imperfect appreciation of signal-to-noise ratio problems and an insufficiently careful reading of the 1988 paper being criticized.

If persistent effects of cloud seeding with silver iodide are real, as seems certain from the available evidence, how can future experiments be assessed, or past ones re-assessed? In principle, one method is to form isohyets of the ratio of precipitation recorded by all gauges within a large area surrounding and including the target area to their long-term historical averages. A lengthy experiment is required to avoid problems caused by heavy precipitation in random parts of the chosen area. There is then the serious disadvantage that long-term changes in the regional distribution of precipitation, unrelated to the seeding, may falsify the result. To minimize such effects, sequences of both seeded and unseeded years is required. The "historical data" can then be drawn from unseeded years between the various experimental periods as well as from pre-seeding periods. In Tasmania, where seeding started in 1964 and has continued to the present time with lengthy unseeded periods, the historical comparison method has been used for many years by the hydroelectric authority's cloud seeders. Judging from the very consistent results obtained, the region has not suffered major natural redistributions of precipitation. The isohyets have consistently suggested an overall increase in total precipitation in the targeted

area of the order of 15-20%. They also suggest that the increase extended considerably beyond the target area, as one might expect if there are persistent effects of seeding not confined to the wind directions prevailing during seeding.

A final request to those wishing to search for persistent effects of seeding in any experiment: calculate the magnitude of the minimum effect your method could detect before publishing a negative result!

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