Comments on "Randomized Cloud Seeding in the San Juan Mountains, Colorado"[1]

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ABSTRACT

Several aspects of the study by Elliott *et al.* (1978) of the Colorado River Basin Cloud Seeding Pilot Project are discussed. Issues addressed include the design of the project, the diffusion of the seeding agent, anomalous ice nucleus concentrations in the target area, and statistical analysis of the randomized experiment.

1. Introduction

Elliott *et al.* (1978, hereafter referred to as E) have done a commendable job of condensing and analyzing the results of the Colorado River Basin Pilot Project (CRBPP), a 5-year randomized cloud seeding experiment carried out in the San Juan Mountains of the Colorado Rockies. Their principal conclusions are that there was no significant statistical difference between precipitation on seeded and unseeded days, but an *a posteriori* analysis, based on 6 h time blocks (in place of the original 24 h day), indicated that positive seeding effects may have been achieved

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during periods when cloud-top temperatures, derived from a model, were ≥−29°C.

In this note, we examine several statements made by E and consider a number of points relevant to their analyses of the CRBPP.

2. Design of the Colorado River Basin Pilot Project

E state that the Climax I and Climax II experiments "demonstrated the significance of cloud-top temperature in relation to the effects of seeding." In fact, the results of the Climax (and Wolf Creek Pass) experiments were reported in terms of 500 mb temperatures. Hobbs and Rangno (1979) have pointed out that there is no evidence to support a relationship between 500 mb and cloud-top temperatures in the Colorado Rockies.

The design of the CRBPP[2] was based on the results of earlier cloud seeding experiments, carried out by Colorado State University (CSU) scientists, in the Climax and Wolf Creek Pass areas of the Colorado Rockies (see, e.g., Grant and Mielke, 1967; Mielke *et al.*, 1970; Chappell *et al.*, 1971; Mielke *et al.*, 1971, 1977). We have recently criticized the physical foundations of the Climax and Wolf Creek Pass experiments (Hobbs and Rangno, 1979) and CSU's statistical analysis of the Wolf Creek Pass experiment (Rangno, 1979). In this connection we note that E state that the CRBPP was confounded when randomized decisions were drawn on storm days specifically excluded by the design; but for storm periods corresponding to the approximate conditions specified by the design, large increases in precipitation may have resulted from the seeding (see E's Table 3). The validity (or otherwise) of the latter statement is important, since the apparently statistically significant effects of seeding on precipitation reported by E for certain cloud types would be strengthened if these cloud types, in fact, had been specified in advance. As indicated below, we do not think this was done with any precision.

A review of the design document[2] for the CRBPP reveals that the operational guidance for the Project was not clear enough to prevent various interpretations. For example, while cloud seeding is specified for cloud top temperatures ≥ −26°C or ≥ −23°C, cloud seeding was also considered suitable for certain categories of the 700 mb equivalent potential temperature (a parameter which, like the 500 mb temperature, is unlikely to bear any relationship to cloud top temperature). In addition, seeding rates were specified for two categories of "cloud-top (*or* 500 mb) temperatures."

[2] Grant, L. O., C. F. Chappell, L. W. Crow, J. M. Fritsch and P. W. Mielke, Jr., 1974: Weather modification. A pilot project. Final Report from Colorado State University to Bureau of Reclamation [NTIS PB-237 085/6GI].

With respect to seeding in convective situations, the design document states that the CRBPP was "not designed as an experiment for seeding cloud systems that are caused by convection or large scale storms." (Ironically, the storms studied by Furman,[3] which have been cited as representative of the storm climatology for the Climax area, consisted of three major trough systems which affected areas extending over several states and contained important contributions from convective elements.) However, no criteria were given in the design document for the CRBPP to help define large-scale storms or the limits of convection. In fact, to our knowledge, no criteria have yet been proposed by the CSU scientists to eliminate such storms or convective episodes either from the Climax or the Wolf Creek Pass experiments (e.g., Grant and Mielke, 1967; Mielke *et al.*, 1971). All storms are apparently perceived as being predominantly "orographic" in nature. It should also be noted that prior to the start of the CRBPP Grant *et al.*[4] reported that the "increase in snowfall when seeding the *unstable* (our italics) events is significant at the 5% level for some of the tests for Climax I and Wolf Creek samples" and that "all three samples (Climax I, Climax II and Wolf Creek) indicate snowfall decreases when seeding the most *stable* (our italics) category." Thus the design document did not define precisely enough the conditions under which seeding should have been carried out in the CRBPP. This permitted a wide range of interpretations during the actual conduct of the Project, as well as in the *a posteriori* analyses offered by E.

Curiously, many of the 6 h blocks excluded from analysis by E on the basis of being convective had average cloud-top temperatures > −26°C (even after subjected to E's model lifting); this contradicts the design limits cited by E. It should also be noted that, contrary to the CRBPP design document, E use cloud-top temperatures derived from a model: project operations were based on unadjusted cloud-top temperatures measured from or near Durango, Colorado, or from the site approved by the designers of the CRBPP.[4] We wonder why E introduced "model lifting" when clearly, from Fig. 9 of E, ice particles nucleated at the top of their model cloud are unlikely to have reached the ground within the target. We strongly recommend that E present findings based on the unadjusted sounding data for the temperature partitions of −23 and −26°C at cloud top.

[3] Furman, R. W., 1967: Radar characteristics of wintertime storms in the Colorado Rockies. Atmos. Sci. Pap. No. 112, Colorado State University, 40 pp.

[4] Grant, L. O., P. W. Mielke, Jr., C. F. Chappell, L. W. Crow, J. L. Rasmussen, W. E. Shobe, H. Stockwell and R. A. Wykstra, 1969: An operation adaption program of weather modification for the Colorado River Basin. Interim Report from Colorado State University to Bureau of Reclamation, 199 pp.

3. Diffusion of the seeding agent

E present an exceedingly generous view of the diffusion of the seeding agent under stable conditions. For example, in their Fig. 6 a plume is shown passing through an inversion. Under *upslope stable* flow, E state that "all nucleant is immediately driven up the slope in a plume which spreads vertically by turbulence and enters the orographic cloud." E cite a study by Cermak *et al.*[5] as providing evidence from both field and laboratory studies for this statement. A review of Cermak *et al.*'s study shows that while modest vertical diffusion was observed in the laboratory under simulated *upslope stable* flow, the field study was carried out in nearly dry adiabatic conditions with clouds and precipitation. This does not seem to support E's contention concerning the vertical dispersion of seeding agents under stable conditions. Three separate airborne sampling programs in Colorado, two of which[6,7] occurred in support of the CRBPP and the other[8] in support of the Park Range Project in northwest Colorado, all found negligible vertical dispersion under stable conditions.

Verification that E's concept of vertical diffusion under stable conditions is too generous can be found in the airborne study carried out by Hobbs *et al.*[6] for the CRBPP on the afternoon of 19 February 1974, in which, after an extensive airborne search, no ice nuclei attributable to silver iodide could be found at altitudes > 150 m above the level of the silver iodide generators. This afternoon was classified as *stable warm-topped* by E and corresponds to the type of situation in which large increases in precipitation due to seeding were claimed by E.

E attribute the anomalously high ice nucleus count (6 ℓ^{-1} at -20°C) measured on a non-seeded (control) day at the CRBPP Piedra site to AgI, which they contend traveled west during a previous seeded day and then back east to the Piedra site the following day. We do not find this explanation convincing since inspection of the ice nucleus record at the Piedra site reveals numerous occasions, separated from seeded days by 2–31 days, in which ice nucleus counts $\geq 4\ \ell^{-1}$ were measured.

[5] Cermak, J. E., L. O. Grant and M. N. Orgill, 1970: Laboratory simulation of atmospheric motion and dispersion over complex terrain as related to cloud seeding operations, Preprints Second Nat. Conf. Weather Modifications, Santa Barbara, Amer. Meteor. Soc., 59–65.

[6] Hobbs, P. V., L. F. Radke, J. R. Fleming and D. G. Atkinson, 1975: Airborne ice nucleus and cloud microstructure measurements in naturally and artificially seeded situations over the San Juan mountains in Colorado. Research Report X, Cloud Physics Group, Atmos. Sci. Dept., UW, Seattle, 89 pp.

[7] Marwitz, J. D., W. A. Cooper and C. P. R. Saunders, 1976: Structure and seedability of San Juan storms. Final Report to the Bureau of Reclamation, 326 pp.

[8] Rhea, J. O., L. G. Davis and P. T. Willis, 1969: The Park Range Project. Final Report to the Bureau of Reclamation, E.G. & G., Inc.

Further, an inspection of all of the ice nucleus measurements[9] made in support of the CRBPP reveals many non-seeded periods when the measured ice nucleus concentrations were $\geq 5\ \ell^{-1}$ at -20°C. These observations raise questions concerning the high background concentrations of ice nuclei in the San Juan Mountains (or the reliability of the measurements). Marwitz *et al.* (1976)[7] provide some insight as to the nature of these high ice nucleus concentrations; the highest ice nucleus count on *any* of their flights (including low passes through seeded storms) was measured in windblown dust near Farmington, New Mexico (well upwind of the generator network). The control days discussed by E did, in fact, involve a storm which brought gale force winds and blowing dust over the region upwind of the San Juan Mountains. It seems likely that the high ice nucleus counts measured at the Piedra site on that day were due to this dust. Another possible explanation for the anomalously high ice nucleus counts is that the CRBPP target area was contaminated by silver iodide from a large commercial cloud seeding operation that was going on in Utah.[9]

4. Statistical analysis

E terminate their statistical analysis of the CRBPP after finding stratifications that yield indications of increases and decreases in precipitation on the seeded days and then attribute this to seeding effects. The danger of this approach has been illustrated by Hobbs and Rangno (1978) and Rangno (1979). It should be incumbent on any investigator reporting seeding effects based on an *a posteriori* stratification to demonstrate that the stratification is unbiased. Remarks relative to this issue are contained in the following comments:

1) Inexplicably missing from E's diagnostic analyses are data pertaining to the many precipitation stations within and surrounding the western San Juan Mountains (west of what E refer to as the "Western Upwind Flank" in their Fig. 8). This region might well serve as a control area since it is unlikely that precipitation resulting from seeding would have reached these stations. (A review of ice nucleus concentrations active at -20°C for the several observation sites west of the CRBPP target area does not reveal clear evidence that silver iodide traveled to the west during E's 6 h "stable, warm-topped" cases.)

2) At first glance, it seems prudent and reasonable to omit from analysis all non-seeded precipita-

[9] Elliott, R. D., R. W. Shaffer, A. Court and J. Hannaford, 1976: Colorado River Basin pilot project comprehensive evaluation report. Final Report to the Bureau of Reclamation, Aerometric Research Inc. [NTIS PB-262 057/3GI].

tion episodes which are suspected of being contaminated by silver iodide, as do E in their 6 h block investigations. However, this may be the cause for the substantial increase in the seed/no-seed ratios from Fig. 3 to Fig. 4 in E's analysis. Usually such an increase is attributed to a "carry-over" effect of seeding increasing precipitation during what should have been non-seeded episodes. However, an artificial inflation in the seed/no-seed precipitation ratios can be expected from elimination of the suspected contaminated episodes because the removed 6 or 24 h blocks are not independent samples, but those biased toward the heaviest natural precipitation within the non-seeded episodes. This is especially true in a project such as the CRBPP wherein large-scale troughs, which often require more than a day for passage through the Rockies and can produce precipitation during two experimental 24 h periods, bring most of the precipitation. This is illustrated by a comparison of the so-called "early call" and "late call" experimental days in the CRBPP. The total precipitation at the Wolf Creek 4 West station on "early call" days, defined as those in which the random seed/no-seed decision was made before 1700 LST, averaged 11.4 mm for the 24 h experimental day ending at 1100 LST the following morning. The total precipitation at this station for the "late call" days, defined as those in which the random seed/no-seed decision was made after 1700 LST, averaged only 4.1 mm during this same period.

Now, the back-to-back experimental days in question (i.e., "seed"/"no-seed" sequences), that resulted in possible contamination of the "no-seed" days, were in every instance characterized by an "early call" on the second day. The reason for this is that cloudiness and precipitation were already well established within the target region by the second day. All of the non-seeded 6 h blocks which E believed were contaminated were the first, and in some cases the first and the second, 6 h blocks of an "early call" day. Therefore, removal of the "early call" precipitation data, on the grounds of possible contamination, eliminates naturally heavier precipitation events from the control list.

This problem is augmented by E because these naturally heavier precipitation episodes were not only removed from the control list but were then placed in the seed list.[10]

Similarly, other days removed by E from the control list because of possible contamination from cloud seeding projects in Utah and New Mexico also involve widespread storminess; the effect of their removal is also to bias the control sample toward the smaller precipitation events.

In view of these serious problems, we believe that E's conclusions concerning the increases in precipitation due to seeding in the CRBPP cannot be considered valid unless the statistical significance can be shown to hold up after the suspected contaminated 6 h blocks are returned to the non-seeded list.

3) A danger in using a time unit (such as E's 6 h block) that is smaller than the original randomized unit (24 h) is that insignificant differences in precipitation may attain unwarranted statistical significance when the sample size is inflated by the use of the reduced time unit. The resulting statistical significance is unwarranted because the independence of the samples has been compromised. The samples are no longer strictly random because "seed" and "no-seed" blocks are obtained in ordered groups not likely to have originated from a random draw, and the serial correlation between consecutive 6 h blocks is appreciable (a heavy storm is likely to be heavy from one 6 h block to the next and a light storm likewise).

One method of circumventing this problem would be to return the 6 h time blocks back to the original 24 h randomized units (assuming that they occurred as whole days), or drawing only one 6 h block from each experimental day and testing whether the resulting smaller sample size still exhibits statistical significance.

4) Since it has been claimed that the primary effect of cloud seeding in the *daily* randomized Climax experiments was to increase the duration of precipitation rather than its intensity (Chappell *et al.*, 1971), it is surprising that this issue was not addressed by E in their analysis of the CRBPP.

5) Finally, the question of multiplicity (Gabriel, 1979) must be addressed. It seems unlikely to us that the criteria for defining "stable, warm-topped clouds" as falling within a "modified stability index" $\leq$ 75 mb and cloud-top temperature ≥ -29°C would be the result of a single *a posteriori* inspection, particularly since there is no evidence in either the CRBPP design document or previous cloud seeding literature of the importance of a "modified stability index." How much searching did E do before they found that this particular stratification of the data indicated positive seeding effects?

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