CORRESPONDENCE

Comments on "Generalized Criteria for Seeding Winter Orographic Clouds"[1]

ARTHUR L. RANGNO AND PETER V. HOBBS

Atmospheric Sciences Department, University of Washington, Seattle 98195

5 February 1980

Vardiman and Moore (1978, hereafter referred to as VM) have attempted to elucidate the conditions under which cloud seeding with silver iodide might affect precipitation from winter clouds in the western United States by reanalyzing seven randomized cloud seeding projects. They concluded that stable orographic clouds with a "crest trajectory," moderate water content, and model-derived cloud-top temperatures between −10 and −30°C showed an 18% increase in precipitation due to seeding; moderately unstable orographic clouds with a "crest trajectory", moderate to high water content, and model-derived cloud-top temperatures between −10 and −30°C showed a 52% increase in precipitation due to seeding; and that unstable orographic cloud-top temperatures below −30°C, low water content, and model-derived cloud-top temperatures below −30°C showed a 54% decrease in precipitation due to seeding.

With regard to these conclusions we raise the following issues and questions:

1) Since profound natural bias can be encountered in surprisingly large random samples of precipitation data (see, e.g., Mielke, 1979), we feel that VM should have investigated whether natural events might have been responsible for any differences in precipitation between seed/no-seed precipitation ratios, and the Wilcoxon two-sample statistic, for adjacent regions with similar exposure to the "crest group."

The fact that there are far more zero 6 h precipitation totals in the nonseeded samples (108) than in the seeded samples (35) suggests that a natural bias may indeed have been present. VM attribute this disparity to seeding having increased the concentrations of ice particles to precipitable levels. However, the concentrations of ice particles required for the release of precipitation are often present in clouds with top temperatures well into VM's cloud seeding "window" (Hobbs, 1974; Hobbs and Atkinson, 1976; Marwitz *et al.*, 1976[2]; Rangno *et al.*, 1977[3]). Consequently, it seems likely that the higher number of zero 6 h precipitation totals in the non-seeded "crest trajectory" samples was due to the natural conditions (such as cloud depth, wind direction, etc.) being less favorable for the production of precipitation than in the seeded samples.

Since the Wilcoxon two-sample statistic assigns an extreme rank to zero precipitation cases, it is important to investigate the extent to which the disparity in the zero 6 h precipitation totals contributed to the statistical significance of the difference between the seed/no-seed precipitation ratios reported by VM.

2) Cloud-top temperatures play an important role in VM's analysis. However, only rarely was this parameter measured directly—instead, VM infer cloud-top temperatures from radiosonde data. It is well known[4] that cloud-top temperatures often cannot be estimated reliably from rawinsonde data alone. Grant *et al.*, 1974,[5] for example, reported that on-site rawinsonde data do not give an accurate estimate of cloud-top temperatures 30–40% of the time. Clearly, this much uncertainty cannot be tolerated in what purports to be a definitive study on the relation between seeding effects and cloud-top temperatures.

Further degradation in cloud-top temperature estimates is bound to occur when on-site data are

[1] Contribution No. 540.

[2] Marwitz, J. M., W. A. Cooper and C. P. R. Saunders, 1976: Structure and seedability of San Juan storms. Final Report to the Bureau of Reclamation, 329 pp.

[3] Rangno, A. L., P. V. Hobbs and L. F. Radke, 1977: Tracer and diffusion and cloud microphysical studies in the American River Basin. Final Report to the Bureau of Reclamation, 64 pp. [NTIS PB-272 426/8GI].

[4] Air Weather Service Manual, 1969: Use of the skew *T*-log*P* diagram in analysis and forecasting. USAF Weather Service Manual, 105–124, 111 pp.

[5] Grant, L. O., C. F. Chappell, L. W. Crow, J. M. Fritsch, and P. W. Mielke, Jr., 1974: A pilot project of weather modification for the San Juan Mountains of the Colorado River Basin. Final Report to the Bureau of Reclamation, 324 pp. [NTIS PB-237 085/6GI].

0021-8952/80/070906-02$04.50

not available and interpolated National Weather Service soundings are used (as in the Climax Experiment which formed an important part of VM's study).

If cloud-top temperature is indeed a critical parameter in determining cloud seeding effects, then this parameter should be measured continuously in future cloud seeding experiments. This can be done, for example, by combining measurements of cloud-top heights with a K_a-band radar (Weiss *et al.* 1979) with radiosonde soundings.

3) The erratic variations in the seed/no-seed precipitation difference curves shown in Fig. 2 of VM suggest to us that the cloud-top temperature data used by VM may not be a good measure of cloud seeding potential. VM attribute the variability in the data shown in their Fig. 2 to "a number of physical factors, acting simultaneously", which affect seedability. However, this view seems to contradict what is apparently VM's major conclusion that "the cloud-top temperature remains an overriding factor in determining a seeding effect." Most surprising in this regard is the seed/no-seed difference curve for the 10-season Climax experiment shown in Fig. 2 of VM. This curve shows generally positive effects of seeding for cloud top temperatures from −40 to −5°C, with particularly pronounced effects for the colder cloud-top temperatures. Grant and Mielke (1967) and Mielke *et al.* (1971), on the other hand, reported that seeding in the Climax Experiment produced decreases in precipitation for cloud-top temperatures $\leqslant -25$°C and increases in precipitation for cloud-top temperatures $\geqslant -25$°C. In view of these discrepancies, it is difficult to see how VM could have concluded that "the results of (their studies) . . . strengthen the physical reasoning of the original Climax results."

4) VM state that the lifted cloud-top temperature "is an index of the concentration of ice crystals active in the precipitation process because of the relation between cloud temperature and nucleation of ice crystals." This is a surprising claim in view of the fact that there is a growing body of field evidence that the relation between cloud-top temperature and the concentration of ice particles in clouds is extremely complex (e.g., Mossop, 1970; Hobbs and Atkinson, 1976; Rangno *et al.*, 1977). Ironically, Vardiman and Hartzell[6] concluded from ground measurements that the ice crystal concentration "does not appear to be a function of cloud top temperature for either seeded or non-seeded cases" for one of the projects that VM analyzed.

5) It is strange that VM would eliminate the Central Sierra Experiment (CENSARE) and the Santa Barbara II Project at various stages in their stratifications because of a suspected precipitation bias in CENSARE and a suspected problem with model-derived cloud top temperatures in the Santa Barbara II experiment, and yet not report the effect on their conclusions of removing the Climax Experiment which appears to have contained Type I statistical error (i.e., natural bias)—see, e.g., Mielke (1979).

6) VM's use of time blocks (6 h) that are considerably shorter than the randomized time blocks (generally 24 h) used in the actual experiments raises further questions. For example, have originally insignificant differences between seeded and non-seeded precipitation amounts become significant because of this artificial inflation of the sample size? Do VM recommend that future experiments be constrained to 6 h randomized units?

7) Finally, VM use the term "orographic" rather loosely. Do they mean by this term clouds which are solely the result of the orographic uplift of air or all clouds which happen to be in the vicinity of mountains? In the former case, the microstructure of the clouds is likely to differ substantially from that of long-lived synoptic-scale cloud masses which happed to impinge on mountain ranges. The precipitation-forming processes, and the effects of artificial seeding, are likely to be quite different in these two cases, even with identical cloud-top temperatures.

Acknowledgments. This work was supported in part by Contract 10990022 from the Pacific Northwest Regional Commission and by Grant ATM79-00948, Division of Atmospheric Sciences, National Science Foundation.

[6] Vardiman, L., and C. L. Hartzell, 1976: Investigation of precipitating ice crystals from natural and seeded winter orographic clouds. Final Report to the Bureau of Reclamation, 129 pp. [NTIS PB-258 71B/BGI].

REFERENCES

Grant, L. O., and P. W. Mielke, Jr., 1967: A randomized cloud seeding experiment at Climax, CO, 1960–65. *Proceedings Fifth Berkeley Symposium on Mathematical Statistics and Probability*, Vol. 5, University of California Press, 115–132.

Hobbs, P. V., 1974: High concentrations of ice particles in a layer cloud. *Nature*, **251**, 694–696.

—— and D. G. Atkinson, 1976: The concentration of ice particles in orographic clouds and cyclonic storms over the Cascade mountains. *J. Atmos. Sci.*, **13**, 1362–1374.

Mielke, P. W., Jr., 1979: Comment on "Field Experimentation in Weather Modification", *J. Amer. Stat. Assoc.*, **74**, 87–88.

——, L. O. Grant and C. F. Chappell, 1971: An independent replication of the Climax wintertime orographic cloud seeding experiment. *J. Appl. Meteor.*, **10**, 1198–1212.

Mossop, S. C., 1970: Concentration of ice crystals in clouds. *Bull. Amer. Meteor. Soc.*, **51**, 474–479.

Vardiman, L., and J. A. Moore, 1978: Generalized criteria for seeding winter orographic clouds. *J. Appl. Meteor.*, **17**, 1769–1777.

Weiss, R. R., Sr., J. D. Locatelli and P. V. Hobbs, 1979: Simultaneous observations of cloud and precipitation particles with vertically-pointing X band and K_a band radars. *IEEE Trans. Geosci. Electron*, **GE-17**, 151–153.