

revealing that a large percentage of the total mass of water in the form of numerous microdroplets was separated from a water drop by freezing. On the basis of these new observations and measurements with the support of photomicrographic evidence, I suggested (4) that the ejection of microdroplets by the freezing of a supercooled water drop may be important in studies of thundercloud dynamics and in the generation of thunderstorm electricity (5).

A spectacular photograph of microscopic particles of water bursting from the drop in the process of rupture appeared in Kachurin and Bekryaev's paper (2). Unfortunately, the water drop was cooled in an environment consisting of a high concentration of carbon dioxide (6). No experimental data and no photomicrographic evi-

dence concerning the ejected microdroplets were presented in the paper by Dye and Hobbs (3).

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References and Notes

1. H. G. Dorsey, *Phys. Rev.* **18**, 162 (1921); N. E. Dorsey, *J. Res. Nat. Bur. Stand.* **20**, 799 (1938); *Trans. Amer. Phil. Soc.* **38**, 247 (1948); O. Bally, *Helv. Chim. Acta* **18**, 475 (1935); D. C. Blanchard, *Trans. Amer. Geophys. Union* **31**, 836 (1950); *J. Meteorol.* **8** (No. 4), 268 (1951).
2. L. G. Kachurin and V. I. Bekryaev, *Dokl. Akad. Nauk SSSR* **130**, 57 (1960).
3. J. E. Dye and P. V. Hobbs, *J. Atmos. Sci.* **25**, 82 (1968).
4. R. J. Cheng, *Science* **170**, 1395 (1970).
5. Theoretical considerations and field observations on this subject will be reported elsewhere.
6. J. E. Dye and P. V. Hobbs, *Nature* **209**, 464 (1966).
7. Work supported in part by a General Electric research grant and research funds from the Atmospheric Sciences Research Center, State University of New York at Albany.

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Cloud Seeding Experiments: Possible Bias

In recent months, *Science* has devoted much attention to weather modification experiments; I refer in particular to the articles on the effects of cloud seeding in Florida by W. L. Woodley (1) and J. Simpson and W. L. Woodley (2). The purpose of this comment is to call attention to a possible source of bias that may have been overlooked in the design of these experiments, or might be overlooked in future experiments.

I refer to what I shall call "selection bias," or bias introduced into an experiment by the manner in which the experimental subjects are selected. In any experiment (such as cloud seeding) in which two treatments are to be compared, it is well known that the results of the experiment may be biased if the experimental subjects (clouds) are selected with the knowledge of the treatment they are to receive. Simpson and Woodley have recognized this difficulty. They wrote (2), "The delivery racks were armed or disarmed in the rear of the aircraft by a 'randomizer,' who opened in secret the sealed envelopes containing the decisions. The envelopes were prepared by a statistician to say 'seed' or 'no seed' according to a procedure roughly similar to tossing a coin (but where long strings of successive identical instructions were precluded)."

Precautions such as these may not be sufficient, however, to prevent the (usually subconscious) introduction of selection bias into the experiment. This

possibility always exists for experiments such as cloud seeding, in which the potential subjects arrive sequentially and are judged "suitable" or "not suitable" by the same scientists who are performing the experiment. This was first studied by Blackwell and Hodges (3), and I have discussed it further elsewhere (4).

Nonmathematically, the potential difficulty can be described by the following example. Suppose the scientist knows (after all, it is his experiment) that the experiment will consist of approximately equal numbers of seeded and unseeded clouds. Envelopes containing instructions are prepared "at random" by a statistician. The scientist then judges a cloud "suitable" or "not suitable" and proceeds with the experiment as if he were seeding. After the plane alights, he is told whether the cloud was seeded or not seeded. It is this "post-trial" information that permits the introduction of bias. Indeed, at each stage of the experiment the scientist can "guess" on the basis of his past information what the next trial will be, which allows him to bias the experiment through his judgment of the suitability of the next cloud for seeding. Even though his "guesses" would not always be correct and this bias would usually operate subconsciously, Blackwell and Hodges have shown that there is no randomization that can eliminate the possibility of bias; in fact, selection bias can significantly distort the results of the experi-

ment regardless of the number of clouds seeded. It is true that the effect of this bias can be reduced by a suitable design when the bias is operating subconsciously (and even made negligible if the experiment is sufficiently large) (4).

There are three ways in which the possibility of selection bias can be eliminated entirely: (i) Do not inform the scientist of the result of a trial until the entire experiment is complete. (ii) Perform a true coin flip at each trial (not "roughly similar to tossing a coin"). (iii) Have the judgment of suitability made by a third party, not informed about any other aspect of the experiment. Unfortunately all these alternatives have drawbacks. The first is often impractical as the scientist wants to know the results of the trials in order to decide when to terminate the experiment (actually, it is better to have the statistician make the decision). The second has the unpleasant possibility of providing a very unbalanced experiment (for instance, almost all clouds are unseeded), which makes a meaningful statistical analysis impossible. The third is often impractical because only those closest to the experiment may be entirely sure what is meant by "suitable." Other ways of eliminating bias are given by Hodges and Blackwell (3).

It is not my intention to imply that the results of the Florida experiment are suspect because of the possibility of bias [particularly since the description of the design given in *Science* is incomplete (2)]. I only wish to alert future experimenters to the dangers of bias associated with this type of experiment (similar difficulties are involved in some clinical trials), so that they may avoid controversy as to the validity of their conclusions. Hammond (5) points out that "even well-documented and randomized early experiments, such as the Whitetop trials . . ., produced ambiguous and disputed results." Weather modification is too important a field to allow even the possibility that large and expensive experiments will be disputed or incorrectly interpreted because of a faulty experimental design.

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References

1. W. L. Woodley, *Science* **170**, 127 (1970).
2. J. Simpson and W. L. Woodley, *ibid.* **172**, 117 (1971).
3. D. Blackwell and J. L. Hodges, Jr., *Ann. Math. Stat.* **28**, 449 (1957).
4. S. M. Stigler, *Biometrika* **56**, 553 (1969).
5. A. L. Hammond, *Science* **172**, 548 (1971).

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