Reply

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I welcome the comments of Mr. Cataneo on my paper. I have great respect for him and his colleagues at the Illinois State Water Survey. Without their pioneering efforts over the years to derive *Z-R* relationships as a function of location, season and storm type, my research would have been immeasurably more difficult.

Before treating Mr. Cataneo's comments, let me review the points of my paper that are relevant to this discussion. During May 1968 it was found that randomized silver iodide pyrotechnic seeding of isolated supercooled cumulus clouds increased their size and duration and, as a consequence, their precipitation production compared to non-seeded clouds (Woodley, 1970). Analysis of an improved repeat of this experiment that was conducted over Florida during the summer of 1970 strengthens these conclusions.[1] The precipitation calculations were made using cloud base 10-cm PPI radar observations, the Miami *Z-R* relation

$$Z=300\,R^{1.4}, \qquad (1)$$

and the analysis scheme that was described. [Eq. (1) is based on ground droplet-camera measurements that were made by the Illinois State Water Survey in the Miami area.] A radar-raingage comparison indicated that the radar represented unmodified shower rainfall to a probable accuracy of 30% (Woodley and Herndon, 1970), implying that the seeding results represented real increases at the ground, provided (1) is as valid for seeded as it is for non-seeded clouds.

To investigate this uncertainty, particle measurements that were made in the experimental clouds at 20,000 ft and at cloud base with an airborne continuous hydrometeor sampler were used to derive *Z-R* relationships for seeded and non-seeded clouds. The length of time between the end of seeding and hydrometeor sampling averaged 18 min for the 20,000-ft samples and 11 min for the cloud base samples. These in-cloud *Z-R* relationships were not used in any of the rainfall calculations because of many uncertainties associated with particle measurements from an aircraft (I heartily support Cataneo's caution in this regard); rather, they were used as indicators of the validity of (1) for seeded clouds.

When compared, the derived seeded and non-seeded *Z-R* relations were not different at the 5% level (specifically, the cloud base relations are significantly different at the 35% level; the slopes of the 20,000-ft

[1] A paper on this work will appear in the June issue of the JOURNAL OF APPLIED METEOROLOGY.

equations are different at the 20% level and the intercepts are different at the 10% level), suggesting but not proving that (1) is as valid for seeded clouds as it is for the non-seeded clouds.

Cataneo apparently believes that the small differences between the seeded and non-seeded relations represent real effects of seeding. Certainly physical reasoning supports at least momentary changes in the drop spectrum of seeded clouds at 20,000 ft. But the 20,000 ft *Z-R* equations are not critical to the validity of the radar-derived precipitation increases. All 10-cm PPI radar measurements of the experimental clouds were made as near cloud base as possible, and in all instances the clouds were contoured well below the 20,000-ft level. Therefore, the most critical equations are the cloud base *Z-R* relations. The calculations of Takeuchi (1969) and the interesting mathematical exercise by Cataneo clearly show that there are no important differences in the seeded and non-seeded cloud base *Z-R* relations. Based on this information one must conclude that (1) is equally valid for the seeded clouds and that the precipitation increases ascribed to seeding are real and not spurious because of an alteration of the droplet spectra at the bases of the seeded clouds. [This is an indirect method of verifying the validity of (1) for seeded clouds. During 1970 several seeded clouds passed over recording raingages and we may be able to take a direct approach to this question by comparing gage-recorded rainfall from the seeded clouds with that indicated by radar.]

Because the 20,000 ft *Z-R* equations are not pertinent to the validity of the cloud base rainfall calculations, I will not belabor the details of Cataneo's mathematical development. However, certain assumptions apparently critical to this development are not compatible with the main conclusions of my paper which were that the precipitation increases induced by seeding were due primarily to increased areal coverage and duration of the echoes of the seeded clouds. Seeded echo lifetimes exceeded those of the controls (including radar controls) by 50% and the areas of the seeded echoes exceeded those of the controls (including radar controls) by 60% during the first 40 min after the initial seeding run. Cataneo's assumptions of equal echo durations and an increase in the echo intensity of the seeded clouds are not compatible with these findings.

The 20,000 ft *Z-R* relations remain a puzzle. I, like Cataneo, expected changes in the hydrometeor spectrum at this level as a result of seeding, and it is still likely that some transitory changes take place. However, in my opinion, the evidence for changes is not conclusive at this time. A major difficulty in this regard is aircraft sampling in the seeded region before the affected hydrometeors are carried above the ceiling of the aircraft during the intense growth phase that frequently follows seeding. To circumvent this difficulty a continuous hydrometeor sampler was flown on the RFF B-57 during our 1970 Florida cloud seeding program and particle measurements were made in the rising cloud tops.

Even if our expectations of momentary seeding-induced changes in the drop-size distribution prove correct, it is questionable that these changes would be as evident at the bases of Florida convective clouds as they apparently are in Arizona. I have had the pleasure of studying clouds in both regions, and the major differences between the clouds is the greater depth of warm cloud and greater shower intensity in Florida (the latter is related to the former). During the summer the freezing level averages 14,000–15,000 ft MSL in both areas while cloud bases are typically 12,000 ft or greater in Arizona and 2000 ft in Florida. As a consequence, there is a greater depth of cloud below the freezing level in Florida in which cloud physical processes might work to mask any seeding-induced drop-size changes.

Support for this intuitive reasoning is found in the work of several scientists. In a coalescence calculation for precipitation from Florida clouds, Simpson and Wiggert (1971) find that as much as 90% of the precipitation mass that reaches the ground is collected by the precipitation fallout from the actively rising tower. If the seeded region (the actively rising tower) contributes only 10% of the precipitation mass, it is doubtful that any changes could be evident at cloud base; coalescence and breakup of the growing precipitation mass in transit to cloud base would probably mask any changes.

Blanchard and Spencer (1970) hypothesize that the drop-size distribution for heavy showers is determined mainly by raindrop breakup and very little by the microphysical processes that initiate the rainfall. Assuming their hypothesis is correct, and armed with the knowledge that on the average the showers are heavier in Miami than in Flagstaff, initial drop-size differences in the supercooled regions of the clouds would less likely be preserved to cloud base in Florida than in Arizona.

In all of the above we have assumed that a large fraction of the hydrometeors in the seeded region reach cloud base. However, it is possible that a significant portion of the seeded volume is evacuated with the anvil that frequently forms following seeding in Florida. If this is the case, the altered drop-size distribution will rarely be seen at cloud base here.

Finally, I am not an advocate of blind statistics in any scientific experiment; it is but a tool to aid in interpretation of the data. However, I would contend that there is frequently more information in a "significance number" than there is in a subjective, perhaps biased, evaluation of the data.

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