Reply

A. L. RANGNO AND P. V. HOBBS

Cloud and Aerosol Research Group, Department of Atmospheric Sciences, University of Washington, Seattle, Washington

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We have prepared a detailed point-by-point reply to Rosenfeld's (hereafter R) comment on our critique of the Israeli cloud seeding experiments (Rangno and Hobbs 1995a, hereafter RH95a). However, since our detailed reply involves even more pages than R's comment (!) and this exchange necessarily involves much minutiae, it tends to obscure the forest for the trees. Therefore, we have chosen not to have this detailed reply printed in the *Journal of Applied Meteorology* (it is available on request from the corresponding author). Instead, we discuss here some broader and more important issues relevant to the Israeli experiments and their various interpretations, with particular reference to R's comment.

1. General remarks

Over the past several years we have spent considerable time studying the Israeli (Rangno 1988) and the Climax (Hobbs and Rangno 1979; Rangno and Hobbs 1987, 1993, 1995b) cloud seeding experiments. We did so because these experiments represent, in many respects, the culmination of half a century of research evaluating the efficacy of artificial seeding to increase precipitation. We thought it important that the results of these experiments, as reported by the researchers that carried them out, be critically evaluated. Reanalyzing other scientists' work is generally a thankless task, often resulting in controversy. Our goal was to be as objective as possible, but objectivity is in the eyes of the beholder. We did not, as R claims, make any personal attacks.

Rosenfeld (1997) categorizes our critique of the Israeli experiments as ''a scattergun attack.'' In fact, we considered in great detail the precipitation climatology of Israel, the structures of clouds in that region, the statistical results of the Israeli I and II experiments, and operational aspects of the seeding experiments. Our overall conclusion was that there are too many weak links in the chain of arguments that have been presented for a prudent scientist to accept the claim that cloud seeding in these experiments produced statistically significant changes in rainfall. The interested reader can judge the merits of this conclusion by careful comparison of our original paper (RH95a), R's comment, our detailed reply to his comment (available on request), and the remainder of this relatively short reply.

The credibility of the Israeli cloud seeding experiments rests on the validity of the physical hypothesis for anticipating increases in rainfall due to artificial seeding, the manner in which seeding was carried out, and the statistical results of the experiments. These issues were addressed at some length in our original paper, but R's comment prompts us to make some further remarks on these critical issues.

2. Is the ''static'' seeding or the ''dynamic'' seeding hypothesis applicable in Israel?

The physical hypothesis for anticipating that cloud seeding might increase precipitation from clouds in Israel was based on reports of the microstructure of these clouds by Gagin and associates. The second column of Table 1 (labeled pre-1988) summarizes some important features of these early reports. In summary, they suggested that clouds in Israel rain inefficiently because of the lack of sufficient concentrations of natural ice nuclei to nucleate ice particles and the lack of sufficient concentrations of large drops to promote either ice particle production by ice multiplication or the growth of raindrops by the collision–coalescence mechanism. These reports conformed to the ideal ''seedable'' cloud (e.g., Mason 1971), and they provided the basis for the artificial ice nucleus static seeding hypothesis, which the Israeli cloud seeding experiments were designed to test (Gagin 1986). Indeed, it was concluded by Gagin (1975, 1981) that if clouds in Israel did not correspond to this model the static seeding potential would be seriously compromised, if not eliminated.

The last column of Table 1 summarizes reports on the structures of clouds in Israel since 1988 that differ

Corresponding author address: Prof. Peter V. Hobbs, Dept. of Atmospheric Sciences, Box 351640, University of Washington, Seattle, WA 98195-1640.
E-mail: phobbs@atmos.washington.edu

TABLE 1. Summary of reports on the microstructure and seedability of clouds in Israel published prior to 1988 and thereafter.

	Pre-1988	1988–present
Highest cloud-top temperature (°C) at which concentrations of ice particles reach 1 L^{-1}	-14[a,b,c]	≥ -10[j,k,l]
Average cloud-top temperature (°C) for ice concentrations of 1 L^{-1}	-17[a,b,c]	≥ -10[j,k,l]
Highest ice particle concentration (L^{-1}) measured [at lowest cloud-top temperature (°C) sampled]	25 (-28)[a,b,c]	50 (-12)[k]
Do ice particle concentrations increase as clouds age?	No[c]	Yes[m]
Does significant rain form from ice aggregates?	No[d,e]	Yes[m]
Range of droplet concentrations (cm^{-3})	350–1500[a,b]	250–400[k]
Does rain form by collision–coalescence?	No[c,f]	Yes[j]
Are there ≥23-μm-diameter droplets in the riming–splintering zone?	No[c,e]	Yes[m]
Does ice multiplication occur?	No[a,b,c,d,e,f,g,h,i]	Yes[j,k,l]
Would ice multiplication seriously reduce the seeding potential in Israel?	Yes[c,e]	No[n]
Can seeding decrease rainfall?	No[b]	Yes[n,o]
Was the intensity of rainfall higher on seeded days than on control days in the northern target area of Israeli II?	No[d,h]	Yes[p]

[a] Gagin (1971).
[b] Gagin and Neumann (1974).
[c] Gagin (1975).
[d] Gagin (1980).
[e] Gagin (1981).
[f] Gagin (1986).
[g] Gagin and Neumann (1976).
[h] Gagin and Neumann (1981).
[i] Gagin and Gabriel (1987).
[j] Rangno (1988).
[k] Levin (1994).
[l] Rangno and Hobbs (1988, 1995a).
[m] Expected from Rangno (1988) and Levin (1994).
[n] Rosenfeld and Farbstein (1992).
[o] Rosenfeld (1996).
[p] Ben-Zvi (1988).

from the earlier reports of Gagin and colleagues. The later reports are almost completely dichotomous to the earlier ones, in that plentiful ice at relatively warm temperatures, as well as large drops, were found in the clouds of Israel. Clearly, if the reports since 1988 are correct, a static seeding potential to produce significant rainfall on the ground is unlikely to exist in Israel.

We are pleased that R now subscribes to our (post-1988) view of the microstructure of clouds in Israel. We certainly agree with R's statement that ''the microstructure of clouds in Israel is not unique.'' Indeed, it was because the pre-1988 reports suggested that the clouds over Israel were different from those in many other parts of the world that we first questioned the Israeli reports (Rangno and Hobbs 1988). Unlike us, R still believes that the Israeli statistical experiments demonstrated that seeding significantly affected rainfall. To support this belief, R has proposed some new physical hypotheses, which are outlined below.

Rosenfeld attributes high ice particle concentrations in Israeli clouds to *two* types of ice multiplication. The first type (which might, from R's viewpoint, be termed ''good'' ice multiplication) is that traditionally associated with relatively large supercooled drops (e.g., Koenig 1963; Hallett and Mossop 1974; Mossop 1985; Hobbs and Rangno 1985), which previously was believed not to operate in Israel (Gagin 1975; Gagin 1981; Gagin 1986). Rosenfeld believes that even in the presence of high ice particle concentrations produced by this type of ice multiplication, rainfall was enhanced in the Israeli experiments by the glaciogenic seeding agent serendipitously acting on *suitable clouds*, *in sufficient quantities*, and *at just the right time* to produce a dynamic seeding effect. We think it most unlikely that the ''broadcast'' seeding, designed for static effects, used in the Israeli experiments would have satisfied the stringent requirements of seeding for dynamic effects.

Since R believes that the statistical results of Israeli II indicate that under certain conditions cloud seeding *decreased* rainfall in some regions, he has postulated a second type of ice multiplication (''bad'' ice multiplication from R's viewpoint). Bad ice multiplication is attributed to dust/haze particles acting as super ice nuclei (Rosenfeld and Farbstein 1992), which glaciate clouds virtually instantaneously so that there is no ''window of opportunity'' to increase rainfall by artificial seeding for either static or dynamic effects. In fact, to explain the apparent decreases in rainfall due to seeding in Israeli II, R postulates that the addition of artificial ice nuclei to clouds already affected by dust/haze particles caused ''overseeding'' and, therefore, decreased rainfall.

This is indeed a complex scenario, and one far removed (in many respects just the opposite) from the

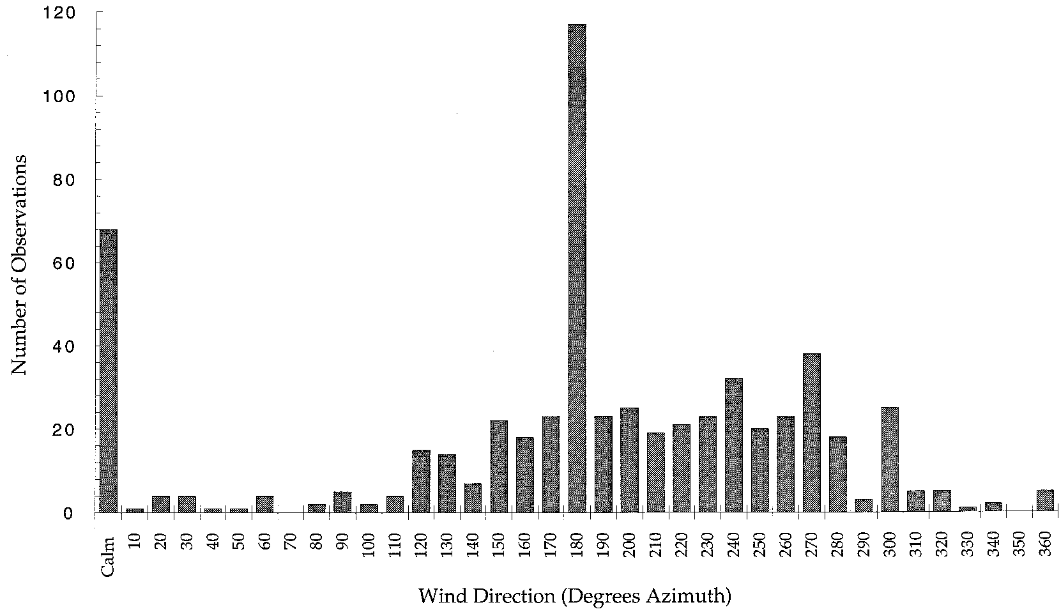

FIG. 1. Surface wind directions for Bet Dagan, Israel, for rawinsonde launches when rain was falling at or within 60 km of Bet Dagan, and at or within the hour of launch time, for the periods January–March 1978, November–March 1978–79 through 1984–85, January–February 1986, and November 1986–March 1987.

relatively simple static seeding hypothesis that was both the foundation for the design of the Israeli cloud seeding experiments and that, for so many years, was claimed to have been verified by those experiments. In fact, R now claims that in Israeli I artificial seeding decreased rainfall in the center target area while increasing rainfall substantially in the northern target area. While such a result would be compatible with Rosenfeld and Farbstein's (1992) analysis of Israeli II and their dust/haze super ice-nucleus hypothesis, it is contrary to Gagin and Neumann's (1974) analysis of Israeli I, which reported increases in rainfall due to seeding in the center target area and slightly positive but nonsignificant results in the northern target area.

In our paper (RH95a) we presented evidence that rainfall was *naturally* heavier in those target areas for which apparent increases in rainfall due to seeding were reported for Israeli I and II. Therefore, we concluded that neither experiment provided unambiguous evidence for seeding affecting rainfall. In the remainder of this reply we discuss briefly several important statistical aspects of the Israeli experiments.

3. Was the "buffer" zone seeded in Israeli I, or was there a type I ("lucky draw") statistical error?

The buffer zone (BZ) was a region located between the northern and southern target areas of Israeli I, which was designed *not* to be seeded. However, it appeared from statistical analyses that seeding increased rainfall in the BZ by greater amounts than in either of the two target areas (Wurtele 1971; Gagin and Neumann 1974)! This enigmatic result was due either to the BZ being seeded more efficiently than the two target areas, or, as argued by us (RH95a), it indicates that a type I statistical error occurred in Israeli I.

The chief meteorologist for the seeding operation in Israeli I concluded that inadvertent seeding of the BZ could have occurred only 5%–10% of the time (Wurtele 1971; RH95a). We provided further evidence to support the view that inadvertent seeding of the BZ was unlikely (RH95a). Rosenfeld, on the other hand, has postulated a complex scenario whereby the BZ might have been inadvertently seeded. In this scenario the seeding agent (AgI), which was released at cloud base, is first carried eastward in a westerly airflow. As the AgI plume spreads vertically, its lower potion enters a shallow easterly flow just above the surface and is carried westward to seed appropriate convective clouds in high enough concentrations and far enough offshore that precipitation particles can grow, be carried back eastward, and fall out in the BZ (and other locations on the Israeli coastline).

There is no question that AgI released at cloud base will be transported eastward (as intended in the original design) and that the AgI plume will increase in depth. How likely is it that a portion of the plume that reaches close to the surface will be carried westward toward the coast? Figure 1 shows the frequency with which surface winds blow from various directions when rain is reported at Bet Dagan, which is located about 9 km from the Israeli coast. These observations show that winds blow toward the coast (from $\leq 160°$ azimuth) less than about 25% of the time. Hence, even the first step in R's

TABLE 2. A summary of the statistical results of the Israeli I and II cloud seeding experiments. The presumed effect of seeding on rainfall (%) is shown in parentheses after the test statistic. For crossover analyses, root double ratios[a] are given. Single-area ratios[b] are given for separate regions of the experiment.

	Israeli I (Gagin and Neumann 1974)	Israeli II (Gabriel and Rosenfeld 1990)
Overall (crossover analysis of both targets)	1.15 (+15%)	0.98 (−2%)
Northern target area	1.08 (+8%)	1.15 (+15%)
Buffer zone (center seeded days)	1.31 (+31%)[c]	1.08 (+8%)[d]
Center (or southern) target area	1.22 (+22%)	0.83 (−17%)

[a] The root double ratio statistic is the square root of the product of the single-area ratio statistics $(SAR)^2$ for the two target areas.
[b] The SAR statistic is the average rainfall on seeded days in a target area divided by the average rainfall in a control area.
[c] Center seeded days.
[d] Northern seeded days.

multistep scenario has a low probability of occurrence. Also, only about 60% of the rain days allocated to seeding in Israeli I were actually seeded (Wurtele 1971), and Rosenfeld and Farbstein (1992) postulated that half of those days were unsuitable for seeding to increase rainfall due to the presence of dust/haze!

We stand by our much simpler explanation for the higher rainfall in the BZ on days in which the center target area was seeded in Israeli I, namely that rainfall was naturally higher on those days (RH95a).

4. Did ''lucky draws'' occur in both Israeli I and II?

The chances of lucky draws occurring in *both* Israeli I and II are very slim. However, two ''lucky draws'' did not occur if the experiments are analyzed according to their original crossover designs.

A statistically significant result indicating increases in rainfall due to seeding occurred in Israeli II only when the analysis was confined to the northern target area (NTA) and a target–control statistical evaluation was used (rather than the originally intended crossover design). There is no seeding effect on rainfall in the NTA when the southern target area (STA) is used as a control on NTA seeded days, as called for in the original design (Gagin and Neumann 1974). Further, in the target–control evaluation of the NTA, a disproportionate number of control stations were used from a tiny coastal strip that had anomalously low seed/no-seed ratios (see Fig. 17 of RH95).

5. What are the statistical results of Israeli I and II?

It is widely believed that Israeli I demonstrated significant increases in rainfall due to seeding and that Israeli II confirmed this conclusion (e.g., Young 1993). However, this is not the case if a crossover analysis is performed for each experiment (see first row in Table 2). Moreover, the apparently strong seeding effect (+22% increase in rainfall from the single-area ratio) observed for the STA in Israeli I was replaced by a −17% effect (i.e., an apparent 17% decrease in rainfall due to seeding from the single-area ratio) in Israeli II (see last row in Table 2). Also, the nonsignificant +8% effect in the NTA for Israeli I escalated to +15% in Israeli II (see second row of Table 2).

Clearly, Israeli II did not replicate Israeli I. Therefore, after some 35 years of experimentation, the question remains, What is the effect (if any) of cloud seeding on rainfall in Israel?

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