Has Hail Suppression in Eastern Yugoslavia Led to a Reduction in the Frequency of Hail?

FEDOR MESINGER *

Institute of Meteorology, University of Belgrade, Belgrade, Yugoslavia

NEDELJKA MESINGER

Federal Hydrometeorological Institute, Belgrade, Yugoslavia

(Manuscript received 22 October 1990, in final form 20 April 1991)

ABSTRACT

An earlier attempt to estimate the effect of hail suppression by silver iodide seeding in eastern parts of Yugoslavia, based on hail-frequency data at stations having professional observers, is extended here. Hail-frequency data only are considered, rather than the hail- and the ice pellet-frequency data taken together. The period of the data is extended from 37 to 40 years. A statistical analysis of the probability of the observed result being obtained by chance is made, based on the permutation test; a sensitivity test of the possible observer-subjectivity effect is done; and several tests of and corrections for any climate and observing practices change are also made.

The ratio of the average hail frequency during the seeding activities in the area of the station and the average frequency before these activities shows a reduction in the hail frequency by about 25%. A synthetic histogram of the frequency ratios resulting from 10 000 random permutations (station by station) of the observed frequency data gave the probability of this observed frequency reduction being obtained by chance, if in fact no positive effect of seeding or climate change existed, of about 2 in 10 000.

A sensitivity test of the observer-subjectivity effect was made by removing from the available sample of 23 stations the station showing the greatest reduction in hail frequency. This decreased the apparent effectiveness from about 25% to about 23%, and the probability of the positive result became 4 in 10 000.

Tests as well as corrections for the effects of possible climate fluctuations and/or a change in hail-observing practices were performed by using the two neighboring regions of Vojvodina and Bosnia and Herzegovina, which had no hail suppression programs as the control area. The effectiveness calculations as well as the permutation tests were then repeated using "corrected" data. These various corrections reduced the effectiveness of the seeding activities from about 25% to between 22% and 15% and increased the probability of the positive result being obtained by chance to between about 6 and 141 in 10 000. Thus, it appears unlikely that the seeding activities have no positive effect whatsoever; and the reduction in hail frequency seems to be of the order of 15%–20%.

1. Introduction and description of analyses performed

Hail suppression by silver iodide seeding is controversial for several reasons. One reason is the widespread and costly operational activities in place concurrent with the objections on the choice of statistical methods used to arrive at claims of effect. Another is that the physical hypothesis underlying the seeding approach is a matter of some argument. Thus, for example, weather modification statements regularly drafted by an expert working group of the World Meteorological Organization (WMO) and adopted by the WMO Executive Council (e.g., WMO 1985) repeatedly use very cautious language regarding hail suppression possibilities, with only an indirect mention of the claims of highly effective results by Soviet and other groups (e.g., Sulakvelidze 1967). This is clearly in contrast with substantial funds used for hail suppression activities on one hand, and large potential economic benefits if the effect of seeding is indeed positive and the cost-to-benefit ratio low, on the other.

This situation persists due to the extremely large expenditures as well as lengths of time needed for a carefully designed experimental project to be brought to completion. Thus, two large-scale and costly projects, the National Hail Research Experiment (Foote and Knight 1979) and Grossversuch IV (Federer et al. 1986), which were organized to verify the possibility of suppressing hail following the Soviet method, ended without answering the basic question of the existence

* Current affiliation: UCAR Visitor Scientist Program, National Meteorological Center, Washington, D.C.

Corresponding author address: Fedor Mesinger, National Meteorological Center, W/NMC2, WWB, Room 204, Washington, D.C. 20233.

of a positive result. One reason for this is that the length of the experiment needed for a statistical answer at a given confidence level becomes prohibitively long as the presumed effectiveness of the suppression method becomes relatively modest (e.g., Table 2 of Schickedanz and Changnon 1970). Notably, a 60% potential decrease of kinetic energy of falling hail was presumed in arriving at the 5-yr period necessary for Grossversuch IV to achieve results at a desired confidence level (Federer et al. 1986). A much smaller degree of success, perhaps at the level of only about 10% in the frequency of intense hail, may be sufficient to justify operational suppression activities from the cost-to-benefit ratio point of view. Any degree of success, no matter how small, is of course of interest regarding the basic scientific question of the feasibility of the modification of hail.

It is this situation that makes it attractive to consider extracting information from datasets reflecting a possible effect of hail suppression in operational activities, in spite of design problems and the lack of randomization. The long record available, say, in cases of hail suppression activities in the eastern parts of Yugoslavia of the order of 20 years' duration, may enable one to discern whether desirable significance levels have been achieved for less impressive effectiveness. An imperfect design is to be expected to reduce the effectiveness of the activities if the effectiveness exists in principle, but hardly to the extent as to eliminate it altogether. Thus, the existence or nonexistence of a positive result and the order of magnitude of the effect, if any, are the questions we are addressing in this study.

The desirability of evaluating operational weather modification projects has indeed been repeatedly stressed (e.g., Changnon et al. 1979). Furthermore, issues of the statistical evaluations of operational projects were debated, and simulations of such evaluations were performed aimed at comparing the relative benefits of various statistical techniques (e.g., Hsu and Changnon 1983). Finally, actual evaluations of operational hail suppression projects were made (Changnon 1975, 1977; Hsu and Changnon 1984). These studies addressed both the utilization of hail-day data (Changnon and Schickedanz 1969; Schickedanz and Changnon 1970) and the use of the permutational procedure in obtaining the significance levels (Hsu and Changnon 1984) that will be characteristics of our effort. In comparison with aforementioned evaluations, however, two features of our study will be stressed. First, the overall volume of the data sample we use, with 10–22-yr duration of the seeding project covering about 50 000 km^2 area and including 23 seeded area hail-day stations, is probably substantially larger than that of the projects earlier assessed. Second, the magnitude of our computing effort, with multiple 10 000 randomizations of the 40-yr, 23-station sample, may be greater than what was practical to perform at the time of the earlier studies. As a result of these two features, a higher confidence level of the conclusion on the existence of a positive seeding effect can be expected.

Our work is a follow-up to that of Radinović (1989), who looked into the change in the frequency of hail during the suppression program in Serbia compared to that before the program, as recorded at so-called main synoptic stations. Here we extend and attempt to refine his work through efforts in the following.

- We consider the frequency of hail (symbol ▲) only, rather than the frequency of hail and ice pellets (symbol △) taken together, as done by Radinović. This is appropriate in view of the competition hypothesis being the foundation of the silver iodide seeding technique used in Serbia following the Soviet method. The seeding should, if the hypothesis is correct, increase the number of hail particles and thus reduce their size and consequently the frequency of hail (particles of diameter of 5 mm and greater when recorded as hail), and perhaps increase the frequency of ice pellets (particles of diameter of less than 5 mm). This effort has involved synthesis of the "target area" dataset by going back to the original records, consisting of two equally authentic originals kept at the Serbian and the Federal Hydrometeorological Institute.
- Since more years of data are now available, we have extended the dataset by 3 yr, making it a 40-yr set at 19 out of 23 stations on the seeded area. The length of the protection period has thereby increased also by 3 yr, so as to range from a maximum of 22 yr (at two stations) to a minimum of 10 yr (at four stations). The median length of the 23 protection periods is now 19 yr, and the average length is 16.3 yr.
- For the apparent effectiveness of the seeding, we calculated the ratio of the average hail frequency, in numbers of days on which hail was observed per year, during the seeding periods, and the average frequency during the no-seeding periods. Averaging was performed first over time for each station, and subsequently over the 23 stations; so that each station affects the resulting average with the same weight irrespective of the length of its seeding period.
- To arrive at the probability of this observed frequency ratio being obtained by chance (sample significance level, or p value), we performed the permutation test by making random permutations of the frequency values (numbers of hail days per year), station by station, and by calculating the resulting synthetic frequency ratios. In this way we rerandomized the sample 10 000 times and subsequently found the number of synthetic frequency ratios out of 10 000 that are less than the observed frequency ratio. This number over 10 000 is the estimate of the probability of the observed frequency ratio being obtained by chance, or the p value.
- Various reasons could exist for a reduction in hail frequency to be observed concurrently with a seeding program. One is observer subjectivity. For a sensitivity

test of the observer-subjectivity effect, we eliminate from the sample the station showing the greatest reduction in hail frequency and repeat the preceding calculations with this reduced sample of 22 stations, comparing the results with the complete sample values. This is a stringent test in view of the large spread of the observed reductions in hail frequency over the 23 stations and because there are five observers at each station. Nevertheless, we have also performed tests with two and then with three stations showing the greatest reductions in hail frequency eliminated from the sample.

- The primary reason, other than seeding, for a reduction in hail frequency to be observed concurrently with a seeding program is a climate change. For an estimate of, as well as a correction for, a possible climate change effect, we compiled a control set of hail frequencies observed at main synoptic stations in the two neighboring regions of Vojvodina and Bosnia and Herzegovina, which have no hail suppression programs. These two control regions are located upwind from the prevailing west-northwesterly airflow, so they should be largely free of the possible effects of seeding. We then calculated the ratio of the average frequencies of this control sample for two different choices of the representative suppression starting year: the median (1970) and the average (1973) of the 23 values of the starting years of the suppression activities in the seeded area. These frequency ratios are in turn assumed to reflect the climate change effect. Note that the obtained ratios would also reflect a possible change in observing practices, and a possible reduction in the frequency of hail events which may have occurred due to a high natural variability of hail. Therefore, we shall refer to the effect depicted in this way as to that of an *apparent* climate change. To account for the apparent climate change we then multiply the frequency values of the protected stations for the representative seeding period by the reciprocal of the frequency ratio of the control stations. Still another correction for the apparent climate variability was performed by removing the linear trend from all of the seeded area data, as observed in the control area. Following each of these three corrections, we repeated the calculation of the frequency ratios and the permutation test, arriving thus at our climate change–corrected estimates of the seeding effectiveness along with the associated sample significance levels.

2. The dataset

a. The seeding program

The seeding program in eastern Yugoslavia became operational in 1967, at that time covering the area of stations Bukovička Banja and Smederevska Palanka in central Serbia (Fig. 1). From the beginning to the present time, the seeding technology has been patterned after the Soviet method (Sulakvelidze 1967), always considered a proven technology. In Serbia the system is based on a very dense network of rocket launchers, with an average spacing of about 5 km. The system has gradually expanded, so that as of 1979 it covered practically all of central and southern Serbia (Fig. 1, stations denoted by full circles). It now comprises a total of about 1300 rocket-launching stations, directed from one central and 12 regional radar centers. The system operates during the 6-month hail season, which is 16 April–15 October each year. Hail in Yugoslavia is extremely rare outside of this period.

Various rules are in place regarding seeding decisions depending on the presumed type of cloud, reflectivity values, etc. (e.g., Aleksić 1989). Rules have changed in the course of years, as have rockets and the properties of the seeding material. Thus, in the first half of the period (up to and including 1978) rockets with a range of 3500 m were used, carrying 400 g of silver iodide each. Starting in 1979, rockets with a range of 8500 m were used. They carry the same quantity of silver iodide, but the number of ice nuclei per gram of the AgI-burning material mixture has increased. At present, seeding decision is the result of consideration of a number of parameters, including whether the synoptic and thermodynamic conditions are favorable for hail, occurrence of the radar echo above the $-6°C$ isotherm, the value of the maximum equivalent radar reflectivity, and a possible report by rocket operators of hail occurrence on the ground. For single-cell clouds, and multicell clouds with maximum reflectivity below 45 dBZ with no hail reported on the ground, the volume defined by the echo above the $-6°C$ isotherm is seeded. With higher reflectivities, or hail reported on the ground, or for supercell clouds, a quarter-annulus–shaped seeding zone of 3-km radius is defined, bound by $-8°$ and $-12°C$ isotherms. The number of rockets to be used for a particular seeding is calculated from the known volume of the seeding zone, so that according to rocket specifications, 10^5 active nuclei are delivered for each cubic meter of the zone. Seeding is repeated every 5 min as long as the seeding criteria are satisfied. The total rocket expenditure is thus quite high, running up to about 25 000 rockets in some seasons (Aleksić 1989).

Objections could be raised as to the ability of the system to perform in various situations the way it is presumed to perform after the competition hypothesis; for example, from the point of view of the maximum height achievable by the rockets in use at present and earlier. We shall not be concerned with details of this type since, as stated, we presume that imperfections and/or faults in the operational design could reduce the effectiveness of the system if the effectiveness exists in principle, but typically not to the extent as to eliminate it altogether. Also, we shall look into the effectiveness of the system in terms of a possible change in hail frequency, which differs from the basic objective

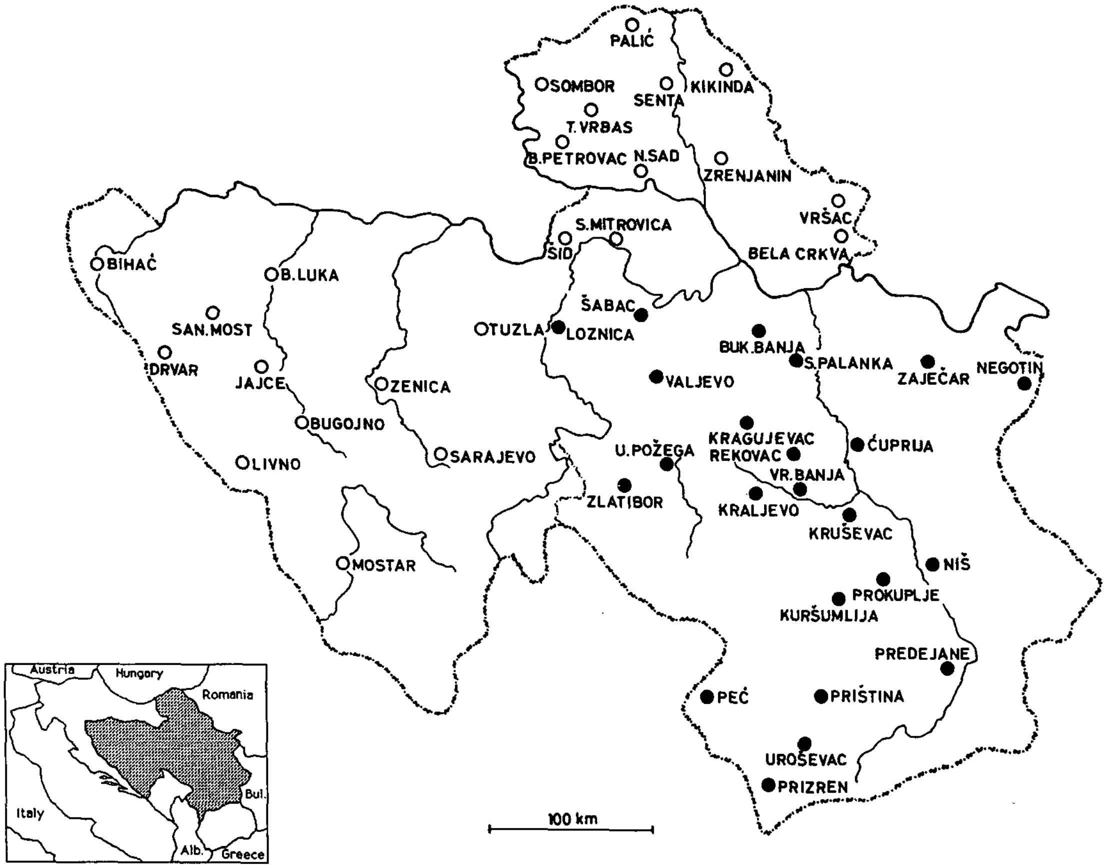

FIG. 1. Main synoptic stations within the central and the southern part of Serbia, covered by the hail suppression system, full circles; stations within the northern part of Serbia (Vojvodina) and Bosnia and Herzegovina, not covered by the hail suppression system and used as control stations for the evaluation of apparent climate change effect, empty circles. Insert in the lower left-hand corner shows the considered region (shaded) relative to the remaining parts of Yugoslavia and surrounding countries.

of the system to reduce hail damage in a cost-beneficial way. In other words, we set out to test if the hail-frequency data indicate with a given confidence level that the effectiveness in terms of hail days exists with the system as it is and as it has been over the course of years, and, if so, what has been its apparent effectiveness. We did not deal with questions about whether the system is performing as originally intended. Readers who do want to have more information on the technical details and concepts of the seeding project are referred to Aleksić (1989) and Radinović (1989).

b. Hail-frequency data

Hail-frequency data used for this study are those of the so-called main synoptic stations of two of the Yugoslav federal republics: Serbia, and Bosnia and Herzegovina. Stations of the central and the southern part of Serbia covered by the seeding program, denoted by full circles in Fig. 1, are the same 23 stations used by Radinović. As control stations, the main synoptic stations of Vojvodina, the northern province of Serbia, and the republic of Bosnia and Herzegovina were taken. They are denoted by open circles in Fig. 1.

The first year for which hail-frequency data from most of the protected stations are available is 1949. Thus, as done by Radinović, we have taken 1949 as the starting year of our dataset. Hail-frequency data at protected stations, in numbers of days with observed hail per year, are shown in Table 1. An empty space denotes a year with no observations available, and a slash denotes the beginning of the seeding program at the area of the station.

In Table 2, hail-frequency data of the 23 control stations are displayed for the same 40-yr period. One of these stations had no data available for the initial 3 yr of the period (Drvar), denoted by empty space.

3. Results

a. Apparent effectiveness and significance level for constant climate

To arrive at the apparent effectiveness of the seeding, we calculated the frequency ratio

TABLE 1. Number of hail days per year at main synoptic stations within target area of central and southern Serbia, 1949–1988. Slash denotes the beginning of the seeding program at the area of the station. Empty space denotes years for which no observations are available.

Bukovička Banja	0, 2, 1, 1, 5, 1, 1, 2, 0, 1, 1, 1, 2, 0, 2, 1, 0, 0/0, 0, 1, 5, 3, 1, 1, 2, 0, 0, 0, 1, 0, 1, 0, 0, 0, 1, 0, 0, 0, 0
Ćuprija	1, 1, 3, 0, 1, 1, 2, 1, 6, 0, 0, 0, 3, 2, 2, 0, 3, 1, 3, 1/1, 2, 1, 2, 1, 2, 2, 0, 0, 0, 1, 2, 2, 1, 0, 0, 0, 0, 0, 0
Kragujevac	1, 0, 1, 2, 4, 1, 2, 1, 1, 1, 0, 1, 2, 1, 0, 0, 1, 3, 0, 0/1, 1, 0, 1, 1, 1, 4, 2, 1, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0, 0
Kraljevo	2, 0, 0, 1, 3, 1, 2, 2, 4, 1, 4, 0, 0, 1, 0, 1, 1, 0, 2, 0, 0, 2, 2, 3, 0, 2, 2/1, 2, 1, 2, 1, 1, 0, 1, 1, 0, 1, 0, 2
Kruševac	1, 0, 1, 1, 0, 0, 4, 3, 1, 2, 3, 2, 1, 2, 0, 0, 1, 1, 2, 0, 1/2, 0, 0, 0, 2, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0, 0, 1, 0, 0
Kuršumlija	0, 1, 3, 2, 3, 2, 0, 1, 1, 1, 2, 0, 0, 2, 1, 1, 2, 0, 2, 0, 1, 0, 0, 1, 2, 4, 0/1, 1, 0, 1, 3, 0, 1, 1, 1, 2
Loznica	2, 2, 2, 1, 3, 0, 2, 0, 2, 2, 0, 3, 1, 3, 2, 2, 0, 2/1, 2, 0, 0, 1, 1, 0, 3, 0, 0, 2, 0, 0, 0, 1, 1, 0, 0, 0
Negotin	0, 0, 2, 0, 2, 1, 0, 3, 1, 3, 1, 1, 1, 0, 1, 0, 1, 0, 1, 1/2, 1, 2, 0, 0, 0, 2, 0, 0, 0, 1, 1, 0, 0, 0, 0, 2, 0, 0, 0
Niš	1, 1, 1, 0, 2, 0, 2, 1, 1, 1, 1, 0, 1, 2, 2, 0, 0, 2, 2, 0/3, 2, 1, 0, 1, 2, 4, 3, 2, 0, 0, 0, 1, 0, 1, 0, 1, 0, 1, 1
Peć	0, 1, 1, 0, 1, 2, 1, 2, 0, 0, 0, 0, 2, 1, 1, 0, 2, 0, 1, 1/0, 1, 0, 0, 1, 0, 5, 0, 2, 0, 0, 0, 0, 2, 1, 1, 0, 0, 0, 1
Predejane	0, 3, 2, 4, 0, 4, 1, 2, 4, 2, 5, 2, 2, 5, 1, 2, 2, 3, 2, 0, 0/3, 1, 1, 0, 2, 4, 0, 0, 4, 2, 0, 0, 1, 0, 1, 1, 0, 0, 0
Priština	0, 0, 2, 2, 1, 2, 1, 1, 1, 1, 0, 0, 1, 1, 0, 2, 3, 1, 2, 3, 3, 0, 2, 1, 0, 1, 1, 0, 0, 1/1, 0, 0, 0, 1, 0, 1, 0, 3, 0
Prizren	0, 1, 0, 0, 1, 0, 1, 2, 0, 0, 0, 1, 0, 2, 0, 3, 1, 0, 0, 0/1, 0, 1, 1, 0, 1, 2, 1, 0, 2, 0, 0, 2, 1, 1, 0, 1, 2, 1, 0
Prokuplje	0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 1, 0, 1, 0, 0, 0, 2, 0, 0, 0, 1, 1, 1, 0, 0/1, 1, 0, 0, 1, 3, 1, 1, 0, 0, 2, 0, 1
Rekovac	1, 0, 0, 1, 1, 0, 1, 0, 2, 1, 0, 1, 0, 0, 1, 0, 3, 4, 2, 0, 2, 0, 2, 2, 0, 1, 4/1, 0, 1, 1, 1, 2, 1, 0, 0, 1, 2, 2, 1
Smederevska Palanka	0, 0, 0, 1, 0, 3, 0, 5, 2, 1, 0, 1, 0, 0, 0, 2, 2, 1/1, 0, 2, 0, 0, 2, 1, 0, 1, 0, 0, 1, 0, 1, 3, 0, 1, 1, 0, 0, 3, 0
Šabac	1, 0, 1, 1, 1, 2, 1, 1, 1, 1, 1, 1, 2, 1, 0, 0, 2, 1, 0, 0, 1/0, 0, 2, 3, 2, 0, 0, 0, 1, 0, 0, 1, 1, 2, 0, 0, 1, 0, 0
Uroševac	0, 2, 2, 1, 3, 1, 1, 1, 7, 0, 1, 2, 1, 0, 0, 0, 2, 2, 3, 2, 0, 0, 2, 1, 0, 1, 2, 1, 1, 0/0, 0, 0, 1, 1, 0, 1, 1, 0, 2
Užička Požega	0, 1, 0, 3, 2, 3, 2, 0, 0, 0, 3, 4, 0, 2, 4, 3, 1, 1, 1, 2, 4, 3, 2, 3, 1/4, 0, 1, 2, 0, 1, 1, 2, 1, 3, 1, 0
Valjevo	1, 0, 2, 1, 0, 0, 1, 2, 3, 1, 2, 0, 1, 3, 2, 0, 5, 1, 1, 2, 1/4, 3, 1, 2, 1, 1, 2, 1, 4, 2, 2, 0, 2, 0, 1, 1, 1, 1, 0
Vrnjačka Banja	0, 0, 1, 1, 1, 0, 2, 3, 3, 2, 0, 1, 0, 3, 1, 1, 2, 2, 4, 2, 3, 1, 4, 0, 2, 1, 0, 2, 2, 0/4, 1, 4, 1, 1, 3, 0, 2, 0, 1
Zaječar	1, 1, 1, 0, 0, 1, 1, 2, 5, 0, 0, 2, 0, 2, 1, 1, 2, 1, 3, 1, 2, 2, 3, 3, 0, 1, 3/3, 1, 0, 0, 1, 0, 0, 1, 0, 1, 0, 0, 2
Zlatibor	1, 3, 4, 1, 3, 3, 5, 4, 2, 3, 1, 3, 5, 0, 2, 1, 1, 0, 0, 0, 2, 4, 5, 3, 4, 6, 0/3, 2, 3, 2, 1, 3, 2, 2, 2, 0, 3, 5

$$[\bar{n}^{s}][\bar{n}^{ns}]^{-1}, \qquad (1)$$

where n is the number of hail days per year, the overbar denotes averaging over time, with index s denoting the seeding period and ns the nonseeding period, and the brackets denote averaging over stations of the sample. We then define the apparent effectiveness of the seeding as

$$E = 1 - [\bar{n}^{s}][\bar{n}^{ns}]^{-1}. \qquad (2)$$

This, obviously, defines the effectiveness of the seeding in terms of the reduction in hail events; it should be kept in mind that this is not necessarily the same as the effectiveness of the seeding in terms of the goals of the seeding project. In other words, we shall *not* be concerned with an evaluation of the seeding project in terms of its modification hypothesis. For an assessment of the achievement of projects goals, of course, various types of data additional to or different from ours would

TABLE 2. Number of hail days per year at main synoptic stations of northern Serbia (Vojvodina), and Bosnia and Herzegovina, 1949–1988 (control stations). Empty space denotes years for which no observations are available.

Bački Petrovac	1, 2, 0, 2, 0, 0, 1, 5, 2, 1, 3, 1, 1, 1, 3, 2, 2, 0, 2, 3, 0, 0, 1, 3, 0, 2, 1, 5, 1, 3, 1, 1, 2, 0, 1, 0, 0, 0, 1, 0
Bela Crkva	0, 0, 1, 0, 1, 4, 0, 2, 2, 1, 2, 3, 2, 0, 4, 1, 3, 1, 1, 1, 0, 3, 4, 1, 3, 2, 5, 3, 2, 1, 1, 0, 0, 0, 3, 0, 1, 1, 0, 2
Kikinda	0, 0, 0, 0, 0, 2, 0, 1, 1, 0, 0, 1, 2, 2, 4, 2, 2, 4, 2, 1, 0, 3, 3, 2, 1, 2, 1, 1, 0, 2, 3, 0, 0, 2, 2, 1, 1, 0, 1, 0
Novi Sad	0, 1, 1, 2, 0, 1, 1, 3, 3, 0, 0, 1, 0, 0, 1, 0, 1, 1, 3, 1, 1, 1, 3, 3, 1, 0, 1, 4, 2, 3, 0, 1, 0, 1, 2, 1, 0, 0, 0, 0
Palić	0, 1, 0, 0, 1, 2, 1, 3, 1, 1, 0, 0, 1, 1, 2, 0, 2, 1, 0, 0, 0, 2, 1, 0, 2, 1, 1, 1, 1, 2, 0, 1, 1, 0, 1, 1, 0, 0, 0, 0
Senta	0, 2, 1, 1, 0, 1, 0, 0, 0, 0, 1, 0, 1, 1, 0, 0, 1, 0, 0, 1, 1, 0, 2, 0, 1, 0, 1, 0, 1, 1, 0, 0, 1, 0, 2, 2, 1, 1, 3, 0
Sombor	0, 0, 0, 0, 0, 0, 1, 3, 1, 1, 0, 1, 4, 1, 2, 1, 1, 1, 0, 1, 1, 2, 1, 1, 1, 1, 1, 1, 1, 1, 0, 1, 1, 1, 3, 1, 0, 1, 4, 1
Sremska Mitrovica	2, 1, 1, 2, 1, 4, 1, 4, 2, 0, 2, 1, 0, 0, 1, 0, 0, 0, 1, 0, 1, 1, 1, 3, 1, 0, 1, 0, 0, 0, 1, 0, 1, 1, 2, 5, 1, 2, 1, 0
Šid	2, 1, 0, 0, 2, 0, 0, 1, 1, 1, 0, 0, 2, 1, 0, 0, 1, 0, 0, 1, 1, 0, 2, 0, 1, 0, 1, 0, 1, 1, 0, 0, 0, 0, 3, 0, 2, 1, 2, 1
Urbas	0, 0, 0, 0, 1, 1, 0, 3, 0, 4, 2, 5, 2, 0, 1, 1, 2, 0, 2, 3, 0, 0, 3, 0, 0, 2, 0, 0, 0, 1, 0, 0, 1, 0, 1, 1, 1, 0, 0, 0
Uršac	0, 0, 1, 1, 2, 1, 0, 2, 2, 3, 1, 4, 1, 1, 2, 2, 2, 0, 0, 2, 1, 2, 0, 1, 1, 2, 1, 1, 0, 2, 0, 0, 0, 2, 2, 1, 0, 0, 0, 0
Zrenjanin	0, 1, 0, 2, 2, 0, 0, 0, 4, 2, 1, 0, 0, 1, 1, 0, 0, 0, 0, 0, 2, 2, 2, 1, 0, 1, 0, 0, 1, 1, 0, 1, 0, 0, 0, 0, 0, 0, 2, 0
Banja Luka	1, 0, 1, 1, 4, 0, 1, 2, 2, 0, 2, 0, 1, 1, 9, 1, 0, 0, 0, 1, 0, 1, 0, 3, 0, 0, 2, 2, 2, 2, 0, 1, 1, 0, 1, 4, 0, 3, 0, 2
Bihać	0, 0, 2, 2, 1, 0, 1, 3, 0, 2, 0, 0, 1, 2, 2, 0, 1, 0, 0, 1, 2, 0, 0, 1, 2, 1, 0, 0, 2, 5, 1, 0, 1, 0, 0, 0, 0, 0, 0, 1
Bugojno	0, 0, 1, 0, 0, 0, 0, 0, 2, 0, 0, 1, 3, 1, 2, 1, 1, 1, 0, 1, 1, 1, 1, 3, 1, 1, 0, 0, 1, 2, 0, 1, 1, 1, 0, 4, 0, 1, 0, 1
Drvar	1, 0, 0, 0, 0, 0, 0, 1, 0, 2, 0, 0, 1, 0, 1, 0, 1, 0, 0, 0, 0, 1, 0, 0, 0, 1, 2, 0, 1, 1, 2, 1, 3, 0, 0, 0, 1
Jajce	1, 0, 2, 2, 2, 1, 1, 3, 0, 0, 0, 0, 0, 1, 1, 0, 0, 0, 1, 1, 1, 0, 0, 2, 2, 1, 0, 0, 1, 0, 0, 1, 0, 5, 0, 1, 1, 1, 0, 0
Livno	1, 1, 0, 0, 0, 1, 0, 1, 3, 0, 0, 0, 1, 0, 2, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1
Mostar	0, 0, 1, 0, 1, 1, 1, 0, 0, 0, 0, 2, 1, 0, 1, 4, 2, 2, 3, 3, 1, 4, 0, 1, 2, 5, 1, 1, 0, 2, 0, 1, 4, 2, 0, 0, 2, 3, 0, 2
Sanski Most	1, 0, 2, 0, 2, 3, 1, 1, 1, 0, 0, 0, 2, 3, 1, 1, 1, 1, 1, 1, 0, 1, 0, 2, 0, 0, 0, 1, 1, 0, 0, 1, 3, 0, 0, 0, 2, 2, 0, 1
Sarajevo	0, 0, 4, 0, 1, 0, 1, 3, 2, 0, 4, 1, 1, 3, 7, 0, 4, 1, 1, 2, 0, 1, 1, 0, 2, 3, 4, 0, 2, 1, 0, 0, 1, 1, 2, 1, 0, 0, 1, 2
Tuzla	1, 0, 0, 1, 0, 6, 0, 4, 2, 2, 2, 2, 4, 2, 6, 2, 1, 3, 1, 4, 3, 5, 1, 1, 0, 1, 2, 0, 1, 2, 3, 0, 3, 0, 2, 1, 0, 2, 0, 0
Zenica	1, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 1, 1, 0, 0, 1, 0, 2, 3, 0, 0, 0, 0, 1, 2, 0, 0, 0, 2, 0, 0, 1, 0, 0, 0

be needed, including data of a nonmeteorological nature.

Using the data in Table 1 we obtained $E = 0.248$. Thus, assuming constant climate, we found that the hail-frequency data exhibited an apparent effectiveness of the seeding program of about 25%.

To arrive at the probability of this observed effectiveness being obtained by chance (sample significance level, or p value), we made random permutations of frequency values of Table 1, station by station for each of the stations, and calculated the resulting frequency ratio. In this way, we rerandomized the sample 10 000 times. The histogram of the synthetic frequency ratios we obtained is shown in Fig. 2. Out of these 10 000 frequency ratios, 2 were less than the observed frequency ratio of 0.752. This number over 10 000, $p = 2/10\,000$, is the estimate of the p value, again, under the assumption of constant climate and no other time-dependent effects except for seeding.

b. *Observer subjectivity*

A reduction in hail frequency could be observed concurrently with a seeding program due to observer subjectivity. Recall that there is a decision involved in reporting a case of hail having to do with the diameter of the hailstones. Since observers at the main synoptic stations used for our study are not a part of the seeding program, it seems justified to expect that observer subjectivity is random and independent of the seeding program. However, if a subjectivity related to the seeding program were to be present, it would likely be at a specific station, or stations, for a given time period relative to an observer at that station.

For a sensitivity test of the observer-subjectivity effect, we therefore eliminated from our sample the station showing the greatest reduction in hail frequency. Then we repeated the preceding calculations with this reduced sample of 22 stations. The station with the greatest observed reduction in hail frequency is Kruševac, showing the apparent effectiveness of the seeding defined in the manner of (2) of 0.70. The reduction of our sample in this way had the effect of decreasing the apparent effectiveness of the seeding from about 25% to about 23%, and of increasing the probability of the positive result being obtained by chance to about 4 in 10 000.

In judging whether this is an adequate test of the observer-subjectivity effect, two points should be noted. First, the stations of Table 1 display a very large variability of the frequency ratios (1). The 23 values of these ratios, in ascending order, are 0.30, 0.39, 0.46, 0.48, 0.48, 0.55, 0.55, 0.58, 0.62, 0.64, 0.74, 0.75, 0.76, 0.77, 0.88, 0.93, 0.93, 0.95, 1.11, 1.15, 1.16, 1.42, and 2.86. Thus, at as many as 5 out of 23 stations hail frequency during the seeding period was recorded higher than before seeding. Second, at each station there are normally five observers. Thus, contribution of individual observers to the hail frequencies recorded at their stations is relatively small, and should not account for much of the variability of the ratios shown. The removal of the station with the ratio (1) most favorable for the seeding program, 0.30, is therefore an adequate if not a severe test of the observer-subjectivity effect.

Nevertheless, for the benefit of the readers who might suspect otherwise, we have performed tests with two and then with three stations most favorable for the seeding program removed from the sample. With two stations removed, the apparent effectiveness of the seeding dropped to about 20%, and the probability of the positive result being obtained by chance increased to about 9 in 10 000. With three stations removed, the effectiveness decreased to 19%, and the p value went up to $31/10\,000$.

We thus conclude that results $E = 0.248$ and $p = 2/10\,000$ are rather robust to the existence of a local observer-subjectivity effect.

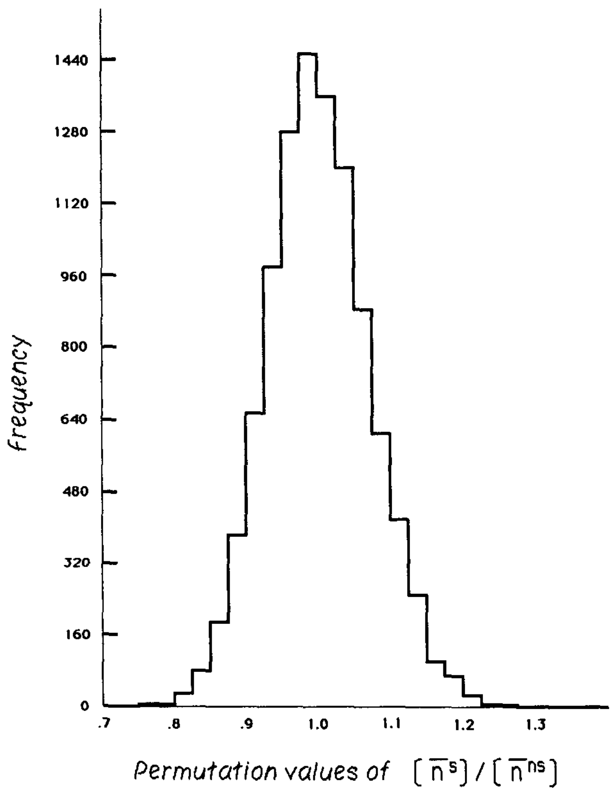

FIG. 2. Histogram of the frequency ratios (1) obtained by 10 000 permutations, station by station for each of the stations, of the hail days data of Table 1. The observed frequency ratio is equal to 0.752. Two of the 10 000 values of the permutation test are less than 0.752.

c. *Correction for an apparent climate change*

There are a number of possibilities other than seeding or data errors to explain the reduction of hail frequencies observed concurrently with the seeding program. A reasonable list of them might be as follows.

• Frequency of hail could be decreasing due to a climate change.

• Observers might be less inclined to report cases of hailfall due to a change in the formulation of instructions given. Such a change is conceivable associated with, say, new editions of observer's handbooks as various WMO rules are refined and/or updated.

• Due to a high natural variability of hail, for random reasons a significantly smaller number of hailstorm-generating weather situations could have occurred during the seeding period.

Since the impact of the last two effects on our seeded stations data is indistinguishable from that of the actual climate change, we shall refer to the collective impact of these three effects as to that of an "apparent" climate change. As noted, for an estimate of as well as a correction for the apparent climate change, we have compiled a "control" set of hail frequencies observed at the main synoptic stations in the two neighboring regions of Vojvodina and Bosnia and Herzegovina, which have no hail suppression programs (Table 2). A climate change here is obviously assumed to occur predominantly on a space scale larger than our total area displayed in Fig. 1. Note that the control set should also reflect a possible systematic change in observing practices, since all of the Yugoslavian stations are required to follow the same observer guidance material issued by the Federal Hydrometeorological Institute.

We performed three separate tests and corrections for the apparent climate change effect. For two of them we calculated the ratio of the average frequencies of the control sample (1) for two different choices of the "representative" suppression starting year: the median (1970) and the average (1973) of the 23 starting years of the suppression activities of the stations in the seeded area. Each of these frequency ratios is in turn assumed to reflect the climate and observing practices change effect, or apparent climate change. To account for this assumed change we then multiply the frequency data of the protected stations for the representative seeding period by the reciprocal of the frequency ratio of the control stations. These frequency ratios were 0.940 (19 versus 21 yr) and 0.854 (16 versus 24 yr), respectively. Corrections of the last 19 and the last 16 yr of Table 1 data for these ratios lead to the corrected seeding effectivenesses of $E_{19} = 0.208$ and $E_{16} = 0.147$, respectively. Subsequent permutation tests have resulted in significance levels of $p_{19} = 7/10\,000$ and $p_{16} = 141/10\,000$.

A legitimate argument is that a climate change is not an abrupt phenomenon, but rather one that is slow and thus could be approximated by a linear trend over the 40-yr period. As another correction for the apparent climate change, we therefore removed the linear trend from all of the seeded-area data, as observed in the control region, obtaining this trend via linear regression. The control region of hail days per station and year, and the resulting regression line and equation, are displayed in Fig. 3. For comparison, the same diagram for the seeded stations is shown in Fig. 4. Having removed the linear trend from the seeded stations as observed in the control region, we have once more repeated the effectiveness calculation and the permutation test. This time we obtained $E_{LR} = 0.222$ and $p_{LR} = 6/10\,000$.

Thus, the various apparent climate change corrections have reduced the effectiveness of the seeding activities from about 25% to between 22% and 15%, and have increased the probability of the positive result being obtained by chance if in fact no effect of seeding existed to between about 6 and 141 in 10 000.

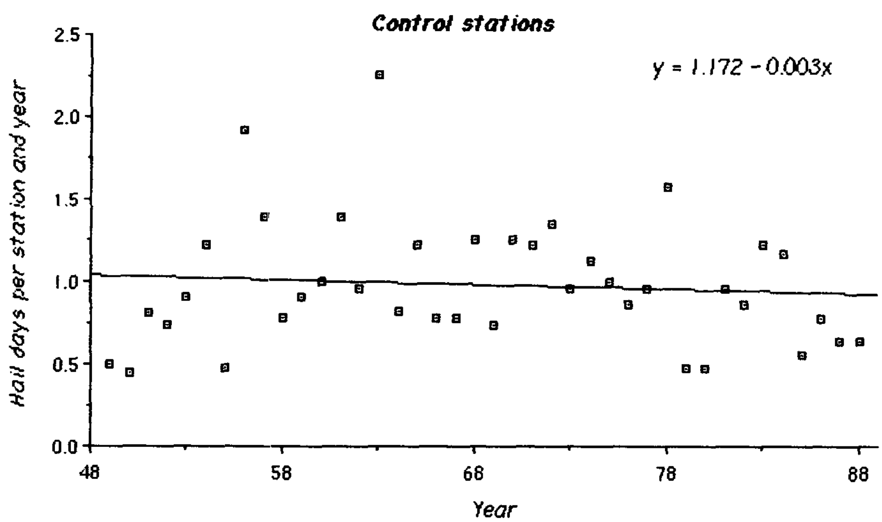

FIG. 3. Average number of hail days per station and year, as observed in the control area of Vojvodina and Bosnia and Herzegovina with no seeding program, and the resulting regression line and equation.

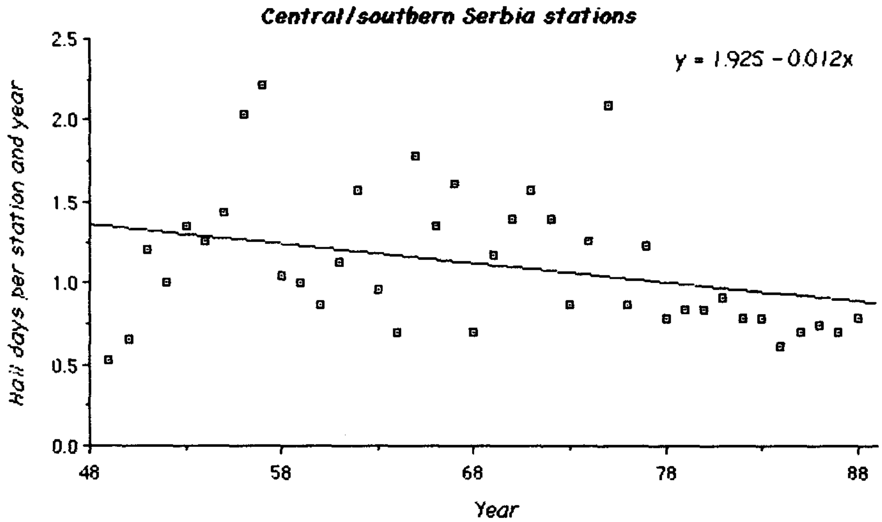

FIG. 4. As in Fig. 3 except for the seeded stations.

4. Conclusions

We, therefore, conclude that it appears unlikely that the seeding activities, performed in the eastern part of Yugoslavia and following the Soviet method, have no positive effect whatsoever. The reduction in hail frequency achieved seems to be of the order of 15%–20%.

The 98.5% or more statistical confidence of our positive result is well above what is usually required of significance tests in meteorology. A remaining possible reason for doubt is a general mistrust of the synoptic stations data. Could the observers be inclined, for whatever reason, to report hail less frequently once they know that there is a hail suppression program in place covering the area of their station? This is perhaps unlikely in view of the attention that a case of hailfall attracts, but cannot be entirely excluded. Realistically, an opposite inclination may be equally if not even more likely. Further considerations of this kind, however, are beyond the scope of this paper.

Acknowledgments. Use of the permutation test has been suggested to us by Dr. Nenad Aleksić, of the Institute of Meteorology, University of Belgrade. Dr. Aleksić has also read the draft manuscript and has made a number of valuable suggestions. Dr. Stan Changnon and two anonymous reviewers have made further suggestions in the reviewing process that has increased the completeness and clarity of the paper. Dr. Changnon has in addition provided extensive editorial advice on our earlier text. All of these contributions are appreciated. Our work has been partly supported by the Science Association of Serbia, Belgrade.

REFERENCES

Aleksić, N., 1989: Precipitation effects of hail suppression in Serbia. *Theor. Appl. Climatol.*, **40**, 271–279.

Changnon, S. A., Jr., 1975: Evaluation of an operational hail suppression project in Texas. *J. Wea. Mod.*, **7**, 88–100.

——, 1977: On the status of hail suppression. *Bull. Amer. Meteor. Soc.*, **58**, 20–28.

——, F. A. Huff, and C. F. Hsu, 1979: On the need to evaluate operational weather modification projects. *Bull. Amer. Meteor. Soc.*, **60**, 770–774.

——, and P. T. Schickedanz, 1969: Utilization of hail-day data in designing and evaluating hail suppression projects. *Mon. Wea. Rev.*, **97**, 95–102.

Federer, B., A. Waldvogel, W. Schmid, H. Schiesser, F. Hampel, M. Schweingruber, W. Stahel, J. Bader, J. Mezeix, N. Doras, G. Daubigny, G. der Megreditchian, and D. Vento, 1986: Main results of Grossversuch IV. *J. Climate Appl. Meteor.*, **25**, 917–957.

Foote, G. B., and C. A. Knight, 1979: Results of a randomized hail suppression experiment in northeast Colorado. Part I: Design and conduct of the experiment. *J. Appl. Meteor.*, **18**, 1526–1537.

Hsu, C.-F., and S. A. Changnon, Jr., 1983: On the evaluation of operational cloud seeding projects. *Water Resour. Bull.*, **19**, 563–569.

——, and ——, 1984: Using historical data to evaluate two large-area operational seeding projects. *J. Wea. Mod.*, **16**, 40–45.

Radinović, Dj., 1989: Effectiveness of hail control in Serbia. *J. Wea. Mod.*, **21**, 75–84.

Schickedanz, P. T., and S. A. Changnon, Jr., 1970: The design and evaluation of hail suppression experiments. *Mon. Wea. Rev.*, **98**, 242–251.

Sulakvelidze, G. K., 1967: *Showers and Hail.* Gidrometeorologicheskoe Izdatelystvo, 412 pp. (in Russian).

WMO, 1985: Review of the present status of weather modification. *Thirty-Seventh Session of the Executive Council,* Geneva, World Meteor. Organ., 167–173.