

## The Rain Enhancement Experiment in Puglia, Italy: Statistical Evaluation

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### ABSTRACT

A randomized rain enhancement experiment was carried out during 1988–94 in the area of Bari and Canosa, Italy, on the Adriatic coast. It was commissioned by the Italian Department of Agriculture and Forestry and the region of Puglia, with TECNAGRO, a nonprofit Italian company, as overall manager, and with EMS, an Israeli company, as field operator. The original purpose was to study rain-producing weather systems in southern Italy, establish similarities with Israel, and transfer Israeli technology. The experiment was a cross-over design with two alternating target areas, a buffer in between, and two additional control areas. Seeding was by injection of silver iodide into clouds by aircraft flying near the bases of clouds along predetermined tracks upwind of the target area. The experimental units were rainy days. Based on historical rain gauge data, it was estimated that 303 rainy days were required to establish a 15% rain increase at a significance level of 0.05 and 90% power.

In 1995, TECNAGRO asked the Scientific Committee for a statistical evaluation to investigate if a seeding effect could be established before the original goal of 303 seeding days was reached. The results of the analysis of the 260 available rainy days were that no discernable seeding effect could be found. This was evident from the root double ratio (RDR) and root regression ratio (RRR), which yielded  $RDR - 1 = -0.083 \pm 0.089$  and  $RRR - 1 = -0.004 \pm 0.057$ , respectively (the  $\pm$  sign represents the standard error of the estimate). Based on that result, it was decided to terminate the Puglia seeding experiment.

Preliminary exploratory studies suggest that the two target areas might have been affected differently by seeding and that an apparent substantial seeding effect occurred in the Bari area under conditions of moderate precipitable water between 700 and 850 mb. If these findings are confirmed by the recommended meteorological analyses and airflow studies, a new experiment with an appropriate design might be justified.

### 1. Introduction

The major component of the Italian “Progetto Pioggia,” carried out during 1988–94, has been a rainfall enhancement experiment in the region of Puglia on the

coast of the Adriatic Sea (Dell’Angelo et al. 1994). Its original objectives were “(i) To study the rain-producing weather systems in southern Italy and establish similarities with Israel; (ii) To apply technology used in Israel, which suggested increases in rainfall of 10–20%; (iii) To analyze the results with pre-established statistical methods, with target and control areas, for the assessment of increased rainfall and to prove statistically and physically that it was caused by the seeding; (iv) To transfer scientific and technical know-how to an Italian team for planning and execution of future rain en-

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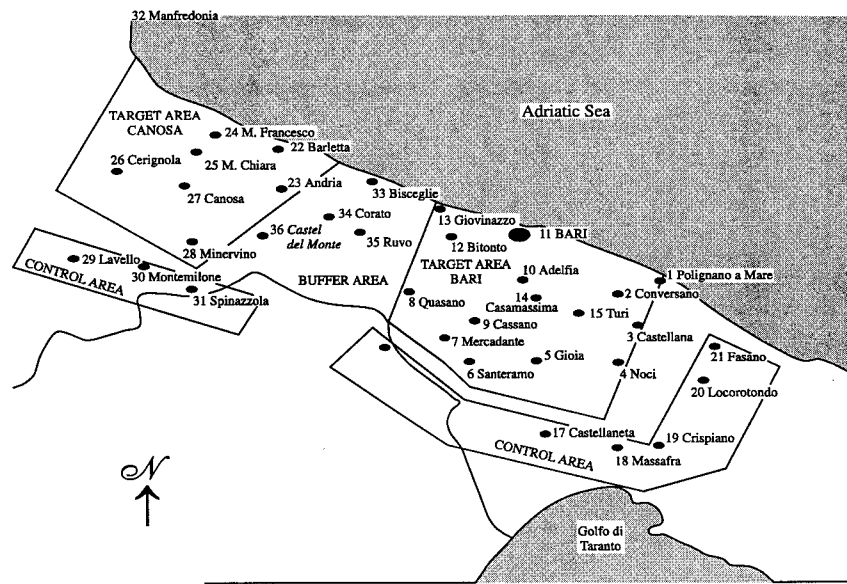


FIG. 1. The target and control areas and stations of the Puglia experiment.

hancement projects in other areas of Italy” (Scientific Committee 1993).

Rain in the Puglia region falls mainly in the winter from late November to late April from clouds that are mostly stratiform with embedded convection. The region is characterized by a large number of rainy days with low precipitation. The seasonal average is 400–500 mm. It is noteworthy that a good share of the annual average is due to a small number of rainy days with extensive precipitation, considering that about 30% of the seasonal quantity of rain falls in 10% of the rainy days. One such heavy precipitation event can provide about 20 mm of rain and about seven such days occur in each season (EMS 1987). This enhances the natural variance of the daily precipitation, thus making the statistical analysis more difficult.

During the rainy season, winds in the Puglia region blow from all directions. The most prevalent wind is from the southwest to the northwest ( $225^{\circ}$ – $315^{\circ}$ ); however, some rainy days originate from storms carried by northerly winds. The analysis of the rain climatology and the local wind conditions led the designers of the experiment to the conclusion that seeding could not be performed on all rainy days. As a result the target areas, the control areas, and the seeding lines were chosen to take advantage of about 90% of the cases in which the winds come from the southwest to northwest direction.

Progetto Pioggia was designed to test the static seeding method in which aircraft are used to disperse glaciogenic nuclei just below the base of convective clouds along predetermined flight tracks. The method incorporated several features from each of the two Israeli experiments (Gabriel 1967; Gagin and Neumann 1974; Gagin and Neumann 1981; Gabriel and Rosenfeld 1990) as follows: 1) two alternating targets located roughly

across the direction of prevailing rain-bearing winds; 2) experimental units initially defined as 24-h days, but excluding, at the stage of analysis, “dry” days defined as having no more than 0.2 mm of precipitation at any station in a buffer zone between the two targets; 3) randomized allocation of seeding to one or the other target, that is, Bari or Canosa, on each day (“cross-over” design); 4) the response variate defined by comparing rainfall on the two targets, that is, Bari versus Canosa rainfall; 5) rainfall observations at stations in several “control” areas located generally upwind of the targets (see Fig. 1) to be used in the analysis for statistical adjustment of target rainfalls (covariates); and 6) analysis by ratio statistics. For the majority of synoptic situations upwind means motion from the quadrant ( $225^{\circ}$ – $315^{\circ}$ ).

The experiment, as proposed by the late Abraham Gagin, was carried out under the auspices of TECNAGRO, an Italian nonprofit organization devoted to technological innovation in agriculture, and was designed (Shimborsky 1988) and carried out by EMS, a subsidiary of Mekorot Water Company, Ltd., of Israel (Scientific Committee 1993).

Seeding was carried out from late fall to early spring on days that satisfied the following criteria: 1) cloud-top temperatures colder than  $-8^{\circ}\text{C}$ , 2) cloud-base height lower than 2400 m MSL, and 3) wind direction at 700 mb such that the control areas would not be contaminated by seeding (wind direction as determined by radiosonde at 0000 and 1200 LT in Brindisi and from radar storm track observations).

The project started in 1985 when the Italian Department of Agriculture and Forestry and the region of Puglia commissioned TECNAGRO to set up a seeding experiment. The practical aspects were arranged in 1986

TABLE 1. Total hours of aircraft flying time, seeding and radar operation, for the different seasons of operations (no operations in 1990–91).

| Year        | Flight (h) | Seeding (h) | Radar operation (h) |
|-------------|------------|-------------|---------------------|
| 1987–88     | 45:07      | 34:48       | 397:03              |
| 1988–89     | 63:47      | 42:26       | 286:15              |
| 1989–90     | 55:23      | 34:30       | 356:15              |
| 1991–92     | 30:50      | 21:02       | 299:16              |
| 1992–93     | 151:10     | 90:07       | 1163:31             |
| 1993–94     | 147:35     | 97:57       | 894:00              |
| Total hours | 492:72     | 319:7       | 3395:80             |

by agreement between TECNAGRO and Agridev (Agriculture Development Company, Ltd.) from Israel. This was followed by a feasibility study in which clouds were assessed by observations from aircraft in 1987. Randomized seeding began in 1988 and continued with interruptions until 1994. The experiment was controlled from an operation center at the Italian air force base at Bari, which was equipped with a C-band radar and facilities for radar data processing, meteorological and satellite data receiving, and preparation of the silver iodide solution for the burners.

Over the entire seeding experiment radar volume scans were collected over 3396 h, while seeding and aircraft operation occurred over 320 and 493 h, respectively (Table 1). Two seeding airplanes were kept on alert, although only one airplane at a time carried out the seeding operation. On days selected for seeding that conformed to the seeding criteria, a seeding airplane was instructed to fly back and forth along the prescribed seeding line upwind of the target area and release AgI particles at a rate of  $500 \text{ g h}^{-1}$  by burning a AgI–NaI in acetone solution. The length of the seeding lines was about 40 km. The plane was instructed to fly as close as possible to cloud base at an altitude of about 800 m.

Due to limitations imposed by the air traffic control, the plane was, at times, forced to fly at higher altitudes (about 2600–3000 m). This may have introduced another variable whose effect on the seeding could not be estimated and had to be assumed to be random.

Evaluation of the results was based on the data collected by the existing rain gauge network of the Ministry of Public Works (Lavori Pubblici) (for stations see Fig.

1). A second, independent network of recording rain gauges was set up by the Central Office for Agricultural Ecology (UCEA) in 1993 in a regular lattice with a 10-km spacing. These UCEA data were not used in the present statistical evaluation because they covered only the last two seasons of the experiment.

In 1990 TECNAGRO set up its scientific committee to oversee the scientific aspects of the experiment. The committee did not propose changes in the existing design of the project because that would have prevented the collection of a homogeneous dataset for the entire experiment. In addition to verifying the integrity of the execution of the randomized experiment and the unbiased analysis of its results, the committee dealt with physical, statistical, and manpower training aspects of the project. In particular, it laid out the plans for 2D and 3D mesoscale modeling and extended physical studies by cloud physics aircraft and radar, coupled with mesoscale and synoptic investigations. Circumstances did not permit these plans to be carried out.

The activities and studies of TECNAGRO and EMS are documented in numerous reports; many of them include full datasets. Radar–rain gauge time comparisons have been presented by Nania (1994, 1996).

## 2. The experimental units

The experimental units were days, from 0800 to 0800 LT the following day, on which there was at least 0.2 mm of precipitation at any station in the buffer zone. This definition is objective and independent of treatment allocation or seeding operation. It is, however, post hoc, and cannot be used in real time. Seeding was therefore carried out independently of this definition by flying along the seeding line and dispensing AgI whenever the clouds looked suitable. The airplanes were deployed day and night. Because the decision to seed and the definition of the experimental day were not dependent on each other, there were days defined as experimental units that were not seeded and there were also days seeded but later not found to qualify as experimental (Table 2).

This lack of congruence, while irritating, is the price paid to obtain unbiased evaluations. Actually, the days that were experimental but not seeded and the days that were seeded though not experimental were mostly days with little precipitation, so the inconsistency has little

TABLE 2. Days during experiment, by season, seeding, and rainy or dry days.

| Dates                   | Days | Rainy days |      |         | Dry days |      |         |
|-------------------------|------|------------|------|---------|----------|------|---------|
|                         |      | Total      | Seed | No seed | Total    | Seed | No seed |
| 6 Mar 1988–5 May 1988   | 61   | 32         | 14   | 18      | 29       | 1    | 28      |
| 6 Feb 1989–11 May 1989  | 95   | 40         | 15   | 25      | 55       | 2    | 53      |
| 24 Mar 1990–15 May 1990 | 53   | 22         | 10   | 12      | 31       | 2    | 29      |
| 1 Apr 1992–30 Apr 1992  | 30   | 15         | 8    | 7       | 15       | 0    | 15      |
| 22 Oct 1992–10 May 1993 | 201  | 92         | 32   | 60      | 109      | 2    | 107     |
| 15 Jan 1994–31 May 1994 | 136  | 59         | 34   | 25      | 77       | 1    | 76      |
| Total                   | 576  | 260        | 113  | 147     | 316      | 8    | 308     |

TABLE 3. Stations and available data.

| Station          | Area                | Available            | Interpolated <sup>a</sup> | Missing        |
|------------------|---------------------|----------------------|---------------------------|----------------|
| Polignano        | Bari                | 571                  | 5                         | 0              |
| Conversano       | Bari                | 569                  | 7                         | 0              |
| Castellana       | Bari                | 567                  | 9                         | 0              |
| Noci             | Bari                | 568                  | 8                         | 0              |
| Gioia            | Bari                | 438                  | 2                         | 136            |
| Santeramo        | Bari                | 540                  | 28                        | 8              |
| Mercadante       | Bari                | 560                  | 15                        | 1              |
| Quasano          | Bari                | 332                  | 8                         | 236            |
| Cassano          | Bari                | 567                  | 8                         | 1              |
| Adelfia          | Bari                | 570                  | 6                         | 0              |
| Bari             | Bari                | 440                  | 0                         | 136            |
| Bitonto          | Bari                | 570                  | 6                         | 0              |
| Giovinazzo       | Bari                | 574                  | 2                         | 0              |
| Casamassima      | Bari                | 565                  | 11                        | 0              |
| Turi             | Bari                | 572                  | 4                         | 0              |
| Altamura         | Bari control        | 576                  | 0                         | 0              |
| Castellaneta     | Bari control        | 574                  | 2                         | 0              |
| Massafra         | Bari control        | 563                  | 10                        | 3 <sup>b</sup> |
| Crispiano        | Bari control        | 525                  | 45                        | 6 <sup>b</sup> |
| Locorotondo      | Bari control        | Omitted <sup>c</sup> | 5                         | 142            |
| Fasano           | Bari control        | 570                  | 6                         | 0              |
| Barletta         | Canosa              | 576                  | 0                         | 0              |
| Andria           | Canosa              | 430                  | 10                        | 136            |
| M. S. Francesco  | Canosa              | 400                  | 4                         | 172            |
| M. S. Chiara     | Canosa              | 566                  | 9                         | 1              |
| Cerignola        | Canosa              | 569                  | 0                         | 7              |
| Canosa           | Canosa              | 493                  | 0                         | 83             |
| Minervino        | Canosa              | 561                  | 15                        | 0              |
| Lavello          | Canosa control      | Omitted <sup>c</sup> | 5                         | 337            |
| Montemilone      | Canosa control      | Omitted <sup>c</sup> | 0                         | 140            |
| Spinazzola       | Canosa control      | Omitted <sup>c</sup> | 0                         | 367            |
| Manfredonia      | Outside control     | 573                  | 3                         | 0              |
| Bisceglie        | Buffer <sup>d</sup> | 209                  | 0                         | 367            |
| Corato           | Buffer <sup>d</sup> | 569                  | 7                         | 0              |
| Ruvo             | Buffer <sup>d</sup> | 562                  | 13                        | 1              |
| Castel del Monte | Buffer <sup>d</sup> | 506                  | 17                        | 53             |

Bari average was calculated as the daily mean of the available stations in the Bari area.

Canosa average was calculated as the daily mean of stations available in the Canosa area.

Covariates were the six individual stations in the control areas that were not omitted.

<sup>a</sup> Interpolated by the Italian meteorological service.

<sup>b</sup> Records were interpolated by regression on the other stations used as covariates.

<sup>c</sup> Used only for the computation of Table 6.

<sup>d</sup> Stations used to define days as rainy or dry. (In the original design only buffer stations were to be used, but there were too many missing values among those, so two other control stations were added.)

effect on the precipitation totals used in the present analysis.

It had been estimated that some 303 experimental units would provide 90% power for a 5% significant finding of a hypothetical 15% increase of rainfall (Gabriel 1991). The Scientific Committee considered this number to be adequate and expected it to be accumulated during four seasons. For administrative reasons, however, and due to lack of funds, the experiment was carried out only during parts of the 1988–89, 1989–90, 1991–92, 1992–93, and 1993–94 seasons (there were no activities in 1990–91). By the end of spring 1994, only 260 experimental units had been accumulated (Table 2). The experiment was terminated because the results then available, which are presented and discussed here, showed it to be extremely unlikely that a positive seeding effect could be established with 5% significance

at 90% power by the addition of an additional 43 units to reach the intended number.

### 3. Method of analysis

The current analysis uses data based on mean daily precipitation at 15 stations in the Bari area and at 7 stations in the Canosa area (Table 3). Since data were missing for some stations on some of the days, daily precipitation has been averaged over the stations with available data. For covariate adjustment only the six control stations with complete or near-complete records were used: Altamura, Castellaneta, Massafra, Crispiano, Fasano, and Manfredonia. For station location, see Fig. 1.

The experimental design called for a confirmatory analysis of the daily Bari versus Canosa target area comparisons, contrasting Bari-seeded days with Canosa-

seeded days to test whether seeding had any effect on precipitation. The adjective “confirmatory” is used to indicate the experiment was designed to test an hypothesis, and the analysis was run to confirm or reject that hypothesis. The hypothesis was that of no-seeding effect, as measured by the difference between the alternate targets’ precipitation adjusted for upwind control area precipitation. This formulation was implicit in the design chosen. The actual measurements of precipitation on the targets and the regression adjustment on the controls were not specified in advance, so all available stations’ data were used. The measurements for the targets were averaged, and for the few available control stations they were used individually in a regression equation. The choice of control stations for the regression was

very limited because so few of the intended stations had adequate precipitation records. Indeed, none of the stations in the Canosa control area had enough data to allow them to be included, so it was decided to include the Manfredonia station on the coast northwest of the Canosa target, which was far enough away to make contamination unlikely. The analysis was to include all rainy days according to which of the targets seeding had been allocated to, irrespective of whether the days had actually been seeded or not.

The analysis was by ratio statistics as these had been found useful in similar studies. The basic statistic divides seeded by unseeded precipitation on each target and takes a geometric mean of these ratios of the two targets; this is the root double ratio:

$$\text{RDR} = \sqrt{\frac{\text{Precipitation on Bari when Bari is seeded}}{\text{Precipitation on Bari when Canosa is seeded}} \times \frac{\text{Precipitation on Canosa when Canosa seeded}}{\text{Precipitation on Canosa when Bari seeded}}}.$$

An improvement on this statistic was obtained by adjusting it by the value predicted from control areas to give the root regression ratio

$$\text{RRR} = \text{RDR}/(\text{Estimate of RDR from control stations}).$$

Approximate formulas were available for computing these ratios and estimating their standard errors under randomization (Gabriel 1991, 1999). Because these approximations are known to be very close (Petrondas 1981), they were used here for tests of significance instead of actual rerandomizations of the experimental data.

The adjustment of RDR to obtain RRR used the regression of the Bari–Canosa target difference onto the six control stations for which adequate data were available. The calculations for this regression included all the experimental days, seeded or unseeded on either target. This procedure is used for a randomization test in which the same computations are applied to all the experimental data under the actual randomization and under all rerandomizations. The scatterplot with the fitted regression line is shown in Fig. 2. (The two apparent outlier days had been included in fitting the regression line.) The dashed curves on Fig. 2 provide a 95% confidence band for the linear regression, which is represented by the equation

$$\begin{aligned} \text{REGRESSION FIT OF BARI–CANOSA DIFFERENCE} \\ = -0.041 + 0.033\text{ALTAMURA} \\ + 0.078\text{CASTELLANETA} + 0.172\text{MASSAFRA} \\ - 0.209\text{CRISPIANO} + 0.406\text{FASANO} \\ - 0.440\text{MANFREDONIA}. \end{aligned}$$

In this equation the daily precipitation at each area or station has been expressed as a percentage of the total precipitation at that area or station during the 260 days.

The coefficients for the six control stations vary from large negative to large positive according to the station’s location on a southeast–northwest gradient. The southeast–northwest difference in the control locations of the Bari and Canosa targets has evidently been reproduced by the gradient of the control contributions to the re-

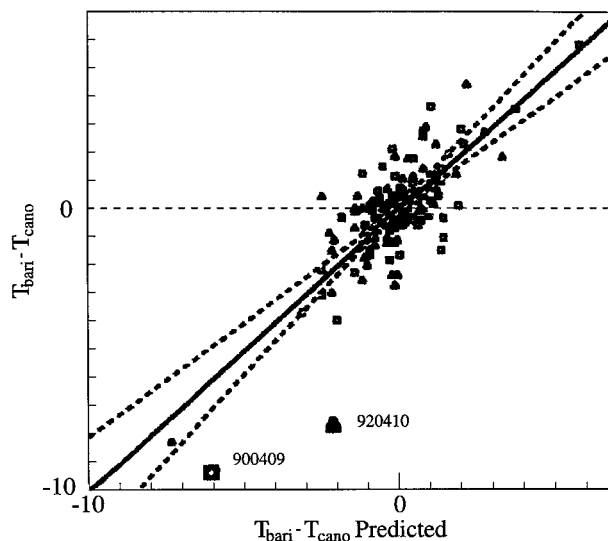


FIG. 2. Regression of Bari–Canosa targets difference on six control stations. (The two outliers from the general pattern, which were included in the regression calculations, are flagged with their dates by year, month, day; the dashed lines represent the 95% confidence band for linear regression.)



TABLE 4. Estimated proportional effect of seeding for rainy days, all days, seeded, and other days, with standard error. ("Seeded" and "unseeded" are biased estimates due to selection of days for seeding.)

|                          | Number of days | RDR-1              | RRR-1              |
|--------------------------|----------------|--------------------|--------------------|
| Rainy days               | 260            | $-0.083 \pm 0.089$ | $-0.004 \pm 0.057$ |
| Two-sided <i>P</i> value |                | 0.35               | 0.94               |
| All days                 | 576            | $-0.081 \pm 0.088$ | $+0.003 \pm 0.057$ |
| Seeded rainy days        | 113            | $-0.028 \pm 0.109$ | $+0.048 \pm 0.064$ |
| Other rainy days         | 147            | $-0.222 \pm 0.139$ | $-0.172 \pm 0.108$ |

gression. Since the multiple regression, which is well fitted as it has a multiple correlation of 0.585, is designed for optimal prediction, this reproduction of the geographical gradient of the targets by that of the predictors is not surprising. Also, regressions tend to stress the most extreme predictors, and this explains why Manfredonia and Fasano, the stations farthest to the northwest and southeast, respectively, have the largest coefficients.

The formulas used in the paper's analyses are discussed in detail in the companion paper by Gabriel (1999).

#### 4. Results of the confirmatory analysis

The proportional effect of seeding could be estimated from RDR-1 or, with greater precision, from RRR-1. These estimates are given in the first line of Table 4.

The estimates of seeding effect are very close to zero, within less than one standard error; the *P* values are way above the 5% level of significance, and a 95% confidence interval on the proportional effect of seeding ranges from  $-11\%$  to  $+12\%$  (as calculated from a logarithmic transformation). This means that there is no evidence of a seeding effect.

The Scientific Committee's decision not to recommend continuation of the experiment for an additional 43 rainy days was based on estimating that there was very little chance that completion of the planned 303 rainy days of experimentation would have changed the finding of nonsignificance. Roughly speaking, it would have required a  $+89\%$  effect of seeding during the additional 43 rainy days in order for the 303 day RRR to achieve 5% significance. (This calculation is based on comparing logarithms of RRR values.)

#### 5. Analyses by various definitions of experimental days

The confirmatory analysis was based on the rainy days since these had been chosen as the experimental units in the initial design. The restriction to rainy days had been intended to exclude the large number of "dry" days that were thought unlikely to be affected by seeding and thus add mere random error to the analysis. This restriction has been considered unbiased since the definition was in terms of buffer area rainfall and that

should not have been affected by seeding. Actually, the restriction made little difference to the results. Table 4 shows the RDR and RRR and their standard errors to be almost exactly the same for the 260 rainy days as for all 576 days of the experimental periods.

As explained above, seeding was carried out mostly, but not always, on days that turned out to satisfy the definition of rainy days. Again, analysis in terms of actually seeded days had to be avoided because of the bias created by seeding only on occasions when conditions were favorable for precipitation on the allocated target. Confirmation that such a bias would have been introduced is found in Table 4, which shows an apparent negative effect of seeding on days that remained unseeded.

#### 6. Preliminary exploratory analyses

Despite the failure to find confirmatory evidence of a seeding effect, some exploratory analyses were carried out in an effort to find a seeding signal in a physically meaningful subset of the data.

Brindisi rawinsonde data were analyzed in search of thermodynamic variables that could serve as a basis for subdividing the experimental data into subsets, the evaluation of which might suggest the presence of seeding effects. One such classification variable was the precipitable water (PW) between 700 and 850 mb, as given by the sounding prior to the commencement of seeding. Appropriate data were obtained for 258 of the 260 experimental rainy days and divided into approximately thirds based on the magnitude of PW that ranged from 0.01 to 0.70 cm. This resulted in the dry (D), intermediate (I), and moist (M) classes of days used for exploratory analysis.

An evaluation was carried out on each of the three classes but showed no evidence of a seeding effect; the estimated proportional effect of seeding (Table 5) in each class was very close to zero and within less than one standard error.

A review of the single ratios (SRs) that compose these RDRs suggested the possibility that Bari and Canosa were responding differently to seeding. To test this premise, an evaluation was carried out on Bari and Canosa seeding separately using the double ratio (DR) of each target with respect to its control area. (For this purpose, each control area's daily precipitation was estimated by

TABLE 5. Estimated proportional effects of seeding for rainy days with different degrees of moisture. (Two days were not classified because of missing data.)

|                      | All days           | <i>D</i> days      | <i>I</i> days      | <i>M</i> days      |
|----------------------|--------------------|--------------------|--------------------|--------------------|
| Number of rainy days | 260                | 87                 | 87                 | 84                 |
| RDR-1                | $-0.083 \pm 0.089$ | $-0.145 \pm 0.180$ | $-0.066 \pm 0.149$ | $-0.106 \pm 0.133$ |
| RRR-1                | $-0.004 \pm 0.057$ | $-0.072 \pm 0.108$ | $-0.140 \pm 0.107$ | $-0.103 \pm 0.079$ |

the mean of all the area's stations for which data were available on that day, including stations that had not been used in the confirmatory analysis above.) The resulting DRs (Table 6) did not show indications of seeding effects except at Bari on days of the *I* class, where the proportional effect of seeding was estimated as  $+0.388$  with a standard error of  $0.208$ , suggesting a possible substantial seeding effect on those days.

The physical plausibility of the results of the preliminary exploratory analyses should be confirmed through independent meteorological studies before embarking on more extensive exploratory analyses. If these studies indicate that further exploratory analyses are warranted, they will provide the basis for selecting site-appropriate, physically meaningful stratification variables.

## 7. Historical perspectives

The Puglia experiment was designed to test the transferability of Israeli cloud-seeding technology to the meteorology and topography of Puglia. The justification for this test was that the available analyses of the Israel I (1961–67) and Israel II (1969–75) experiments appeared to confirm the efficacy of that technology in augmenting precipitation by about 15% (Gabriel 1967; Gagin and Neumann 1974, 1981). It will therefore be useful to review these experiments briefly and relate them to the Puglia project.

Israel I had been designed in 1961 on the basis of a physical model incorporating the Wegener–Bergeron–Findeisen process and assuming that clouds over Israel contained much supercooled water that would not freeze and precipitate naturally because of an inadequate supply of natural freezing nuclei and the lack of an active coalescence process. The hypothesis to be tested was that introduction of AgI particles would stimulate freez-

ing and thus initiate precipitation of this water, thus augmenting total precipitation over Israel. The methodology chosen was the “static” seeding mode in which AgI particles were dispersed from airplanes flying along preselected routes at heights near the basis of cloud and from ground generators. The experiment was designed as randomized seeding to alternate targets (the cross-over design), and analysis of its results showed a significant effect of seeding, an estimated 15% increase in precipitation (Gabriel 1967; Gabriel and Baras 1970).

Exploratory statistical analyses suggested the main effect to have been in the hilly center of the country, some 40 km from the seeding line, and this was interpreted as partly resulting from orographic lifting.

Following on this apparently successful experiment, Israel II was designed mainly as a replication with some adjustments, such as focusing on the inland hilly region target closer to the Sea of Galilee. The physical mode was not questioned, and alterations were mostly introduced to improve statistical sensitivity by using upwind control areas of the coast. At a later stage it was decided to uncouple the analysis of the alternate targets, so the initial analyses of Israel II related only to the northern target, which was of more interest for potential water use. The results of these analyses were very much a repetition of the findings of Israel I (Gagin and Neumann 1981) and appeared to confirm its effects by replication.

Analyses that included both targets were carried out much later (Gabriel and Rosenfeld 1990) and produced equivocal findings. There might have been positive effects only in the north, and negative effects in the south, or no real effects at all—a mere chance variation.

Subsequent physical measurements in the Israeli clouds during the late 1980s and early 1990s (e.g., Levin et al. 1996) demonstrated that the basic physical model, which suggests that the clouds over Israel are deficient in ice crystals and an active coalescence process, is not always correct. To some extent, this undermined the logic behind the AgI seeding that had been used in Israel I and II.

The initiative for experimenting with cloud seeding in Puglia came after the initial encouraging analyses of Israel II had been published and before the subsequent physical research and statistical reanalysis had cast doubt about the effectiveness of cloud seeding in Israel. At that time, it was reasoned that a viable technology existed, based on a widely accepted physical model, and it had been confirmed statistically by an experiment and

TABLE 6. Estimated proportional effects of seeding on each target for rainy days, as classified by air moisture: DR with standard error. There are fewer than 260 Canosa days available because of lack of some Canosa control data.

|                |             | Bari target-control |             | Canosa target-control |  |
|----------------|-------------|---------------------|-------------|-----------------------|--|
| Moisture class | No. of days | DR-1                | No. of days | DR-1                  |  |
| <i>D</i> days  | 87          | $-0.104 \pm 0.228$  | 64          | $-0.171 \pm 0.337$    |  |
| <i>I</i> days  | 87          | $+0.388 \pm 0.208$  | 65          | $-0.144 \pm 0.250$    |  |
| <i>M</i> days  | 84          | $-0.085 \pm 0.133$  | 68          | $-0.101 \pm 0.214$    |  |

its replication. It, therefore, was reasonable to expect that the same technology would be similarly effective in other Mediterranean areas in similar latitudes. Negotiations with Italian authorities led to the initiation of the experiment, with Puglia being chosen as the location for reasons associated with water shortages and agricultural concerns. From the scientific point of view the Puglia area seemed less than ideal as a replication of Israeli conditions since its targets were in the lee of mountains. Only minor efforts were made to check how the conditions in the two countries differed before the experiment was launched.

Importation of an Israeli team and equipment ensured transferability of technology, but differences in orography may have made its application doubtful.

The use of the cross-over design was a fundamental part of the replication of the Israeli technology in the Puglia area. Shimborsky (1988) established the viability of the cross-over design in the Puglia area by showing that the rain correlation between the Bari and Canosa targets was 0.61. This is confirmed by the similar correlation of 0.68 between the two targets' precipitation during the 260 experimental days. In addition, seeding lines as a function of wind direction were established to avoid the possibility that the seeding of one target would contaminate the other target area. However, no attempt was made to examine the meteorology of the two target area to ensure that cloud conditions were simultaneously similar in both areas, despite the fact that the precipitation data showed a strong rain gradient between Bari and Canosa.

Both the designer of that experiment, Abraham Gagin, and the present authors, who were asked to form the core of the Scientific Committee after the experiment had been launched and was well under way, repeatedly stressed the need for extensive physical measurements and modeling to accompany the cloud seeding. These additional activities were deemed essential for any reliable interpretation of the possible effects of seeding and, indeed, for checking whether the assumed precipitation model held and justified the seeding technology that was used. Budgets for cloud physics measurements were, unfortunately, only available during one year when no cloud physics aircraft was available on short notice, so some of the underlying questions could not be answered.

The Puglia experiment was carried out as a "black box" replication of a given technology in a new location according to the state of the art at that time. The methodological lesson is not that black box experiments with statistical evaluation are unsuitable. Once a seeding conceptual model is postulated and a hypothesis is formulated, the hypothesis can be tested by incorporating it into a black box experiment and carrying it out meticulously until the statistical test confirms or rejects the hypothesis. Again the lesson that is to be learned is that an aggressive program of physical measurements, numerical modeling, and analysis is needed before and

during the experiment to establish the applicability of the seeding conceptual model to the conditions in the experimental area (in this case transferability of the Israeli technology) and to understand the physical significance of the statistical results. Budgetary and political considerations all too often shortchange the physical part of an experiment and thereby make a reasonable physical interpretation of the statistical findings difficult if not impossible.

## 8. Conclusions and comments

The analysis of the experimental results along the lines recommended in the initial design shows no discernable seeding effect during the Puglia rain enhancement experiment. The somewhat early termination of the experiment is most unlikely to have affected that conclusion.

Exploratory analyses suggest that the clouds over the Bari and Canosa areas may have been different and that the Bari target might have responded more favorably to seeding under intermediate moisture conditions. This suggestion needs to be confirmed by further analyses and, if physically plausible, by a future seeding experiment. At present time, it cannot be considered conclusive.

The difference between the results of the experiments in Puglia and Israel may be due to the different orographies relative to the main weather situations, with the main airflow in Puglia being downslope as compared to the upslope situations in Israel. Some 2D flow simulations (Paccagnella and Simonini 1993) have shown some differences between the two regions. Further 3D flow simulations for different synoptic situations, combined with aircraft microphysical in-cloud measurements, could serve to verify whether seeding during southeasterly to northwesterly airflow might have affected the Bari and Canosa areas differently because of their situation relative to the Gulf of Taranto and the inhomogeneities of the Apennines.

Weather modification as a whole is an exciting and intriguing science and leapfrogging previous experiments is always a challenge. As the sophistication of measuring platforms and numerical models, and our understanding of the underlying science and statistics increases, we may finally solve the mystery of the formation of precipitation and with it find a key to a better management of water resources from the sky.

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## REFERENCES

- Dell'Angelo, A., F. Micale, and R. List, 1994: "Progetto Pioggia," the Italian rain enhancement project. *Proc. Sixth WMO Scientific Conf. on Weather Modification*, Paestum, Italy, World Meteorological Organization, 11–14.
- EMS, 1987: The Experimental Design, Phase B of Puglia Experiment. Report to TECNAGRO, 29 pp. [Available from TECNAGRO, Via T. Grossi, 6, 00184 Rome, Italy.]
- Gabriel, K. R., 1967: The Israeli rainfall stimulation experiment: Statistical evaluation for the period 1961–1965. *Proc. Fifth Berkeley Symp. on Mathematical Statistics and Probability*, Vol. V, L. M. LeCam and J. Neyman, Eds., University of California Press, 91–113.
- , 1991: The use of ratio statistics in rain experiments, with special reference to Puglia and Sardinia. TECNAGRO Tech. Report, TECNAGRO, Rome, Italy, 42 pp. [Available from TECNAGRO, Via T. Grossi, 6, 00184 Rome, Italy.]
- , 1999: Ratio statistics for randomized experiments in precipitation stimulation. *J. Appl. Meteor.*, **38**, 290–301.
- , and M. Baras, 1970: The Israeli Rainmaking Experiment 1961–67. Final statistical tables and evaluation. Department of Statistics Tech. Report, Dept. of Statistics, The Hebrew University, Jerusalem, Israel, 47 pp.
- , and D. Rosenfeld, 1990: The second Israeli rainfall stimulation experiment: Analysis of precipitation on both targets. *J. Appl. Meteor.*, **29**, 1055–1067.
- Gagin, A., and J. Neumann, 1974: Rain stimulation and cloud physics in Israel. *Climate and Weather Modification*, W. N. Hess, Ed., Wiley, 454–494.
- , and —, 1981: The second Israeli randomized cloud seeding experiment: Evaluation and results. *J. Appl. Meteor.*, **20**, 1301–1311.
- Levin, Z., E. Ganor, and V. Gladstein, 1996: The effects of desert particles coated with sulfate on rain formation in the eastern Mediterranean. *J. Appl. Meteor.*, **35**, 1511–1523.
- Nania, A., 1994: Cloud seeding and rain time intervals in experimental units. *Proc., Sixth WMO Scientific Conf. on Weather Modification*, Paestum, Italy, World Meteorological Organization, 27–34.
- , 1996: *Progetto Pioggia—La stimolazione delle precipitazioni in Italia*. TECNAGRO, CD-ROM. [Available from TECNAGRO, Via T. Grossi, 6, 00184 Rome, Italy.]
- Paccagnella, T., and G. Simonini, 1993: Interazione fra strutture orografiche e flussi troposferici nel comparto centro-occidentale della regione Basilicata (Parte integrativa). Report, Servizio Meteorologico, Regione Emilia Romagna, 54 pp. [Available from TECNAGRO, Via T. Grossi, 6, 00184 Rome, Italy.]
- Petrondas, D. A., 1981: Two topics in permutation (re-randomization) inference: Double ratio statistics and multiple comparisons. Ph.D. thesis, University of Rochester, 366 pp. [Available from Dept. of Biostatistics, University of Rochester, Rochester, NY 14642.]
- Scientific Committee, 1993: Progetto Pioggia: Recommendations for a five-year plan of activities 1993–1997. TECNAGRO Tech. Report, Rome, Italy, 46 pp. [Available from TECNAGRO, Via T. Grossi, 6, 00184 Rome, Italy.]
- Shimborsky, E., 1988: Puglia, Progetto Pioggia, Phase B: The experiment design. TECNAGRO Tech. Report, TECNAGRO, Rome, Italy, 32 pp. [Available from TECNAGRO, Via T. Grossi, 6, 00184 Rome, Italy.]