RESULTS OF AN EXPLORATORY EXPERIMENT WITHIN THE GREEK NATIONAL HAIL SUPPRESSION PROGRAM

John A. Flueck
CIRES, University of Colorado and NOAA - ERL/ESG
Boulder, Colorado

Mark E. Solak
Atmospherics Incorporated
Fresno, California

and

Theodore S. Karacostas
National Agricultural Insurance Institute (OGA)
Ministry of Northern Greece
Thessaloniki, Greece

Abstract. During the summers of 1984 and 1985 a multi-area operational hail suppression program was conducted in northern and central Greece, sponsored by the Greek National Agricultural Insurance Institute. This operational program included a small exploratory randomized cross-over seeding experiment embedded within one of the three operational project areas. This article summarizes the experiment's design, the network hailpad data and the initial analyses and results. Substantial reductions (e.g., 30 to 75%) in the area of coverage, hailstone size, and concentration are apparent in the two summers' data, and the combined two season sample provides correspondingly strong inferential two-tailed P-value support (e.g., .08 to .02) for evidence of treatment effects.

1. INTRODUCTION

The National Hail Suppression Program (NHSP) of Greece is a three-area (i.e., Emathia-Pella, Serres-Drama, and Larisa-Karditsa in northern and central Greece) summertime (May - September) operational program sponsored by the National Agricultural Insurance Institute of Greece (OGA) and conducted by Atmospherics Incorporated (AI). Its basic objectives and overall design were first touched upon in Karacostas (1984). A summary of the overall program characteristics and operations appear in Henderson (1986), and details of the complete program can be found in Solak et al. (1985). This paper focuses on the design and analysis of an exploratory randomized cross-over experiment which was embedded in the Emathia-Pella operations area in the NHSP during the summers of 1984 and 1985.

This experiment was implemented to investigate and develop evidence of the efficacy of the treatment methodology being applied in the entire program. It was conducted as an exploratory experiment so that its design, implementation and analyses could be changed as one searched for evidence of treatment effects (see Flueck 1978, 1982 and 1986 for descriptions of an exploratory experiment). This cross-over design experiment, near Thessaloniki in the Emathia-Pella region, was a "piggyback" venture on the operational project; Flueck (1976) and Tukey et al. (1978) offer further discussion on small experiments within operational projects. This approach is highly desirable for at least three reasons. First, it provides a quantitative setting within which one can search for the optimal amount of treatment for the given situation, a well used practice in many disciplines including medicine, agriculture and chemical engineering. Second, it provides for monitoring the realized product on every "production day," much like the quality control function in a manufacturing plant. Third, it allows the participants an opportunity to improve their meteorological understanding of the hail processes in this area of Greece.

2. THE EXPERIMENT'S DESIGN

The basic design of the exploratory randomized cross-over experiment was developed in a joint effort by AI and OGA in response to the sponsoring agency's specification in the original project solicitation that "an evaluation" be conducted as part of the overall program. The exploratory philosophy employed allows design adjustments at fixed intervals as experience and findings dictate, while providing sufficient structure to enable useful analysis for treatment effects. Key facets of the experiment are summarized below relating to design characteristics, operational procedures and evaluation. Further details are available in Henderson (1986).

2.1 Design Characteristics

The principal characteristics of the experiment's design are:

(1) The experiment is to be conducted in its exploratory phase for three seasons, 1984, 1985, and 1986. A confirmatory experiment is anticipated to be performed in 1987 and 1988.

(2) The exploratory experiment is a randomized-crossover (target/control) type, with two contiguous areas (designated 1A and 1B, Fig. 1) of approximately equal size

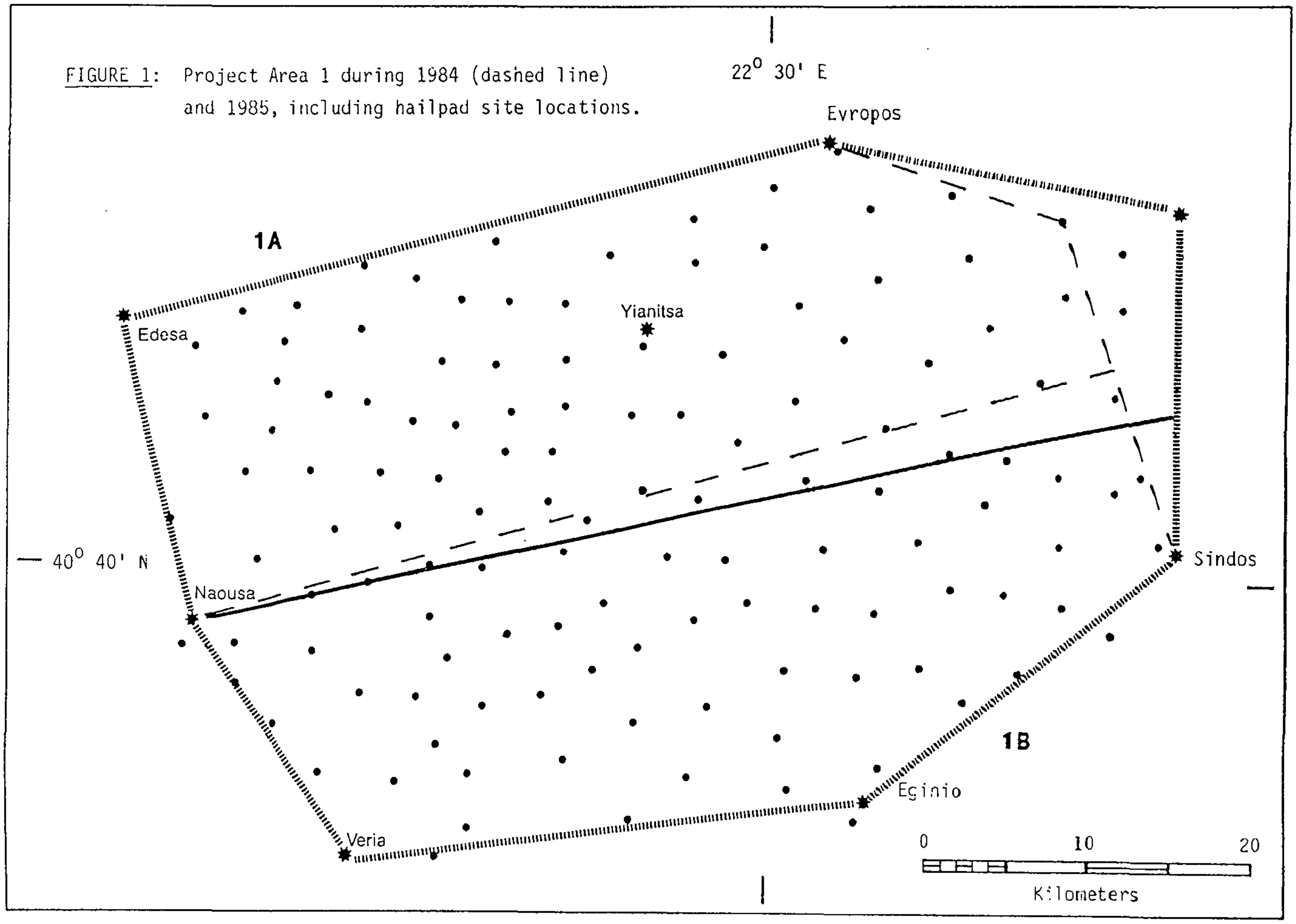

FIGURE 1: Project Area 1 during 1984 (dashed line) and 1985, including hailpad site locations.

encompassing a total of just over 2,000 km^2.

(3) The airborne application of pyrotechnic-generated silver iodide crystals is based upon a simplified statement of the so-called "embryo competition" hypothesis which emerged in the early 1970's (Summers et al., 1972; Gokhale, 1975). This simplified conceptual model is referred to in the NHSP as the "limiting supercooled liquid water" theory.

(4) The experimental units, or "periods at risk," are objectively declared prior to treatment based on real-time radar observations.

(5) It includes operation of a relatively uniformly distributed network of 125-130 hailpads to document hailfall in the two experimental areas (Fig. 1).

(6) This exploratory experiment allows for changes to be made in the design and analyses, typically at regular intervals (e.g., areas 1A and 1B were modified slightly at the end of 1984; Fig. 1).

2.2 Operational Procedures

The principal operational procedures are:

(1) Seeding is accomplished through airborne application of pyrotechnic-generated silver iodide crystals at "cloud base" and/or near "cloud top," using light twin engine aircraft.

(2) Treatment strategy is adjusted in real time, involving careful consideration of airborne observations and radar patterns, as storm characteristics and evolution dictate.

(3) Operations may be conducted around the clock, seven days per week, whenever potential hail-bearing clouds threaten any of the areas.

(4) Experimental unit declaration is based upon a radar reflectivity criterion of ≥ 35 dBZ between the -5° and -30°C levels in thunderstorms over, or threatening, the target area.

(5) Selection of either area 1A or 1B for treatment (protection) is based upon a table of unconstrained random numbers, with the other area serving as the control for that particular experimental unit.

(6) Cloud treatment strategy incorporates at least a 20-min. time lag from release of seeding material to the arrival of affected precipitation in the target area.

(7) The hailpad network is visited immediately following each experimental unit to preserve that event's records and ensure readiness for the next event.

2.3 Evaluation

The principal characteristics of the initial exploratory analyses are:

(1) The primary evaluation focuses on data obtained from the ground-based hailpad network in areas 1A and 1B.

(2) A computerized video scanning system is used for hailpad data quantification and reduction, providing a high degree of objectivity, accuracy, resolution, and repeatability of results (see Henderson, 1985, and Henderson and Allan, 1986).

(3) The computerized hailpad data allow for detailed characterization (e.g., stone-by-stone) of the impacts and analysis of hailfall dimensions.

(4) A number of candidate response variables are examined for their ability to detect an effect of treatment.

(5) Visual and algebraic techniques are employed in keeping with the philosophy of proper exploratory analyses.

3. THE DATA

The set of hailpad-derived candidate response variables developed for initial consideration of treatment effects numbered eighteen (i.e., nine measures for each of the two areas; protected or target and non-protected or control). The "cross-over" design allows us to use the control as a natural baseline, and thus we can operate on the difference between the target and control values in these "initial" analyses, thereby reducing our response variable set from eighteen to nine. Table 1 presents the definitions of each of the nine "difference" response variables, and Solak et al. (1985) presents the data for each of the 28 experimental units in the two summer seasons.

A brief review of the data shows the majority of the experimental units (i.e., 17 cases) had no hail in either target or control areas. Furthermore, of the 11 cases with hail the majority of the difference values are negative and thus indicate less hail in the target than the control. Lastly, the data for each of the nine response variables seem skewed toward relatively large negative difference values.

4. THE ANALYSES AND RESULTS

In keeping with the philosophy of exploratory analyses (e.g., Tukey, 1977b; Mosteller and Tukey, 1977), we will present both visual and algebraic (classical statistical) results. The idea simply is to provide both types of results to better see and understand what might be occurring with regard to the treatment effects. All results will be viewed as suggestive, or indicative, and hence P-values and confidence intervals are conditional probability statements (i.e., given all the searching) and not confirming statements (e.g., see Mosteller and Tukey, 1977; and Tukey, 1977a, for further discussion of this issue).

Table 1. THE NAMES AND DEFINITIONS OF THE NINE "DIFFERENCE" RESPONSE VARIABLES

Name	Definition
1. Number of Pads Hit	The difference between the total number of hailpads hit by hail in the target area versus the control.
2. Percent Pads Hit	The difference between the percent of hailpads hit by hail in the target area versus the control.
3. Average Number of Impacts	The difference between the average number of hail impacts per hit pad in the target area versus the control.
4. Average Impact Size	The difference between the average size of all hail impacts in the target area versus the control.
5. Median Impact Size	The difference between the median size of all hail impacts in the target area versus control.
6. Mode Impact Size	The difference between the mode size of all hail impacts in the target area versus control.
7. Percent of Hailpad Area	The different between the percent of the area of a hailpad covered by hail impacts in the target area versus the control.
8. Maximum Impact Size	The difference between the maximum of the hail impact size in the target area versus control.
9. Total Number of Impacts	The difference between the total number of hail impacts in the target area versus control.

The general objective of the exploratory analyses will be to answer the important question, "Can we find substantial evidence in the data that we are able to decrease some characteristics of the hail through cloud seeding?"

The analyses will focus on the entire set of 28 experimental units (i.e. 15 days in 1984 and 13 in 1985) on which some cloud seeding for hail suppression was accomplished. In essence these 28 units, or days, were identified by the operational procedures as the "days-at-risk." Hence, the treatment effect analyses must investigate this entire set of days-at-risk, whether or not hail fell in the target and/or control areas.

4.1 Visual Display Results

Figure 2, Panels 1-9, presents box plots of the target (protected, P) values compared to the control values (unprotected, U) for the nine response variables of Table 1. Each of these panels tends to indicate that the hail activity was less in the target than the control area. As an example, Panel 3 presents the two box plots for response variable (3), average number of impacts, and we see that the maximum value for the control is about 380 compared to about 80 for the target. The same relative picture holds for the 75 percentile point of the box plots (i.e., about 70 and 2 respectively).

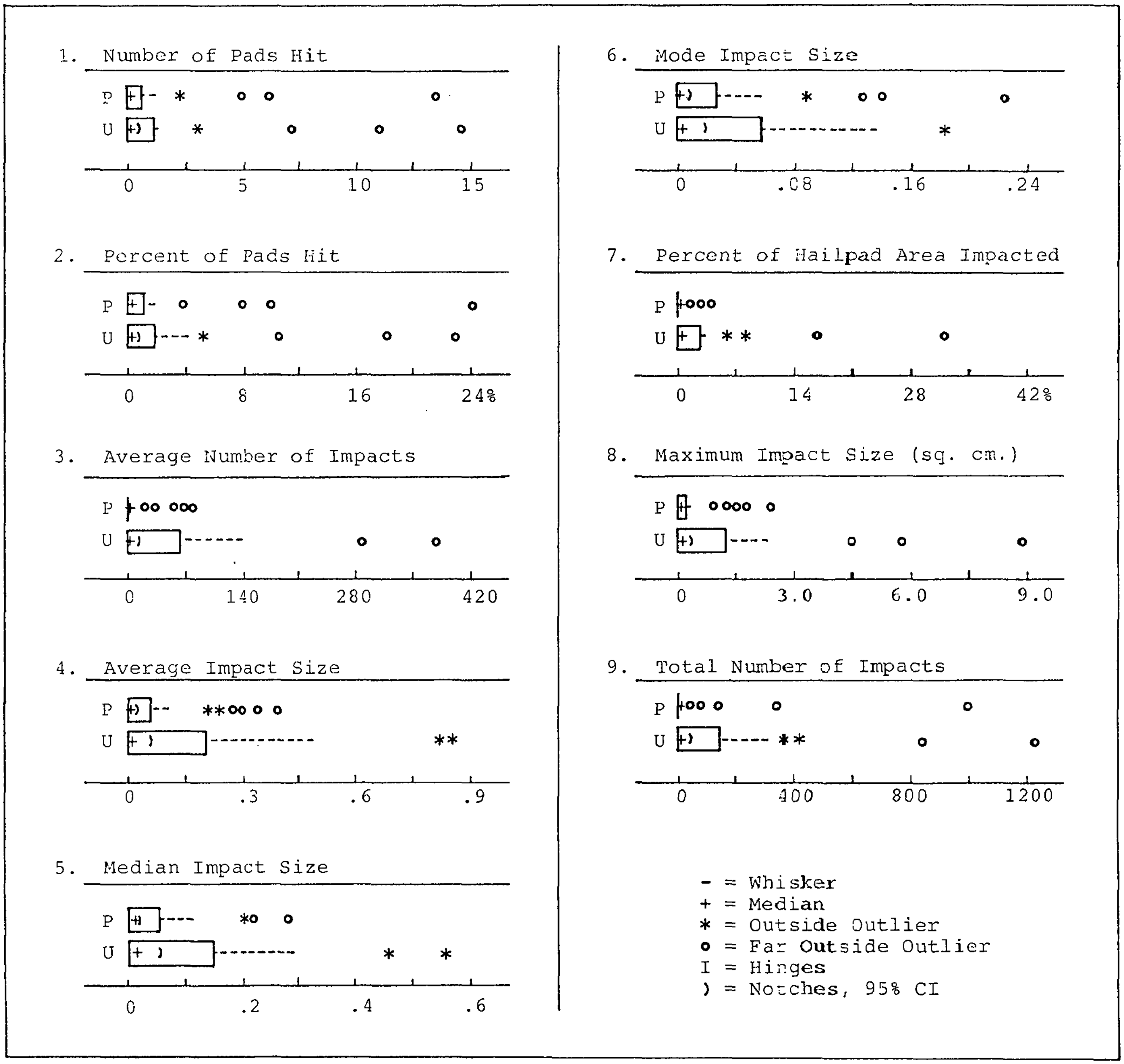

Figure 2: Comparative boxplots for the target (P) and control (U) areas for nine hailpad-derived response variables, all 28 experimental units (1984-85)

Finally, at least five variables [i.e., average number of impacts (3), average or mean impact size (4), median impact size (5), percent of hailpad area (7), and maximum impact size (8)] have substantially different plots between the target and the control values. Thus these five variables appear to be the most responsive to the treatment (seeding).

These encouraging displays, and our crude competing embryo conceptual model of how hail suppression might function, impel us to ask whether the apparent size of the treatment effects is related to the amount of the treatment. Figure 3 presents an example of this analysis using a scatterplot for the average number of impacts per hit pad (response variable 3) versus the amount of treatment (grams of AgI expended) for the eleven cases that had hail. For the target area values (shown by an asterisk, *), the relation between the two variables is negative and has a product moment correlation of -.59 and an attendant P-value of .03. Thus, as the amount of treatment increases the average number of hail impacts decreases. This picture is consistent with the view that the more competing (artificial) embryos supplied to a hail cell the smaller, on average, will be the hailstones and the less concentrated will be the surviving hailstones which fall through the freezing level.

The corresponding scatterplot for the control area values (shown by open circles, O) serves as a baseline, or standard, with which to compare our target value plot. We immediately see that it has a very different picture, and the correlation now is +.56 with an attendant P-value of .04. In short, the average number of hail impacts in the control area increases with the amount of treatment in the target area. This result is consistent with the view that the

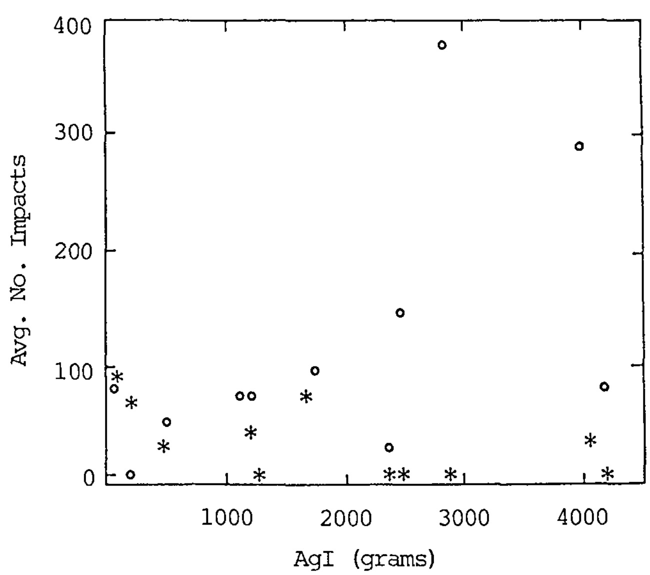

Figure 3: Scatterplot of average number of impacts per hit pad versus quantity of AgI expended per experimental unit (target area = *, control area = O).

"bigger" hailstorms (as measured in the control area) typically receive larger amounts of treatment, as one might assume. Furthermore, the two scatter plots of Fig. 3 suggest that the present treatment method is more effective for big hail storms than for small ones; there is evidence of a variable or conditional treatment effect (i.e., evidence of a relatively bigger reduction in the former than the latter).

One final visual display is presented in Table 2 where each of the 28 cases is cross-classified by presence or absence of hail in both the target and control area. (This is an example of a 2 x 2 contingency table often used in applied statistics; e.g., Snedecor and Cochran, 1967). The table shows 6 days (cases) had hail in both the target and control area, 17 days had no hail in either, 7 days had hail in the target, etc. The pattern one should see in this table, if treatment is entirely suppressing hail, is no counts in the first row (there are 7) and all counts in the second row (there are 21) with the largest count in the lower right hand cell due to the rarity of hail days. Clearly, this pattern has not been achieved.

TABLE 2. A 2 x 2 Contingency Table for Presence of Hail in the Target Versus the Control Area

		Hail Present in Control		
		Yes	No	
Hail	Yes	6	1	7
Present	No	4	17	21
In Target		10	18	28

The pattern in the 2 x 2 table can be quantified by a measure of association between the two variables. Thus, if the treatment is fully effective one would expect no substantial association, or simply statistical independence, between the two variables. The appropriate standard measures of association (e.g., Phi, Kendall's Tau, contingency coeff., etc., see Snedecor and Cochran, 1967) all produce values close to .60, and thus offer some evidence that the presence of hail in the target area is related to presence of hail in the control area. In short, the current treatment method cannot totally eliminate hail in the target area on all hail days, but it may be totally eliminating hail in the target area on some hail days.

4.2 Algebraic Results

As mentioned earlier the exploratory results, using the classical statistical tests, should be viewed conditionally or simply as indications of possible treatment effects. For each of the nine hailpad difference response variables (Table 1) the "algebraic" results of the paired Student "t" and Wilcoxon-Mann-Whitney (WMW) tests and are presented in Table 3 (see Snedecor and Cochran (1967) for details of these tests). The respective columns in the table give the area (T or C), the associated mean ($\bar{x}$), the associated standard deviation of the obser-

Table 3. COMPARISONS OF PAIRED MEANS AND STANDARD DEVIATIONS WITH DIFFERENCES, P-VALUES AND ESTIMATES OF AN ADDITIVE TREATMENT EFFECT FOR TWENTY-EIGHT CASES, 1984-85

Area	$\bar{x}$	S_x	$(\bar{x}-\bar{x}_C)$	"t"	P-Values	Treatment Effect
1. Number of Pads Hit						
T	1.04	2.77	-.50	-1.40	.17[a]	-.32
C	1.54	3.46			.19[b]	
2. Percent Pads Hit						
T	1.78	4.85	-.72	-1.22	.23	-.29
C	2.50	5.62			.21	
3. Average Number of Impacts						
T	10.46	22.18	-34.64	-2.05	.05	-.77
C	45.10	91.13			.02	
4. Average Impact Size						
T	.07	.12	-.07	-1.64	.11	-.50
C	.14	.24			.21	
5. Median Impact Size						
T	.05	.09	-.04	-1.60	.12	-.44
C	.09	.15			.17	
6. Mode Impact Size						
T	.03	.06	-.00	-.35	.73	.00
C	.03	.06			.73	
7. Percent of Hailpad Area						
T	.38	.84	-2.29	-1.81	.08	-.85
C	2.68	6.74			.02	
8. Maximum Impact Size						
T	.29	.62	-.71	-1.83	.08	-.71
C	1.00	2.07			.06	
9. Total Number of Impacts						
T	58.36	197.65	-79.39	-2.04	.05	-.58
C	137.75	288.40			.03	

[a] Two tail P-value based on paired "t" test.

[b] Two tail P-value based on paired WMW test.

vations (s_x), the difference between the two means ($\bar{x}_T - \bar{x}_C$), the "t" statistic value for the paired difference test, the P-values for the "t" and WMW tests, and the estimated additive treatment effect ($\bar{x}_T/\bar{x}_C - 1$).

The typical picture for each of the response variables present in the table is that the target area (T) had; (1) less hail "activity" (i.e., a smaller $\bar{x}$) than the control area (C), (2) less variability (i.e., smaller s_x) (3) an average value which was smaller than the control value (i.e., $\bar{x}_T - \bar{x}_C < 0$), (4) some surprisingly small P-values (e.g., average number of impacts, .05 and .02), and (5) with the exception of modal impact size, negative point estimates of the treatment effects. Four of the response variables (i.e., 3, 7, 8, and 9) present strong support (i.e., negative "t" values and small P-values) for decreases in hail activity due to treatment. (The WMW P-value is probably a better measure of the inferential strength due to possible skew and peakedness in the difference values.) Furthermore, if one "trims" one observation from each tail of the distribution, the "t" test P-values typically are halved (e.g., .17 becomes .08 for number of pads hit).

The additive treatment effect picture, last column in Table 3, is strongly suggestive of a treatment effect that reduces the number of hailstones, reduces the size of the maximum hailstone, and reduces the concentration of the hailswath. The median reduction in these three variables is about 70% (i.e., -58% to -85%).

5. CONCLUDING COMMENTS

This exploratory experiment has well illustrated the concept that research and operational studies can be complementary. This "piggy-back" crossover exploratory experiment has provided for the monitoring and estimation of realized treatment effects in the Emathia-Pella area, in the vicinity of Thessaloniki. The utilization of an embedded experiment for project evaluation is to be encouraged in all future operational hail projects.

The visual and algebraic treatment effect results are supportive and suggestive of a reduction of hail "activity" due to treatment. The principal reductions are indicated to be in the number of hailstones, the maximum size of the stones, and the concentration of the hailswath. In general, these three characteristics are reduced by about 70% with sizeable inferential P-value support. Further careful experimentation and analysis are needed to verify these highly encouraging initial results.

6. REFERENCES

Flueck, J.A., 1976: Evaluation of operational weather modification projects. J. Wea. Mod., 8, 42-56.

_______, 1978: The role of statistics in weather modification experiments. Atmos.-Ocean, 16, 377-395.

_______, 1982: Comparative experimentation: some principles and prescriptions.

Teaching of Statistics and Statistical Consulting, J.S. Rustagi and D.W. Wolfe (eds.), Academic Press, N.Y., 443-463.

_______, 1986: Principles and prescriptions for improved experimentation in precipitation augmentation research. To appear as Chapter 14 in R.R. Braham, Jr., Editor, Glaciogenic Seeding for Precipitation Enhancement, AMS Monograph, Amer. Meteorol. Soc., Boston, MA.

Gokhale, N.R., 1975: Hailstorms and Hailstone Growth, State University of New York Press, Albany, NY, 465 pp.

Henderson, T.J., 1985: The use of a computerized video scanning system for objective analysis of hailpads, Proc. 4th WMO Scientific Conf. on Weather Modification, WMO/TD-No. 43, Vol. 1, Geneva, Switzerland, 199-204.

Henderson, T.J., 1986: The hail suppression program in Greece. J. Wea. Mod., 18.

Henderson, T.J. and R.B. Allan, 1986: The objective analysis of hailpads using a computerized video scanning system. J. Wea. Mod., 18.

Karacostas, T.S., 1984: The design of the Greek National Hail Suppression Program. Proc. 9th Conf. on Weather Modification, Park City, UT, AMS, 26.

Mosteller, F. and J.W. Tukey, 1977: Data Analysis and Regression, Addison Wesley, Reading, MA, 588 pp.

Snedecor, G.W. and W.G. Cochran, 1967: Statistical Methods, 6th Edition, Iowa State University Press, Ames, IA, 593 pp.

Solak, M.E., D.C. Melita, R.B. Allan, T.J. Henderson, D.W. Duckering and S.D. Pinion, 1985: The 1984 - 1985 National Hail Suppression Program in Greece. Final Report to National Agriculture Insurance Institute of Greece by Atmospherics Inc., Fresno, CA, 201 pp.

Summers, P.W., G.K. Maether and D.S. Treddenik, 1972: The development and testing of an airborne droppable pyrotechnic flare system for seeding Alberta hailstorms. J. Appl. Meteor., 11, 695-703.

Tukey, J.W., 1977a: Some thoughts on clinical trials, especially problems of multiplicity. Science, 198, 679-684.

_______, 1977b: Exploratory Data Analysis, John Wiley and Sons, Inc., N.Y., 688 pp.

_______, D.R. Brillinger, and L.V. Jones, 1978: The management of weather resources, II, The Role of Statistics in Weather Resources Management Report of the Statistical Task Force to the Weather Modification Advisory Board, U.S. Govt. Printing Office, 118 pp.