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OPERATIONAL EFFICIENCY ASSESSMENT OF HAIL SUPPRESSION FOR AGRICULTURE IN GREECE

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Abstract. The National Hail Suppression Program (NHSP) in Greece has been basically designed as an operational cloud seeding program with a small research component at its initial stages. During the 9-year history of the NHSP, significant experience and knowledge have been gained. The paper aims at assessing the operational efficiency of the NHSP with the objective of possibly improving operations. The paper focuses on topics such as hail forecasting and nowcasting, radar controlling and siting, flight operations, optimum length of the operational period, systems efficiency, available and required resources and infrastructure, seeding hypothesis and launch criteria. Finally, applied research findings and the incorporation of new technological advancements into the NHSP are discussed in an effort to draw conclusions and inferences towards optimum operation and gradual reduction of the overall program's cost.

1. INTRODUCTION

Hail is internationally considered as a severe threat to agriculture. In Greece, on the average about 4.6 billion drachmas (in constant 1991 values) are spent annually for hail insurance payouts. These payouts could be much larger, but the Hellenic Agricultural Insurance Organization's (ELGA) policy does not cover hail damages of the order of less than 20% in crop production losses, which are the majority of the cases in Greece. The National Hail Suppression Program (NHSP) in Greece was established in 1984 under the auspices of ELGA. The NHSP has been mainly designed as an operational cloud seeding program to reduce hail damage over three distinct agricultural areas, namely two areas: A1 (2,340 km^2) and A2 (1,306 km^2) in northern Greece and one area A3 (2,400 km^2) in central Greece (Fig. 1). The program has been

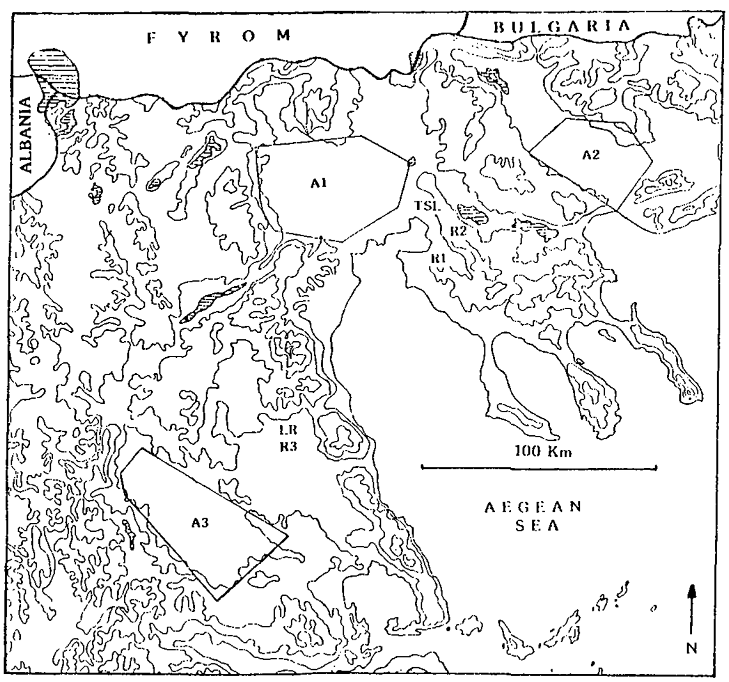


FIGURE 1: *Map of the protected areas in the NHSP. Elevation contours are 200, 600, 1200, and 1800 m.*

operational continuously until 1993 with the exception of 1991. At the beginning there was a 5-year (1984-88) randomized experiment in one of the areas (A1), but the NHSP has been mainly run as a commercial program. The NHSP is currently at a stage of overall evaluation due to its high operational cost, significance for national agriculture, as well as drastic expected changes in international agriculture.

The objective of this paper consists of assessing the operational efficiency of the NHSP with the goal of possibly improving operations and reducing the program's cost. The assessment is based on the annual reports submitted to ELGA by the contractors (Alberta Ltd., 1990 and 1991; Atmospherics, Inc., 1985; C.I.C-3 Delta-Avionic, 1993 and 1994; Intera Technologies Ltd., 1987, 1988 and 1989). Within this framework the various components of the program are analyzed and the upgrading as well as the current structure of the program is thoroughly examined. Specifically, hail forecasting and nowcasting, radar controlling and monitoring, flight operations, systems efficiency, as well as available resources and infrastructure are examined on the basis of 9-year statistics and experience gained. The problem of the optimum length of the operational period is also addressed as well as the technological advancements and the number of the required aircraft and resources. The paper is organized as follows: Section 2 covers a description of the program including design and operations; Section 3 comprises a presentation of how each component performed during the operations based on the available statistics; and Section 4 consists of a discussion of the impact of each component to each other and to the program's efficiency.

2. DESCRIPTION OF THE NHSP

2.1 Design

The adopted seeding hypothesis is based on the conceptual model of the beneficial competition theory (Foote and Knight, 1977). Limited observations in convective clouds in northern Greece support the ice phase or graupel embryo precipitation process and are consistent with the beneficial competition theory (Krauss and Papamanolis, 1989). These observations include the presence of conical graupel embryos, average summertime cloud base temperatures near 10°C and a continental drop size distribution (Krauss and Papamanolis, 1989). Furthermore clouds with tops warmer than -10°C have not been observed to produce precipitation.

Seeding operations were carried out in three agricultural areas (Fig. 1) ranked among the first in the list of annual hail damage insurance payouts. Based on payout statistics for the decade 1970-1980, area A1 covers on the average 15%; area A2, 4%; and area A3, 12% of the annual hail damage payouts, respectively. The three protected areas are orographically similar, since they are mostly surrounded by complex mountain terrain (Fig. 1). This characteristic has a major effect on storm forecast, radar monitoring, and seeding techniques. Five aircraft were employed in the seeding operations lasting from mid-April till the end of September every year.

Seeding was conducted either at cloud base or at cloud top when the following two criteria were met: a cell existed over area A1 or it was within 20 minutes of entering the area; and the cell was exhibiting a radar reflectivity factor of >35 dBz at an altitude between -5°C and -30°C in the cloud. In practice, seeding was begun on storms when the leading edge of the 35 dBz contour first entered the buffer zone, which was defined as a 20 minute upwind boundary (Karacostas, 1984). Frequently, storms reached seeding criteria within the area and were seeded as soon as possible thereafter. Cloud top seeding was conducted within the layer between -8°C and -15°C by penetrating the upshear sides of the tops of the daughter clouds of multicell storms, whereas in single-cells the penetrations were conducted at the upshear edges. The nominal seeding rate for penetrations near -10°C was one to two 20-gr AgI droppable flares every five seconds resulting in a seeding rate of 240 gr/min. Weak to moderate updrafts of 10 m/s were assumed. In practice, these rates were adjusted either upwards or downwards by up to a factor of two depending on conditions.

Cloud base seeding was conducted by seeder aircraft flying at the upshear side of multicell storms within the secondary flow area or within the main inflow area of a single-cell storm. Seeding at cloud base was conducted by burning one or two 150-gr wing flares over a four-minute period, or by burning one or two 75-gr wing flares over a two-minute period. Both methods have resulted in a seeding rate of 40 to 80 gr/min. Side-skim seeding was used when there were no clearly defined feeder turrets. Seeding was conducted by the seeding aircraft making cloud penetration on the upshear side of the storm edge between -5° and -10°C, while burning a wing flare and dropping pencil flares when updrafts were encountered.

Besides operations, a research component was also designed to study the dynamic and microphysical characteristics of the potential hail producing clouds and to permit credible scientific evaluation of the effects of cloud seeding. The research part included a 5-year (1984-1988) statistical evaluation experiment with exploratory and confirmatory stages in area A1 using a cross-over randomization scheme (Karacostas, 1984 and 1989). Area A1 was divided in two sub-areas (north and south), namely the target and control areas, which were randomized and not the experimental unit. The experimental unit was determined to be any declared hail day when the above mentioned seeding criteria were met. Certain procedures were followed during the experiment concerning the designation of target and control areas. When radar reflectivities first reached seeding criteria, one half of area A1 was randomly designated as target and the other half as control. Seeding was conducted in the target only. Data from a hailpad network (Dalezios *et al.*, 1991) were collected after each operational day. Additional sources of data have included surface reports and soundings, synoptic information from weather maps, manually tabulated radar readings and airborne collected microphysical data from one properly instrumented aircraft.

Since the NHSP was initially designed and run as an operational program, the evaluation experiment included a limited number of response variables out of which only a few were processed due to lack of the appropriate infrastructure and lack of advanced technology into the NHSP. The first three years of the NHSP (1984-86) were designated as an exploratory phase wherein various hailpad parameters were identified and examined with respect to their ability to detect differences between target and control hailpad data (Table 1). The specification and bases for selection of the evaluation parameters and statistical testing methodology have been described in Rudolph *et al.* (1987). Based on the data analysis in the exploratory phase, one response variable was selected as primary estimator, namely total hail impact energy, which is defined as the total stone kinetic energy normalized by the number of exposed pads. It is known that this variable is sensitive to hailstone size (diameter to the fourth power) and that it is relatively insensitive to uncertainties in hailpad threshold ressponse. The following two years (1987-88) comprised the confirmatory phase during which the selected hailpad parameter in the exploratory phase was further examined to determine the success of the NHSP from a statistical standpoint. The results of the statistical evaluation of the five year program are summarized in Table 1, where several response variables are presented, along with the selected primary response variable.

Based on the results of this statistical analysis the appropriate modifications in the program were implemented in the subsequent years. In particular, by 1989 the randomization factor was reduced to one seeding unit for three hail days and by 1990 randomization was abandoned. Hailpad network continued to provide data in the years 1992 to 1993.

2.2 The Operational Component

Cloud seeding operations for hail suppression require a forecast of hail/no hail for the protected areas and, if possible, a prediction of the maximum hail size. The primary role of convective forecasting for seeding operations is to assess the operational readiness and efficiency and to set launch criteria for aircraft and the appropriate crew status depending upon the likelihood and probable growth rate of storms, as well as the preferred timing for aircraft maintenance.

During 1984 and 1985, an operational period forecast was issued at 0800 UTC (1100 local time) and a daily status of "GO", "STANDBY", or "NO-GO" was posted. During all "GO" and "STANDBY" situations, a second weather forecast was issued at approximately 1600 UTC (1900 local time). By 1986, the adopted hail forecasting procedure in the NHSP was an objective prediction pattern, in the form of a multiple linear regression model, based on modification of a synoptic index of convection (Strong and Wilson, 1983). This procedure was further

TABLE 1: List of Hailpad Evaluation Parameters with Estimated Treatment Effect (A_T/A_C -1) % and Wilcoxon Signed-Rank, Two-Tailed P-Values.

Year Parameter	1984	1985	1986	1987	1988	84-88
Number of Pads Hit	-12 .834	-40 .281	-74 .208	-11 .715	+04 .379	-19 .392
Total Number of Stones	-44 .208	-68 .178	-92 .094	-45 .361	-39 .551	-52 .006
Median Diameter	-71 .059	+25 .590	-68 .094	-39 .361	+20 .650	-24 .109
Maximum Diameter	-74 .059	-08 .787	-64 .173	-36 .584	+09 .733	-34 .046
Total Volume	-66 .208	-80 .178	-96 .059	-58 .361	-59 .551	-68 .003
Total Impact Energy	-76 .208	-85 .178	-97 .059	-59 .361	-66 .551	-74 .003

improved in 1989 (Riley, 1991). Model input consisted of various meteorological parameters from Thessaloniki soundings. Among others were the 24-hour height and temperature change at 500 hPa, the relative humidity change at 700 hPa, stability indices and other thermodynamic parameters (Riley, 1991). The model was not designed as a forecaster's substitute, but as a valuable aid to accurate forecasting. The predictant was the Convective Day Category (CDC). The CDC for a day was defined as the maximum degree of convective intensity for a region in a number of discrete classes (Table 2). Several indices of atmospheric instability were also incorporated in the forecasting methodologies and were used complementarily to the CDC with satisfactory results (Dalezios and Papamanolis, 1991).

Weather surveillance for the project areas was provided by three radars. Two were S-band, and the third was a C-band. The two S-band radars were tower-mounted at the Thessaloniki (TS) and Larisa (LR) airports and covered areas A1 and A3, respectively (Fig. 1). The C-band radar, which was provided by the contractor, was truck-mounted and located near Nigrita in area A2 during 1984 and 1985 seasons and at Filiron (FL), approximately 20 km north of Thessaloniki, thereafter (Fig. 1). Radar 2 provided an unobstructed view of area A2 and also acted as a backup for radar 1 (TS). In 1988, a continuous 20-hour radar watch was maintained daily by ELGA meteorologists at radars 2 and 3.

The establishment and maintenance of a reliable communication system became a key factor not only for the response time, but also for conducting effective management and coordination during and in between operations. Three radio channels (FM band) were licensed for operational needs. Each was dedicated to radar communications with seeding aircraft when concurrently flying. Aircraft were launched when storms were in the " launch buffer," i.e., storms could enter the project areas within 80 minutes with tops above 6 km and radar reflectivity of at least 25 dBz, or when thunderstorms were forecast regardless of the actual intensity.

In the 1984 and 1985 operational periods, radar watch was decided during the morning briefing by the coordinator on the basis of the daily issued forecast. Radar operators were gradually involved in radar watch. By 1989, radar operators became radar controllers. Launch decision, however, remained the coordinator's responsibility. The project coordinator was following a regular shift and was also available 24 hours per day when needed. Figure 2 is a flow chart of established daily routine in the NHSP since the 1989 operational season.

TABLE 2: Verification Criteria for Convective Day Categories (CDC).

Category (CDC)	Definition	Verification Criteria
-2	TCU,ACC,CC, Virga possible. No precip.	Visual observation. Possible detectable radar echoes.
-1	CB, Isol. RW. No TSTMS	Radar activity below 35 dBz. Brief radar activity between 35 and 40 dBz do not "Bust" the forecast. Visual observation.
0	Sctd RW, TSTMS. No Hail	Radar activity in the range 35-50 dBz at or above -5 C level. Cloud tops extend to -40 C level. Visual observation.
1	TSTMS, Hail "pea" sized up to -1.3 cm	Confirmed hail observation. Hailpad strikes. Verifiable minor crop damage. Radar reflectivity values exceed 50 dBz at or above -5 C level.
2	TSTMS, Hail "grape" sized 1.3-2.0 cm.	Confirmed hail observation. Hailpad strikes. Verifiable crop damage. Persistent radar activity exceeding 55 dBz at or above -5 C level. Tops reach to the tropopause.
3	TSTMS, Hail "walnut" sized 2.1-3.2 cm.	Confirmed hail observation. Hailpad strikes. Verifiable crop damage. Radar reflectivity exceeds 60 dBz at or above -5 dBz C level. Tops penetrate tropopause.
4	Severe TSTMS "golfball" sized 3.3-5.2 cm.	Confirmed hail observation. Hailpad strikes. Verifiable crop damage. Radar reflectivity exceeds 65 dBz at or above -5 dBz C level. Tops penetrate tropopause 1.5 km.

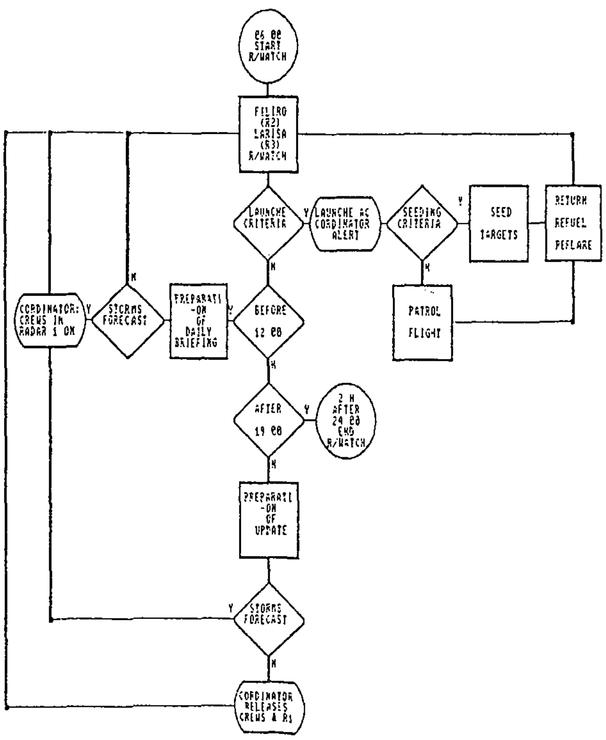


FIGURE 2. *Flow chart of daily operations in the NHSP.*

Cloud seeding operations in areas A1 and A2 were conducted by three aircraft based at Thessaloniki operational center (airport), whereas area A3 was supported by two aircraft based at Larisa airport. This allocation of aircraft has changed since 1990, where four aircraft were based at Thessaloniki and one at Larisa.

3. EFFICIENCY ASSESSMENT OF THE NHSP

3.1 Hail Forecasting

Hailstorms in the protected areas of the NHSP have been characterized as short-lived, moderate to severe and occur mainly during early afternoon (Foris, 1992a; Karacostas, 1991). Thus, reliable and efficient forecast of hail/no hail or even the maximum hail size is very important and can positively affect hail suppression operations in the NHSP. Convective day category (CDC) and flight levels were issued to the radar operators by radio communications. Figure 3 is a diagram showing the average

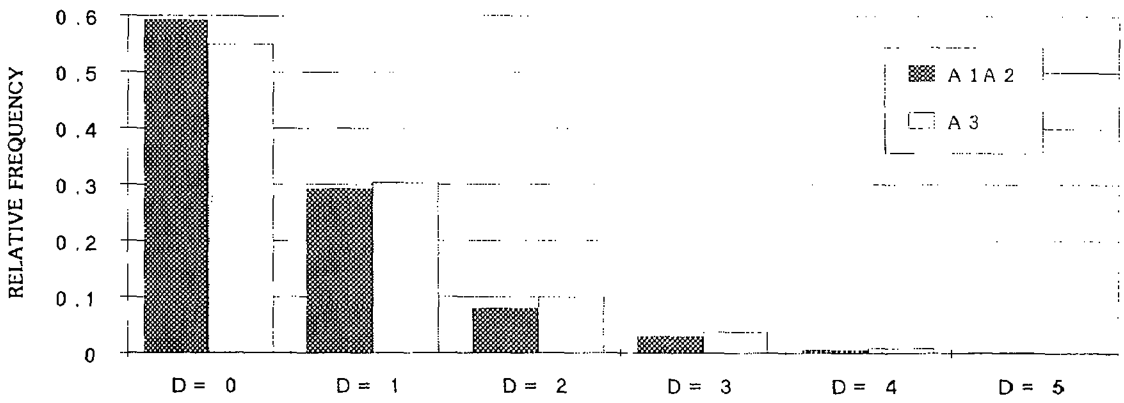


FIGURE 3: *Frequency occurrence of deviation between forecast and observed CDC.*

forecast accuracy in four operational seasons (1988, 1989, 1990, 1992). The forecast that was out by two or more categories (Table 2) was considered as "busts" and never exceeded 20% of the cases (Foris, 1992b). Within this sample (CDC greater or equal to +1) hail was correctly forecasted 70% to 80% of the cases for the three areas.

Update briefings, given at 1600 UTC, were also included in the daily routine by 1986. The need for a detailed update became apparent among the personnel not only in cases of forecast "busts," but also when the duration of convective activity was affecting the staff schedule. The access of forecast office to satellite imagery, which was added by 1990, also contributed towards that direction. Finally, a continuous weather watch was established in the forecast office along with the radar watch.

3.2 Radar Monitoring and Controlling

Only radar 1 has had the data digitized during the 1988 operational season. Radar logs were recorded routinely and showed that most convective cells were observed within the time interval of 1200 to 1800 local time (Karacostas, 1991). After 2000 local time, only 16% of convective cells were observed. Figure 4 illustrates the diurnal variation of total occurrences of convective cells in percent of seasonal values. The examination of reflectivity values within this sample also showed that on active days the weakest activity occurs between 0300 and 1100 local time (Foris, 1992a). Radar 2 was designated as the primary radar watch site for areas A1 and A2, due to the unobstructed view in both areas. During operations the radar 2 controller was responsible only for area A2. Operations in area A1 were conducted from

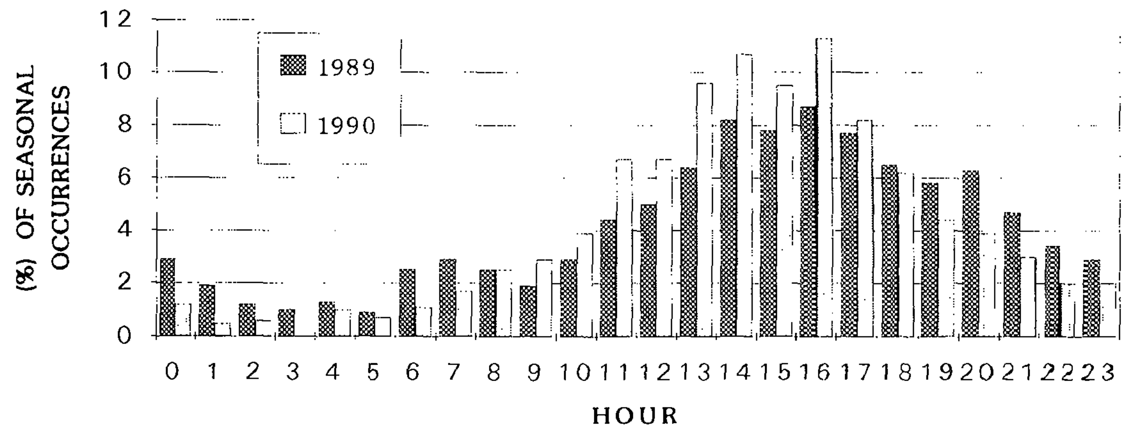


FIGURE 4: *Dirunal variation of convective cell occurrences in (%) of total number of occurrences for two operational seasons (1989, 1990).*

TABLE 3: Number and Hours of Operational Flights (Patrol and Seeding) in Each Month and Year for Areas A1 and A2 (Patrol and Seeding/Seeding).

	APRIL		MAY		JUNE		JULY		AUGUST		SEPTEMBER	
YEAR	FL	HR	FL	HR	FL	HR	FL	HR	FL	HR	FL	HR
1984					21/14	50.2/40.1	4/3	7.1/5.7	44/27	86.3/63.4	13/7	26.2/15
1985			35/20	77.1/49.6	9/2	14.3/5.6	3/0	3.4/0	12/10	25.4/22.2	0/0	0/0
1986	5/2	9.4/4.2	13/4	24.3/10.4	18/11	32.8/22.1	6/4	11.4/8.3	12/7	27.6/17.2	0/0	0/0
1987	5/3	8.3/6.1	14/7	30.3/19.0	9/3	19.7/9.8	25/19	51.1/40.2	25/22	56.2/50.0	11/4	19.3/10
1988	9/4	19.6/10	41/23	88.4/60.0	37/25	81.6/60.8	14/8	33.1/22.1	9/5	18.1/11.4	2/0	3.9/0
1989			12/10	24.6/21.7	39/22	67.9/49.0	23/14	53.4/37.3	10/5	19.6/12.6	9/4	16.1/7.8
1990	5/3	11.5/8.4	21/11	44.2/28.6	16/12	36.2/30.5	20/14	53.9/42.2	12/4	25.9/11.5	3/0	4.7/0
1992					29/22	70.1/56.1	21/16	51.1/42.9	5/2	13.1/5.7	5/4	9.0/7.9
1993	8/6	17.8/14.1	58/44	129.4/119	14/9	31.2/22.5	7/2	14.3/6.4	10/2	16.6/4.6	2/0	4.0/0

radar 1 after being alerted by radar 2. Radar 1 controller was assisting in the forecast preparation when no storms were threatening area A1.

3.3 Flight Operations

The number of flights and flight hours per month during nine years of operations for areas A1 and A2, and area A3 are provided in Tables 3 and 4, respectively, where the numbers in April represent only the operational part of the month. The number of flights and flight hours with two concurrent aircraft and the cases with three concurrent aircraft are also presented in Tables 5 and 6, respectively. It is obvious that the number of cases with three concurrent flights in areas A1 and A2 is considerably low (Table 6). Moreover, in the 9-year operational history only five cases existed with three or more aircrafts concurrently

TABLE 4: Number and Hours of Operational Flights (Patrol and Seeding) in Each Month and Year for Area A3 (Patrol and Seeding/Seeding).

	APRIL		MAY		JUNE		JULY		AUGUST		SEPTEMBER	
YEAR	FL	HR	FL	HR	FL	HR	FL	HR	FL	HR	FL	HR
1984					8/2	12/6.2	0/0	0/0	4/4	6.9/6.9	1/0	2.6/0
1985			11/5	17/11.2	5/3	11.2/7.7	3/1	6.2/3.0	1/0	1.2/0	2/0	3.7/0
1986	2/0	3.8/0	11/4	17.9/9.4	12/5	22.8/11.8	9/4	11.9/6.0	3/1	6.1/1.8	0/0	0/0
1987	6/0	5.9/0	3/0	4.7/0	1/0	1.3/0	8/5	10.9/8.2	6/3	13.5/7.8	3/0	1.5/0
1988	2/1	2.5/1.6	11/7	21.2/14.6	6/3	9.7/5.9	3/2	5.4/4.3	2/0	2.4/0	4/0	3.9/0
1989			1/0	2.3/0	4/2	6.9/4.3	7/2	12.4/4.6	4/2	8.6/4.8	5/3	7.9/6.1
1990	0/0	0/0	2/1	4.9/3.5	1/1	3.1/3.1	0/0	0/0	0/0	0/0	0/0	0/0
1992					8/6	18.8/16.0	10/5	21.3/11.3	2/1	3.9/1.3	0/0	0/0
1993	9/6	18.3/13.3	32/26	77.7/67.3	12/10	25.5/24.0	1/1	2.3/2.3	6/2	12.1/5.3	1/0	2.2/0

TABLE 5: Number of Cases with Two Aircraft Concurrently Flying and the Corresponding Flight Hours for Areas A1 and A2.

	APRIL		MAY		JUNE		JULY		AUGUST		SEPTEMBER	
YEAR	FL	HR	FL	HR	FL	HR	FL	HR	FL	HR	FL	HR
1984					11	19.4	2	3	20	25.3	4	5.5
1985			0		3	3.5	0	0	4	3.2	0	0
1986	1	0.8	2	1.4	4	4.1	6	5.9	7	4.5	3	1.5
1987	0	0	1	0.9	4	3.3	1	0.7	1	1	0	0
1988	1	1.3	20	24.9	14	19.4	5	5.9	0	0	0	0
1989			2	4.9	4	4.1	3	2.7	2	2.9	1	3.2
1990	2	1.6	5	5.3	5	5.4	5	6.1	0	0	0	0
1992					5	3.5	4	4.8	0	0	1	0.9
1993	1	1.3	17	24.7	2	1.1	0	0	0	0	0	0

TABLE 6: Number of Cases with Three Aircraft Concurrently Flying in the 9-year Operational History for Areas A1 and A2.

APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER
0	5	2	1	1	0

flying during May, which is the most active month. Furthermore, during the months of April and September no cases were reported.

The number of aircraft needed in the operations is further examined. To investigate the actual aircraft needs, the number of two concurrent flights as percentage of total monthly flights for north areas was calculated from Tables 3 and 5. The highest mean ratio of two concurrent flights to total flights occurs in June and it consists of only about 30%.

The length of the operational season is investigated in Fig. 5 for areas A1 and A2 and in Fig. 6 for area A3, respectively. Insurance data were obtained from a 13-year (1971-1983) monthly record provided by ELGA. Mean payout values were normalized by annual values to account for inflation. Damaged areas and hail occurrences were similarly normalized. The same approach was also followed in the presentation of flight data. Separate data sets for flights (1984-1993) and crop insurance data (1971-1983) were used. The independent data periods provided the basis for an objective comparison. If the same data period were selected, the seeding effect would be present in the distribution of hail damages.

The comparison showed that the percentage of flights and flight hours regularly followed the same pattern with values similar to the percentage of hailfall for all the months. Major differences, however, existed between flight data and payouts, especially for the months of April and September. In areas A1 and A2 during April, while the number of flights and flight hours constituted on the average 7% of the seasonal values, the crop damage payouts were only 2% for area A1 and less than 1% for area A2, respectively (Fig. 6). Similar values were observed in September. The variation of insurance data in the two northern areas showed that hailfall statistics were similar (Figures 5a, 5b). Significant differences existed in the variation of

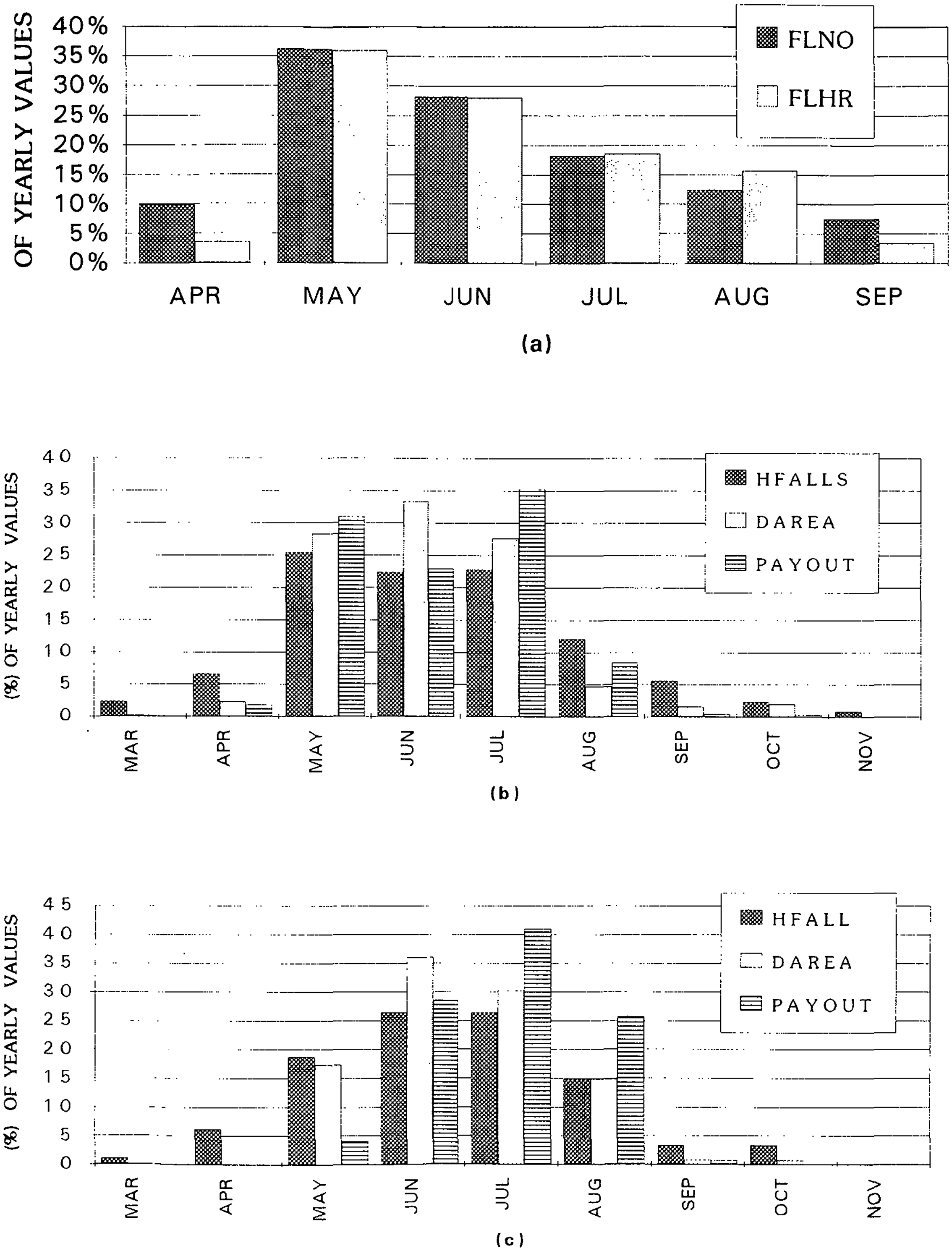
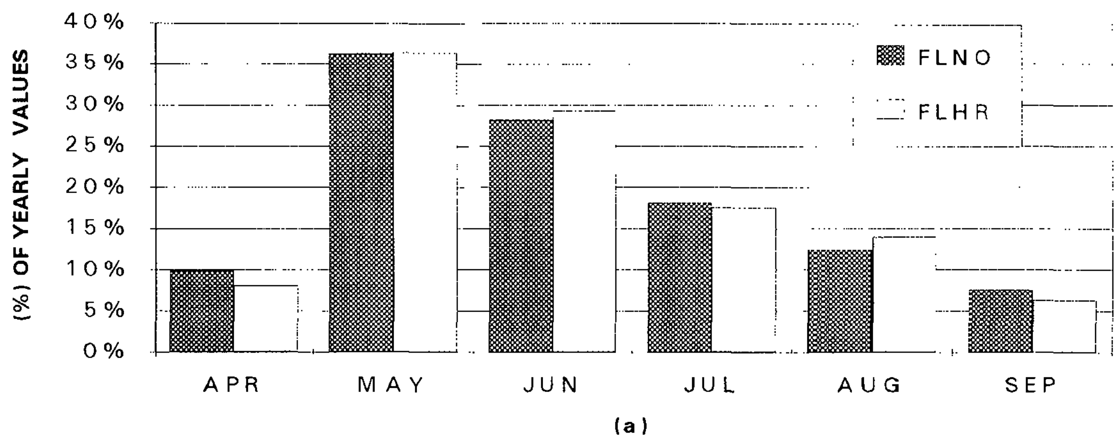


FIGURE 5: *Monthly variation of flight and insurance data for the northern areas A1 and A2: (a) mean flight number (FLNO) and flight hours (FLHR) (%) of yearly values; (b) mean hailfalls, damaged area and payouts (%) of mean yearly values for area A1; (c) as in (b) but for area A2.*



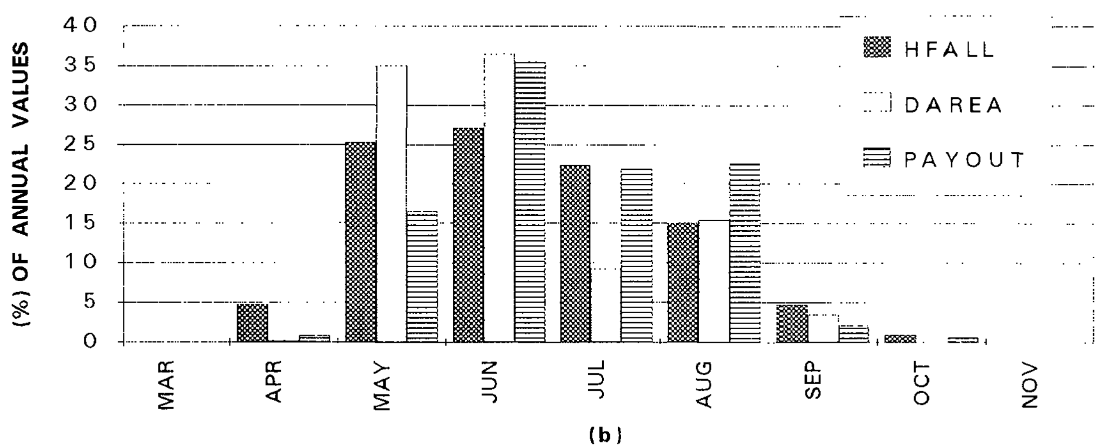


FIGURE 6: *Monthly variation of flight and insurance data for area A3: (a) mean flight number (FLNO) and flight hours (FLHR) (%) of annual values; (b) mean hailfalls, damaged area and payouts (%) of mean annual values for area A3.*

the areal extent of damages, as well as in the payouts. This can be probably attributed to the different crop types in the two areas. Area 1 is cultivated by fruit trees, while area A2 is dominated by wheat, corn, cotton and barley. Areas A2 and A3 are dominated by the same type of crops. In area A3, while the number of flights and flight hours for April constituted 10% and 8% of the annual values, respectively, the crop damage payouts consisted of only 1% (Fig. 6). Similar values were observed in September.

The observed differences in April and September between flight and payout normalized values are further investigated in Fig. 7. Figure 7 shows the variation of the ratio monthly seeding flights to monthly total operational flights and the same ratio for the flight hours. The ratios were low in September (10%) and April (30%) in area A3. However, for areas A1 and A2, the problem existed only in September, which showed a ratio of 30%. The increased number of patrol flights was the main reason for the small ratios in April and September.

3.4 Human Resources and Administration

The lack of advanced technologies in the operational part of the NHSP such as radar digitization, aircraft tracking, centralization of services and similar topics had a significant impact on human resources requirements for operations. The annually involved personnel in the NHSP varied in number, ethnic background and degree of education/training. The variation followed changes in project requirements and the

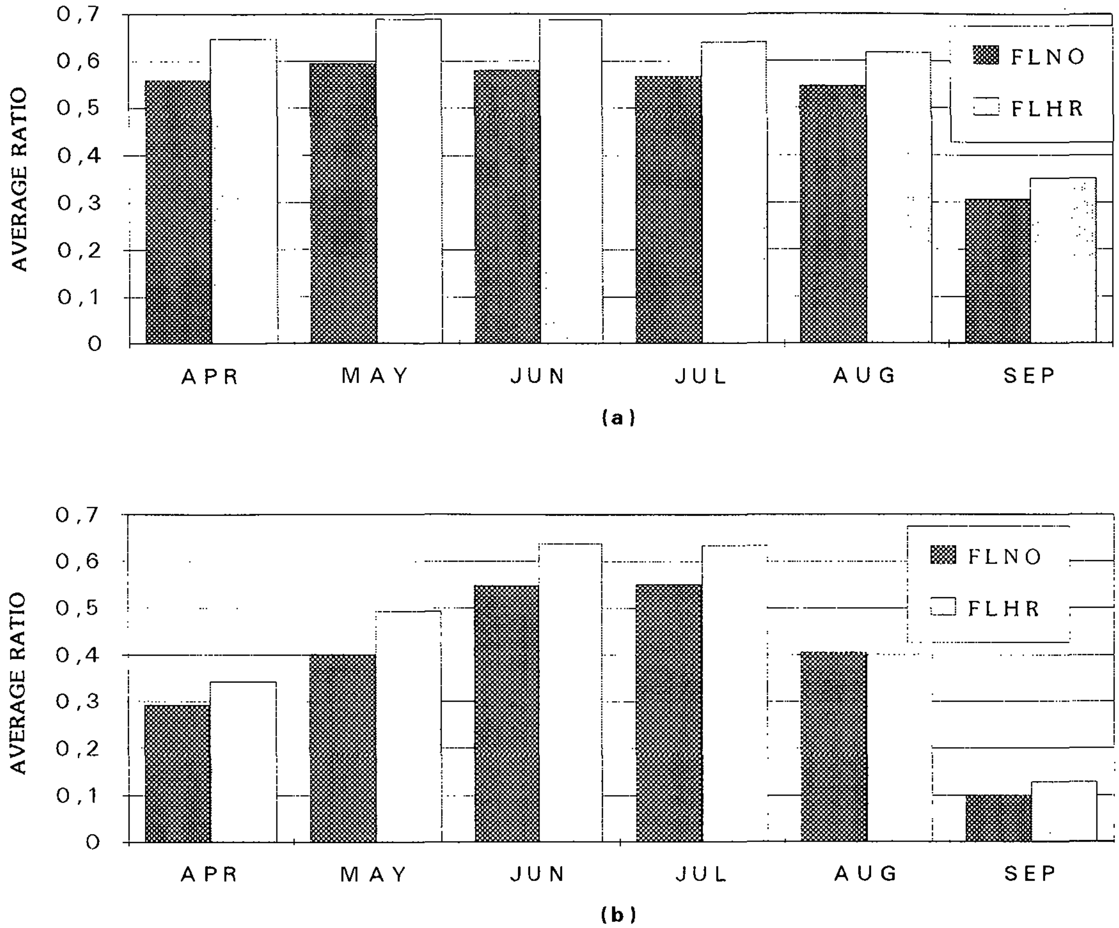


FIGURE 7: *Monthly variation of the mean ratios, seeding flights to total flights and seeding flight hours to total flight hours: (a) for northern areas A1 and A2; (b) for area A3.*

expansion of the protected areas from 3000 to 6000 km^2 in 1989, as well as the adopted technology-transfer policy. This is summarized in Table 7. Furthermore, the personnel distribution during 1992-93 seasons is given in Table 8.

A general assessment of program's efficiency from an administrative point of view can be attempted on the basis of the flow chart shown in Fig. 2, where the primary circuit covers actions and decisions concerning the seeding and patrol flights. The other three circuits are supporting the flight operations and cover forecasting and radar controlling and monitoring. The coordinator's involvement in every decision taken must be noticed. The three sources of information available during briefing, which were used by the coordinator in the decisions procedure were: the condition and operational status of the means from the technical point of view, the personnel schedule, the forecasted weather and the radar information. The 24-hour readiness and availability of the project coordinator had a positive effect on management and administration.

4. DISCUSSION

The seeding effect on hail parameters was investigated by several researchers on the basis of the randomized crossover experiment (Flueck *et al.*, 1986). Studies on crop damage payouts were conducted by comparing target and control values in the same period (Rudolph and Papageorgiou, 1991). The discussion on the operational efficiency of the NHSP that follows also involves various comments on cost assessment. The mean total annual cost in the period 1984-1988 was estimated to be 375 million drachmas (CIC- 3 Delta- Avionic, 1993). At the same time the average annual payouts for the three protected

TABLE 7: Employed Personnel in NHSP.

Year Company	1984-85	1986	1987	1988	1989	1990	1992-93
Contractor	20	26	23	19	22	21	21
ELGA	0	9	16	27	28	31	16

TABLE 8: Personnel Distribution During 1992-93 Seasons.

Specialization Company	Meteorologists	Pilots	Technicians	Secretary
Contractor	4	13	4	0
ELGA	12	3	0	1

areas were 310 million drachmas in constant 1988 values. In current values, the program's annual cost was over 600 million drachmas in 1989-93.

As already mentioned, there are considerable diffferences in the frequency and variation of convective activity between the northern areas A1 and A2 and area A3. During the warm season there is a transition zone with synoptic disturbances usually affecting only the northern areas. Shallow cold fronts that occur during summer rarely penetrate the mountain chains north of area A3. Moreover, area A3 is more than 60 km away from the sea and surrounded by mountains. The unique landscape probably creates boundary layer conditions significantly different from the north areas. Thus, forecasting convection in area A3 on the basis of Thessaloniki 0900 and 1200 soundings is subject to great uncertainty. The forecast success rates for area A3 were usually lower than for the northern areas (Foris, 1992b). A boundary layer study should be conducted for area A3 to provide guidelines and improve the forecast.

There are always limitations in the forecast accuracy (Fig. 3) that even in the northern areas cannot be exceeded. During the last two operational years of the NHSP a different approach was attempted and steps were taken towards nowcasting. Nowcasting seems to be the appropriate direction, since storms in these three areas appear to be short-lived, fast evolving and intense. The continuous weather watch, digital radar monitoring, and the access to satellite images could be major contributions. A very important step, however, seems to be the transfer of radar control and images to the Thessaloniki office. The integration of surface meteorological data, digital satellite and radar images into one unit could strengthen the operational efficiency of the program. Nowcasting procedures based on the above requirements should have a direct effect on personnel for hail forecasting, radar controlling and flight operations.

Once a continuous and detailed weather watch is established, radar shifts can be easily reduced by at least 50%. Radar controllers at Filiron and Larisa should not need to cover two 10-hour shifts per day. Continuous radar watch will be held only at the "Nowcasting Center," which in case of an emergency should alert radar controllers to carry out the operations. The operational needs for radar coverage of northern areas should also be reassessed. The Thessaloniki radar can be removed and sited at Filiron or elsewhere in the vicinity. The new radar site should be selected to meet the requirement of unobstructed coverage for both areas (Dalezios *et al.*, 1989). The effectiveness of controlling two or more operating aircraft from the same radar should be considered. Following the last arrangement, no extra radar provided by the contractor is needed. This will result in a significant reduction of the operational cost.

Flight statistics revealed that the number of aircraft involved in the NHSP can probably be reduced by at least one to two for all operational months and by two in September. The risk taken with such a decision is minimal. Cases of three concurrent flights rarely occur in operational months. It is believed that during September two aircraft for the north areas and one for area A3 are more than sufficient. The policy of keeping one aircarft at the Larisa airport was proven acceptable, but in some cases a second aircraft had to be provided in area A3 by the Thessaloniki air base, although the number of these cases was very limited.

The optimum length of the operational season deserves further investigation. The approach followed in Section 3 was based on a comparison of flight and insurance data on a monthly basis. A more detailed examination is needed on the first and last dates of hail occurrence and the corresponding probabilities. However, some preliminary results about the transitional months of April and September can be discussed. Operational activity during these two months was on the average observed at the same percentage that hailfalls occur, but when a comparison is attempted between the number of flights or flight hours and damaged area or payouts considerable differences exist. The small percentages of payouts during September and April are probably related to the phenological stages of the associated crops, since hailfalls produce less damage per unit area in the early or late stages of plant growth. The areal extent of damages or the dimensions of the hailswaths depend on the development of convection in complexes, as well as on its life cycle. It was evident that in the transitional months organized convection and long-lived cells were rare. Compared to the amount spent for hail damage payouts during the two months, too much effort in terms of the number of flights and flight hours was spent for hail suppression. Hail climatology suggests that hailfalls do occur in March, October and November, but the probabilities are low and the damages are not significant enough to support the need for hail suppression operations. The evidence presented supports the notion to restrict the operations between the months of May and August inclusive. To finalize the result and specify more about the dates, a detailed study of probability of occurrence should be conducted. For area A3, the ratio of seeding flights to total monthly flights has pointed out the increased number of patrol flights. Launch criteria were usually met during transitional months in situations of embedded convection, but seeding criteria were rarely exceeded. The modification of launch criteria to reduce the number of patrol flights especially for the months of April and September deserves further investigation. Digital radar data should also be analyzed to establish a firm relationship between measured reflectivity and probability of hail on the ground.

There is an obvious need for applied research and technological development and advancement in the NHSP, which is expected to improve operations and gradually reduce operational cost. One area of research seems to be nowcasting and quantitative hail forecasting. The study of the protected areas and development of the appropriate boundary-layer models, instability indices and synoptic convective indices could be helpful in this direction. This effort needs to be supported by studies on cloud physics and dynamics with an overall impact on launch criteria and seeding hypothesis, which influence flight operations and the associated costs. Another area of required research and development is weather radars. Needless to say, radar is the core in hail suppression programs and can assist in forecasting and nowcasting, controlling and monitoring, as well as in the evaluation of such programs. Radar digitization seems to be the first step in the NHSP, which is expected to assist in optimum radar siting, hailstorm tracking and forecasting, identification, structure and thresholding of hailstorms and rainstorms, timing of hailstorm occurrence, program evaluation parameters, required personnel scheduling and associated cost of the NHSP. Flight operations is another area for research with an impact on the length of the program, number of required aircraft, seeding rates and material and associated cost. Finally, a study on alternative hail suppression techniques such as canons, and pledge (networks), among others, needs to be investigated.

5. SUMMARY AND CONCLUSIONS

The operational efficiency of the NHSP in Greece was assessed in order to possibly improve operations and lead to gradual reduction of the operational cost. Several components of the NHSP were investigated and the results were summarized. It seems that the incorporation of applied research findings and technological advancement into the NHSP would improve operations. Specifically, since hailstorms in Greece are, in general, short-lived and intense, nowcasting and quantitative hail forecasting could be very helpful for improving efficiency. The incorporation of digital satellite and radar images along with conventional meteorological information into a "nowcasting unit" could strengthen the operational efficiency of the program. Furthermore, radar digitization and optimum radar siting should provide efficient monitoring and radar controlling, as well as a gradual reduction of the operational cost. Moreover, additional research in cloud physics and mesoscale modeling could improve seeding hypothesis and launch criteria with an impact on operations. Finally, the analysis supports an adjustment on the length of the operational period and the number of the necessary aircraft with an overall impact on the required human resources for operations.

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