"REVIEWED"

THE HAIL SUPPRESSION PROGRAM IN GREECE

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Abstract. During the 1984 and 1985 summer seasons in Greece, an operational cloud seeding program was conducted to reduce hail intensity at ground level over three target areas. The program was sponsored by the Greek government and operated by Atmospherics Incorporated of Fresno, California. Five cloud seeding aircraft, two S-band radars, one C-band radar, upper air sounding equipment, a severe storm forecasting unit, a computerized Digital Video Scanning System and the aerial application of pyrotechnic generated silver iodide formed the core operational components of this program. One of the target areas included a network of polyfoam hailpads plus the design and application of a randomized crossover exploratory experiment. The operational aspects are summarized and the preliminary results from the analysis of hailpad data are presented.

1. INTRODUCTION

For several years, the Greek government has followed the progress of weather modification programs conducted throughout many countries of the world. In 1981 this interest evolved into positive action when the National Agricultural Insurance Institute (OGA) in Greece contracted with Atmospherics Incorporated, California, to conduct a two-year hail suppression operations program over an area near Serres in northern Greece. This initial effort was completed at the end of September 1982. The summer of 1983 was a stand-down period for hail suppression operations in Greece.

In 1984 another two-year contract was organized between OGA and Atmospherics Incorporated which included a much expanded program over three separate areas in northern Greece. During the periods 1 May through 30 September in 1984 and 1985, continuous total-area hail suppression operations were conducted within the Serres-Drama and Larisa-Karditsa areas. The overall program in Greece also included an exploratory experiment in the Emathia-Pella area. This experiment involved a randomized cross-over target-control design which included an extensive hailpad network operated to aid in the subsequent evaluations.

Another important facet of the program included formal classroom instructions in basic meteorology and cloud physics, weather modification theory and operations, cloud seeding principles for professional pilots, and practical on-the-job training for Greek meteorologists and pilots. This paper summarizes the various components of the program as operated in 1984 and 1985.

2. PROTECTED AREAS

This hail suppression program was designed to protect three specific agricultural areas in northern and central Greece. These "target areas" consist of the Emathia-Pella and Serres-Drama areas in the north and the Larisa-Karditsa area southwest of Thessaloniki. The specific boundaries for each of the three target areas were specified by OGA. For operational purposes, the three protected targets and their respective land areas were referenced as noted in the following Table 1. The actual locations of these target areas are presented in Figure 1.

TABLE 1

Hail Suppression Target Areas

Target Area	Name	Land area (stremma) 1984	Land area (stremma) 1985
1	Emathia-Pella	2,050,000	2,120,200
2	Serres-Drama	1,028,000	1,028,000
3	Larisa-Karditsa	1,000,000	1,000,000
	TOTAL:	4,078,000	4,148,200

(Note: one stremma = 1,000 m^2)

The three target areas are orographically similar in that they are mostly surrounded by complex high mountain systems. This characteristic has a major effect on virtually every facet of the overall program design. Such considerations include:

- The irregularly-oriented mountain ranges upwind of the target areas are a primary factor in the preparation of a meteorological forecast for local weather conditions.
- High mountain peaks are a substantial source of back-scatter microwave radiation and these echoes dominate the display scopes of the OGA supplied S-band radar sets utilized on the projects at Thessaloniki and Larisa.
- Aircraft operations are often conducted under IFR conditions. Safety is a

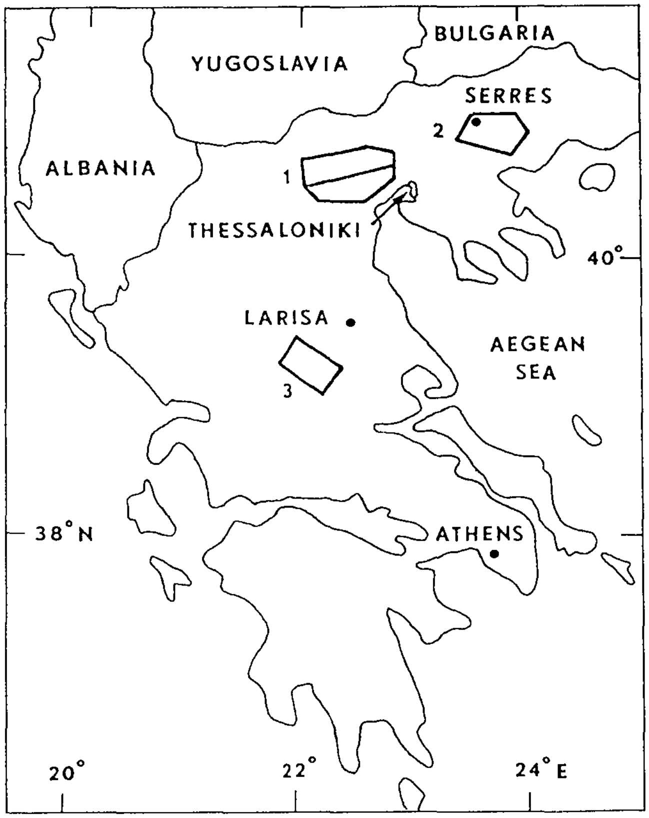

FIGURE 1. Map of Greece and Locations of Target Area

primary concern of any weather modification program and the importance of high terrain in close proximity to areas targeted for cloud seeding operations cannot be overstated.

The Emathia-Pella target area was divided into two sub-areas as shown in Figure 1. This division accommodated the randomized cross-over exploratory experiment described in a subsequent section. The boundary line dividing the Emathia-Pella area was oriented generally west to east with no "buffer zone" between the north and south sub-targets because of terrain constraints and proximity to international borders.

3. PROJECT DESIGN

3.1 The Hail Suppression Hypothesis

For many years all major hail suppression programs in the world have relied on artificial ice nuclei to promote additional freezing centers. This approach has been identified within the scientific community and some operations programs as the "embryo competition" hypothesis. The hypothesis holds that hail damage at ground level can be suppressed by providing these artificially induced freezing centers in sufficiently high concentrations. Frozen droplets and graupel (snow pellets) are prime examples of natural hail embryos. Conventional wisdom further holds that if tiny silver iodide crystals (0.01 to 0.1 microns diameter) can serve as artificial nuclei around which new hailstone embryos are formed, then the subsequent increase in hailstone population within the high altitude regions of cumulus clouds will produce competition among the growing hailstones for the available supercooled liquid water. The result is a greater number but much smaller hailstones which melt before they reach ground level.

In some areas of the world a second approach has been suggested and applied which incorporates a technique of converting supercooled cloud droplets to ice crystals within extremely large cloud volumes of suspected hail-producing clouds and storm systems. However, this "massive glaciation" hypothesis has been set aside because of the very large amounts of nucleating material required for this enormous conversion of cloud droplets even within moderate size cumulus cells. For example, if potential hail-producing clouds within a domain have (1) droplet concentrations of some 200 cc^{-1}, (2) cloud diameters of some 3 kilometers, (3) average updraft velocities of about 5 ms^{-1}, and (4) there are 10 seedable clouds in the domain and a total lifetime of some 2 hours, then the quantity of nucleating material required to satisfy a "massive glaciation" hypothesis approaches 11,000 kilograms!

For some years, we have suggested that these somewhat conflicting hypotheses, particularly in light of the highly complex hail formation and growth mechanisms, are confusing and unnecessary for present operations programs. The single common denominator which transcends all other considerations is the presence of supercooled liquid water. Hailstones must have this ingredient for birth and growth! In the application of this technology all other considerations simply comprise a large number of information sub-sets within a level of total understanding which is extremely difficult and perhaps impossible to reach.

Therefore, we believe the logical hail suppression concept we must use within our present level of understanding is the application of a technique which simply limits the available amount of supercooled liquid water within those specific cloud volumes where hailstone birth and growth occurs. We call this the "limiting supercooled liquid water" hypothesis (LSLW). This simplistic hypothesis provides a strong basis for operations without further debate on the relative merits of "massive glaciation", "embryo competition", or several other concepts dealing with changes of droplet size distribution and the concentrations of either ice nuclei (IN) or cloud condensation nuclei (CCN). We have applied this LSLW hypothesis to several operations programs in the past several years and it was applied to the program operations during the 1984 and 1985 seasons in Greece.

3.2 Personnel

Throughout the field seasons a total of 17-20 project personnel were stationed on a full-time basis at three locations. The field headquarters was organized at the Thessaloniki International Airport. Stationed at this site were 10-13 experienced supervisory, meteorolo-gical, radar, aircraft, hailpad network and administrative personnel. Cloud seeding activities in the Emathia-Pella area (Target Area 1) were supervised by personnel at this location.An additional five persons responsible for conducting operations in the Larisa-Karditsa area (Target Area 3) were stationed at the Greek Air Force Base near Larisa. These persons provided similar meteorological, radar and aircraft support for the program. Two more persons were based at a third site near Serres (Target Area 2). Personnel at this site consisted of a radar controller and a radar observer responsible for radar measurements of storm characteristics and supervision of aircraft seeding flights launched from Thessaloniki.

3.3 Meteorological Support

Basic weather information was accumulated by the project meteorologists at Thessaloniki and Larisa. The meteorologist at Thessaloniki acquired atmospheric data from the Greek Air Force meteorological office at the airport and the Greek Weather Service in Athens. The meteorologist stationed at Larisa utilized data provided by the Greek Military Meteorological Center in Larisa. At 1000 each operational day the two meteorologists would confer via telephone concerning the current atmospheric situation and begin preparation of a weather outlook for northern and central Greece. At 1030 each day the meteorologist would conduct crew briefings for all project personnel stationed at Thessaloniki and Larisa. The Thessaloniki meteorologist would also provide a briefing via telephone to the radar personnel stationed at Serres. These crew briefings included a summary of the synoptic situation over Europe, plus a more detailed and specific overview of the airmass conditions over Greece. Particular attention was given to those atmospheric parameters and mechanisms which may produce significant thunderstorm activity.

Weather forecasts were issued each day for the three target areas and surrounding regions. These detailed forecasts included a brief "word forecast" describing the general synoptic situation which prevailed at the time the forecast was prepared and any modifications expected during the forecast periods. This morning briefing also included an extended outlook for 72 additional hours, or whatever time interval appeared relevant to the anticipated seeding operations.

3.4 Aircraft

Five turbocharged Piper Aztecs (Model PA-23-250T) were the cloud seeding aircraft provided to the program. Three of the aircraft were permanently based at the Thessaloniki Airport and the remaining two were stationed at the Greek Air Force Base near Larisa. The aircraft were fully equipped and licensed for IFR flights and had on-board digital weather radar systems. Each had the capability to reach an altitude of over 5,500 meters msl within 20 minutes, cruise at 120 knots or more during seeding operations, and service ceilings above 7,500 meters msl. Flight duration for each aircraft was in excess of 5 hours.

In addition to the full compliment of navigation/communications instruments, each aircraft was equipped with special holding racks for mounting a broad range of pyrotechnic seeding devices. Nuclei generation was accomplished by the electronic ignition of the pyrotechnic seeding devices from inside the aircraft cabin. Several types of pyrotechnic devices were supplied so each pilot could adjust the quantity of silver iodide dispensed whenever required by rapid changes within individual clouds and storm systems.

One aircraft based at the Thessaloniki Airport was equipped with an airborne data acquisition system. The computer controlled SEA Model 100 Airborne Data Acquisition System (ADAS) was specifically designed to record aircraft and meteorological information. Near real-time data reduction from this system was accomplished through the use of an enhanced Apple IIe computer system located at the field headquarters on the Thessaloniki Airport. This computer and printer system provided listings of all data recorded at 6-second intervals as well as geographical output depicting the aircraft flight track.

3.5 Radar

Three radar sets were utilized on a full-time basis during the 1984 and 1985 field seasons. Two Enterprise Electronics 10cm wave length (S-band) radar sets provided by OGA and operated by AI personnel, were located at the airports near Thessaloniki and Larisa. The third radar system was an Enterprise Electronics 5.5 cm wave length (C-band) radar set which was supplied and operated by Atmospherics. This C-band system was based at the Serres-Drama area and was primarily utilized to direct airborne seeding operations in Target Area 2.

Specifications on the Enterprise 5.5cm weather radar system indicate a peak power of 250 Kw and a receiver sensitivity of -102 db log. This is more than sufficient to provide a detectable signal from rainfall rates of 1 mm/hour out to at least 130 km.

Atmospherics Incorporated provided and installed three complete interrogator/transponder systems which provided the necessary capabilities for aircraft identification and appropriate presentation on the 10cm and 5.5cm radar PPI displays.

3.6 Hailpad Network

Atmospherics personnel organized a 123-site hailpad network as an integral part of the exploratory experiment designed for Target Area 1. At each hailpad location an aluminum frame held a piece of special styrofoam material. Each piece of material presented an exposed surface dimension of 27.2 cm by 27.2 cm resulting in approximately 740 cm^2 of exposed area. These hail indicator pads supplied information concerning several parameters which described the hail occurrence.

The service interval of the total hailpad network during storm-free periods was not allowed to exceed 14 days in order to prevent possible deterioration of the hailpad surface. Ultra violet radiation does tend to slightly modify the untreated surface of the styrofoam material. However, our previous exposure tests have indicated that exposure to sunlight for a period of 14 days or less does not significantly change the surface of the material in such a manner that hail impact energy calculations are altered by more than one or two percent. In addition, a special coating material (dulling spray) was applied which protects the hailpad surface from ultra-violet radiation, yet does not affect the characteristics of hailstone impact.

Sections of the hailpad network within areas of potential hailfall were also visited immediately following any suspected occurrence of a hail event within the target and control areas regardless of the 14-day service criterion. This served to prevent two separate hail events from impacting the same hailpad prior to service. No multiple hail events were noted on any single hailpad during the 1984 and 1985 seasons.

During each service event, the field technicians clearly marked each hailpad with the file number of that particular location, along with the date and time of installation and removal. Additionally, each hailpad was marked and oriented to magnetic north so that any subsequent analysis of elongated hail dents could provide a measure of wind direction and angular velocity.

3.7 Training

During the 1984 and 1985 operational periods, Atmospherics provided an on-going training program for Greek personnel in several areas of atmospheric science, general meteorology, weather modification, radar systems and aircraft operations. The ultimate objective was to provide the Greek personnel with sufficient amount of knowledge so they could eventually assume control of the operational hail suppression program.

It was emphasized that atmospheric science is comprised of a large number of related and overlapping disciplines which describe the physical processes within the atmosphere. As technology and scientific understanding progress, the boundaries between the various sub-disciplines gradually become less distinct and the whole of atmospheric science becomes less isolated from the other scientific disciplines. During this training program, Greek pilots and radar controllers received instruction within four major areas of interest.

- Physical/dynamic meteorology in weather modification
- Basic cloud physics considerations
- Radar meteorology
- Weather modification aircraft operations

4. OPERATIONS

The aircraft flights conducted for the hail suppression program in Greece were classified into three primary categories:

- Flights when seeding was actually logged
- Cloud observation flights when a possible threat of hail existed, but no seeding was required
- Flights for equipment tests, aircraft maintenance flights, ferry flights, and administrative flights including demonstrations and status check flights requested by the sponsor

All seeding was conducted by aircraft dispersal of pyrotechnic generated silver iodide either at cloud base or near cloud top. A total of 282 flights in all categories were conducted in 1984 and 1985 with accumulative flight time of 471.0 hours.

A summary of only the cloud seeding flights is presented in Table 2. A summary of all aircraft flights and operational days is shown in Table 3.

TABLE 2

Cloud Seeding Flights - 1984

Month	Number of flights	Flight Hours	Silver Iodide (grams)
May	0	0	0
June	16	46.3	10,260
July	3	5.7	1,290
August	31	72.1	26,510
September	7	15.2	5,880
1984 Totals:	57	139.3	43,940

Cloud Seeding Flights - 1985

Month	Number of flights	Flight Hours	Silver Iodide (grams)
May	26	60.8	10,450
June	5	13.3	2,170
July	1	3.0	1,320
August	10	22.2	6,110
September	0	.0	0
1985 Totals:	42	99.3	20,050
PROJ. TOTALS:	99	238.6	63,990

TABLE 3

Summary of Aircraft Flights and Operational Days

-- 1984 --

	Total Hours	Ave.Hrs. per Flight
Number of Seeding Flights-57	139.3	2.4
Number of Observation Flights-39	54.2	1.4
Total(Seeding and Observation)-96	193.5	2.0
Number of Other Flights-42	47.2	1.1
Total All Flights-138	240.7	1.7

Number of Program Days:	153
Number of Seeding Flight Days:	21
Number of Observation Flight Days:	9
Total Number of Weather Related Flight Days:	30

-- 1985 --

	Total Hours	Ave.Hrs per Flight
Number of Seeding Flights-42	99.3	2.4
Number of Observation Flights-38	56.5	1.5
Total()Seeding and Observation)-80	155.8	1.9
Number of Other Flights-64	74.5	1.2
Total All Flights-144	230.3	1.6

Number of Program Days:	153
Number of Seeding Flight Days:	21
Number of Observation Flight Days:	14
Total Seeding or Observation Flight Days:	35

5. RESULTS AND CONCLUSIONS

During the 1984 and 1985 seasons, a specific hail suppression technology was applied to three areas for the primary purpose of reducing severe hail damage. Beyond this, the program in Greece included an important evaluation component which incorporated a ground-truth hailpad network in the Emathia-Pella area for evaluation of the randomized cross-over target-control seeding experiment. This field experiment was considered exploratory. In addition, sufficient meteorological data were obtained to support analyses of all three project areas. Finally, basic cloud characteristics as observed by the three project radars were documented manually and by scope photography.

The following sub-sections provide information on these various aspects.

5.1 Meteorological Data and Forecasts

From an examination of the type and distribution of severe weather events observed during the 1984 and 1985 operational periods, it was noted that each of the seasons exhibited non-typical distributions of severe weather and hail events. However, due to the fact that each year was characterized by a massive surge of convective activity, the total number of severe weather events with a potential for hail was near the climatological average.

The continuing development of severe weather forecast criteria for northern and central Greece was one of the primary objectives of the project meteorologists. Insight which has been gained from the 1984 through 1985 effort include the following general conclusions:

- Overall, the Thessaloniki sounding data have consistently provided information which most accurately characterizes the air mass of northern Greece.
- The Thessaloniki severe weather threat (SWEAT) index can be effectively utilized as an indicator of extremely severe weather. Data suggests that a SWEAT index threshold value of 250 would be applicable in Greece during summer months.
- The wet bulb 0° level is noted as a good indicator of hail activity in Greece. Most hail events are logged under conditions when the wet bulb 0°C height is approximately 2,000 to 2,750 m msl. The occurrence of hail rapidly diminishes as the wet bulb 0°C level moves outside this range.
- Local phenomena have been found which serve to enhance and/or inhibit hail formation in northern Greece. These include the persistent high velocity surface winds which are formed by the topography of northern Greece during a particular synoptic situation. This condition inhibits convective development.
- Enhancement of significant convection develops from strong moisture advection occurring each afternoon during the summer months due to the land-sea breeze circulation system.
- In the presence of other parameters necessary for convection, such as instability, moisture and low level convergence, synoptic scale lifting aloft produces significant hail events. This synoptic scale lifting aloft is associated with shortwave troughs and jet maxima (sources of upper level divergence) increasing PVA with height, low level warm air advection over, as in most situations, a combination of these factors.

5.2 Radar Data

During this two year period a total of 1,188 radar scope Polaroid photographs were obtained at the three radar sites. "Ground clutter" problems at the Thessaloniki and Larisa S-band radar sites confused most possibilities for any significant analyses of these photographs. However, there were several cases where this ground clutter did not interfere with storm cell analyses of basic radar data and the relevant radar scope Polaroid photographs.

Although there were too few cases of storm events with quality radar data during the 1984 and 1985 field seasons for an in-depth radar analysis of seeding effects, when the radar echoes of seeded cells were compared against nearby non-seeded cells there is strong support for the following:

- Seeded cells grow to higher altitudes
- Seeded cells exhibit stronger radar reflectivities for a short time period
- Seeded cells ultimately cover more area
- Seeded cells continue to produce rainfall for longer time periods

5.3 The Hailpad Network

The hail measurement network was established to support the randomized cross-over exploratory experiment organized within Target Area 1. This network was fully operational throughout the two-season contract period. Tabulations of data from the comparative hailpad analysis are shown in Table 4.

TABLE 4

Comparative Hailpad Analysis

Experimental Unit: 1984-85 Seasons-All Hail Days

	Target (Seeded)	Control (Not Seeded)	T/C (S/NS)
No. of Pads Impacted	2.6	3.9	0.68
Pads Impacted/Exposed	4.5%	6.4%	0.71
Avg No Impacts/Hit Pad	56.3	89.7	0.71
Avg Indiv Impact(sq cm)	0.27	0.43	0.63
Avg Median Impct (sq cm)	0.19	0.24	0.79
Avg Mode Impact (sq cm)	0.09	0.06	1.50
Avg Impacted Area/Hit Pad*	2.1%	5.2%	0.40
Max Indiv Impact Area(sq cm)	2.36	8.74	0.27

*Based on an exposed pad area of 740 sq. cm.

When combining statistics for the two-season sample as shown in Table 4, a significant average reduction in all measured parameters is observed as follows:

- The percentage of the network affected by hail was reduced by 29%
- The hailstone concentration was reduced by 37%
- The amount of area per individual pad which received hail impacts was reduced by 60%
- The average individual hailstone size was reduced by 37%
- The maximum individual hailstone size was reduced by 73%

For purposes of conducting an independent evaluation, Dr. John Flueck, a recognized authority in weather modification statistics, was supplied with hailpad records from the Target Area 1 randomized experiment in two basic forms, raw hailstone dent size records and comparative hailpad data summaries partitioned by target (seeded) and control (not seeded) areas. Dr. Flueck was charged with formulating and conducting a formal statistical investigation of these records for evidence of hail suppression seeding effects. His full report is presented elsewhere in these proceedings although his concluding comment may be useful in this paper.

"The visual and algebraic treatment effect results are suggestive of a reduction of hail 'activity' due to treatment. The principle reductions are indicated to be in the number of hailstones, the maximum size, and the density of the hailswath. In general, these three characteristics are reduced by about 75%. Further careful experimentation and continued analyses are needed to verify these highly encouraging results".

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