"REVIEWED"

KEY VARIABLES TO ASSESS SEEDING OPERATIONS ON THE GREEK NATIONAL HAIL SUPPRESSION PROGRAM

Michalis V. Sioutas
ELGA Weather Modification Centre
Thessaloniki Greece

Randy C. Rudolph[1]
Colorado International Corporation
Boulder CO USA

Abstract. Key variables were examined to assess the operational performance of cloud seeding using data from the 1993 Greek National Hail Suppression Program. These operational variables included: aircrew response time, controller launch time, fraction of storm complexes seeded, seeding start and end time, duration of seeding compared to duration of seeding criteria and seeding location. Seeding rates were not considered. A seeding coverage was calculated as the product of the fraction of storms seeded, the seed time and location of seeding using a 0-100% scale. GNHSP data resulted in a coverage value of about 40% (83% complexes seeded • 58% seeding when seeding criteria were met or exceeded • 84% correct location). Important improvements at the GNHSP, such as shortening the aircraft take-off time and identifying the need for earlier launches by controllers, have resulted from the simple act of measuring the performance of seeding operations.

1. INTRODUCTION

It is taken for granted today that management accounting and control systems contribute substantially to the success of organizations of all sizes. Moreover, companies and projects are subject to "continuous improvement" under a variety of quality-control initiatives (i.e., Crosby, 1979). Key variables (Wichmann et al., 1990) can be used to monitor project activities and alert managers to characteristics of the operating environment that affect the attainment of project goals. These variables are commonly considered to be financial or economic in nature, but the concept is applied equally well to operations (Kaplan and Norton, 1993).

Cloud seeding operations in Greece which are conducted under the auspices of the National Agricultural Insurance Institute (ELGA) are carefully monitored. The main goal of this analysis is to identify from a program management perspective areas of operations than could be improved by additional training, equipment upgrades and procedural changes. A secondary goal was to establish a method of determining the "quality" of seeding, in order that meaningful comparisons could be made to other operational seeding programs.

2. DESCRIPTION OF CLOUD SEEDING OPERATIONS AND DATA

The GNHSP is operated in three agricultural valleys in northern Greece (Figure 1). Weather surveillance is provided by 10-cm and 5-cm weather radars located near each of the project areas. Aircraft (light twins and prop-jets) are based at Thessaloniki to serve Areas 1 and 2 and at Larisa for Area 3. Operations in Areas 1 and 2 are coordinated through Hail Control located at ELGA's Thessaloniki airport office. During operations, a radar watch is maintained at two sites 7 days per week, 20 hours per day (06:00 to 02:00 local) and extended to 24 hours if storms are observed or forecast.

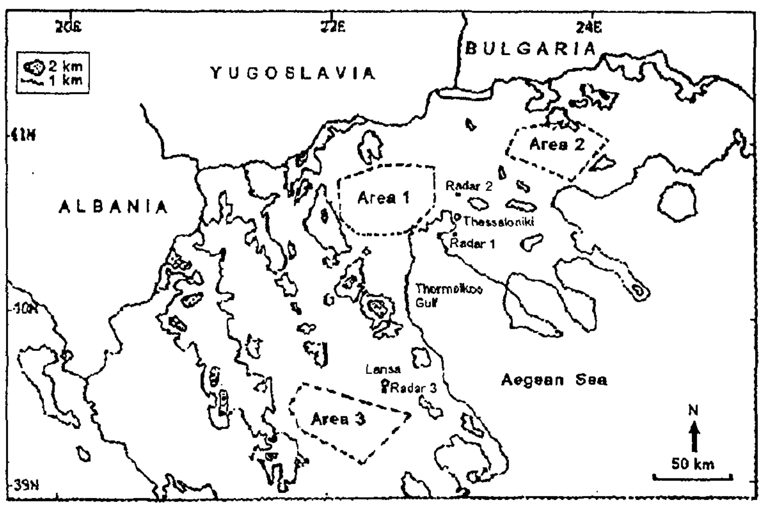

Fig. 1 The three operational seeding areas of the GNHSP, 1993. Contour elevations in km.

[1] Current affiliation: Conor Pacific, Calgary, Canada

"REVIEWED"

Several seeding methodologies are used depending on factors including storm type, visibility, terrain proximity and time of day to enable delivery of seeding material to actively growing storm regions in as many conditions as possible. Seeding material is usually released in growing cloud towers (feeder cells) on the upshear flanks of mature multicell storms or regions of identifiable liquid water and/or updraft in single convective cells.

In 1993, seeding was conducted in the three project areas using five aircraft equipped with seeding racks containing both droppable and end-burning silver iodide flares. No more than two aircraft conduct seeding operations in any of the operational areas at any time due to Air Traffic Control (ATC) policy. The seeding criteria are a threshold reflectivity of 35 dBZ or more measured in convective cells located either inside, or within 20 minutes of entering, the project area at altitudes corresponding to temperatures between -5 and -35°C (Karacostas, 1984). Seeding is to commence as soon as the 35 dBZ threshold is reached, and to continue until storm reflectivities fall below the threshold value.

The nominal seeding rate during cloud penetrations near -10°C is one 20-g flare every 5 s, resulting in a seeding rate of 240 g/min, which was estimated to achieve ice concentrations > 1000/L. Seeding at cloud base is conducted by burning one or two 150-g flares over a 4 minute period, a seeding rate of 40 to 80 g/minute.

The database produced by the operational cloud seeding program and analyzed for this study included:

- Digital PPIs and RHIs manually recorded 10-20 minutes apart at three radar sites;
- Radar controller written narrative and records of cloud parameters;
- Aircraft flight logs recording seeding amounts, location and time;
- Hail Control notes on general program coordination; and
- " Situation maps" of northern Greece plotting surface winds, temperature and moisture to assist in nowcasting.

Radar data were imported into the Corel™ graphics programs which were used to create storm tracks and annotated seeding locations. Figure 2 is an example of the output. These plots were generated for each storm above seeding criteria, each seeded storm and every seeding run during 1993.

The final set of operational performance indicators or key variables used in this analysis included: aircrew response time, controller launch time, fraction of storm complexes seeded, seeding start and end time, duration of seeding compared to duration of seeding criteria and seeding location. These key variables, important to the success of operations, are measurable and change with changes to operations initiated by program management.

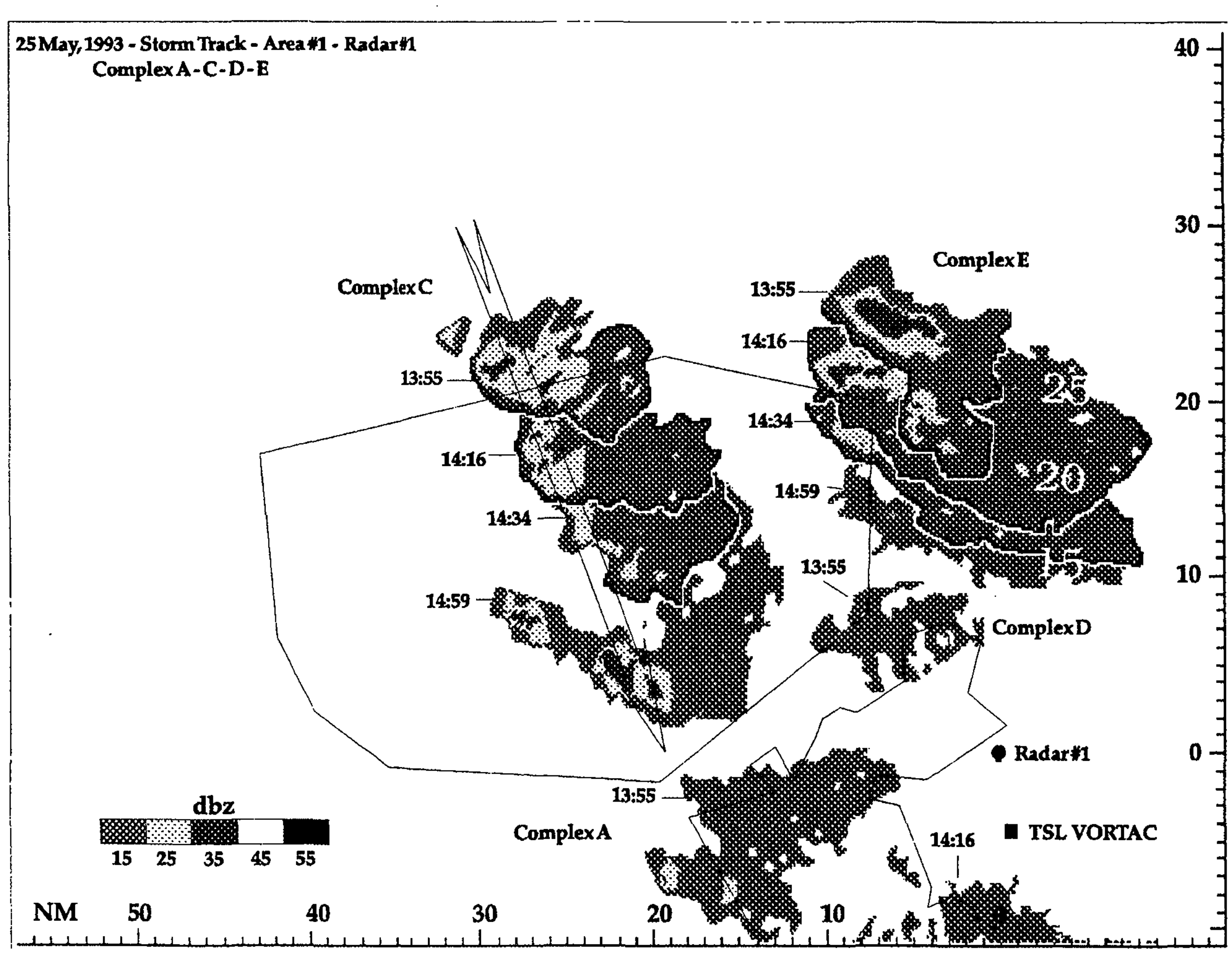

Fig. 2 Sample storm track analysis, 25 May 1993.

3. PERFORMANCE ASSESSMENT

3.1 Aircrew Response

Aircrew response measured the time between a call for launch by the radar controller and aircraft take-off. Average aircrew response for all *seeding flight* launches except call-ins after hours, but including those with all other delays, was 19 minutes, with a standard deviation of about 8 minutes. This was just less than the unofficial target of 20 minute response. The average response time for seeding flights without documented delays was 17 minutes with a 5 minute standard deviation. Documented delays are those recorded in radar logs, flight logs or coordinator notes. Other delays may well have occurred without being documented.

Delays due to various factors affected almost 20% of seeding flight launches. The most common type of delay was caused by ATC primarily at Thessaloniki when project aircraft deferred to airline traffic. When they occurred, ATC delays increased response times by 7 minutes on average. Other delays included commercial fuel truck delays (serving airline traffic or called during rain) which increased average response by 31 minutes and aircraft technical problems which increased response by 19 minutes.

Response was also examined on seeding flights when crews were called to the airport late in the evening or early in the morning. Six call-ins with seeding occurred in 1993 and call-in response averaged 45 minutes from controller request to take-off. Response showed a substantial improvement during the year, from an average of 57 minutes for the first two call-ins to 32 minutes for the last two. Five of the six call-ins requiring seeding occurred late at night.

3.2 Launch Time Difference

The launch time difference (LTD) is the difference between the time a seeding aircraft was launched and the time it *should* have been launched for seeding to begin when seeding criteria were first met inside the target area or seeding buffer zone. Patrol flights were not considered. Generally speaking, only the controller decision to launch affects the LTD. For example, if the controller launched "on time" and ATC or refueling delays resulted in a late start to seeding, the launch was considered to be good.

Data in Table 1 suggest that aircraft should have been launched about 14 minutes earlier on average. About 54% of launches resulted in seeding within 10 minutes of the storm meeting seeding criteria, a time delay which we considered reasonable to allow aircraft patrolling in the immediate vicinity of the storm to get into seeding position.

Table 1 Frequency of Launch Time Difference (LTD) for seeding flights in 1993.

LTD (Minutes)	Frequency (%)	Cumulative Frequency (%)
0	44	44
1-10	10	54
11-20	15	69
21-30	14	83
31-40	9	92
> 40	8	100

Table 2 lists the causes of LTDs greater than 10 minutes. About one-half of the LTDs between 10 and 40 minutes concerned controller and pilot decisions. Six of the 29 involved underestimation of aircraft station time remaining. The largest LTD of the season (95 minutes) occurred when two factors contributed. The first was a faster-than-usual use of flares by the seeding aircraft. The second factor was a safety issue - the threat of lightning during continuous rain which fell for over 2 h and prevented refueling of the aircraft promptly after its first mission.

Operational limitations such as weather-induced delays to refuel and first cells of the day that developed to seeding criteria inside a project area contributed to the second largest number of LTDs between 10 and 40 minutes and greater than 40 minutes. The "first cells of the day" limitation is, in part, the result of the relatively low seeding threshold. Growth on storms from just above the detection threshold (say 20 dBZ) to 35 dBZ routinely occurred within 10 to 20 minutes. This is much less than the time required for an aircraft to be launched and begin seeding. These "first cells" could have been seeded had aircraft patrolled beginning at first light, but the additional cost of operations was considered greater than the risk of hail from these storms. Furthermore, LTDs of more than 40 minutes often occurred on flights other than the first of the day, suggesting that, on days with multiple flights, flare/fuel use was not well communicated, aircraft turnarounds on the ground were delayed or aircraft/crews were unavailable.

Table 2 Reasons for LTD > 10 minutes and number of seeding flights affected.

Reason	Number of Seeding Flights	
	LTD 11 - 40	LTD > 40
Controller or Pilot Decisions	29	6
Equipment Problems	3	0
Hail Control Delays	7	0
Operational Limitations	12	2
ATC, Fuel Truck Delays	1	0

The days with most hail damage were generally those with the greatest number of seeding flights and, for this reason, active days were examined separately. Days with five or more flights were considered, with 9 days in 1993 meeting this criterion. Table 3 shows that about one-half of all seeding launches for the entire season took place on these 9 days. 53% of launches were "on time" on active days as opposed to 35% on less active days. This suggests that all staff (especially controllers) were more responsive and alert on major operational days. On the other hand, there were proportionately three times as many LTDs over 40 minutes on active days as on less active days. This might be due to a stretching of aircraft/crew resources or widespread convective activity.

Table 3 LTD number, frequency and cumulative frequency during seeding flights on 9 active days in 1993.

LTD	Active Days		Rest of Days	
	Freq.	Cum. Freq.	Freq.	Cum. Freq.
(Min.)	(%)	(%)	(%)	(%)
0	53	53	35	35
1-10	9	62	14	49
11-20	9	71	20	69
21-30	13	84	14	83
31-40	4	88	14	97
> 40	12	100	3	100

3.3 Seeding Coverage

Summary of the Concept

Seeding coverage identifies how well seeding was conducted on individual convective complexes. As defined in this analysis, seeding coverage is composed of three seeding elements: opportunity, time and location (Rudolph and Davison, 1986). We considered "opportunity" to be the ratio of seeded storms to the total number of storms that met or exceeded seeding criteria. Seed time is the fraction of time that the storm was seeded while seeding criteria were met. Seed time is influenced by late starts to seeding, premature stops and by gaps in seeding (which occur, for example, when an aircraft alternately seeds several complexes or when there is a gap between the end of seeding by one aircraft and the start by another).

Seed location was referenced to the new growth zone (NGZ) of the complex. In general the new growth zone was identified as the location of the "tightest" reflectivity gradient on the PPIs comprising the storm track, with the assumption that this location would be coincident with either low-level storm inflow or feeder cells. Pilot reports of "inflow or updraft" were also considered. Assessment of seeding location was on the basis of GOOD-FAIR-POOR. GOOD meant all seeding runs took place in the NGZ. FAIR meant most but not all runs were in the NGZ. POOR indicated most seeding runs took place away from the estimated NGZ.

Total seeding coverage was defined as the product of the fraction of storms seeded, the seed time and location of seeding using a 0-100% scale. Seed amount was not included in the product.

Fraction of Complexes Seeded

Of more than 300 complexes that occurred near the project areas on days with seeding operations, 190 met seeding criteria. A total of 33 complexes that met seeding criteria were unseeded, leaving 83% seeded. There was little monthly variation. Complexes that did not meet seeding criteria were also seeded if pilots observed active growth or if seeded complexes did not enter the buffer zone but were near enough to be seeded as a precaution. A total of 170 complexes were seeded. About 11% of seeded complexes did not meet seeding criteria at any time during their lifetimes.

The nine active days with five or more seeding flights were examined separately and stratified by area. Table 4 shows 80% of complexes above criteria were seeded on nine active days, leaving an average of 85% seeded complexes for the remainder of the season. These percentages varied little between project areas.

Table 4 Number of seeded storms and those meeting seeding criteria for nine days in 1993 with five or more seeding flights, by project area.

Date	A1	A2	A3	Total
	Complexes Meeting Criteria			
3 May	2	2	8	11
16 May	4	1	5	10
17 May	4	1	6	11
18 May	4	2	5	11
22 May	7	4	2	13
23 May	2	4	0	6
24 May	5	4	4	13
25 May	3	0	8	11
4 June	0	2	14	16
	Complexes Seeded			
3 May	2	2	7	10
16 May	4	1	4	9
17 May	4	1	3	8
18 May	4	2	5	11
22 May	4	3	1	9
23 May	2	4	0	6
24 May	3	2	3	8
25 May	3	0	8	11
4 June	0	2	9	11

Seed Start Time

This and subsequent analyses of seeding coverage involve only 155 seeded storms in 1993, except as noted. On average, seeding started 16 minutes after complexes met seeding criteria. Only 24% were seeded as or before criteria were met. The most delayed seed start time (SST) was 132 minutes on a moderate multicell storm when a combination of late launch and equipment problems contributed equally. The longest in advance that a complex was seeded was 53 minutes, when late evening convective cells with reflectivity just below 35 dBZ were seeded.

Table 5 shows the frequency of SST. If a 10 minute buffer is allowed for aircraft maneuvering after a go-ahead to seed, then about one-half of the complexes were seeded "on time". About 14% of the complexes were first seeded more than 40 minutes after seeding criteria were met.

Table 5 Seed Start Time (SST) for 155 seeded complexes in 1993.

SST (minutes)	Frequency (%)	Cumulative Frequency (%)
< 1	24	24
1 - 10	26	50
11 - 20	15	66
21 - 30	14	79
31 - 40	7	86
> 40	14	100

The SST is relevant when compared to the total time that the complex remains above seeding criteria. On one hand, a short-lived complex must be seeded within minutes of reaching seeding criteria for coverage to remain high. On the other, long-lived cells are more likely to produce large hail and therefore an early start to seeding is equally essential. The complexes in 1993 had an average duration of 49 minutes when seeding criteria were met or exceeded. Therefore, an average delay of 16 minutes in the start of seeding corresponded to about 33% of the time that seeding criteria were met or exceeded. The longest-lived complex above seeding criteria was 267 minutes when seeding began 10 minutes after criteria were first met.

SST statistics for the nine days with five or more seeding flights were examined separately which accounted for 82 complexes or just over 50% of the 1993 total. The mean SST was 14 minutes, not statistically different from the season as a whole. The maximum SST on active days was 68 minutes. The mean time that seeding criteria were met or exceeded was 52 minutes.

It should be noted that almost all seeding operations in 1993 were conducted at cloud top. The main reason is that visibility is typically poor at cloud base and therefore visual targeting is limited. In addition, cloud bases altitudes are near mountain top height which can be an important safety consideration in the relatively small project areas in Greece. Time to climb to the -10°C level was typically 12 to 18 minutes using light twin-engine aircraft and less than 10 minutes using prop-jets. Had more base seeding been conducted, SST statistics would likely have improved. Separate statistics on base seeding and its effect on performance were not kept.

Seed End Time

On average, seeding ended 2 minutes after seeding criteria were no longer met, suggesting a prompt and responsive stop to seeding. The earliest stop to seeding was 69 minutes prior to the end of seeding criteria, although the end time of the seeding criteria was difficult to estimate from the storm tracks. The latest end to seeding appeared to continue 50 minutes beyond the end of seeding criteria. On the nine active days in 1993, seeding ended on average 1 minute after seeding criteria were no longer met, not significantly different from the season average.

Seed Time

The seed time represents the combined effects of seeding start and end time, and any gaps in seeding, expressed as a fraction of the length of time the seeding criteria were met or exceeded. Data showed the average seed time was 58%. Seed times on the nine active days were not significantly different (60%).

Table 6 shows the frequency of seed time for all seeded complexes in 1993 and those occurring on active days. The data show little variation in seed time with seeding activity.

Seed Location

For this investigation, all 170 seeded complexes were examined, not just those which met or exceeded seeding criteria. 129 (76%) were classified as GOOD locations, 12 (7%) as FAIR and 29 (17%) as POOR. A total of 84% of the seeding locations were therefore classified as FAIR to GOOD.

Table 6 Seed time frequency for all seeded complexes and those on the nine most active days in 1993.

	All Days		**Nine Active Days**	
Seed Time (%)	**Freq.** (%)	**Cum. Freq.** (%)	**Freq.** (%)	**Cum. Freq.** (%)
0 - 10	9	9	6	6
11 - 20	9	18	10	16
21 - 30	6	24	11	27
31 - 40	9	33	5	32
41 - 50	11	44	10	42
51 - 60	9	53	7	49
61 - 70	9	62	8	57
71 - 80	8	70	10	67
81 - 90	9	79	10	77
91 - 100	21	100	23	100

Seeding locations were also examined on the nine active days. Of 89 seeded complexes, 73% were good, 11% were fair and 16% were poor. This is similar to the season as a whole. However, there was substantial variability in the quality of the seeding locations among the nine active days. Seeding on three of the most active days was most often judged to be poorly located when:

- Radar did not give clear indications of new growth;
- Seeding occurred downwind of the target area; and
- Seeding occurred on cells that might (or might not) propagate into the target area.

4. CONCLUSIONS AND RECOMMENDATIONS REGARDING GNHSP OPERATIONS

This study presented the results of the first comprehensive and objective review of seeding operations on the GNHSP. Rudolph and Davison (1986) used a similar approach to examine seeding coverage during the 1984 - 1985 seasons of the Alberta Hail Project. They computed a seeding coverage as the product of the fraction of storms seeded, the seed time and location of seeding using a 0-100% scale. Seeding rates were not considered. Unpublished data suggested that coverage was near 30-50%. GNHSP 1993 data result in a coverage value of about 40% (83% complexes seeded • 58% seed time • 84% location).

While the following changes to operations would lead to the most improvement in seeding coverage on the GNHSP, the comments are also of a general nature and could be applied to any seeding operation designed to reduce hail. The comparatively low values for the key variable "seed time" suggest this should be the first area for improvement.

Take-off Delays

All aircraft should be preflighted when the first aircrew arrives at the airport. This will lead to better detection of "snags" and, in the event of problems with one aircraft at launch time, a second can be used with minimum delay. ATC and commercial fuel truck delays, which also contribute to long LTDs, were considered to be beyond the direct control of the program.

Launch Decisions

Changes to procedures on the project can make launch decisions easier. For storms that advect toward the project areas, the locations of seeding buffer zones and *launch buffer zones* should be prepared based on forecast storm motion. For advective storms, aircraft should be launched before the storm reaches the launch buffer zone to enable seeding to begin before the storms reach the seeding buffer zone.

Storms that develop within the launch or seeding buffer zones or the project areas cannot be addressed by the above technique. This category of storm can be addressed by frequent radar observations and prompt launching of aircraft, or by routine patrols.

On several occasions with wide-spread and intense convection, seeding aircraft burned all flares within 1 to 1.5 h. Delays in launch of replacement aircraft can be overcome by good communications. The deployment of additional base flares on the aircraft or the use of high-yield acetone generators are also considerations, but of limited utility given the operational restrictions on seeding at cloud base.

Can better nowcasting improve launches? Experience has suggested that satellite data available on the project in 1993 did not have sufficient spatial or temporal resolution to provide a launch aid to specific storms. Nowcasting using hourly surface observations to predict the onset of convective activity was attempted but resource intensive. In all cases, radar did a better job.

Fraction of Seeded Complexes

Usually, storms were not seeded for one of two main reasons: late launch and multiple storms in the area at the same time.

Multiple storms often occur on the few active days which produce most of the hail damage (Rudolph and Giannaris-Papageorgiou, 1991; Miller and Fuhs, 1987) and so finding ways of seeding them successfully is essential. In 1993 GNHSP controllers chose the most intense storms as the highest priorities and, if required, left the lower intensity storms unseeded. Or, they directed seeding aircraft to fly back and forth among equally intense storms. One way to improve coverage of multiple storms is to have two or more aircraft simultaneously seeding large storms within a project area on a much more regular basis than has previously occurred on the program. We suggest that, contrary to the recommendations of Dalezios and Spanos (1995), the number of aircraft should not be based on the number of simultaneous aircraft flights compared to the total number of aircraft available, but rather on the need for those aircraft to effectively treat all storms above seeding criteria on the most active days. This is, in effect, a switch from tactical to strategic risk-based thinking in terms of aircraft standby costs.

Seed Stop Time

Seeding stop times could be made more realistic. Currently, seeding is to be conducted until storms above criteria exit the area, while it is to begin at least 20 minutes before storms enter the area. Stopping seeding about 10 minutes before a storm is forecast to leave the area should have no effect on damage within the target area. Furthermore, this would free the seeding aircraft to target other storms that may be developing. Seeding these storms 10 minutes earlier may be critical to reducing damage.

Seed Location

Although seeding was reasonably targeted during 1993, one of the root causes of missed locations was positioning of the aircraft due to the performance of project IFFs. It is expected that the introduction of GPS-based positioning will alleviate many of these problems.

Finally, it has been our experience that the simple act of measuring operational performance on the GNHSP brought about important improvements between 1992 and 1993. Examples were a reduction by 50% in seeding start time delays, reduction by more than 100% in the seed end time difference, and improvement in pilot response times for late-night call-ins. Heightened controller and pilot awareness was likely the major contributing factor to the improvements. Implementation of recommendations based on our analysis of key operational variables will contribute to further progress.

ACKNOWLEDGMENTS

Norm Ostrander and John Welker of Colorado International Corporation performed the arduous task of preparing storm tracks from the digital radar data. Anonymous reviewers provided valuable comments.

REFERENCES

Crosby, P.B., 1979: Quality is free - the art of making quality certain. McGraw-Hill Book Company, New York. 309 pp.

Dalezios, N.R. and S.I. Spanos, 1995: Operational efficiency assessment of hail suppression for agriculture in northern Greece. *J. Wea. Modif.*, **27**, 21-35.

Kaplan, R.S. and D.P. Norton, 1993: Putting the balanced scorecard to work. *Harvard Business Review*, September-October, 134-142.

Karacostas, T.S., 1984: The design of the Greek National Hail Suppression Program. Preprints, *9th Conf. Wea. Modif.*, Park City UT, Amer. Meteor. Soc., 26-28.

Miller, J.R. and M.J. Fuhs, 1987: Results of hail suppression effects in North Dakota as shown by hail crop insurance. *J. Wea. Modif.*, **19**, 45-49.

Rudolph and Giannaris-Papageorgiou, 1991: Effects of cloud seeding on hail insurance statistics in northern Greece. Preprints, *2nd Yugoslav Conf. Wea. Modif.*, Mavrovo, Yugoslavia, 202-209.

Rudolph, R.C. and D.S. Davison, 1986: Seeding corridors - a targeting aid for airborne cloud seeding of multi-cell Alberta hailstorms. Preprints, *10th AMS Conf. Planned and Inadvertent Wea. Modif.*, Arlington, VA.

Wichmann, H. Jr., H.M. Nix and S.M. Rehnberg, 1990: Key variables as a management tool. *CMA Magazine.*, March, 22-26.