Planned Weather Modification and the Severe Weather Threat in the Central High Plains

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ABSTRACT

Operational and experimental convective cloud-seeding projects are often planned without regard to the number of seeding-opportunity days that can be lost because of the need to suspend operations during the threat of severe weather. June daily rainfall, severe storm and tornado watches, and observed tornadoes within a hypothetical (proposed) operational area over southwest Kansas were compared within the context of five procedures for severe weather related operations suspensions. These procedures varied in the restrictions placed on operations. The results show that anywhere from 45–87% of the June rain can fall when operations have been suspended. The length of a scientific seeding experiment could be increased anywhere from 45–426%. Finally, 46% of the tornadoes occurred when there were no concurrent tornado watches. This failure rate is so large that severe weather watches may not be useful for operations suspension procedures..

1. Introduction

The dry years of the middle 1970's have stimulated weather modification activities (cloud seeding for the purpose of increasing rainfall from convective clouds) over parts of the Middle West and High Plains agricultural areas. These same areas are often frequented by severe weather (excessive rains, large hail, damaging winds and tornadoes) during most of the crop growing season. When there is sufficient advance knowledge of the threat of severe weather, the field managers may shut down cloud-seeding operations to ensure the safety of project personnel and to avoid the charge that the seeding caused or enhanced the severe weather. This possibility was raised with regard to the flood-producing storm at Rapid City in 1972 (St. Amand *et al.*, 1972: Dennis *et al.*, 1973).

The design for the *HI*gh *PL*ains *EX*periment (HIPLEX) (Bureau of Reclamation, 1973) called for careful consideration and use of a shutdown approach for severe weather periods during the field experiment (Ackerman *et al.*, 1976). The criteria to identify days with the threat of severe weather were to be based on the tornado and severe thunderstorm watches issued by the National Severe Storms Forecast Center (NSSFC).

Five hypothetical suspension criteria express various relationships between June daily rainfall, severe storm and tornado watches and reported tornadoes for a hypothetical (proposed) operations area located over southwest Kansas. Kansas was selected for the study area because of its central location in the plains and because it is the location of one of three sites for the HIPLEX. The study addresses the following two important subjects relating to severe weather aspects of the design of convective cloud-seeding projects.

1) How much must an experiment be lengthened to make up for the loss of seeding opportunity days?

2) Is the severe weather watch information of sufficient accuracy to be useful for suspension criteria?

2. Data

The data for this study have been extracted from the NSSFC logs of tornado, severe thunderstorm and aviation severe thunderstorm watch areas for the entire United States from 1952–75. The watch areas are defined by a specified distance in nautical miles (1 n mi = 1.85 km) either side of a line connecting two points given in latitude and longitude. A second magnetic tape contains the NSSFC tornado logs from 1950–74. Included are cumulative sums of tornadoes by day and state, detailed specifications of conditions under which the tornadoes occurred and information concerning their locations, path lengths, widths, etc. A third data set contains the daily rainfall records for Kansas.

The study area (Fig. 1) was divided into nine "operations" squares, each 175 km on a side. This is equal in area to a circle of 100 km radius, typical of an operations area as viewed from a radar scope. Ten-year (1965–74) total June tornadoes (above line) and April–September seasonal tornadoes (below line) for each square are shown. The average areal daily rainfall for 22 precipitation recording sites within the square centered around Dodge City (DDC) was provided from a general covariate study (Achtemeier *et al.*, 1978).

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3. The suspension criteria

Because of limitations in the data used for this study, several basic assumptions had to be made in the development of the suspension criteria. All June rainfall was assumed to be convective. The seeding opportunity day was assumed to be a day with seeding opportunities, i.e., a day with rainfall anywhere within an operational area. Therefore, cloud seeding is assumed to be much more effective in the augmentation of natural rainfall than in the initiation of rainfall on days in which natural rainfall would not have occurred.

Support for these assumptions is found in the large-amplitude June diurnal rainfall frequency and amount curves for the Dodge City area (Fig. 2). Most rain fell during the late afternoon and early nighttime hours. This period is generally considered as the period most favorable for convective rainfall. Further, the frequency curve shows that fewer than 20 storms occurred during the late morning (0900–1200 LST), thus establishing that multiday storms were relatively uncommon. Thus, given that rain occurred during a 24 h period (0700–0700), the rainfall most likely occurred during the convective period which is most favorable for seeding opportunities.

Additional assumptions were required to develop the relationship between the severe weather watch areas and the daily rainfall. The latitude and longitude coordinates and widths of the NSSFC watch areas were converted to a Lambert conformal map image frame and compared with the coordinates of the operational areas. An example is given in Fig. 1. If any part of a watch box falls within any part of an operational area, that area is designated as under a severe weather watch. Watches issued during the late afternoon often overlap into the early morning hours of the next day. Since the frequency of valid watch times is a minimum during the morning hours, the severe weather watch day is defined as a day with a severe weather watch valid sometime during the period from 0700–0700. This definition conveniently makes the watch day correspond to the daily rainfall period.

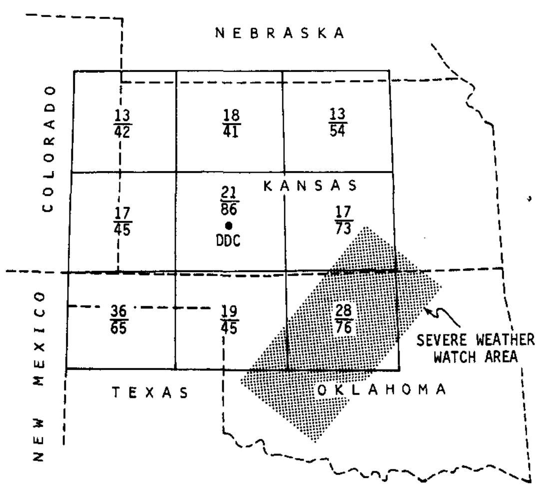

FIG. 1. Map of the Central Plains showing the locations of the nine box total analysis area including the Dodge City (DDC) experiment area.

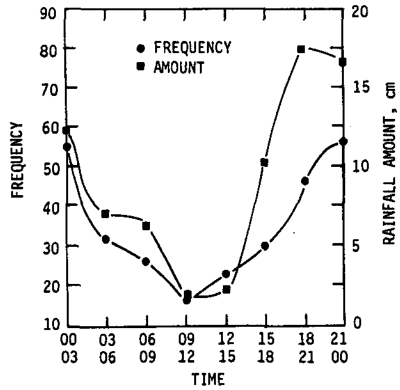

FIG. 2. 1965–73 total 3 h rainfall frequencies and amounts for the Dodge City (DDC) area.

When the severe weather threat is predictable, watches may be issued several hours prior to the actual valid times. In less predictable situations the watches may be issued as weather conditions deteriorate. It is assumed that all watches are issued before actual aircraft operations are initiated. Then if operations are suspended on severe weather watch days, that day and its rainfall, if any, can be extracted from the set of seeding-opportunity days.

The design of an operational or experimental cloud-seeding project should consider the severe weather problem as it relates to human activities and land usage. Thus, the restrictiveness of the shutdown criteria may vary from one location to another. Five criteria which vary according to the type of watch and the areas covered by the watch have been developed in anticipation of a variety of design requirements. Watch information drawn from the eight areas that surround the operations area shown in Fig. 1 enter decision making in two ways. First, if a watch is issued for areas upwind from the Dodge City area, operations may be suspended for concern that severe weather watches will soon be issued for the project area and/or that severe weather will move in later in the day. Second, if a watch is issued for areas downwind from the Dodge City area, operations may be shut down for concern that seeding material may drift downwind into the valid watch area and interact with storms there. Thus, in some situations, weather conditions in the total area (Dodge City plus eight surrounding areas) might need to be monitored.

The five criteria for the severe weather related suspension of cloud seeding operations are as follows:

1) Total area watches—This is the most conservative approach. In the event that a severe weather watch of any kind is issued either within the DDC area or within the surrounding areas, operations are suspended. Thus,

TABLE 1. Summary of June 1965–74 tornado and severe weather watch information taken from NSSFC weather logs.

	Year										
	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	Average
Tornadoes (total area)	20	22	37	17	18	18	34	5	5	7	18.3
Tornado days (total area)	13	11	21	11	14	11	15	4	4	7	11.1
Tornado days (DDC area)	0	0	4	2	0	2	1	0	1	1	1.1
All watch days (total area)	29	24	23	15	15	15	14	9	11	10	16.5
Tornado watch days (total area)	9	6	11	8	10	5	10	1	6	5	7.1
Severe thunderstorm watch days (Total Area)	16	12	6	4	5	10	4	8	5	5	7.5
Aviation watch days (total area)	4	6	6	3	—	—	—	—	—	—	4.8*
All watch days (DDC area)	19	13	15	8	9	9	12	5	5	4	9.9
Tornado watch days (DDC area)	8	2	9	4	6	4	7	0	4	3	4.7

* Based on period 1965–68.

that day and its rainfall, if any, is extracted from the set of seeding opportunity days.

2) DDC area watches—This conservative approach leads to the termination of operations for any severe weather watch that falls within the DDC area. Weather conditions within the surrounding areas do not influence the decision making.

3) Total area tornado watches—Watch information from the total area is taken into consideration but operations are cancelled only upon the issuance of tornado watches.

4) DDC area tornado watches—Same as 3), but only for the Dodge City area.

5) Perfect tornado forecast—Operations are suspended on those days with a tornado reported within the DDC area.

The last three criteria consider the tornado threat as the only reason for suspending cloud seeding activities. In fact, this is not true. Some suspension criteria should be defined for damaging hail, damaging winds and flooding rains. The derivation of these criteria is beyond the scope of this study.

4. Results

The results of this study address four major topics that involve severe weather with precipitation enhancement activities. First, the reduction of the number of seeding-opportunity days has important implications for the effectiveness of commercial seeding projects and the advisability of scientific experiments. Second, the projected increases in the lengths of scientific experiments is dealt with directly. Third, the suitability of the severe weather watch for the suspension criteria is exexamined. Finally, tornado frequencies for July and August are used in the estimation of the severe weather problem for these months.

a. Loss of seeding-opportunity days.

June tornado and severe weather watch information from 1965–74 have been summarized to show the relative numbers of the various watches and their annual variabilities. These are listed in Table 1 with respect to the DDC area and the total area. The watch days have been categorized into tornado, severe thunderstorm, and aviation severe thunderstorm watch days in the following manner. Any day that had a tornado watch was designated as a tornado watch day regardless of the number of other watches valid during that day. Any of the remaining days that had a severe thunderstorm watch was designated as a severe thunderstorm watch day regardless of the number of aviation watches.

The annual number of tornadoes within the total area varied from five in 1972 and 1973 to 37 in 1967. Many of these were "family" tornado situations and the number of tornado days in any June was usually less than the number of tornadoes. On the average, 11.1 total area tornado days could be expected during any given June. When the area under consideration was reduced to the DDC area, the number of tornado days decreased to only 1.1 per June, or about 4% of the month.

The watch summaries reveal that 16.5 days or an average of 55% of June days are subject to some type of total area severe weather watch. The tornado and severe thunderstorm watches are split evenly with 7.1 (24%) and 7.5 (25%) watch days. If the first 4 years are representative of the 10-year period, there would have been an average of 4.8 aviation severe storm watches per June. These watches were discontinued from the data set after 1968.

Looking at the DDC area only, the summaries show that approximately one-third (9.9) of the June days are severe weather watch days. Of these, 4.7 days are tornado watch days. A comparison of the tornado watch days with the average number of tornado days shows that the DDC area tornado days were overforecasted by a factor of 4. By contrast, the total area tornado days were underforecasted.

Table 2 expresses the loss of operational opportunities in terms of the percentages of June precipitation that fell on days on which operations would have been suspended. The bottom line gives the June rainfall in millimeters for each year and the average rainfall. The wet

TABLE 2. Percentage of June precipitation that occurred on days when operations would have been suspended.

Suspension criteria	Year 1965	1966	1967	1968	1968	1970	1971	Average
1. All watches (total area)	100	99	90	97	62	93	58	87
2. All watches (DDC area)	91	85	57	58	16	90	55	66
3. Tornado watches (total area)	64	9	48	65	16	67	55	50
4. Tornado watches (DDC area)	62	9	42	42	16	67	52	45
5. Tornado days (DDC area)	0	0	28	9	0	51	7	14
Total June precipitation (mm)	155	50	165	78	75	70	73	95

years, 1965 and 1967, had approximately twice the rainfall of any of the other 5 years.

June 1965 was not a good year if cloud-seeding operations had been conducted within the guidelines of the all watches (total area) suspension criteria. Table 1 shows that only one day was without some type of severe weather watch. There was measurable precipitation on this day but almost 100% of the average areal precipitation for the DDC area fell on severe weather watch days. Table 2 also shows that operations would have been shut down during the fall of more than 90% of the June precipitation in 5 of the 7 years.

With the exception of the first suspension criterion, June of 1969 was an "outlier" with only 16% of the month's precipitation falling during suspended operations. About 60% (45.8 mm) of the month's rainfall fell during the period 12–17 June. Daily weather maps revealed this to be an unseasonably cloudy, cool period with stratiform rains associated with the passage through the area of two upper level cyclones. During this period, severe weather was held far to the south of the DDC operational area; on 16–17 June the extreme southwest corner of the analysis area was included in severe thunderstorm watches.

These system type rains are not candidates for convective cloud seeding (Ackerman *et al.*, 1976). They have not been stratified from the monthly rain analysis shown in Table 2 and in the following tables. Therefore the percentages presented in Table 2 may be optimistically small with respect to the rain that actually fell in association with convective systems.

About two-thirds of the June rainfall occurs when operations are shut down if severe weather watches within the surrounding areas do not enter into the decision process. If the suspension criteria are relaxed so that damaging hail and damaging wind days are not considered, approximately half of the precipitation would have escaped possible treatment (criteria 3 and 4). The fifth criteria, based on the currently unattainable perfect tornado forecast, shows that only 14% of June rains fall on tornado days.

Severe weather watches are more likely to be issued on days with widespread moderate to heavy rainfall according to Table 3 which shows the relationship between watches and rainfall in amount categories. About 72% of the very light (0.3–3.0 mm) rainfalls as compared to anywhere from 81–100% of the rainfalls greater than 3.0 mm would have been eliminated if the operations were subject to the most conservative suspension criterion. These percentages decrease as the restrictions are relaxed. The tornado watches (DDC area) criterion would suspend operations on only 31% of the potential seeding opportunity days. By contrast, only 8% of the seeding opportunity days would also be tornado days.

Table 4 summarizes the watch information by seeding opportunity days. For the 7-year period, there averaged only 3.1 June wet days without any total area watch. There would be 7.7 potential operational days per month with the all watches (DDC area) suspension criterion in effect. The tornado watches (DDC area) criterion would allow 11.3 potential operational days.

b. *Severe weather and length of a scientific experiment*

The design of a seeding experiment should take into consideration the sampling requirements to determine an effect in the presence of considerable background variability (Ackerman *et al.*, 1976). The sampling requirements may address the following question: "Given so may samples per year, how many years must an experiment be conducted in order to detect a certain percentage change in rainfall at a specified level of significance and precision?" The length of a scientific seeding experiment designed to verify a given seeding hypothesis may be substantially increased if the number of samples per year is decreased because of the severe weather related shutdown of operations.

TABLE 3. Percentage of June seeding opportunity days (rain days) for which operations would have to be suspended.

Rain amount (mm)	Percent by suspension criteria 1	2	3	4	5	Total number of rain days, June 1965–71
0.3–3.0	72	43	26	16	0	61
3–6	100	84	58	53	21	19
6–12	81	63	44	38	13	16
12–25	86	64	64	57	21	14
>25	100	50	25	25	0	4
Total	81	55	39	31	8	114

TABLE 4. Summary of watches valid on wet days for seven Junes.

	Year							
	1965	1966	1967	1968	1969	1970	1971	Average
Wet days without any total area watch	1	1	1	1	7	5	6	3.1
Wet days without any DDC area watch	6	8	7	6	11	8	8	7.7
Wet days without any DDC area tornado watch	14	14	11	9	11	9	11	11.3

If n is the number of days required to verify a hypothesis and α is the percentage of days eliminated by the suspension criteria, then the total number of days N that the experiment must be run in order to have n operational days is given by

$$N=100n/(100-\alpha).$$

Table 5 gives the factors by which the projected length of a seeding experiment must be multiplied so that there will be n operational days. For example, if 100 operational days are required to verify a hypothesis, the total length of an experiment must be increased to include 526 potential operational days if operations are terminated when a total area severe weather watch of any kind is issued. More modest increases in experiment duration are expected if the suspension criteria are based upon tornado watches alone. The 9% project length increase brought about by the perfect forecast criterion serves as a reminder that it is the forecasting (not the actual number) of tornado days that presents the challenge to Central Plains cloud-seeding operations.

c. Reliability of watch criteria

The four currently attainable operations suspension criteria have been developed exclusively from the NSSFC severe thunderstorm and tornado watch information. Throughout this development it has been assumed that the days on which severe weather actually occurred were always severe weather watch days. Now it is recognized that no forecast system is completely fail-safe. However, the failures, those severe weather days for which watches were not issued, are critically important for cloud-seeding operations. These circumstances can bring forth the charge that seeding caused severe weather when severe weather would not have occurred under natural conditions.

The accuracy of the NSSFC tornado watches was determined for the DDC operations area. There were 11 June tornado days in the DDC area from 1965–74, but on only 6 of these days were tornado watches valid in the same area. In this case, the failure rate was 46% (5 of 11 tornado days were not forecast). Further, there were no tornado watches valid in any of the surrounding extra areas on those days; 3 days had severe thunderstorm watches, 1 day had an aviation severe thunderstorm watch, and 1 day had no watch of any kind. The more conservative suspension criteria can minimize the number of failures but would lead to the elimination of a large number of seeding-opportunity days.

TABLE 5. Factors by which the length of a scientific seeding experiment must be multiplied so that there will remain n operational days after the suspension criteria removal of opportunities.

	Suspension criteria				
	1	2	3	4	5
Factor	5.26	2.22	1.64	1.45	1.09

d. The tornado problem in other months

It is clear that the avoidance of severe weather in cloud-seeding operations in the Central Plains can lead to the elimination of many potential seeding-opportunity days. Is this problem as critical for months other than June? This study was conducted only for Junes, but inasmuch as there is a direct relationship between the number of tornado days, the number of tornado watches, and the amount of rain that falls on watch and nonwatch days, some inferences on the number of stand-downs for the other months can be made. Fig. 3 shows the mean monthly number of tornado days for the total analysis area for April–September (1965–74). The maximum number of tornado days occurs in June. June is followed by May with 7.2 tornado days. The remaining months have fewer than four tornado days, less than one-third of the June total. It would be expected that tornadoes in April, July, August and September would be much less an obstacle to cloud-seeding operations than in June. May is a transition month. May is characterized by many more "family-type" tor-

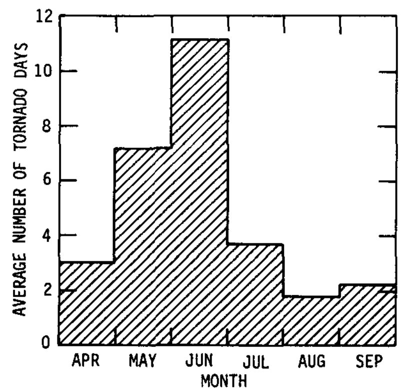

FIG. 3. Average monthly number of tornado days in the total analysis area for April–September for the 10-year period, 1965–74.

nado days than is June. Family events are usually easy to predict and this would tend to reduce the high failure rate as found with the June tornado watches. Thus, though tornadoes are an operational problem for all months in the period, the loss of potential seeding opportunities should not be as great as in June.

5. Possible alternative criteria

The results of the preceding section have demonstrated that the severe weather watch is not well suited for suspension criteria. The large number of severe thunderstorm and tornado watches remove many potential seeding opportunities, thereby placing the effectiveness of commercial seeding programs in jeopardy and increasing the length of scientific seeding experiments. Because of the high failure rate for the tornado watch, operations conducted on days for which no watch has been issued leave program operators open to the charge that seeding increased the potential for tornadoes on days that severe weather was not expected.

But is there a better data source for suspension criteria than the severe weather watch? A seeding project may provide its own severe weather data. This approach is attractive because project forecasters can concentrate their efforts toward weather events over the operational area. However, the NSSFC has the benefit of years of forecast experience, and the performance of the tornado watch should be credited mostly to the complexity of the tornado forecast problem.

Perhaps suspension criteria developed from severe weather warnings issued by local Weather Service offices would be useful. These warnings are usually issued when severe weather has already been reported by the public or when storms approach severe limits as determined by radar. If seeding operations are being conducted when the warnings are given, even though operations are terminated, the continuing dynamical and microphysical interactions of seeding material with nearby storms could lead to implications of property damage liability.

Another approach would be to redefine what constitutes severe weather according to land usage and human activities within the operations area. If the severe weather threat is from flood rains, project operators should be aware of the locations of population centers relative to streams. Slopes of drainage surfaces, vegetation and soil types help determine runoff rates. In some areas there can be virtually no threat from excessive rainfall whereas, in other areas, potential heavy rain conditions should be viewed with caution.

Hail poses little threat to range land; however, the loss to cash crops such as wheat, corn, and soybeans can be considerable (Changnon, 1972). Then, according to the above approach, hailfall over range land would not be classified as severe weather. Tornadoes are most hazardous to life and above-ground structures. They pose little economic threat to crops because of the relatively small damage paths. Thus, in some very sparsely populated areas, cloud-seeding operations in conditions that may produce tornadoes may be a low risk venture.

6. Conclusions

Some criteria to suspend operations are necessary if severe weather is to be avoided in the planned modification of Central Plains convective clouds. This study has explored the use of severe weather watches, particularly tornado watches, for such criteria. For western Kansas, the number of seeding-opportunity days lost ranges from 31–81% depending on the restrictions in the suspension criteria. These very high loss percentages place in jeopardy the effectiveness of commercial seeding programs that use criteria based on severe weather watches to suspend operations. Some suspension criteria can more than double the length of scientific seeding experiments (range of increase is 45–426%).

A fifth criterion, designated as the perfect tornado forecast, revealed that only 14% of the June rainfall occurred on tornado days. Thus the suspension criteria problem is a problem of forecasting rather than a problem of widespread occurrence—at least for tornadoes. Furthermore, it was found that 46% of the tornadoes occurred in the absence of appropriate tornado watches. This forecast failure percentage is so large that tornado watch derived suspension criteria may not serve the intended purposes of the project design. Several alternative criteria were briefly discussed; however, these were not without problems. If the severe weather threat is to be taken into consideration in cloud seeding programs, some suspension criteria superior to those described here must be found.

This study has been limited to Junes in the central High Plains. This does not mean that the severe weather threat is nonexistent elsewhere. Severe weather is frequent during the summer growing seasons throughout the plains and the Midwest. This threat may vary according to the month, land usage, human activities and maturity of the crop. The June tornado problem may give way to hail later in the summer. Flooding rains may need to be avoided throughout the season.

Severe weather threat information for the site of any cloud-seeding operation should be available to program planners prior to the onset of projects. The avoidance of severe weather may or may not be an integral part of the project design. However, the designers should have the opportunity to preview the potential hazards.

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