METROMEX: LESSONS FOR PRECIPITATION ENHANCEMENT IN THE MIDWEST

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SUMMARY

The evluation of 3-years of METROMEX field operations and data interpretation have resulted in valuable design information for purposeful weather modification in the Midwest. The operational experience gained in METROMEX has shown the efficacy of mid-cloud level seeding and the necessity for either two radar systems or a sophisticated single system to serve the dual purpose of evaluation and aircraft guidance. The interpretive analyses for the establishment of the METROMEX precipitation anomaly exemplify the wisdom of combinatorial evaluation of statistical, physical and climatological data from surface and airborne meteorological instruments and from other geophysical observations related to precipitation modification. The sensitive evaluation methodology developed for METROMEX is considered directly applicable to future weather modification experiments in the Midwest.

1. INTRODUCTION

One of the primary values of the study of inadvertent weather modification was recognized as early as 1969 (Changnon, 1969) to be the use of its results in planned weather modification. In the subsequent planning for METROMEX and its specific impacts, it was thus clear that results for a program designed 1) to measure an urban-related precipitation anomaly, and then 2) to describe its causes would have many direct benefits to planned weather modification (Changnon et al., 1971). Basically, these applications or lessons have since been realized in two general areas: 1) the operational aspects of the field experiment, and 2) in the research-analytical aspects of a program.

The Illinois State Water Survey has been involved for several years in the orderly planning for weather modification experiments in Illinois. The general thrust of these plans has been to develop experimental designs that were essentially applicable to all areas of the Midwest and other regions with similar precipitation climatologies. Basically, these design-related programs have concerned all possible topics including social-economic impacts and interactions, seeding systems, operations, cloud physics, and evaluation, and in essence they have been hopefully addressed to all aspects of well-designed weather modification experiments. Two such experiments have been under intensive study of the design for optimum execution. The first, concerning precipitation management in Illinois, has been a multi-year program sponsored partially by the National Science Foundation (Schickedanz and Huff, 1971), and also by the Bureau of Reclamation (Changnon, 1973). In parallel, in the last 7 years we also have been in the process of designing a midwestern hail suppression experiment (Changnon et al., 1974). Both of these design programs were to a degree built upon results expected to be generated in METROMEX.

2. OPERATIONAL LESSONS

The operational effort of METROMEX involving a daily forecasting module, operations of 2 radar systems, and extensive network of raingages and other meteorological instruments, field and network crews, and an aircraft which was performing updraft releases of tracer materials, as opposed to seeding materials, have provided us with a wealth of experience relating to operational aspects of a planned program to modify convective storms. The operational aspects of METROMEX, the only large inadvertent weather modification field research program in the world, are described elsewhere (Cataneo, 1974).

a. Radar

Certain aspects of the radar operations in METROMEX have provided several important lessons for planned weather modification efforts in the Midwest. Our echo climatological studies of the past (Changnon and Huff, 1961) established the frequent complexity of convective precipitation systems in the area. Complex cellular zones and multi-line activity are not uncommon, and as such they have required, for the METROMEX "target (study) area", considerable flexibility in radar operations.

The 2 radars used by the Water Survey in METROMEX have included a 10-cm FPS-18 set operated in a PPI and CAPPI mode, and a 3-cm TPS-10 radar system operated in a RHI mode. The PPI and CAPPI modes of operation have been extremely useful in the evaluation program of METROMEX (Huff, 1973), and the value of radar data as an evaluation tool in Midwest seeding experiments is unquestionable. The RHI radar has been used in conjunction with the PPI to discern the most active cells for vectoring aircraft in a simulated seeding (tracer release) operation. Effective seeding projects in Illinois must include capabilities for extensive nocturnal operations because 32 percent of all Illinois hail (Changnon, 1970) and 50 percent of all convective rainfall occurs at night (Huff, 1971). This necessitates radar vectoring of seeding systems to complex multi-cellular systems.

Hence, radar requirements for a well-executed weather modification project, as based upon the lessons of METROMEX, tell us that for a moderate sized area, either 2 radar systems are needed, or a very flexible and sophisticated single system is required. Essentially, a radar system operating in some 3-dimensional mode of observation is required for directing seeding aircraft. In addition, since radar data are to be used in evaluation of the seeding activities (Mueller, 1974), radar data are needed from a rather semi-fixed mode collecting 3-dimensional precipitation data on a frequent basis over the target area and possibly over the surrounding control areas. If a single 10-cm system is used, it must be capable of a 3-dimensional programmable operations with 1) a facility for storage of information for real-time operational decision-making, and with 2) a digital recording of reflectivity data in a fixed mode (sector) must be available. METROMEX evaluation efforts coupled with the occurrence of convective precipitation at all times in the Midwest clearly shows the need for a 24-hour opearational requirement for the radar. This reflects on the requirements of an engineering-technical support staff, and on standby capabilities such as FPS-18 radar system with its standby dual channel. This dual channel feature of the FPS-18 proved to be an extremely important feature in providing backup radar support to METROMEX. A standby power system at the radar site is also needed to prevent loss of data in severe electrical storms.

b. Seeding System

METROMEX has taught invaluable lessons regarding the requirements for seeding systems. The tracer aircraft operation in METROMEX concerns release of tracers into updrafts of cells approaching a rather small fixed area of 700 mi^2. Semonin (1972) has described some of the difficulties encountered in releasing tracers into Midwest convective systems. The METROMEX results shown by Semonin (1972) and Gatz (1974) clearly indicate that more than one seeding aircraft would be needed for an area of 1000 mi^2. The frequency of cells, and the difficulties of maneuvering aircraft between multi-cellular systems, suggest that a system for cloud base seeding over an area of 2000 mi^2 would require 3 to 4 aircraft.

The METROMEX tracer results further show the possibility of successful ground-based seeding. Tracers released from ground-based generators have been observed in rainfall within the 700 mi^2 target area. However, it is also clear from these experiments, as with the aircraft, that many generators would be required to affect a target area of 2000 mi^2. This successful finding on surface tracers is complicated by the fact they were performed in the urban area during the afternoon convective periods, and various vertical currents created by mechanical friction and heating of the city may have greatly assisted in the transport of the tracer material to cloud base levels. Ground releases of seeding agents certainly would not be as effective during nocturnal hours due to the surface inversion/s.

Flights of our Precipitation Enhancement Project in the METROMEX area in 1973 often involved mid-cloud, near freezing level penetrations to sample showers and growing congestus. Their aircraft operations prove that the number of seeding aircraft would be less if mid-cloud (12,000-20,000 ft) seeding could be used. However, this requires a tradeoff to more expensive, higher performance aircraft capable of shower-storm penetrations with seeding systems. Results from METROMEX and our other design studies suggest that the mid-level or high-level seeding approaches are likely the optimum seeding delivery systems to be employed in planned weather modification efforts in the Midwest. The tracer experiments of METROMEX have taught us that there are many difficulties encountered at cloud bases including detection of updrafts due to visual limitation for detecting new turrets (unless sophisticated radar detection of updraft areas can be reliably developed).

3. RESEARCH-ANALYTICAL LESSONS

a. Evaluation

One of the major lessons, or series of lessons, learned from METROMEX concern the evaluations of rain and hail anomalies. Prior Survey research (Schickedanz and Huff, 1971; Schickedanz and Changnon, 1970) has addressed the subject of statistical evaluation of advertent weather modification.

Precipitation anomalies, both in time and space, exist in various locales and these can be assessed as due to 1) natural sampling variations, 2) urban-industrial effects, 3) orographic-marine effects, 4) observer errors, 5) man-made purposeful modifications, and 6) exposure-site changes. The climatological-statistical identification of urban-related precipitation changes in METROMEX has required a variety of techniques integrated with theoretical considerations, good judgement, and continuing awareness of three important considerations (Changnon and Schickedanz, 1971).

First, an initial consideration has been that statistical evaluations are always based on some degree of space-time dimensional comparisons (point-to point, point vs area, etc). The second consideration is that the climatological-statistical assessment of inadvertent precipitation modification is a problem somewhat similar to that in planned weather modification, but importantly there are problems inherent in the inadvertent investigation and evaluation that do not exist in planned experiments that are carefully designed and executed. The chief problem in the statistical evaluation of inadvertent modification is that the treatment effect (urban effect) is not assigned at random and is uncontrollable. This eliminates the usual treatment versus non-treatment comparisons so useful in planned weather modification. Also, in this same consideration is the problem that the target area for the precipitation alteration is not as well defined or known as it is in planned weather modification. Thus, theoretical models and actual surface precipitation observations must be employed and evaluated just to define the presumed "target" for inadvertent precipitation modification.

Finally, it is important to include physical analyses (often case studies) as well as historical and statistical analyses in analyzing the effects. In fact, physical observations and theory must be employed to help ascertain the effects as well as to explain the results of the statistical analyses. In essence, the evaluation of METROMEX has been a rigorous training experience in developing evaluation techniques and expertise and as such has taught many valuable lessons for evaluating planned weather modification.

In essence, there have been three principal lessons learned about evaluation from METROMEX. The first concerns utilization of the raincell concept as the basic rain evaluation entity (Schickedanz, 1972). The dense raingage network and radar data of METROMEX allowed objective delineation of the isohyetal patterns of each convective entity (see Fig. 1 - a raincell example), and within the 2000 mi^2 study area, 600-900 such raincells have been found each summer (Schickedanz, 1973). Such a detailed time and space classification of individual storms has permitted the comparison, essentially on a target-control basis, of raincells under city influences with those in various surrounding rural control areas and other potential rural effect areas such as the large river bottomlands and Ozark Hill areas. The raincell as an evaluation entity has proven to be an extremely powerful tool in developing a large volume (sample) of information in a relatively short period. The data not only provide information on surface rainfall quantity, but they also provide useful information for ascertaining various cell properties including the lifetime, length, width, etc. As shown in Table 1, raincell analyses for METROMEX have established 1) the percentage change (increase) that occurs in storms over St. Louis, as opposed to rural cells, 2) the alteration of storms occurring over the Mississippi-Missouri River Bottomlands northwest of St. Louis, and 3) the changes in storms produced over the Ozark Hills to the southwest of St. Louis. The raincell analysis has also discerned that there is a change produced in some raincells that occur over the large but distinctly separate industrial area of Alton-Wood River (Fig. 1) north of St. Louis (Table 1).

The second major evaluation lesson learned from METROMEX was the importance of using geophysical data, other than rainfall and meteorological data, to validate the precipitation anomalies. To this end, Changnon (1973) employed crop yield data, water quality data, runoff data, and hail damage data to reveal the existence and magnitude of the local rain and hail anomalies. The use of geophysical data in supporting a weather modification effort is a very powerful tool for planned weather modification. First, it is unquestionable (non-biased) supportive data, and secondly, it also reveals the degree of impact in a social-economic sense.

The third and most important lesson learned about evaluation of METROMEX was that a qualitative yet comprehensive means of combining all the results and evaluating them jointly provides the most informative and positive proof of modification. When one takes the raincell data, the storm and monthly rainfall data, our case study results, and the synoptic findings and combines them to form a logical meteorological argument, one has a very powerful result that both offers statistical evidence and explains the precipitation alterations (Semonin and Changnon, 1974). This complete analysis approach involving physical evidence compiled simultaneously with the in-depth large sample of climatic-statistical evaluation plus theory provides an important lesson for planned weather modification in the Midwest.

b. Synoptic System Analyses

The thrust of the METROMEX analyses has been to interpret all of the precipitation results in light of synoptic weather analyses. That is, storms and raincells have been investigated and compared on the basis of the synoptic condition associated with rain production (Beebe and Morgan), 1972). This approach has been used to provide the final interpretative and predictive skills, not only for understanding when and how the urban effects occurred, but to predict their occurrence. Hence, great importance has been given to the synoptic analysis which in turn clearly provides information for planned weather modification on seeding opportunities, both for operational and for evaluation purposes. Such a statement is based upon the assumption that some, if not all, of the physical causes for altering urban precipitation, are identical to those achieved through purposeful seeding.

Certain results for the first two years of METROMEX are summarized in Table 2. These are based upon the 123 rain periods, each a distinct period of rain with a given synoptic type over the 2000 mi^2 network. Each rain period was classed as to whether it exhibited urban effects, as derived from a careful analysis of the rain cells and a variety of other information, or did not exhibit any discernible effects. Although probably not entirely a correct definition of urban effects, the results certainly provide some guidelines as to those atmospheric conditions when apparent maximization occurred.

The number of rain events with each of four synoptic types is shown in Table 2, and these reveal that air mass was the most frequent followed by squall lines. The number of urban effect periods in each of these four categories was expressed as a percent of the total number and these appear in the second column of Table 2. This shows the greatest frequency (61%) of effects occurred with squall lines followed by warm-stationary frontal conditions. Markedly lower influences of urban effects were found in the air mass and cold front cases. The lack of a high frequency of urban effects in air mass situations is somewhat surprising as is the large percentage of the squall lines. Effected squall line percentages, as based on moderate (≥0.25") and heavy (≥1.0") point rainfall amounts (Table 2) reveal that the effects are even more frequent in squall line situations capable of heavier rain production. One might suspect that enhancement of precipitation would not be likely in such well organized systems, but the METROMEX results to date indicate differently.

The importance of the effect rainfall by the synoptic classes is further revealed in the last two columns of Table 2. Forty percent of the 2-summer rainfall in the network was in the effect category and was produced by squall lines. Squall lines with no apparent effects produced 20 percent of the total. Hence, the enhancement of rain in squall lines, which were clearly the major rain producer, is the primary condition in which the urba-industrial complex has affected precipitation in the St. Louis area. A possible lesson from these METROMEX results is that precipitation enhancement in the summer would be best achieved by modification of squall lines.

However, of concern and interest for planned weather modification in the Midwest is the fact that a comparable study of hail events in METROMEX (Changnon and Huff, 1973) has shown that sizeable down-city increases in hail, both in frequency and intensity, also occur largely during the squall line conditions. Some of the most important lessons from METROMEX are that
a) squall lines which produce most of the summer rainfall can be modified,
b) that rainfall can be measurably increased from squall lines, and
c) enhancement of rainfall through squall line modification will also result in increases in hail. Of further interest is the fact that Changnon's (1973) analysis of crop yields and hail losses downwind of St. Louis and Chicago shows that the net benefit of the increased rainfall and hail is an increase in yields because the effect of the additional rainfall, which leads to greater yields, is greater than the losses from the increased hail.

Modification of thunderstorms and convective systems is an essential feature of a planned weather modification experiment in Illinois. Investigations of potential economic benefits to the water supply and agriculture from rain modification shows that much of the benefit lies in precipitation augmentation for agriculture (Changnon, 1973). Furthermore, most areas of Illinois start crop growth seasons with adequate soil moisture. Hence, to benefit agriculture the increased rainfall by modification must be effected during July and August, the prime water need months for corn and soybeans. Changnon (1957) has shown that 80-85% of the precipitation in Illinois in these 2 months is from thunderstorms. This finding has been verified in METROMEX, and hence, beneficial weather modification in the summer must deal with thunderstorms.

4. SUMMARY

The field operations and the evaluation procedures of the METROMEX project have provided valuable lessons applicable to the design of a planned weather modification experiment in Illinois. Our experience in conducting the tracer release experiments requiring skills in synoptic and radar meteorology has taught us that the real-time display of quantitative radar data is necessary if cloud base aircraft seeding is to be used. The complexity of the convective systems common in the Midwest and their 24-hour occurrence require excellent radar and communications to provide guidance and a margin of safety for the flight crews involved in such a seeding experiment.

The METROMEX project has also demonstrated the efficacy of the raincell concept for evaluation of precipitation modification. Of course, this approach necessitates the implementation of a surface network of raingages sufficiently dense to discern the raincell entity. As pointed out above, however, such data in concert with all other supporting evidence, provide a statistical sample enhanced by physical reasoning for the confirmation of seeding effects.

The METROMEX synoptic-rain results are most encouraging for planned weather modification. The fact that squall lines exhibit the potential for rainfall enhancement is particularly important since they are the major rain producers of the summer. A capability to provide sizeable increases in air mass rainfall would have little net benefits since they produce so little of the total summer rainfall. On the other hand, the synoptic results do suggest that increases in rainfall from squall lines will be accompanied by increases in hail, unless further METROMEX results can discern the subtle differences as to how the rain is increased when the hail is not increased.

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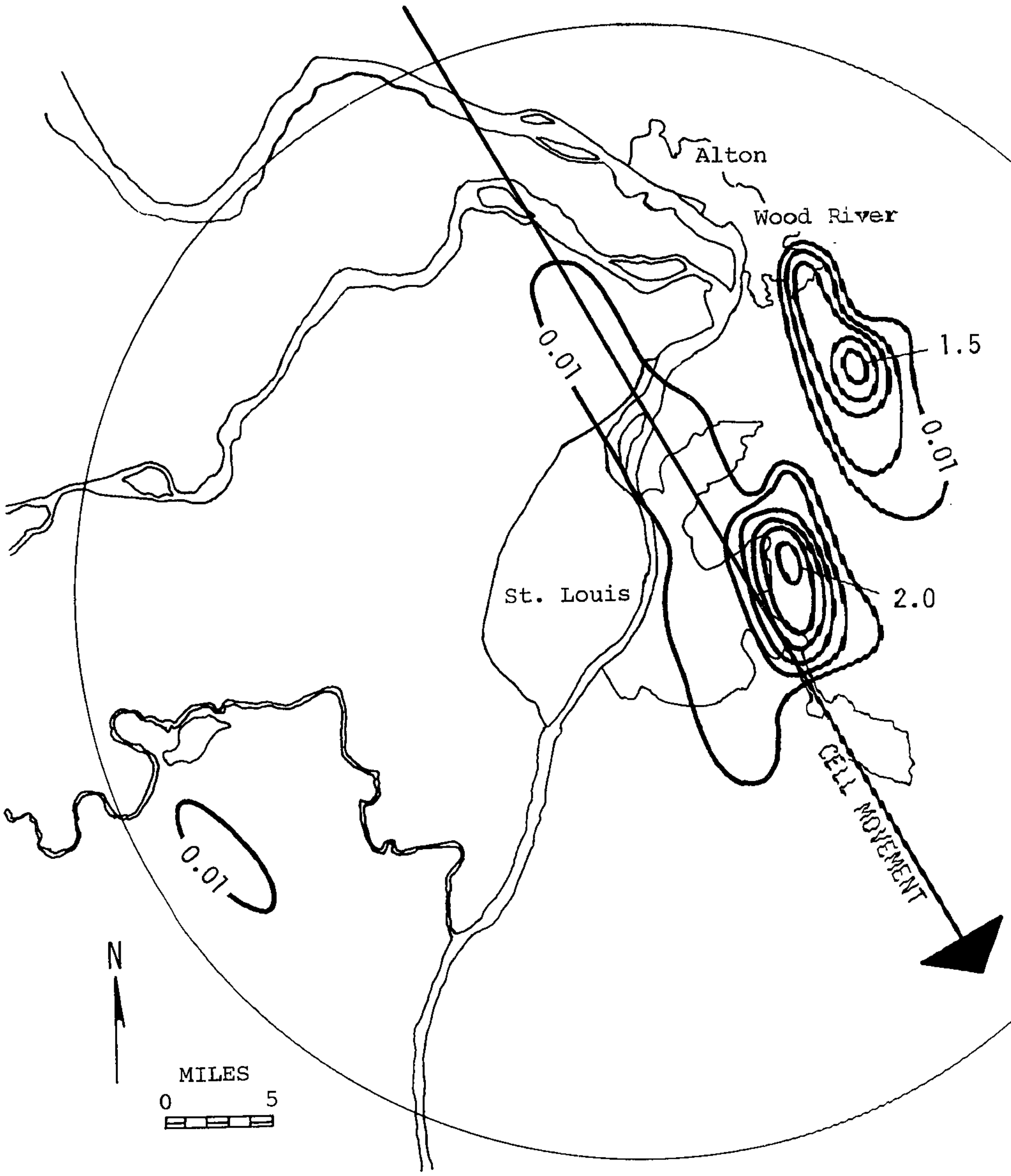

Figure 1. *Raincells during a 5-minute period on 18 June 1972, rain rate in inches/hr.*

Table 1. Average Characteristics of Rain Cells (1971-72) over St. Louis, over the Alton-Wood River Industrial Complex, over the River Bottomlands, over the Ozark Hills, and over the Rural (control) Areas.

	Rain volume, acre feet	Cell duration minutes	Cell area miles^2	Maximum 5-min rain amounts, inch
Rural	128	27	22	0.05
St. Louis	296	34	42	0.07
percent[1]	131	24	90	40
Alton-Wood River	416	31	36	0.08
percent	225	15	61	73
Bottomlands	152	29	27	0.06
percent	19	6	21	27
Hill	189	28	33	0.07
percent	48	3	48	40

(1) given value expressed as percent of rural control value

Table 2. METROMEX Rainfall in 1971-1972 Classed by Synoptic Weather Types.

Synoptic type	Number of rain events	Percent of all rain periods that were effect	Percent, for events whose maximum point rainfall ≥ given values, inches ≥ 0.25"	≥ 1.0"	Percent of 2-year total rainfall In effect category	In no-effect category
Cold front	21	26	42	60	9	12
Warm-Stationary front	16	50	50	50	5	4
Air Mass	55	42	46	43	5	5
Squall Lines	31	61	64	69	40	20