"REVIEWED"

A PERSPECTIVE ON WEATHER MODIFICATION EVALUATION

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Abstract. Evaluation of outcomes of weather modification has been a necessity and an evolving process. Early efforts were largely based on statistical techniques of surface weather variables, but over the past 20 years use of physical processes assessment has grown. Great progress has been made in learning how to effectively use physical and statistical approaches for the assessment of weather modification, both operational and experimental efforts.

1. INTRODUCTION

This paper presents a perspective on efforts to evaluate planned and inadvertent weather modification, based on the thoughts of one who has been involved in the evaluation of weather modification efforts for the past 25 years. This is not intended to be an exhaustive review of evaluation practices, techniques and findings, but rather a personal view of the highlights of the past and a focus on areas of progress in evaluation techniques and philosophy.

The scientific community has been performing weather modification including its evaluation for 35 years and some interesting inconsistencies are obvious; further, some techniques and beliefs have made full revolutions from use to criticism, to non-usage, and now to usage and credibility again. However, in general, real progress has been made in learning how to design, conduct, and evaluate operational experimental weather modification projects to get meaningful assessments.

For those who seek in-depth information on various evaluation issues and techniques, please see Hsu (1981), a major report which annotates more than 1200 documents dealing with evaluation. Several in-depth reviews of the statistical techniques and varied efforts to evaluate weather modification projects have been issued over the past 25 years. Among those I commend to an interested reader are those by Court (1960, 1967), by the National Academy of Sciences (1966, 1973), Mielke (1967), Stinson (1969), LeDuc (1971), Changnon (1973), Grant and Cotton (1979), and Bradley et al., (1980).

I claim that considerable clarity in the use of statistical techniques in evaluation has occurred in recent years. Changing attitudes on the philosophy of physical and statistical assessments, and on more powerful assessment approaches, have been revealed in the papers of Braham (1979), Gabriel (1979, 1980), and the Statistical Task Force (1978). One emerging theme is greater consideration of empirical evidence, as opposed to solely statistical evidence, in weather modification assessment. This is not a new concept; even Dr. J. Neyman (1969), one of the statisticians long involved in weather modification and its evaluation, criticized many statistical techniques in use. Neyman (1969) and Court (1980) discussed several of the limitations of statistical assessment in weather modification. Another leading scientist also urged the use of empirically based evidence as the best general approach to weather modification assessment (MacDonald, 1969). This evolution in assessment philosophy is revealed by Simpson (1974) who advocated the Bayesian approach, as well as other physical approaches, to help break from the traditional statistical approaches. Elliott (1980) presented a useful resume of various physical factors for use in evaluation efforts. Also, collective evidence of the results from several projects was used to get a single assessment as early as 1957 (Thom, 1957) to help get a sense of success from a combined view of weather modification efforts.

2. BACKGROUND ISSUES: SOME KEY REALITIES

The evaluation of weather modification projects has been generally found to be a necessity, whether designed into a project or not; furthermore, evaluation has been a significant part of the modern science of weather modification. At times, debates based on differing evaluations of the same project and data sets have occurred, often raising questions among unknowing outsiders of the real outcome. Some evaluation-related debates have centered on interpretations of major field experiments including Project Whitetop (Braham et al., 1971; Decker et al., 1971; Lovasich et al., 1971); on the CLIMPAX program (Mielke et al., 1971; Hobbs and Rangno, 1979); and on the Florida Area Cumulus Experiment (Flueck et al., 1981; Nickerson, 1981). There are many more sources of information about these experiments than cited here, but these are offered to illustrate the point that different approaches to evaluation have yielded different results.

The strong early tendency to depend on statistical analysis came about because of our general inability to totally understand and to measure adequately the expected physical outcomes of modification. Hence, the scientific community turned to statisticians and their techniques for discerning differences, either in atmospheric conditions or surface weather variables. Clearly, there is a shift away from this view as more knowledge of key atmospheric variables have developed in the past 30 years.

In early years, the field also was uncertain about how to integrate physical measurements with statistical techniques. For example, use of statistical techniques faced major problems relating to sample size, and knowledge and use of the correct test to apply to the often skewed distributional characteristics of clouds and precipitation conditions.

In general, the evaluations of weather modification experiments which were typically randomized, and of operational projects which were non-randomized, have rested on some form of use of target versus control approaches. The 12 major experiments in the United States during the past 25 years have all used some form of randomization involving comparisons of various conditions including individual clouds, storm or rainfall periods, or on daily rainfall (Changnon, 1979). Randomization has been the primary tool used to insure against bias.

It appears, however, that most of the statistical design and techniques used from 1950 to 1975 unfortunately embraced activities that caused bias, multiplicity, and/or subjective judgments that have helped confound the statistical interpretations of the outcomes of most major field experiments. After many mistakes, I believe the field has learned how to correctly design and conduct experiments with a correct mixture of physical factors and statistical tests to ensure interpretable outcomes in the shortest possible time period.

A multi-year study of how to evaluate operational projects (Changnon et al., 1981) developed new statistical techniques. Principal component regression was found to be the single most powerful test. This project provided new information about how to better evaluate operational projects.

All major weather modification experiments in the United States have also been recently assessed in another effort to discern the kinds of confounding problems their design and operations have created (Hsu, 1985). This study was done to avoid such problems in the design and operation of the Precipitation Augmentation for Crops Experiment (PACE), a midwestern experiment now under development in Illinois.

3. SOME FACTORS AFFECTING EVALUATION OF OPERATIONAL PROJECTS

One of the major recent lessons learned about obtaining a convincing evaluation of operational (non randomized) projects is that high quality records of their operations are needed if their outcomes are to be believed by most (Huff and Changnon, 1980). Views of one recent advisory body are that assessments of non-experimental projects should rely on well planned and conducted operations with various records such as written flight logs, radar film, cloud observations, etc. that allow assessors to discern exactly what was done, why, where, and when (Changnon et al., 1981). It should be realized however that useful assessments of projects without such records have been made (Henderson, 1966).

Secondly, any evaluation of operational projects depends largely on use of target-control relationships. These need to be developed between the target (seeded area) and adjacent (control) areas, and/or between both of these areas and the historical records of each (Changnon et al., 1981). The use of target-control relationships, such as developed through regressions of historical pre-modification data, have had an interesting history. In the 1950's this was the key evaluation approach in use, (Thom, 1957; Court, 1960), but the approach came under fire (Neyman, 1967) and fell out of favor. In more recent years, the target-control approach involving more sophisticated statistical techniques and projects with high quality data has been supported (Bradley et al., 1980; Changnon et al., 1981). Questions are still raised in assessments based on individual daily conditions (rain, hail) versus those based on monthly and seasonal values. Bias can occur in the selection and partitioning of storm events, a situation which led Dennis and Kriege (1966) to group all storm events for their evaluation..pp Operational projects can be meaningfully evaluated by assessing certain secondary effect indicators that accumulate (in space and time) the modification effects such as streamflow (Henderson, 1966) and crop yields (Sonka, 1979; Eddy et al., 1979). These indicators can not be used in randomized experiments.

All operational projects utilize existing scientific theory and observations as the basis for their modification efforts. Where, when, what, and how to see clouds are based on concepts of producing microphysical changes of cloud, ice, and water particles based on various techniques (and seeding materials) for delivery of the materials to the critical parts of the clouds.

Some major operational projects have been carefully designed around scientifically - established modification experiments (Changnon et al., 1980). For example, the current Moroccan - United States winter orographic precipitation project is operational in design (seeds all opportunities), but employs techniques for enhancing winter snowfall and rain bands that have been scientifically established to produce predictable increases in snowfall in projects in the Sierras and Colorado, and increases in rainfall in the Israeli and Santa Barbara experiments. Furthermore, there are sufficient on-going atmospheric measurements with radar, radiosondes, and aircraft in Morocco to help make meaningful scientific, as well as statistical, interpretations of the seeding efforts. This is an example of how to "layer science" on an operational effort.

The Statistical Task Force (1978) to the U. S. Weather Modification Advisory Board made key recommendations about how to "piggyback" science onto operational projects. If carefully done, it was seen as a cost-effective means of advancing our knowledge of cloud seeding while simultaneously attempting to modify all events. Gabriel and Changnon (1981) further assessed the mixing of scientific learning and operations and offered recommendations such as employment of various seeding techniques with randomized applications.

Studies and field experiments of inadvertent weather modification by large cities and industries have involved a mixture of statistical and physical evaluations (Changnon et al., 1981; Hobbs et al., 1970). Urban effects on the atmosphere leading to changes in clouds and precipitation are analogous to operational cloud seeding projects. Essentially, something is being injected into the atmosphere (heat, moisture and particles) and is causing potential changes. The METROMEX field effort revealed that data from a mixture of atmospheric measurements (radars, tracers, meteorological aircraft, pibals, satellites, and radiosondes) established linkages of the surface to clouds and to in-cloud changes, and the statistical analysis of rainfall (radars and gages) established the changes in raincells and storm rainfall. The assessment of inadvertent weather modification is not dissimilar from that for operational projects. Basically the St. Louis results on rain change were based on empirical evidence with sufficient physical linkages found to be considered convincing (Statistical Task Force, 1978). However, the early urban effect results based largely on climatic data and target-control analyses (Changnon, 1968) were disputed Holzman and Thom (1970) by taking different data sets and difficult analyses, a comparable debate found in assessments of operational projects.

4. SOME KEY LESSONS FOR EXPERIMENTAL PROJECTS

Analysis of most major United States weather modification experiments (Changnon, 1978) revealed that several problems had affected their evaluations. The randomized approach had not presented noncontroversial assessments, and most experiments are considered inconclusive. Interestingly, a key issue was not scientific of technical but was rooted in a lack of institutional commitment, defined as not enough funding at any one time, and too little support of the project for a long enough time to get a sample size adequate to discern effects (Changnon, 1973b; 1980). The conduct of a major experiment requires strong leadership and military-type operations that have been too infrequently achieved.

These types of management-related problems in most experiments were often further compounded by a mixture of improper statistical design and evaluations. A recent assessment of 13 major worldwide projects dealing with cumuliform cloud modification looked at 7 factors including: 1) sampling and experimental units; 2) features used to separate seeded from unseeded effects; 3) cloud physics parameters used in evaluation; 4) seeding techniques; 5) response variables; 6) statistical methods used; and 7) investigations of extra-area efforts, and several confounding problems were identified (Hsu, 1985). Two main problems concerning statistical evaluation of the projects were (1) problems of multiplicity, and (2) "subjective judgment" in making decisions about seeding operations. Most multiplicity problems were caused mostly because of many analyses performed on the data (mainly various stratifications) without prior specification in the design. This rendered the computed significance levels less conclusive than they originally appeared (WMAB, 1978). Projects which appear to have the multiplicity problems include FACE 1, Israeli I, NDPP, Stormfury, Tasmania, and Whitetop.

Examples of "subjective judgment" problems include the posterior definition of "floating target" in FACE 1, and the choice of deciding to seed rain or hail in the NDPP operation. Another concern expressed has been whether data handling persons are allowed to know the seed/noseed random plan before processing any data (WMAB, 1978). Questions were expressed on the positive seeding effect of the Santa Barbara 2 results (WMAB, 1978).

In FACE 1, the large rainfall increases were largely due to rainfall on 5-6 seeded days. The rainfall increase in FACE 1 was re-analyzed by Nickerson (1979) using neighboring area as controls and claimed to be due to natural variability; although the neighboring area might have been contaminated by seeding (Flueck _et al_., 1981). The failure of FACE 2 to confirm the results of FACE 1 was shown to be due to the unusually heavy rainfall on one "unseed" day (Woodley _et al_., 1983). This represents an unfortunate design relating to how to treat and assess heavy rain days. Yet, Dennis (1967) pointed to ways to design field experiments so as to exclude effects of such extreme events, and Brier and Meltesen (1976) also addressed this problem.

Another type of problem found in many experiments was related to some phase/s of the operations. For example, too few raingages or hailpads were installed; or project radars tried to serve too many masters - both for operations and data collection; or the wrong seeding technique was used.

Some experiments were confounded by post mortem analyses. For example, in the most United States experiments, our scientists did not clearly recognize the difference between "Exploratory" and "Confirmatory" statistical approaches. Hence, the statistical analysis, which was being too heavily relied upon, was compromised. The scientific literature is filled with papers providing diverse and conflicting results form the evaluations of experiments. One result of this has been confusion, disregard, and loss of credibility about scientific studies among the scientific community and the general public. Yet with all these problems, several field trials have been concluded satisfactorily and with thorough evaluations of several physical factors, as well as statistical assessments of precipitation, streamflow and other effected factors (Dennis and Koscielski, 1969; Williams and Lehman, 1970; Changnon _et al_., 1980).

5. SUMMARY

The evolution in evaluation approaches suggests that after many trials and errors, the field is now able to design and conduct projects, either operational or experimental, to allow for meaningful, nonconfounding evaluations of field efforts. I consider this to be a major achievement in the field of weather modification.

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