# USE OF MODELS IN WEATHER MODIFICATION - SOLUTIONS OR CONFUSION?

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One measure of our understanding of natural and artificially modified cloud and precipitation processes is our ability to simulate the essential features of their evolution through the use of numerical cloud models. I emphasize in this statement that modelers attempt to simulate only the essential features of clouds, the characteristic sequence of events manifested by these processes. It should be recognized that even if precise initial conditions were known, the physical assumptions and numerical techniques required to make models computationally tractable would make the exact simulation of a particular cloud unlikely. However, a model can provide insight into the characteristic behavior of clouds that develop in the air mass represented by a given sounding. By making several runs with reasonable variations in initial conditions that are deduced from observations, it should be possible to describe the range of cloud types that could be expected.

In forming a model, one specifies a scale and selects the properties deemed to be of greatest importance to the phenomenon being modeled. Usually the modeler then has to parameterize some of the processes in order to transform the equations into a readily solvable form. This process of simplification may be carried so far that what remains is a small fraction of the complete set of equations; for example, the Lagrangian steady-state model of convection. Yet for some limited but important purposes, this is a useful model in weather modification since it is capable of diagnosing the convective potential of the atmosphere and the dynamic effects of AgI seeding. In general, though, for a model to have a high degree of relevance to precipitation modification, a great deal more of the detail of the full set of equations must be retained or the parameterizations must be a rather faithful representation of these equations. It should also be noted that a model solution that is physically accurate in principle but inaccurate in detail is still useful for weather modification experiments if it can simulate important features of the differences between final states that result from different initial states or inputs. A model that does predict the correct precipitation process but does not predict the correct precipitation amount is, therefore, still useful if it can predict the differences in precipitation amount that result from a variety of seeding applications. Since a model, unlike the atmosphere, has reproducible inputs and outputs, it can, within limits, be used to study the effects of varying the initial conditions in a systematic manner. It can thereby direct attention to those parameters in the system that seem to have the greatest effects on the outcome of the experiment. If, then, these quantities are measured in the field, the experiments can be partitioned on the limited number of parameters or covariates which have been predicted to be most significant. This procedure should be interative, for the analysis of the partitioned data helps evaluate not only the experiment but also the numerical model.

Models can therefore be a useful tool in weather modification in three primary ways:

1. In gaining insight and understanding of natural and modified processes

2. In developing modification hypotheses

3. In determining predictor variables or covariates for use in identifying opportunities and in evaluation

At this point I must inject a note of caution. It is imperative that we be ever mindful of the limitations of the models, being careful not to draw unwarranted conclusions. If confusion exists, as the assigned title implies, it stems from a lack of appreciation of this point. Misapplication of models, encouraged by the exaggerated claims of some modelers and the lack of objective standards for verifying models, has created in the minds of some scientists a lack of credibility in their usefulness. I have heard a number of respected atmospheric physicists, primarily observationalists, say that models are oversimplifications of the facts and are, therefore, useless. The first part of their statement is, to some extent, true, but the second part is far from true. A model, when used appropriately, is but one tool in the rather limited arsenal of tools that we can bring to bear on weather modification problems, and we would be remiss, indeed, if we did not use it. Utility of all the tools is maximized when they interact iteratively with feedback from one to the other in a mutually supportive fashion. Except for a few notable cases, recognition and implementation of this approach has been lacking. Interaction between modelers and observationalists, when it did occur, was usually after the fact rather than during the planning, execution, and analysis of the experiment.

The history of model development and application in atmospheric physics has a theme which has much in common with those of other developments in science. A good analog might be the laser. The theme, stated briefly, is as follows: When the new technology first comes on the scene, it captures the imagination of the scientists who envision rather lofty applications for it. They rely on it to solve many of the problems with which they are frustrated, almost as a panacea. After several years pursuing these goals with only limited success, a period of disillusion sets in, understandable only in hindsight, and the technology begins to be thought of as not being worth much at all. All of this time, however, a number of more realistic scientists have been developing more limited but very useful applications of the technology, recognizing its use as a tool that can be used as a means to many ends rather than as an end in itself. In the last phase, this philosphy takes hold, reason prevails, and the no-longer-new technology makes significant contributions to a host of problems.

I believe we have only recently entered this last phase of technology development and application in numerical cloud modeling. A number of exciting advances have been recently made. I would like to describe briefly just a few examples, those with which I am most familiar.

## CONVECTIVE CLOUD MODELING WORKSHOP

A convective cloud modeling workshop was convened by the Bureau of Reclamation's Division of Atmospheric Water Resources Management in Denver, Colorado, on June 11-13, 1975. (Silverman, et a., 1976). The main objective of this workshop was to design a specific and continuing effort to close the gap between models and observations and thereby maximize the utility of models to contribute to our understanding of natural and artificially modified convective clouds. The workshop focused its discussions on (1) model initiatization data requirements, (2) model verification data requirements, including the method or methods by which model predictions can be time-synchronized with observations of cloud development, and (3) objective model verification criteria.

To lay the foundation for these discussions, each participating modeler presented the results of his model for two standard input data sets, which were sent to him beforehand. The models were compared first to each other and then against such verification data as were available, which were first presented to the modelers at the workshop.

Twenty-two scientists representing several universities, Government agencies, and industrial groups participated in the workshop. Results from three one-dimensional, steady-state models (1D, SS), five one-dimensional, time-dependent models (1D, TD), four two-dimensional, time-dependent, axi-symmetric models (2D, TD, Axi), and two two-dimensional, time-dependent, slab-symmetric models (2D, TD, SLAB) were presented. I will only summarize the results of the model inter-comparison.

Data used in the workshop were collected on August 10 and 17, 1973, in the vicinity of St. Louis as part of Project Metromex. They were graciously provided by Dr. Bernice Ackerman of the Illinois State Water Survey, who also participated in the workshop.

The sounding for August 10 was quite unstable, while that for August 17 was less unstable. This resulted, as we shall see later, in the development of clouds with different growth and precipitation characteristics, which is the reason why these 2 days were selected for the workshop cases. Since the input and verification data sets were limited, we were anxious to see if the model predictions could at least distinguish the nature of the convective activity on these 2 days.

Tables 1 and 2 give results of the various model runs for clouds with base dimensions which fit approximately the size of the observed clouds for that day, except for the slab-symmetric models, which predict their own size clouds. Table 1 is for August 10 and Table 2 is for August 17.

In general, the models predicted the characteristics of convection on these 2 days and gave quantitative information about rainfall rates and quantities of rain from individual cells in most cases and from the whole field of convective clouds in two cases. The factor-of-three difference in rainfall rate in the observations was predicted in some of the models. The vertical velocity of the observations came from the rise of echo heights, which is probably an underestimate of the vertical velocity.

The modeling workshop was an extremely useful first step in narrowing the gap between models and observations. It provided encouragement to the modelers by showing the ability of most models to properly characterize cloud development on the 2 test days. In no case were modelers trying to predict the actions of a particular cloud. They did, however, try to predict important precipitation mechanisms, types, and regions, and the detection in quantitative terms of the importance of ice process on August 10 and its unimportance on August 17 is significant.

The workshop produced a list of observations for initializing and verifying models and suggested objective vertification criteria. In the future, another workshop may be called to consider a more complete data set which is being collected primarily for this purpose as part of the Bureau of Reclamation's High Plains Cooperative Program (HIPLEX).

Table 1

AUGUST 10, 1073 - CLOUD MODEL RESULTS

| | (3) ID,SS | (3) ID,TD | (2) 2D,TD,SLAB | (4) 2D,TD,Axi | Observations |
|---|---|---|---|---|---|
| Radius (km) | 2.0 | 1.0-2.0 | 1.5-5.0 | 1.5-2.5 | 2.0 |
| Cld Top (km) | 11.4-14.0 | 8.4-10.6 | 9.0-10.0 | 9.0-10.0 | 9.0-14.5 |
| Cld Base (km) | 1.2 | 1.0-1.5 | 1.0-1.4 | 1.0-1.5 | 1.2 |
| Max W ($ms^{-1}$) | 14.7-25.0 | 16.0-19.8 | 10.6-16.7 | 20.0-29.0 | 14-15* |
| Max RR ($mm\ hr^{-1}$) | - | 47.9-54.0 | 50.0 | 12.0-53.0<br>(130.0)** | 21.8-68.0 |
| Total Rain (mm) | 8.0-40.0 | 2.5-8.4 | 11.7 | 3.0-10.8 | 2.8-14.0 |
| Hail at Gnd | - | Yes (2) | No | Yes (2) | Yes |

* Observed values are rate of rise of radar echo tops.

** Extreme centerline value predicted by one of the models.

Table 2

AUGUST 17, 1973 - CLOUD MODEL RESULTS

| | (3) | (4) | (2) | (3) | Observations | |
|---|---|---|---|---|---|---|
| | | | 2D,TD | 2D,TD | Single | Cloud |
| | ID,SS | ID,TD | SLAB | Axi | cloud | complex |
| Radium (km) | 2.0 | 2.0 | 1.0-2.0 | 1.5-2.5 | 1.2 | 2.0 |
| Cld Top (km) | 6.1-10.2 | 5.7-9.8 | 7.0-7.5 | 4.5-5.6 | 5.0 | 7.5 |
| Cld Base (km) | 1.2-1.5 | 1.0-1.4 | 1.0-1.2 | 1.0-1.3 | 1.4 | 1.4 |
| Max W ($ms^{-1}$) | 9.2-16.5 | 11.4-21.5 | 6.1-13.8 | 8.0-13.2 | - | 12.0 |
| Max RR (mm $hr^{-1}$) | - | 36.4-78.0 | 16.0 | 0.4-18.0<br>(215.0) | 6.6 | 18.0 |
| Total Rain (mm) | 4.0-22.6 | 1.6-9.5 | 2.0 | 2.9-5.0 | 0.6 | 7.4 |
| Hail at Gnd | - | Yes (1) | No | No | No | No |
| Proper Tendency 10 to 17 Aug | Yes (4) | Yes (1)<br>Partly (2) | Yes (2) | Yes (3) | | |

## MODEL EXPERIMENTS ON HAIL SUPPRESSION AND RAIN AUGMENTATION

### Nelson's Results

A detailed microphysical cold-cumulus model has been developed in-house at the Bureau of Reclamation by Loren D. Nelson (1976) to provide a quantitative framework for the testing of hypotheses concerning the effects of AgI and hygroscopic seeding on the rainfall and hailfall from ice and hail-bearing summer convective storms.

In an effort to assess possible differences in cloud type and their response to seeding among the various weather modification projects in progress today, test soundings were selected from the HIPLEX and National Hail Research Experiment (NHRE) programs in the U.S.A., the Soviet Union hail suppression program near Labinsk, and the South African hail suppression program at Nelspruit.

Model computations were made for both "natural" clouds and clouds seeded with 10 kg of silver iodide (1,600 nuclei per liter at -10°C) simulating the dropping of pyrotechnic flares from an aircraft into the top of the cloud. Some of the results are summarized in Table 3.

Early results from the model indicate that there are two major competing processes by which the model convective storms generate hailstone embryos: the freezing of large supercooled water drops to form frozen-drop hailstone embryos, and the generation of small ice crystals which then rime with supercooled liquid water to form graupel hailstone embryos.

The frozen-drop mechanism dominates in warm-cloud-base storms that generate significant numbers of millimeter-sized supercooled drops by the coalescence mechamism, while in colder-cloud-base storms where the coalescence growth of liquid drops is inefficient, the dominant hail embryo generation mechanism is in the growth of small ice crystals, some of which ultimately become large enough to serve as efficient hail embryos. Cold-cloud-base, graupel-embryo hailstorms seem to be the climatologically favored type in the high plains of the central U.S.A., while warm-cloud-base, frozen-drop-embryostorms are common in the region of the Soviet Union hail suppression program near Labinsk, U.S.S.R.

It appears, though, that there are clouds in which neither of the hail-embryo generation mechanisms is clearly dominant and that these clouds can occur anywhere.

It can be seen from table 3 that clouds with different dominant hail-embryo generation mechanisms respond differently to the modeled AgI seeding. The model predicts that clouds in which the graupel-embryo mechanism is dominant result in hail and rain increases due to seeding. Clouds in which the frozen-drop-embryo mechanism is dominant result, on the other hand, in hail and rain decreases when seeded. Marginal but generally coupled effects result when those clouds without a clearly dominant hail-embryo generation mechanism are seeded. The response of these clouds to seeding is probably more sensitive to the rate, timing, and location of the seeding and perhaps how the seeding is simulated in the model.

Model sensitivity studies and further analysis of embryo generation and growth zones are now being conducted by Nelson. At this stage in the continuing model development, attention is drawn only to the preliminary indications that hail suppression seeding technology may not be directly transferable from warm-cloud-base, frozen-drop-embryo storms to hailstorms of the cold-cloud-base, graupel-hail-embryo type. It is likely that partitioning of experimental hail suppression seeding results by cloud base temperature may be a realistic and physically based way to reduce variance in the observed effects of AgI hail suppression seeding. In many of the test cases presented, hailfall and rainfall are positively coupled, and thus beneficial hail decreases could be offset by deleterious rainfall decreases. Nelson is pursuing further studies to assess the physical reasons for this effect in the modeled clouds.

## Orville's Results

Numerical experiments on the effect of AgI seeding on rainfall and hailfall have also been conducted by Orville (1975). A two-dimensional, time-dependent model with parameterized microphysics was the vehicle for these computations. Light, moderate, and heavy seeding with AgI-$NH_4$I-Acetone generators at cloud base was simulated, which corresponds to 16, 160, and 1,600 nuclei per liter at -10°C, respectively. The temperature at which cloud water was instantaneously converted to cloud ice was assumed to be -35°C for the natural and light and moderate seeding cases and -17°C for the heavy seeding case. Some of the results of these experiments are shown in table 4.

## Table 3

### RESULTS OF NELSON'S (1976) MODEL SEEDING EXPERIMENTS

| Sounding | Labinsk, USSR, 29 June 72 | Labinsk, USSR, 10 Aug 72 | Sterling, Colo., USA, 9 July 73 | St. Louis, Mo., USA, 10 Aug 73 | Miles Ct., Mont., USA 28 July 75 | Nelspruit So. Africa 10 Nov 73 |
|---|---|---|---|---|---|---|
| Cloud base temp. (°C) | 14.8 | 10.6 | 6.1 | 17.8 | -0.8 | 11.7 |
| Cloud depth (km) | 9.0 | 8.7 | 8.5 | 8.4 | 8.1 | 10.7 |
| Dominant hail embryo | frozen drops | mixed | graupel | frozen drops | graupel | mixed |
| Total hail-fall (mm) | 2.4 | 3.0 | 0.4 | 1.17 | 0.5 | 1.2 |
| Total rain-fall (mm) | 4.2 | 8.8 | 1.74 | 8.3 | 2.1 | 0.5 |
| Response to 10 kg AgI seeding (%) | | | | | | |
| Rainfall | +2 | +1 | +16 | -20 | +12 | +4 |
| Hailfall | +1 | -4 | +46 | -15 | +32 | +3 |

Table 4

RESULTS OF ORVILLE'S (1975) MODEL SEEDING EXPERIMENTS

| | Percent change in precipitation | | |
|---|---|---|---|
| | Rain | Hail | Total |
| **Case 1** | | | |
| 10-km cloud top | | | |
| Light AgI | +19.1 | +8.0 | +17.8 |
| Moderate AgI | +55.0 | +116.0 | +60.5 |
| Heavy AgI | +18.3 | +56.0 | +21.7 |
| **Case 2** | | | |
| 13-km cloud top | | | |
| Light AgI | -0.6 | +5.0 | +0.7 |
| Moderate AgI | +20.2 | +45.0 | +25.5 |
| Heavy AgI | -32.7 | -20.0 | -30.0 |
| **Case 3** | | | |
| 16-km cloud top | | | |
| Light AgI | +4.5 | 0.0 | +4.5 |
| Moderate AgI | +7.6 | 0.0 | +7.6 |

It can be seen from table 4 that light seeding increases the total precipitation from the model cloud, moderate seeding increases it still further, and heavy seeding, on the other hand, produces either smaller increases or decreases in the total precipitation. The results also suggest that the AgI seeding effects are larger for moderate-size clouds than for large clouds.

In view of the differences in model type, techniques in simulating the relevant physical processes, and assumed seeding modes, it is difficult to compare Orville's results with those of Nelson. There is, however, general agreement that modifications to the hail and rain are positively coupled in all cases of above-marginal seeding effect.

## CONCLUSIONS

It has been suggested that the cloud simulation ability of models is primarily limited by the size and speed of existing computer facilities. It is felt that the next generation computer will make it economical to eliminate some of the parameterizations, to model the three-dimensional features of cloud systems, and to develop and use more exact numerical techniques for solving the nonlinear partial differential equations. This will undoubtedly be beneficial but will be a sterile exercise if it is not accompanied by a similar advance in our observational capability. It is the responsibility of modelers to produce models with assumptions and predictions that are verifiable with observations. Observationalists should, on the other hand, make the necessary measurements, even if it means developing new instruments to measure parameters that models indicate are highly significant. Models currently in hand embody much physical understanding which has not yet been adequately tested by observation. Progress will proceed most rapidly by providing the observational basis for these models. Knowledge thereby gained can then serve as a guide to more sophisticated modeling, observation, and experimentation.

In conclusion, I come back to the question in the assigned title, "Models in Weather Modification - Solution or Confusion?" My unequivocal answer as this paper has tried to indicate is Solution.

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