"REVIEWED"

THE USES OF CLOUD MODELS IN WEATHER MODIFICATION

Harold D. Orville[1]
Institute of Atmospheric Sciences
South Dakota School of Mines and Technology
501 E. St. Joseph Street
Rapid City, South Dakota 57701-3995

Abstract. This paper updates a report to the World Meteorological Organization (WMO) in 1981 made by a "panel of experts" in cloud modeling, chaired by the author. The primary uses of cloud models are reviewed and two tables constructed, one which details the types and uses of cloud models in weather modification and references to the models, and a second table describing the computational tasks involved in running the models. Some outstanding problems are mentioned and reasons given for hope regarding the numerical simulations of cloud seeding effects.

1. INTRODUCTION

Cloud models have been used in weather modification research for over 20 years, with more promise than performance -- but perhaps more has been expected of them than possible. Recent developments concerning new observing equipment and faster, larger computers give hope that the model predictions can be checked in well-designed field experiments. For example, multiparameter radars and specially instrumented aircraft provide the capability to measure the initiation, development, and dissipation of both liquid and ice precipitation in convective and stratiform clouds. More significant to cloud modification scientists is that this precipitation development can now be followed in both seeded and unseeded clouds and simulated numerically. Cloud physicists have powerful new means to test theories of precipitation development and modification.

The purpose of this paper is to review the various types of cloud models and their application to cloud modification problems. I use as the basis of the review, a report prepared for the World Meteorological Organization (WMO) in 1981 by a panel of experts in cloud modeling (WMO, 1981). An update of portions of that report are given below, in particular, revised tables of cloud model applications and computer resources required, and appropriate references to papers published since 1981 regarding cloud modeling applications to cloud modification. Unfortunately, this update of references applies to the western literature. Articles from the Soviet, Yugoslavia, Chinese, and other scientific journals would have increased the number of articles and representativeness of the list.

2. THE PRIMARY USES OF CLOUD MODELS

The 1981 report outlines several uses of cloud models in weather modification research and operations. The first, hypothesis development, has been an important use of cloud models for many years. The dynamic stimulation of clouds by cloud seeding was first observed in the 1940's (Kraus and Squires, 1947) and later capitalized on by Joanne Simpson. A one-dimensional, steady-state cloud model was an important part of the project development. More recently, multidimensional, time-dependent models are providing results that aid in hypothesis development.

The second use, the assessment of cloud seeding potential, relates to the evaluation of the "seedability" of a given cloud or cloud type or collection of clouds in a geographical region. Large numbers of soundings can be evaluated in the simpler models for such characteristics as enhanced cloud growth after seeding with ice nucleants. Fewer cases, but more complex interactions of the cloud microphysics and dynamics after cloud seeding, can be tested in the fully interacting multidimensional cloud models.

The development of these more sophisticated models allows quantitative estimates to be made of the effects of seeding and the conditions that optimize the treatment. For example, questions as to seeding location, seeding time, and seeding amount can be answered through a series of modeling calculations. The results may then impact on the design of a field experiment, a third use of cloud models.

The increase of computer resources and power has made it possible to apply a greater variety of models to operational projects, although this capability has not been utilized much. Again, the one-dimensional models have been utilized most often for this task, a fourth use of cloud models.

Finally, cloud models have often been used to help evaluate field experiments. Important effects, such as enhanced cloud growth or time of first echo can be predicted by the models and used in the statistical analyses. Also, categories of days can be established by the predicted reaction of the clouds to modification, thus helping to stratify the data for analysis purposes.

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3. TABLE OF CLOUD MODEL USES

Several characteristics of cloud models, as applied in cloud modification research and operations, have been summarized in the two tables included in this review. A brief discussion of the various models and their characteristics is included here.

Many types of cloud models have been developed. In 1981, the models were classified as zero, one, two, or three-dimensional, steady-state or time-dependent, coupled or uncoupled, and finally as treating bulk water microphysics or more detailed microphysics. The zero-dimensional models are essentially parcel models or those models that treat a group of particles or, in some cases, single particles.

Coupled and uncoupled models refer to the degree of interaction between the microphysics and dynamics of the cloud and the environment (if included in the model). Steady-state airflow assumptions preclude microphysics/dynamics interactions and are hence used in models that are classified as uncoupled. Multidimensional models which solve nonlinear thermodynamic, dynamic, microphysical, and electrical equations are normally fully coupled models. A change in one dependent variable due to cloud seeding can affect every other dependent variable.

The bulk water or detailed microphysics terminology alludes to the degree of complexity of the simulated cloud microphysics. The detailed microphysical models normally treat a number of categories for the condensate fields and, as part of the solution, solve for the evolution of the size distribution of the particles. As many as 50 or more equations may be needed to represent the precipitation and cloud particles. In contrast to this, the bulk water microphysical models assume a size distribution for the particles and require only one equation for each type of precipitation (rain, snow, graupel/hail). Consequently, these simpler microphysical models take only a fraction of the computer time required for the more detailed microphysical models.

The models depicted in Tables 1 and 2 are categorized as to the type of cloud seeding effects to be expected -- precipitation initiation, precipitation change and the amount, precipitation redistribution, hailstone size and impact energy change, fog visibility change, and

TABLE 1

Uses of Models in Cloud Modification

Models	A1	A2	A3	A4	A5	A6	A7	B	C	References	Remarks
0D - closed parcel	X	-	-	-	-	-	-	-	-	6, 19, 20, 21, 25, 26, 27, 40, 42, 44	
1DS - uncoupled (kinematic)	X	-	-	-	-	-	-	-	-	24, 33, 49	
1DS - coupled	X	X	0	-	-	-	-	X	X	2, 3, 16, 23, 32, 43, 46, 47	
1DT - coupled	X	X	0	-	X	-	-	X	-	8, 10, 15, 34	
2DS - uncoupled (kinematic)	X	X	X	X	-	-	-	-	-	5, 17, 41, 48	Snow models
2DT - coupled	X	X	X	X	X	X	X	X	X	1, 7, 9, 14, 18, 22, 28, 29, 30, 36, 37, 38, 39, 45	Cloud interactions part of solution. Potential for C limited by computer resources.
3DT - coupled	X	X	X	X	-	-	-	-	-	4, 31	
3DT - mesoscale	-	X	X	X	-	-	-	X	X	11, 12, 13, 35	Ref. (13) has no explicit clouds.

A1 - Precipitation initiation in cloud
A2 - Sign of the change (plus or minus seeding effect)
A3 - Amount of precipitation
A4 - Location of precipiation
A5 - Hailstone size and associated parameters

A6 - Fog dissipation
A7 - Lightning frequency
B - Operational use
C - Evaluation, covariates, etc.
0 - Needs other related measurement to make quantitative estimate

TABLE 2

Computational Task (CDC 6600)

	Model	Grid Points	Peripheral or Core Storage	Computer Time 1 Cloud Case CDC 6600*	Real Time Simulation
0D		1	10^3	10 seconds	
1DS		10^2	10^4	10 seconds	
1DT	Bulk+	10^2	$10^3 - 10^4$	6×10^2 to 10 min 6×10^3 seconds 100 min	60 min 120 min
	Warm cloud (detailed)**	10^2	10^5	2×10^3 seconds	60 min
2DT	Axisymmetric or Slab-symmetric (single cell)	10^4	$10^5 - 10^6$	10^3 to 10^4 seconds (0.25 to 3 h)	60 min
	Slab-symmetric (multicell)	10^4	$10^5 - 10^6$	10^4 to 10^5 seconds (3 to 30 h)	180 min
3DT	Bulk	10^5	$10^6 - 10^7$	10^5 to 10^6 seconds (30 to 300 h)	60 min
3DT	Mesoscale	10^5	10^6-10^7	10^4 to 10^6 seconds (3 to 300 h)	Several hours

* Divide by 30 for CRAY-1 times or 100 for CRAY X-MP machines.
\+ "Bulk" refers to bulk water microphysics.
** "Detailed" refers to simulations of the evolution of the particle spectra. In general, models with detailed microphysics will take several times longer to solve than the bulk water models of the same dimension, depending on the number of size categories.

lightning frequency change. Most of these seeding effects are tested in convective-type clouds, but a few models also treat stratiform clouds and fog.

Finally, in Table 1 various auxiliary uses are noted for the models, such as their operation status, and the use of models to provide covariates for statistical evaluation purposes.

Table 1 then summarizes the uses of cloud models in cloud modification, updated from the 1981 report.[2] Nearly all the models have been used for precipitation initiation studies, very few for operations or evaluation of field projects or for predictions of hailstone size distribution changes. As indicated in the table, the amount of precipitation predicted by the one-dimensional models is more worthwhile and dependable if a study has been made of cloud top versus rainfall and used in the quantitative estimates of precipitation. Several references have been added to this table.

Table 2 gives some estimates of the computational resources that are needed by the various models, in terms of a Control Data Corporation 6600. These numbers should be divided by 30 or 100 for the equivalent time needed on a CRAY-1 or CRAY X-MP machine, respectively.

4. SOME OUTSTANDING PROBLEMS

One of the biggest problems is attracting more young scientists to the problems of cloud modification and cloud modeling. This should occur as the models improve and the results indicate new and effective ways of modifying clouds.

Various needed developments of the models were indicated in the 1981 report and some are still pertinent. More effort needs to be applied towards the simulation of cloud seeding effects in warm rain models. More than likely this will involve the development and use of detailed microphysical cloud models in cloud seeding modes.

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[2] The updates to this table have been made by the author and are not necessarily the views of the original panel.

The cold rain models would be more effective if the rain simulations were improved in the bulk water microphysics and the ice parameterizations were also improved. Priority items for better parameterizations are ice initiation, cloud ice to snow transformations, aggregation, and snow to graupel transformations. Cloud seeding simulations of silver iodide in Eulerian type models also require some development.

The modeling of hailstorms and hailstone evolution is developing effectively in two-dimensional and three-dimensional cloud models, but is stretching the capacity of even the largest, fastest supercomputers. The complexity of hailstone growth involves variable density hailstone, variable shapes, and complex terminal velocities, among other things. The use of hybrid microphysical models for hailstorms needs assessment. It is necessary for cloud seeding simulations of hailstorms to treat the evolution of the hailstone size distribution, because a change in the distribution is one of the desired outcomes of the seeding.

Of course, improvement of numerical techniques is always desirable. Significant improvements have been made in the treatment of particle category simulations so that "numerical spreading" of particles into neighboring particle categories is eliminated. This work is largely due to Peter Smolarkiewicz at NCAR and applied by Richard Farley and students at SDSM&T to the hail problem. Modeling techniques to improve scale interactions and the treatment of open boundary conditions are also advancing. Lastly, turbulent mixing, entrainment calculations, and lightning discharge simulations are receiving attention of the modelers.

All of these model developments require good data sets to assess the quality of the model results. Of particular importance to the modelers is to have data sets available to them of both unseeded and seeded storms. With the dropoff of field experiments in cloud modification in the United States, very few opportunities exist to obtain seeded storm observations.

A big impetus to the comparison of cloud models with high quality data sets has been the sponsorship of international cloud modeling workshops by the World Meteorological Organization. Very successful meetings were held in 1985 in Irsee, FRG, and in 1988 in Toulouse, France. Good interactions between the modelers and observationalists have occurred in these meetings.

5. SIGNS OF HOPE

The literature is beginning to show examples of very good comparisons of cloud modeling results with observations of clouds involving ice microphysical processes. These results involve the interactions of microphysical and dynamical processes. In some cases, they show the strong compensating effects of changes that occur when one microphysical process is affected by seeding or by ice multiplication. In other cases, they show realistic development of ice precipitation and hail and the associated cloud circulations. Realistic cloud seeding simulations are involved in some of the studies. Cloud physicists are becoming more aware of the effects of ice processes in hurricanes and mesoscale convective systems and the development of lightning. The cloud modelers are more cognizant of the importance of aggregation and graupel to the precipitation processes.

Most of these effects have been described in observations, simpler cloud and precipitation models, and one or two-dimensional, time-dependent cloud models. However, three-dimensional cloud models with many precipitation ice processes are coming on line and should lead to many more exciting results involving storm development, particularly in association with the new radar and aircraft observations now available which are focused on ice processes.

Another important modeling development is the greater advancement and use of mesoscale models. This should allow the effects of cloud seeding on the cloud scale to be more readily incorporated into mesoscale models. Several questions were posed in the 1981 report regarding area-wide effects and are still pertinent.

1) How would the distribution of precipitation over an area be altered by cloud seeding?

2) Can seeding of individual clouds within a cloud group lead to a more favorable environment through the redistribution of heat, moisture, and momentum to facilitate the development of successive generations of clouds?

3) Can seeding of individual clouds within a cloud field result in suppression of neighboring clouds or in the creation of new or bigger and longer-lasting clouds through the processes of downdraft interaction or cloud merging?

4) What is the mode and mechanism of interaction between a seeded cloud field and the mesoscale environment?

Posing these questions emphasizes the importance of modeling to the weather modification problem. It seems unlikely that observations could, by themselves, sort out the many complexities and effects of cloud seeding on the mesoscale precipitation patterns and amounts. Consequently, it will take strong efforts in modeling on the cloud and mesoscale to identify the signals to look for in the observations. Neither models nor observations can be expected to solve the problems; used in concert, they may bring success to a field that has suffered much from declining support, but which holds so much promise for the present and future water problems of the world.

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