weather modification and three-dimensional mesoscale models

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Abstract

The application of three-dimensional time-dependent models to weather modification experiments along with the ways in which mesoscale simulations may be used as an aid in clarifying and formulating the physical basis of a weather modification hypothesis is discussed. It is furthermore pointed out that such models can be an aid in the design of field experiments, in the evaluation of field experiments, and in decision making during the daily operations of the experiment. Not only does the challenge of weather modification require considerable advancement in our understanding of the complex physics and dynamics of mesoscale processes, but it is also essential that we develop parameterizations of these processes in order for a mesoscale model to be of value in the post hoc analyses of weather modification experiments and as a decision aid.

1. Introduction

Although most techniques and basic concepts of weather modification are associated with small-scale (individual cumuli) and microphysical-scale processes, an appreciation of mesoscale (horizontal scales from 10 to 150 km) phenomena is essential to the proper design of field experiments, for the efficient operation of these experiments, and to avoid false interpretation of field experimental data. In addition, at the National Hurricane and Experimental Meteorology Laboratory of NOAA,[1] field experiments are presently being extended toward actual modification of mesoscale structure (Simpson and Woodley, 1971), thus introducing the need to further understanding of the complex interactions between mesoscale and local cloud-scale phenomena. The importance of mesoscale processes to the modification of orographic clouds and lake-effect storms is most obvious since the clouds themselves are directly formed as a result of mesoscale meteorological processes. Less obvious, perhaps, is the importance of mesoscale processes to the modification of cumulus clouds and moist convective-scale systems. Malkus and Riehl (1964), Matsumoto *et al.* (1967), Chang and Orville (1973), Pielke (1974), Cho and Ogura (1974), and Uccellini (1975) have all shown that mesoscale processes play an important role in determining the intensity and organization of cumulus convection. It is also apparent that the intensity and structure of mesoscale systems are quite dependent upon the structure of synoptic-scale meteorological systems.

The purpose of this paper is to illustrate how three-dimensional time-dependent mesoscale models employing current numerical prediction techniques can be of value in furthering our understanding of the complex physics and dynamics of the meteorological systems we wish to modify as well as an aid in the design, analysis, and day-to-day decision making of actual weather modification field experiments and operations.

2. Mesoscale models as an aid in clarifying and formulating the physical basis of a modification hypothesis

Because the foundation of most weather modification hypotheses involves the alteration of the microstructure of a cloud, the physics and dynamics of associated mesoscale meteorological systems are often viewed as external to the basic physical hypothesis rather than an integral part of it. One of the obvious uses of a mesoscale prediction, however, is to improve one's skill in specifying or predicting the rate of production of condensate. Since any precipitation process, whether natural or modified, is directly dependent upon the rate of production of condensate, any improvement in skill in predicting such a process will increase the likelihood of a positive outcome of the experiment.

Perhaps the best example of cloud formation directly by mesoscale circulations is orographically induced clouds. The weather modification experiments in Climax, Colo. (Grant, *et al.*, 1971), Elk Mountain, Wyo. (Veal *et al.*, 1971), and the Cascade Mountains, Wash. (Hobbs *et al.*, 1973), are excellent examples of experiments based on a microphysical concept of modification where the application is highly dependent on the nature of the mesoscale circulation. In fact, each of these experiments has utilized either laboratory models (Cermak *et al.*, 1970), or analytic models (Fraser *et al.*, 1973), or simplified numerical models (Veal *et al.*, 1971) to study the structure of its respective mesoscale circulation. These simulations, however, lack the ability to represent the full three-dimensional time-dependent character of mesoscale systems.

The main advantage of a three-dimensional time-dependent numerical prediction model, then, is that it

[1] Formerly the Experimental Meteorology Laboratory (EML).

can simulate the horizontal variability in production rate of condensate due to variability in terrain as well as the development of transient disturbances due to local forcing and its nonlinear interaction with the synoptic-scale flow.

Another problem in seeding orographic clouds is that the plume of seeded crystals is highly variable. In fact, Grant *et al.* (1971) have found that the seeded plume appears to have moved out of the target area under certain wind regimes. Here again, a three-dimensional mesoscale numerical prediction model could further aid the experimentalist by improving the stratification of the data, by optimizing the location of seeding site, and by determining to what extent transient mesoscale disturbances could have contributed to the observed plume behavior.

Weather modification experiments are often performed in regions where mesoscale circulations are induced by land-sea or lake-land thermal contrasts. One such experiment is the Great Lakes Project summarized by Weickmann *et al.* (1970). The basic hypothesis behind the experiment is that by artificially increasing the snow crystal concentration through seeding, precipitation from "steady-state" lake-effect storms can be redistributed downwind of the lake as a consequence of creating more precipitation particles having a lower terminal velocity. During the course of the experiment it became obvious that a more quantitative model of the mesoscale circulation of lake-influenced storms was essential to the design of an experiment to test the hypothesis. To meet this objective, Lavoie (1972) developed a highly simplified, yet very informative, three-dimensional model of the mesoscale circulation over Lake Erie. The results of numerical experiments with the model aided in the design of the actual field experiments by showing that the morphology of lake-effect storms is strongly influenced by horizontal asymmetries and that the location and intensity of convective cloud activity and subsequent precipitation are controlled by the mesoscale disturbance. Magaziner (1973) extended the Lavoie model by introducing microphysical models simulating crystal growth by vapor deposition and accretion of cloud droplets. Numerical experiments with the model supported the original qualitative hypothesis by illustrating that optimum strategies can shift the characteristic localized snowfalls to areas where their effect will be less damaging.

A number of researchers have proposed weather modification hypotheses that involve direct modification of a given mesoscale circulation. The value of a three-dimensional time-dependent mesoscale model for clarifying the physical basis of such hypotheses is most apparent.

It was suggested by Black (1963) that black non-reflective petroleum coatings produce surface temperature changes that might be large enough to initiate convective rainfall if applied to sufficiently large areas. Black *et al.* (1971) later discussed the simulation of such a surface modification with a three-dimensional steady-state model covering a domain of 19.5 km $\times$ 20 km $\times$ 4 km. Because the best locations for such an experiment are in arid regions near lakes or seas where moisture sources are available, it is important that one determine the organization of the mesoscale circulation in the region of interest as a function of location, synoptic wind direction and intensity, and time of day. The importance of mesoscale circulations on the supply of moisture to the asphalt strip modification area can best be investigated with a three-dimensional time-dependent mesoscale model.

Recently, Gray *et al.* (1976) suggested that solar energy absorption by carbon dust introduced in the atmospheric boundary layer can destabilize the atmospheric boundary layer sufficiently to directly enhance mesoscale convergence. It is then hypothesized that the enhanced mesoscale convergence will lead to the formation of clouds and subsequently enhance precipitation. There is little question that a three-dimensional mesoscale model would be an invaluable tool for the quantitative analysis of the hypothesis.

Because the results of single cloud-seeding experiments by Simpson and Woodley (1971) demonstrated that the largest precipitation yields from seeded cumuli followed the merger of the seeded tower with neighboring cumuli, they hypothesized that significant increases in precipitation can be produced by inducing cloud merger by dynamic seeding of "neighboring" cumuli. As a consequence of extending the modification hypothesis from a single cloud problem to a multiple cloud, small mesoscale problem, the question of the nature and role of the mesoscale circulations in organizing convection over south Florida has become crucial.

Pielke (1974) developed a three-dimensional mesoscale model in an attempt to explain the patterning of showers over the region as a function of the sea breeze convergence zones.

As a result of a number of experiments using this model, several important conclusions have been reached. First, on synoptically undisturbed days with a small temporal and spatial variation of the synoptic wind across south Florida, and with little synoptic wind shear with height, the dry sea breeze plays a dominant role in determining the locations of cumulonimbus activity. An example of this is presented in Fig. 1 in which radar echo patterns as depicted by the Miami WSR-57 radar on a day with the geostrophic wind from the east-southeast are compared with a model experiment using synoptic data for that day as initial input. The agreement between the observation and the model predictions illustrates that the dry sea breeze exerts a strong influence on cumulonimbus organization over south Florida on disturbed days.

Second, in response to the sea breeze circulations, there are substantial alterations of the thermodynamic field from the synoptic state. Using the one-dimensional time-dependent cumulus model discussed by Cotton (1975), Cotton *et al.* (1976) found that the pressure, temperature, and moisture fields perturbed by the sea

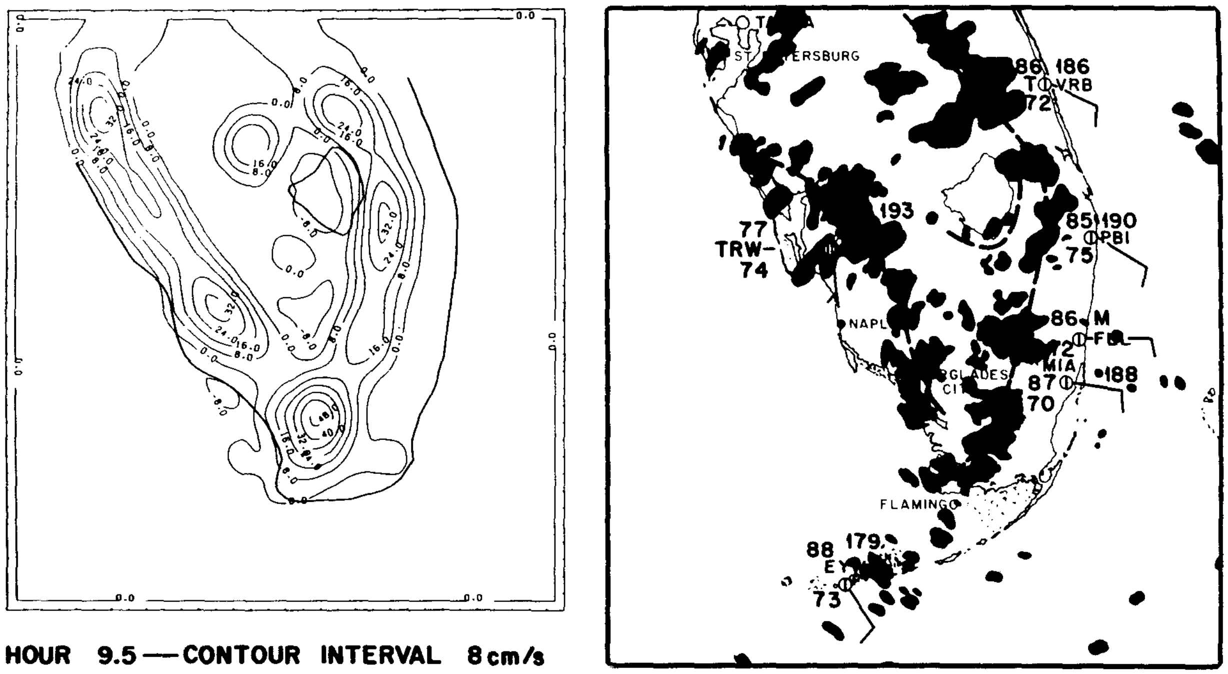

FIG. 1. (Left) Predicted vertical velocity at 1.22 km, 9.5 h after sunrise on 29 June 1971, geostrophic wind 2.5 m/s from 110°. (Right) Shower location as seen by the Miami WSR-57 10 cm radar, at 1449 EST, 9.5 h after sunrise on 29 June 1971.

breeze (as illustrated in Fig. 2) led to significantly deeper, longer-lifetime precipitating clouds than did the unperturbed environment.

In addition to the thermodynamic perturbations to the synoptic environment discussed above, the sea breeze: 1) alters the surface fluxes of momentum, heat, and moisture and the depth of the planetary boundary layer; 2) changes the vertical shear of the horizontal wind in the lower levels of the atmosphere; and 3) develops intense, horizontal convergence regions of heat, moisture, and momentum.

It is expected that these modifications to the synoptic environment can have a significant impact upon the rate and intensity of convective cloud merger. A preliminary analysis of the relationship between the positions of observed cloud merger and the position of pre-

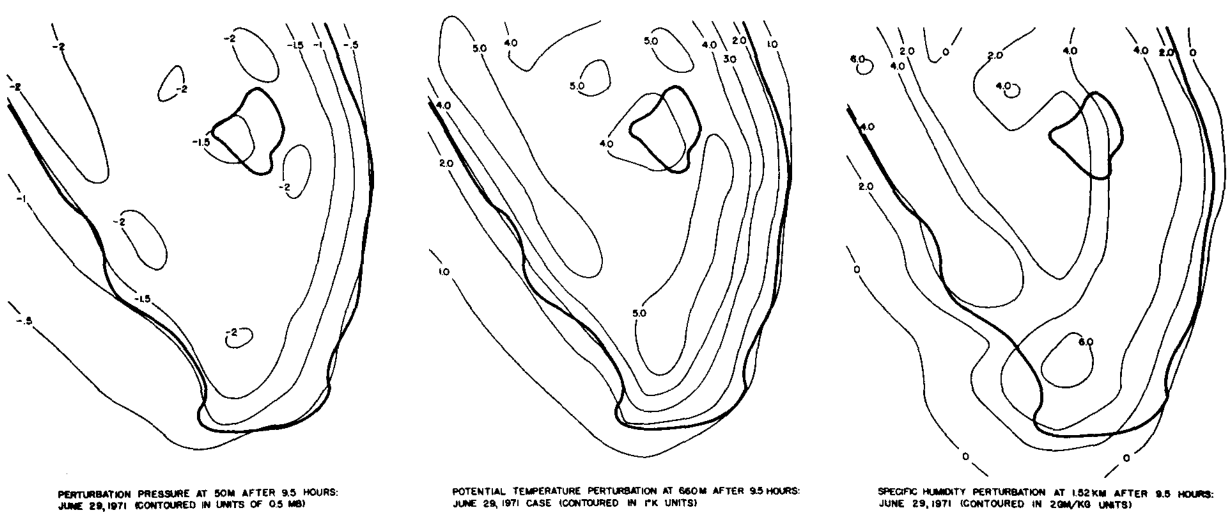

FIG. 2. Predicted sea breeze perturbation pressure, potential temperature, and specific humidity fields 9.5 h after sunrise on 29 June 1971.

dicted intense regions of moisture convergence over south Florida (Simpson and Westcott [2]) suggests that the predicted regions of maximum convergence are indeed quite favorable for cloud merger. Thus it can be concluded that a three-dimensional mesoscale model capable of simulating the complex, nonlinear patterns of the atmosphere at that scale is required to aid in the complete understanding of the basic physics of the modification hypothesis.

Not only are numerical models useful for clarifying hypotheses, but also the insight gained from numerical experiments with them can aid in the formulation of a new hypothesis. Perhaps the best example of the use of a dynamic model to aid in the formulation of a modification hypothesis is the reformulation of the Project Stormfury [3] hurricane modification hypothesis as a result of the work of Rosenthal (1971) and Hawkins (1971). On the basis of calculations with a two-dimensional axisymmetric hurricane model, Rosenthal (1971) concluded that seeding of hurricanes with silver iodide at radii greater than that at which the surface wind maximum occurs might be more effective in decreasing the surface wind maximum than seedings at or within the wind maximum. In a parallel paper, Hawkins (1971) added credibility to the Rosenthal numerical experiments by showing that there were many similarities between the observed structure of seeded Hurricane Debbie and Rosenthal's numerical simulation experiments. The suggestion that seedings at radii less than that of the surface wind maximum would produce temporary increases in the strength of the maximum wind was in direct contradiction to the original Stormfury modification hypothesis proposed by Simpson and Malkus (1964). As a consequence, Gentry and Hawkins (1971) modified the original Stormfury hypothesis by hypothesizing that a decrease in the surface wind maximum can best be achieved by seeding at radii greater than the surface wind maximum or in the region of the inner rainband of the storm. It is clear that our concepts of hurricane modification are still in a state of evolution and that a fully three-dimensional simulation of the effects of seeding major hurricanes may result in further modification of the Stormfury hypothesis.

A number of researchers have suggested that extended area effects may have occurred during intensive modification programs (Brier *et al.*, 1967, 1973, 1974; Janssen *et al.*, 1974). The hypotheses explaining these effects range from direct microphysical effects to mesoscale dynamic effects. A three-dimensional mesoscale model would be useful for elucidating the nature of transport and diffusion of both seeding material and ice crystals in the region surrounding the primary target area. In addition, a model that is capable of responding to the dynamic effects of seeding would be helpful in determining the likely downwind dynamic influences of seeding.

The development and application of three-dimensional mesoscale models to the formulation and clarification of weather modification hypotheses are limited only by the scientific insight and total computer resources available to the scientist. That is, a clever scientist may be able to gain physical insight into a problem by designing and performing a few well-chosen numerical experiments. In conjunction with these experiments, the scientist can make use of a large amount of the scientific information that is currently available to him or that can be developed by a parallel theoretical and experimental effort in order to develop weather modification hypotheses. In the model applications that we will discuss in subsequent sections, however, the number of necessary numerical experiments can be quite large; in addition, one is often bounded by severe time constraints associated with real-time decision making. Under such constraints, the models must be streamlined to only their essential physics and must be as economical and computationally fast as possible.

3. Mesoscale models as an aid in the design of field experiments

One of the values of a mesoscale model is that the prediction of the circulation and convergence patterns over a proposed experimental area under a variety of synoptic wind fields can bring to the attention of the experiment designers possible subtle orographic or topographic influences that may, due to their local persistence, have significant impact on the climatology of precipitation.

Suppose, for example, an experimenter attempts to test a weather modification hypothesis using a randomized cross-over design (Adderley and Twomey, 1958; Gabriel, 1966). The experimental areas are chosen for analysis in such a manner that one area is randomly selected as the seeding target, while the other acts as a control. If, when assessing two proposed target areas for the experiment, the experimenter had access to predictions of the boundary layer convergence fields over the proposed target areas under a variety of synoptic wind fields expected during the period of the experiment, he would be in a much better position to determine if the two targets were comparable. If he found that under a given synoptic wind direction, one experimental area has a more intense predicted mesoscale convergence field than the other, then by choosing such sites he would be running the risk that the "luck of the draw" may determine the outcome of the experiment instead of the hypothesis being tested.

A similar analysis can be performed on a single target area randomized on a daily basis such as the EML (Simpson *et al.*, 1973) multiple cumulus experiments in south Florida (Fig. 3). Boundary layer convergence patterns over a proposed experimental area appear to be a strong function of wind direction and of the orientation of the experimental area with respect to the immediate topography. For example, to illustrate the moisture convergence in the target area as a function of synoptic wind direction and speed, the flux of

[2] Personal communication.
[3] Project Stormfury is a NOAA-sponsored project.

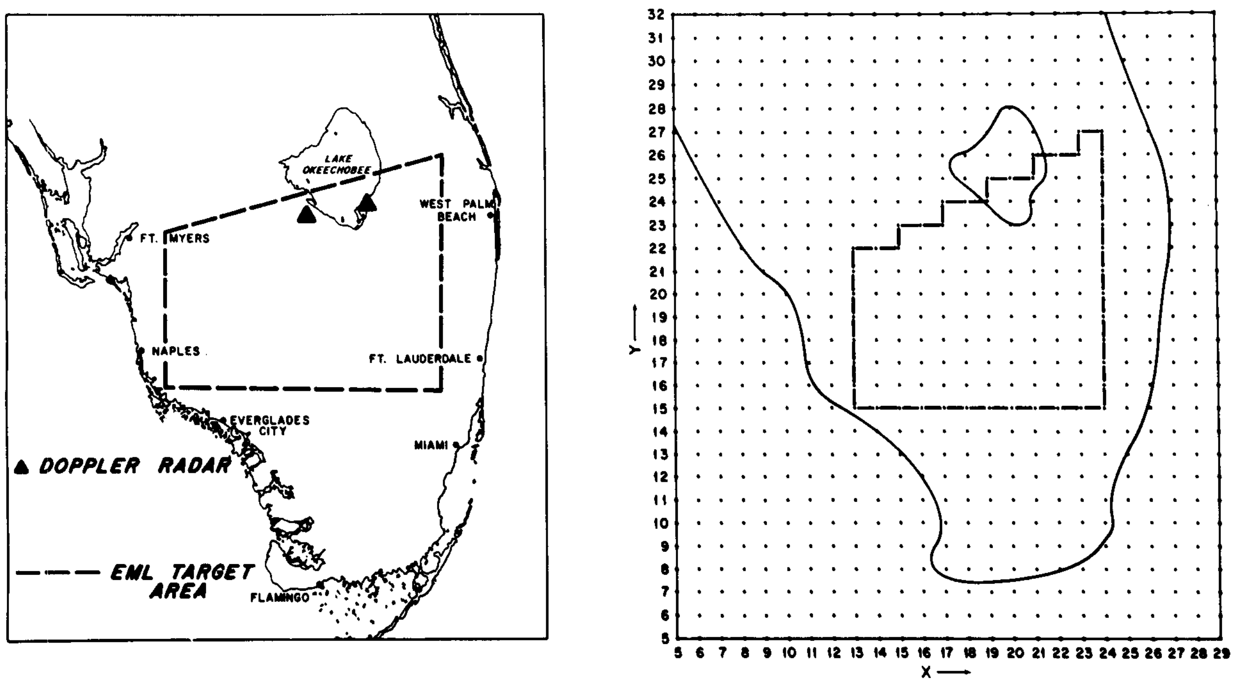

FIG. 3. (Left) Map of south Florida and outline of the EML experimental area (dashed line). (Right) Smoothed map of south Florida coastline used in the model and outline of target area used for theoretical analysis (dot-dashed line).

moisture through the Pielke (1974) model level at 1.22 km (which is near the typical cloud base height) was computed for a set of experiments in which only the large-scale wind was varied. As shown in Fig. 4, the model suggests that target area moisture convergence is strongly dependent on wind direction and speed. Although this result must be verified observationally, it suggests that in the EML target area, the total rainfall is a strong function of the prevailing flow. Thus, one must be concerned that the "luck of the draw" on seed versus no-seed days may determine the outcome of the experiment. All is not lost, however, since the model can serve as an aid in stratifying the data in the post analysis of the experiment.

4. Mesoscale models as an aid in the evaluation of field experiments

One of the biggest detriments to a weather modification experiment is the large natural variability of precipitation. Unless the modification effects are extremely large, they can easily be lost in the "noise" introduced in the data sample by the natural precipitation variability. Thus, the major use of mesoscale models in the evaluation of weather modification experiments would be to provide covariates and predictors to aid in the reduction of the natural variability. If, in the example cited in the previous section, it can be shown that wind speed and direction indeed do strongly influence total target precipitation, then this variable and, perhaps, the predicted total moisture convergence, can be used as a predictor in the statistical analysis of the data.

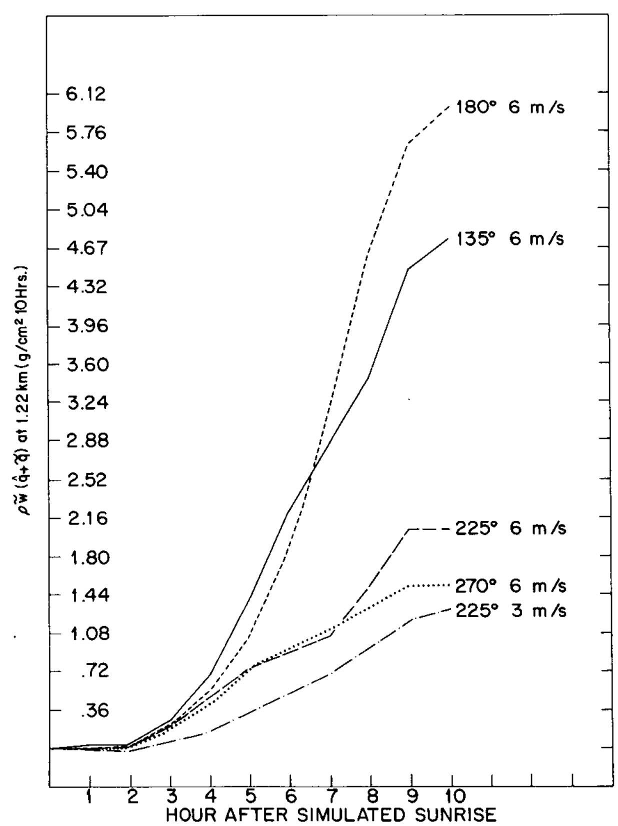

FIG. 4. Predicted target area moisture convergence as a function of time for a selected wind direction and wind speed of 180° at 6 m/s, 135° at 6 m/s, and 225° at 3 m/s.

Since no model at the present time on the mesoscale can simulate all the essential physics of importance to a weather modification experiment, it may be desirable to couple mesoscale model-predicted data with other predictors. In addition, although the use of a model for post hoc evaluation of a field experiment is not under the severe time constraints of a model used for routine decision making, models nonetheless must be sufficiently simple to be run in as little computer time as possible. Thus, since it may be cost prohibitive to use a model with the necessary level of physics, we again may require the coupling of model-predicted data with other predictors. Examples of other predictors include synoptic-scale analyses and predictions, simple cloud model predictions of cloud seedability (see, e.g., Simpson and Wiggert (1969, 1971); Cotton and Boulanger (1975a, b)), and special local observations such as soundings and mesoscale surface data. Fortunately, the time, cost, and forecast skill constraints placed on a model for post hoc analysis of a field experiment are not nearly as great as those placed on a model for routine forecasting and decision making.

5. Mesoscale models as an aid in decision making in weather modification experiments and operations

If we turn now to the use of three-dimensional mesoscale models as an aid in decision making, three factors must be considered: 1) Is the physical basis of present mesoscale models of sufficient quantitative accuracy to be of predictive value? 2) Can such models be employed as a predictive tool with present generation computer technology? 3) What is the cost-benefit ratio with such models? The answer to the first question depends largely on the user's needs. If the prediction of general regions of mesoscale convergence and crude wind trajectories is sufficient for the user, then the present level of physics appears to be adequate at least if the mesoscale boundary layer forcing is reasonably intense. As the user's requirements become more stringent, such as the prediction of cloud base height, preferred cloud scales, or mesoscale cloud condensation rates and precipitation rates, the present inadequacy of our quantitative physical understanding of the problem may limit the predictive value of the model.

The physical inadequacies of present generation models are most apparent under the presence of strong vertical shear of the horizontal wind in the basic flow. Pielke and Mahrer (1975) have shown, for example, that a planetary boundary layer that grows into an atmosphere with strong shear has somewhat different sea breeze convergence patterns than one that grows into an atmosphere with no synoptic shear. Under such conditions, realistic parameterizations of cumulus convective transport of horizontal momentum are inadequate, and even the parameterization of the convective transport of horizontal momentum in dry air may be inadequate. The model still may serve as a prediction aid to a clever forecaster. That is, the forecaster can subjectively couple the predicted mesoscale convergence field and available National Meteorological Center (NMC) synoptic-scale forecasts to obtain a hybrid local-scale forecast of precipitation patterns as a function of time of day. An alternate process might be the combination of model simulation and statistical methods. That is, one could build on the short-range forecasting techniques that have been developed by the Techniques Development Laboratory as reported by Klein (1970) and Glahn and Hollenbaugh (1969). One could thus match mesoscale layer model-predicted data with NMC operational synoptic-scale forecast data, simple one-dimensional cumulus model data, and observational data to compute regression equations. These equations could then serve as daily quantitative precipitation forecasts to be used for the decision-making process of a weather modification experiment. Of course, this technique requires the user to have access to NMC forecast data, good local observational data, and sufficient computer power and access rate to run a mesoscale model and regression equations.

The manner and sophistication with which the mesoscale model is used depend on the capabilities of present generation computers as well as available computer time. If one requires a model with detailed formulations of convective transport, precipitation physics, and radiation physics on a horizontal grid of from 1 km to 10 km resolution and 10 or more vertical levels, then present generation computers would not be able to make a forecast fast enough to make the product useful to a decision maker. On the other hand, if one chooses to use a simple mesoscale boundary layer model forecast that is then coupled to upper level forecast data by an experienced forecaster or by the use of statistical methods, then a 12 h forecast over a 9×10^4 km^2 horizontal domain with 10 km horizontal resolution can be made in 0.3–1.5 h of computation time with machines of the level of a CDC-7600 or IBM-360/195. In some regions of the country such as the south Florida experiments, the EML mesoscale model in its present form can be applied to synoptically undisturbed days by simply running a set (perhaps a dozen or more) of experiments for different wind directions and speeds and cataloging the results on film or magnetic tape for daily reference. The scientific user can then assess the probable locations and intensity of convection on a given day by referring to the appropriate cataloged forecast and then employing simplified cumulus-scale models to assess the thermodynamic potential of seeding as a function of the observed moisture and thermal stratification. Alternately, these cataloged forecasts could be combined with synoptic forecast data and observed data to form a statistical prediction of precipitation, wind speed, etc.

As was the case with questions 1 and 2 above, when we estimate the cost-benefit ratio of employing mesoscale models to a weather modification experiment or operation, we must specify the level of sophistication of the model one envisages using. Obviously, if one chooses to use a model with sophisticated precipitation physics, radiation physics, etc., the cost-benefit ratio would be prohibitively high. On the other hand, if one runs a conceptually simpler mesoscale boundary layer model that contains only weak explicit coupling with the upper troposphere and is then coupled subjectively by an experienced forecaster or by statistical techniques, then a 12 h forecast can be performed for a cost of about[4] \$625. If one were to use a set of cataloged mesoscale forecasts as input data, then the cost could be further reduced. A set of 24 wind speed and direction 12 h forecasts could be made for approximately \$15 000. The cost of these forecasts could then be amortized over the duration of the experiment or operation. In addition, a statistical forecast model that couples the synoptic forecast to the observed data and the cataloged mesoscale data could be run at a cost of approximately \$140/day.

The actual quantitative benefits of such a forecast capability to the decision maker are far more difficult to assess. The greatest benefits could be made from an aircraft-oriented experiment or operation. The availability of a high-resolution, short-range forecast can aid the decision maker both in the decision of whether or not to put the aircraft into operation on a given day and in the optimum positioning of the aircraft over the experimental area in both time and location.

One of the logistically difficult problems with cumulus modification is that, even in active regions of convection such as south Florida, only about 25% of a total target area may be covered with clouds of a seedable character at any given time. Thus, a great deal of aircraft time is employed in reconnoitering the area to locate potential "seedable" clouds. The efficiency of the experiments might be improved by concentrating the cloud seeding in that portion of the target area where the most active convection is predicted.

The availability of such a forecast would have two immediate benefits. First, by reducing the amount of wasted time involved in reconnoitering the area, the amount of total aircraft time could be decreased or the need for multiple aircraft might be reduced or eliminated. In the case of the EML Florida Area Cumulus Experiments (FACE), the operating cost for a C-130 aircraft is approximately \$1000/h. If the use of such a forecast could reduce the amount of aircraft time per experimental day by 30%, then based on an average of 20 experimental days per year and prorated over a three-year experiment, the amount of saving could approach \$120 000. If the model were run for a total of 94 potential experimental days per year at a cost of \$625/forecast for three years, the cost would be \$176 000. This would give a cost-benefit ratio of 1.47, which is rather high. If one used a set of cataloged forecasts at a cost of \$13 500, coupled with daily statistical forecasts at a cost of \$140/day, the total three-year cost would be \$52 980. This would give a much more favorable cost-benefit ratio of 0.44. A second benefit could be achieved if the need for a second aircraft in an experiment could be eliminated by the availability of a precision mesoscale forecast. In the case of the EML/FACE experiment, a second high-performance aircraft may be needed for a total of 57 days over a three-year period flown for an average of 5 h/day at a cost of \$550/h. The elimination of such an aircraft would save \$156 750. The combined savings by eliminating a second aircraft and a 30% saving in total aircraft time would be approximately \$276 750. The resultant cost-benefit ratio for daily running of the mesoscale model would then be 0.64, and with the use of catalogued forecasts, 0.19.

Finally, it has been our experience during the operation of the EML/FACE experiment that a number of days could not be rejected as no-qualify experimental days until an aircraft was actually employed for reconnoitering and once put in flight, flown for a minimum of 4 h as a requirement to burn off fuel. If we consider that the need for placing such an aircraft in flight for reconnoitering purposes could be eliminated by the availability of a precision forecast, this would result in a saving of approximately 18 flight days per year. Considering a cost of \$1000/h for 4 h/day over a three-year experiment, this would save approximately \$216 000. The cost-benefit ratio for a daily operation of a model for the period would be 0.81, and the use of cataloged forecasts, 0.25. Combining this with a potential 30% saving in aircraft time on qualify days gives us a potential saving of \$336 000 over a three-year period. This in turn, gives us a cost-benefit ratio of 0.52 for daily operation of a model, and 0.11 for the use of cataloged forecasts.

It is clear from the above that the high cost of daily operation of a mesoscale model can only be offset by major savings in aircraft time. Considering that the NOAA/C-130 aircraft operated by the EML is far more expensive than the aircraft employed by commercial cloud seeders or such experiments as the National Hail Research Experiment, the cost-benefit ratio of daily operation of a mesoscale model is presently rather high for general use. There is a far greater possibility that the use of a series of cataloged mesoscale forecasts in a given region coupled with synoptic forecast data, local observations, and multiple regression formulas will result in cost-benefit ratios that are sufficiently small to allow their general use in weather modification experiments.

Another major factor that should be considered in a cost-benefit ratio analysis of a model is related to the use of a model for the purpose of post hoc analysis of the weather modification experiment and clarification of the basic hypothesis. In the former case, should a model provide a useful covariant or predictor, the total data sample necessary for obtaining a statistically significant conclusion may be reduced. Thus, for example, a seven-year experiment may be reduced to five years at a saving in some experiments of from 2 to 4

[4] The cost is based on the ability of the Pielke mesoscale model to perform a 12 h integration in 15 min of CPU time on the National Center for Atmospheric Research CDC-7600 at an estimated cost of \$2500/h.

million dollars. Furthermore, it is entirely possible that the 'noise' level of the basic data is so large that a large positive effect will never be seen in the analysis unless strong covariants or predictors are introduced. In the latter case, the use of a model to clarify a hypothesis may illustrate that the hypothesis is quantitatively so weak (or is actually wrong) that a five- to seven-year field experiment is never carried out in the first place. The potential savings may be on the order of 10 million dollars. Likewise, a model may clarify a hypothesis to the extent that an experiment may be carried out more efficiently or a new hypothesis formulated that can have unmeasured economic and social value to mankind.

6. Summary

There is probably no better example of the need to develop mesoscale prediction capability than for the application to weather modification. Nearly every weather modification hypothesis seriously considered today is highly dependent on the state of the mesoscale system. It is the opinion of these authors that existing three-dimensional mesoscale models can be of value in clarifying and formulating the modification hypothesis as it applies to the atmospheric problem and as an aid (at least qualitatively) in the decision process involved in daily operation of the experiment. Moreover, such models may help in the evaluation of the impact of the weather modification program on the total environment.

Future improvements to the existing mesoscale models will provide an even better tool to aid in weather modification programs. These include: 1) an accurate parameterization of the influence of cumulus convection on the thermodynamic and dynamic structure of the mesoscale environments; 2) an adequate initialization of the mesoscale variables from observable data; 3) a consideration of radiative flux divergence; 4) an adequate planetary boundary layer parameterization over irregular terrain under nonsteady conditions; and 5) more accurate and economical solution techniques for the model equations.

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New sonde system enters test stage

A prototype of a new balloon-borne sounding system that uses Doppler techniques for balloon tracking was scheduled for flight testing this summer at Wallops Station, Va. The test is part of the SESAME (see p. 829) program to evaluate the Doppler system, which is designed to track balloons more accurately than conventional radiotheodolites and to provide automatic data processing in a one-person operation.

The need for a network of at least 20 wind-finding sonde systems was identified early in SESAME planning; after studying technical requirements, NOAA chose a Doppler tracking system as the most promising option.

Control Data Corporation is developing the ground-tracking and data-handling system under contract to NOAA; partial contract funding is supplied by NCAR and the Bureau of Reclamation. Michael Exner of NCAR's Global Atmospheric Measurements Program is assisting SESAME planners in specifying technical requirements.

The test will compare the system's wind measurements with wind data derived from accurate radar tracking of the balloons. A computer terminal at Wallops will communicate with a 7600 computer at the Control Data Corporation in Minneapolis to test the real-time data-processing capability of the system.

Control Data Corporation will follow the flight tests with data reduction and data comparisons, reporting final results in the fall. The SESAME project planners will then determine the feasibility of the system for the SESAME field experiments and for similar operational and research applications. Scientists interested in learning more details about the system's development and potential applications should consult the articles by V. E. Lally and R. M. Passi (MONTHLY WEATHER REVIEW, **103**, 21–26) and by K. S. Gage and W. H. Jasperson (BULLETIN, **55**, 1107–1114).

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