Numerical Simulations of an Idealized Convective System: Comparisons Between Parameterized and Explicitly Resolved Clouds

C.-Y. J. Kao
J. E. Bossert
Earth and Environmental Sciences Division
Los Alamos National Laboratory
Los Alamos, NM 87545

Introduction

One of the objectives of the U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) program is to improve the parameterization of clouds in general circulation models (GCMs). The approach we take in the current research is to examine the behavior of cumulus parameterization schemes by comparing their performance in mesoscale simulations with the results from explicit cloud simulations.

Kao and Ogura (1987) compared the "semi-prognostic" results by the Arakawa-Schubert (A-S) cumulus parameterization scheme with results produced by a cloud ensemble model (CEM) developed by Tao (1983). This earlier study builds the foundation for the present investigation which includes a major refinement. That is, the performance of the A-S scheme is examined in a "fully prognostic" fashion, and the results are compared with those derived from a fully time-dependent cloud model (i.e., not a CEM which is normally forced by a prescribed time-independent large-scale lifting process), under identical atmospheric conditions. We believe this approach is superior to the one in Kao and Ogura (1987) associated with the semi-prognostic simulations that cannot simulate the feedback processes between the cloud and large-scale fields.

We shall call the simulation with the A-S scheme the "parameterization case" and the one by a detailed cloud model the "microphysics case." Note that the only difference between the two cases is that cloud effects are parameterized in the former with a coarser resolution; whereas, each cloud is explicitly resolved by the latter with a much finer resolution. The capability of the A-S scheme in reproducing the growth and life cycle of a cloud system can then be evaluated. The numerical model we have recently acquired from Colorado State University, Regional Atmospheric Modeling System (CSU-RAMS) (Cotton et al. 1988), is used in this research. Since a modified Kuo scheme (Tremback 1990) is built in the RAMS, a by-product of this research is a comparison between two established cumulus parameterizations through the methodology described above.

The RAMS Mesoscale Model

The RAMS mesoscale model is a highly flexible modeling system, capable of simulating a wide variety of mesoscale phenomena. The basic model structure is described in Tripoli and Cotton (1982). More recent model developments are described in Tremback et al. (1986) and Cotton et al. (1988). The model framework for the present study incorporates a two-dimensional, terrain-following non-hydrostatic version of the code. At the surface, temperature and moisture fluxes are determined from the surface energy balance, which includes both short- and longwave fluxes (Chen and Cotton 1983), latent and sensible fluxes, and sub-surface heat conduction from a soil temperature model (Tremback and Kessler 1985). The microphysics parameterization (Flatau et al. 1989) used in the explicit cloud simulation describes the physical processes leading to the formation and growth of precipitation particles within a cloud. The cloud particles can be liquid or ice, or some combination, and may have a regular or irregular shape. The scheme categorizes these particles as cloud droplets, rain drops, ice crystals, snow crystals, aggregates of ice crystals, and graupel or hail. Each species can grow independently from vapor deposition or self-collection, or interact with other species through collision and coalescence processes. In the configuration used for this study, the mixing ratio of each species is predicted and the total concentration is diagnosed, using a specified size distribution.

The two cumulus parameterization schemes used in the coarse-grid simulations are briefly described as follows. The A-S scheme employs a one-dimensional steady state entraining cloud model with basic microphysics to represent the clouds. A spectrum of sub-ensembles of clouds are allowed to form simultaneously and modify the environment through compensating downward motion, detrainment, and evaporation of cloud water. Cloud-cloud interaction is considered in a way that the development of one sub-ensemble cloud can affect the growth of other sub-ensembles through its stabilizing effect on the large-scale environment. The exchange processes between the boundary layer and the free atmosphere are also included. The A-S scheme uses a quasi-equilibrium approximation to close the parameterization, which requires that clouds stabilize the atmosphere as the large-scale motion generates moist convective instability.

The Kuo scheme requires a conditionally unstable atmosphere and horizontal moisture convergence for cumulus clouds to form. Once the clouds form, they heat the atmosphere by condensation and produce a cloud heating profile proportional to the cloud excess temperature (i.e., cloud temperature minus environmental temperature). This scheme only allows one type of cloud to form at a given time. A more serious concern with the Kuo scheme is that it requires, in order to close the parameterization, the specification of a parameter (denoted by b in Kuo 1974) which represents the fraction of the total moisture supply that goes into moisture storage. It is expected that b takes a small value in the areas of disturbed weather conditions and takes a large value when the atmosphere is dry.

The Results

A two-dimensional (2-D) model configuration is used in the current study with a domain size of 2100 km in the horizontal direction and 26 km in the vertical. Model simulations with parameterization schemes have a horizontal resolution of 30 km and that with microphysics has a resolution of 2.5 km. A witch-shape mountain with a half-width of 100 km and height of 2 km is located at the center of the domain. The initial condition is a quiescent atmosphere with a weak stratification of about 2.4 K/km from the surface to about 5 km AGL. The relative humidity in this 5 km layer is about 80% so that an earlier development of cloud system can be expected. All model runs begin at 0900 LST on the summer solstice. Because of no initial winds, the modeled circulations can only be generated by the surface differential heating over the terrain.

In the following discussion we concentrate on the evolution of two basic model variables: vertical motion (w) and accumulated surface precipitation. Figure 1 shows the time plots of the vertical motion over the entire domain at a level about 4400 m above the surface. This level is chosen because the strongest upward motion occurs there during the life cycle of the system. Figure 1a is for the case with the fine resolution and microphysics. It shows rather noisy small-scale features, as expected, with the maximum updraft of about 11 m/s and the maximum downdraft of about 3.5 m/s. According to the general characteristics shown in Figure 1a, we can approximately define the period from 0 to 6 hours as the developing stage, from 6 to 12 hours as the mature stage, and from 12 to 17 hours as the dissipation stage of the convective system. A wave propagation is clearly observed in Figure 1a with the propagation speed of about 30 m/s. The time evolution of vertical motion in the two parameterization runs (Figures 1b and 1c) has similar characteristics to that shown in Figure 1a. One noticeable difference is that the Kuo scheme produces more organized vertical motion for both the core and far-field regions than the other two cases. Also, the gradient in w between the core and far-field regions is less in the Kuo scheme case. Due to the sensitivity of the A-S scheme to the variability of the large-scale fields that are the predictors of the parameterization, the A-S scheme generates rather disorganized vertical motion at the core region and more sporadic features in the far-field region.

Figure 2 shows the time plots of accumulated surface precipitation. In the microphysics case (Figure 2a), it shows that only the region over the mountain has surface precipitation during the entire life cycle. The system reaches a precipitation maximum about 80 mm at 11 hours near the center of the domain. The accumulated precipitation patterns produced by the A-S and Kuo schemes (Figures 2b and 2c) show that the parameterization runs tend to produce broader precipitation areas near the core region and generate a significant amount of precipitation during the propagation of the system. These two aspects are most pronounced in the case with the Kuo scheme. The

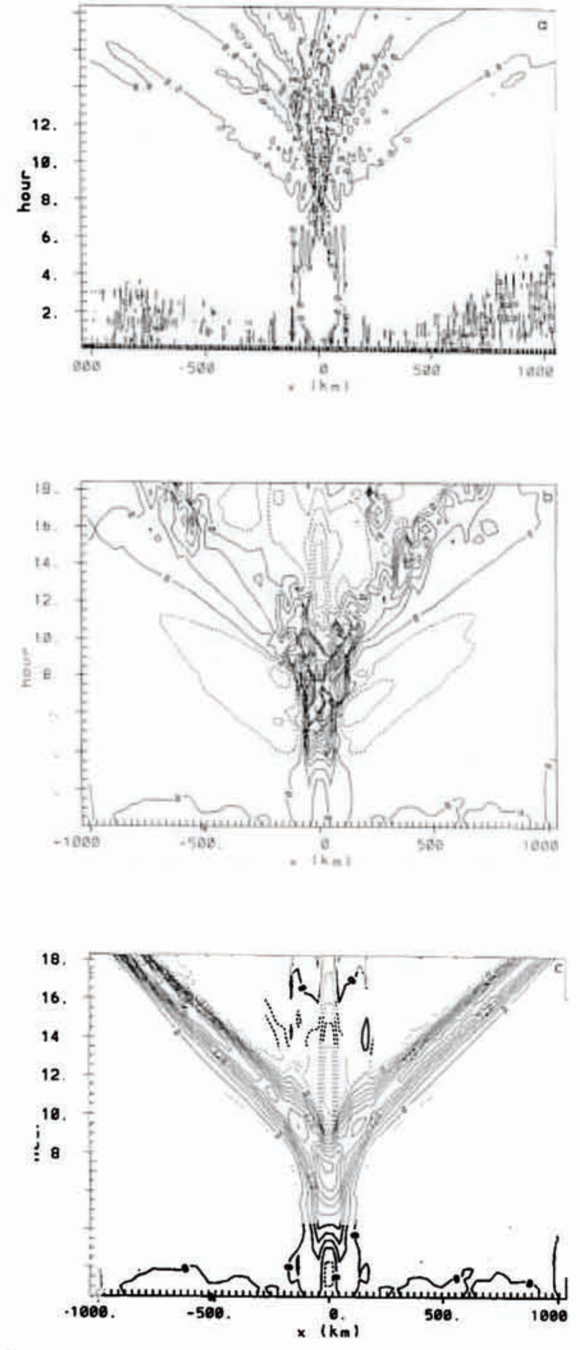

Figure 1. Time plots of the vertical motion at 4400 m above the surface: (a) microphysics case, (b) the A-S case, and (c) the Kuo case.

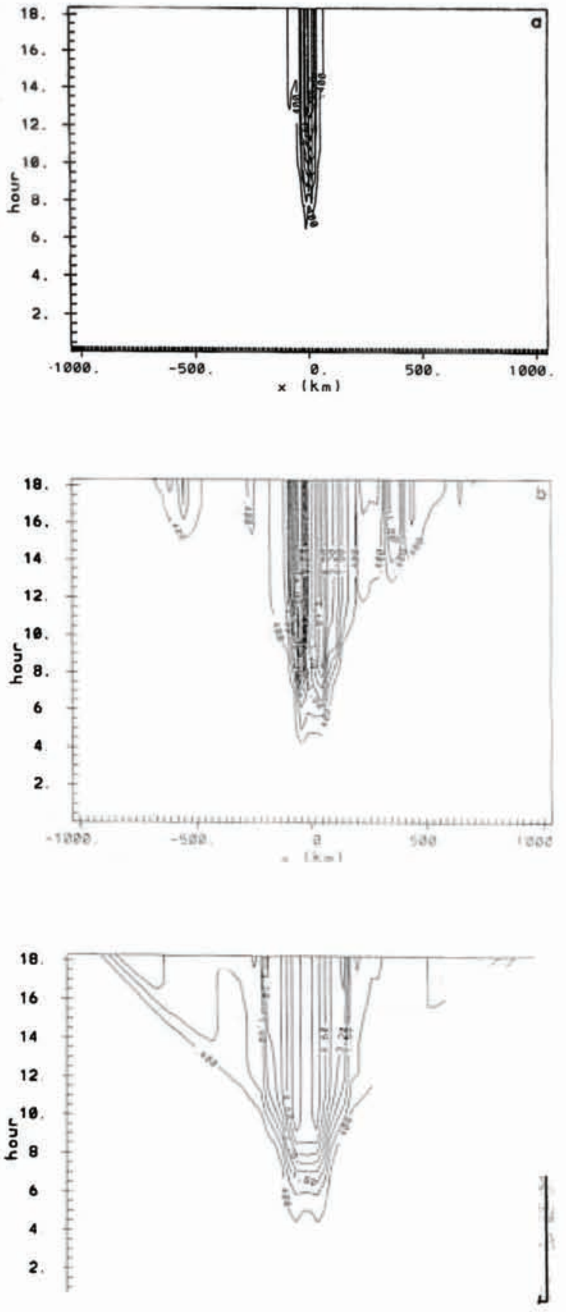

Figure 2. Time plots of the accumulated precipitation at the surface: (a) microphysics case, (b) the A-S case, and (c) the Kuo case.

reasons for the precipitation differences in the parameterization runs, especially in the dissipation stage, are probably twofold: crude microphysics built in the parameterization schemes and the misinterpretation of the vertical motion (compare Figures 1b and 1c) by the schemes at the dissipation stage. It is likely that the w-field in the dissipation stage of a convective system is a mere reflection of a group of dying convective clouds. It may not be appropriate to regard this kind of w as a predictor (or forcing) for cumulus parameterizations.

Concluding Remarks

This article summarizes some of our first-year results under the support of the ARM Program. The set-up of a 2-D idealized convective system provided us an opportunity to investigate the performance of two established parameterization schemes against the results produced by a detailed microphysical model. It is gratifying to learn that both the A-S and Kuo scheme are able to produce gross features similar to those revealed by the microphysics run, especially during the developing and mature stages of the convective system. The similarities include the evolution of vertical motion, surface precipitation, perturbed pressure field, temperature anomaly, and water vapor anomaly. In this paper, only the first two fields were shown.

One of our current tasks along the lines of this research is to include the convective-scale downdraft effects into the parameterization schemes so that cooling and drying effects due to downdrafts on the low levels of the atmosphere can be simulated. We are also incorporating background wind shear into the ambient atmosphere to investigate if the three cases can still maintain the same level of similarity.

References

Chen, C., and W. R. Cotton. 1983. A one-dimensional simulation of the stratocumulus-capped mixed layer. *Bound.-Layer Meteor.* 25:289-321.

Cotton, W. R., C. J. Tremback, and R. L. Walko. 1988. CSU RAMS - A cloud model goes regional. Proc. NCAR Workshop on Limited-Area Modeling Intercomparison, Nov. 15-18, NCAR, Boulder, Colorado, 202-211.

Flatau, P. J., G. J. Tripoli, J. Verlinde and W. R. Cotton. 1989. The CSU-RAMS Cloud Microphysics Module: General theory and code documentation. Atmospheric Science Paper No. 451, Colorado State University, Dept. of Atmospheric Science, Fort Collins, Colorado, 88 pp.

Kao, C.-Y. J., and Y. Ogura. 1987. Response of cumulus clouds to large-scale forcing using the Arakawa-Schubert cumulus parameterization. *J. Atmos. Sci.* 44:2437-2458.

Kuo, H. L. 1974. Further studies of the parameterization of the influence of cumulus convection on large-scale flow. *J. Atmos. Sci.* 31:1232-1240.

Tao, W.-K. 1983. A numerical study of the structure and vertical transport properties of a tropical convective system. Ph.D. dissertation, University of Illinois at Urbana-Champaign, 228 pp.

Tremback, C. J. 1990. Numerical simulation of a mesoscale convective complex: Model development and numerical results. Ph.D. dissertation, Colorado State University, Dept. of Atmospheric Sciences, Fort Collins, Colorado, 247 pp.

Tremback, C. J., and R. Kessler. 1985. A surface temperature and moisture parameterization for use in mesoscale numerical models. Preprints, Seventh Conf. on Numerical Weather Prediction, Montreal, *Amer. Meteor. Soc.*

Tremback, C. J., G. J. Tripoli, R. Arritt, W. R. Cotton, and R. A. Pielke. 1986. The Regional Atmospheric Modelling System. Proc. Internat. Conf. Development and Application of Computer Techniques to Environmental Studies, November, Los Angeles, California, P. Zannetti, Ed., Computational Mechanics Publications, Boston, 601-607.

Tripoli, G.J., and W.R. Cotton, 1982: The CSU three-dimensional cloud/mesoscale model-1982. Part I: General theoretical framework and sensitivity experiments. *J. Rech. Atmos.* 16:185-220.