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On Testing Two Major Cumulus Parameterization Schemes Using the CSU Regional Atmospheric Modeling System

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1. INTRODUCTION

One of the objectives of the DOE ARM Program is to improve the parameterization of clouds in general circulation models (GCMs). The approach taken in this research is two fold. We first examine the behavior of cumulus parameterization schemes by comparing their performance against the results from explicit cloud simulations with state-of-the-art microphysics. This is conducted in a two-dimensional (2-D) configuration of an idealized convective system. We then apply the cumulus parameterization schemes to realistic three-dimensional (3-D) simulations over the western U.S. for a case with an enormous amount of convection in an extended period of five days. In the 2-D idealized tests, cloud effects are parameterized in the "parameterization cases" with a coarse resolution, whereas each cloud is explicitly resolved by the "microphysics cases" with a much finer resolution. Thus, the capability of the parameterization schemes in reproducing the growth and life cycle of a convective system can then be evaluated. These 2-D tests will form the basis for further 3-D realistic simulations which have the model resolution equivalent to that of the next generation of GCMs.

Two cumulus parameterizations are used in this research: the Arakawa-Schubert (A-S) scheme (Arakawa and Schubert, 1974) used in Kao and Ogura (1987) and the Kuo scheme (Kuo, 1974) used in Tremback (1990). The numerical model used in this research is the Regional Atmospheric Modeling System (RAMS) developed at Colorado State University (CSU).

2. 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 Cotton et al. (1988). The model framework for the present study incorporates a 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 scheme (Flatau et al., 1989) used in the explicit cloud simulation describes the physical processes leading to the formation and growth of precipitation particles in 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 from vapor deposition or self-collection, or interact with other species thro[ugh] 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.

3. Cumulus Parameterizations

The two cumulus parameterization schemes used in the coarse grid simulations are briefly described as follows. The A-S scheme employs a 1-D 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 with a cloud-scale downdraft parameterization (Kao and Ogura, 1987) 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. Tremback (1990) modified the Kuo scheme by incorporating convective-scale downdrafts to define a net convective temperature profile. He also assumed that convection is activated only if the grid column is convectively unstable and there is resolved upward motion at the lifting condensation level (LCL).

In order to effectively simulate convective systems associated with organized anvils with the horizontal resolution of 30 to 50 km, we retain the the full microphysics of RAMS throughout simulations. Thus, convective cores will be parameterized by cumulus parameterization schemes and mesoscale anvil clouds will be explicitly simulated with microphysics.

3. Results

3.1 2-D Idealistic Simulations

The model is configured 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 35 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 2.1 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.

3.1.1 Case with no Ambient Winds

Because there are 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 1400 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 Fig. 1a, we can approximately define the period from 0 to 6 hr as the developing stage, from 6 to 12 hr as the mature stage, and from 12 to 17 hr as the dissipation stage of the convective system. A wave propagation is clearly observed in Fig. 1a with the propagation speed of about 30 m/s. The time evolution of vertical motion in the two parameterization runs (Figs. 1a and 1b) has similar characteristics to that shown in Fig. 1a. One noticeable feature is that the gradient in w between the core and far-field regions is less in the Kuo scheme case.

Figure 2 shows the time plots of accumulated surface precipitation. In the microphysics case (Fig. 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 hr near the center of the domain. The accumulated precipitation patterns produced by the A S and Kuo schemes (Figs. 2a and 2b) 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.

3.1.2 Case with Ambient Wind Shear

We introduced a constant background wind shear with the wind speeds of 0 at the surface and 10 m/s at the top of the domain, rendering the previous configuration into a more sophisticated case with mountain flow characteristics, as shown in Fig. 3 where upward motion is present at the upwind side of the mountain

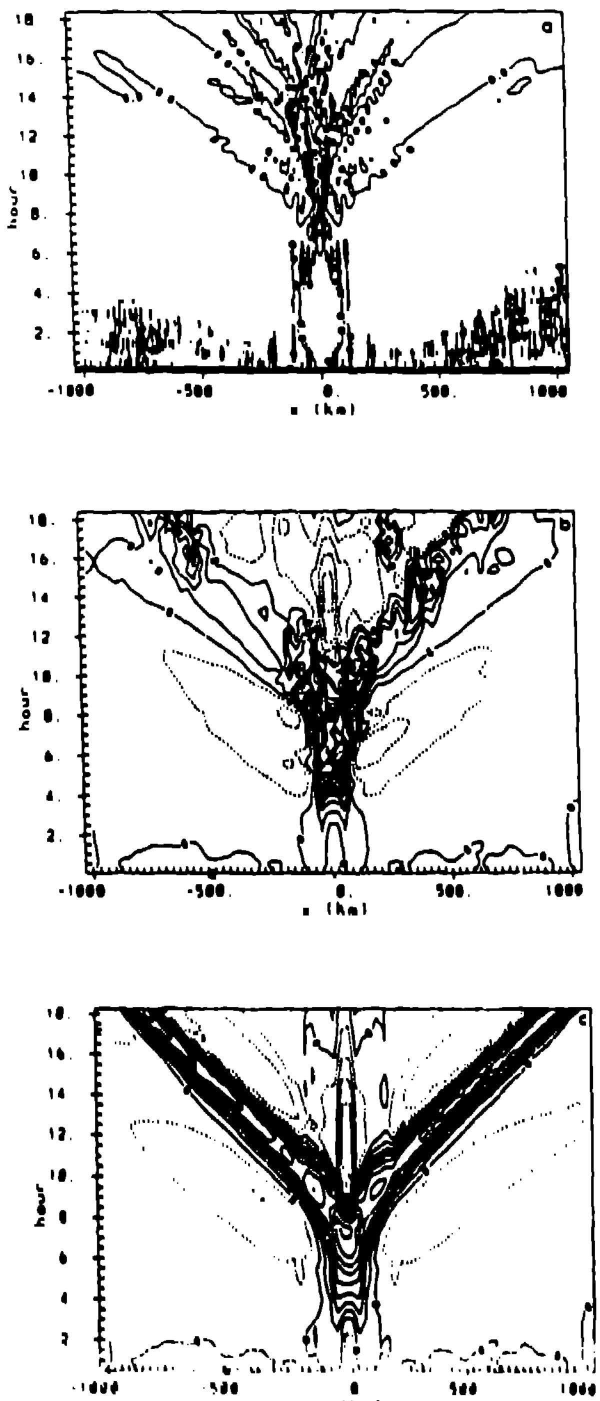


Fig. 1. Time plots of the vertical motion at 1100 m above the surface; (a) explicit case, (b) A-S case, and (c) Kuo case.

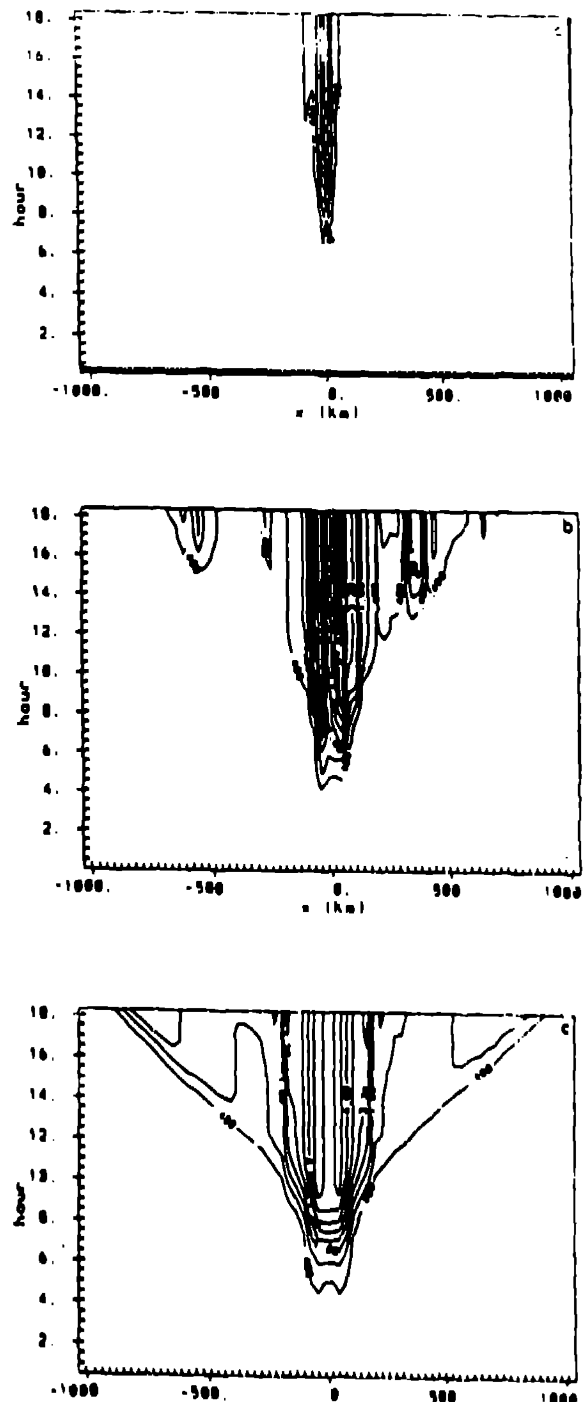


Fig. 2. Time plots of the accumulated precipitation at the surface; (a) explicit case, (b) A-S case, and (c) Kuo case.

and downward motion at the lee side with elevated upward motion above in all the three simulations. Figure 4 shows the temperature perturbation at hour 3. Great similarities are found between the A-S and explicit cases. The Kuo scheme produced enhanced warming above the monatain peak and excessive surface cooling at the upwind side of the mountain. This

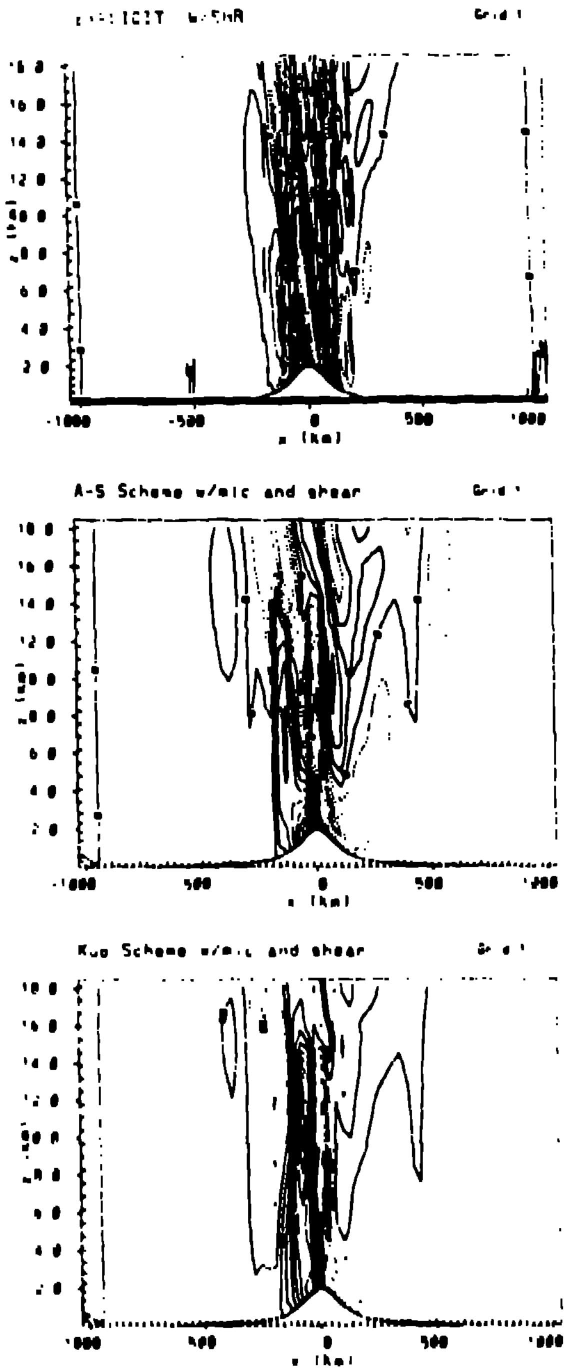


Fig. 3. Simulated vertical motion at Hour 1: (a) explicit case, (b) A-S case, and (c) Kuo case.

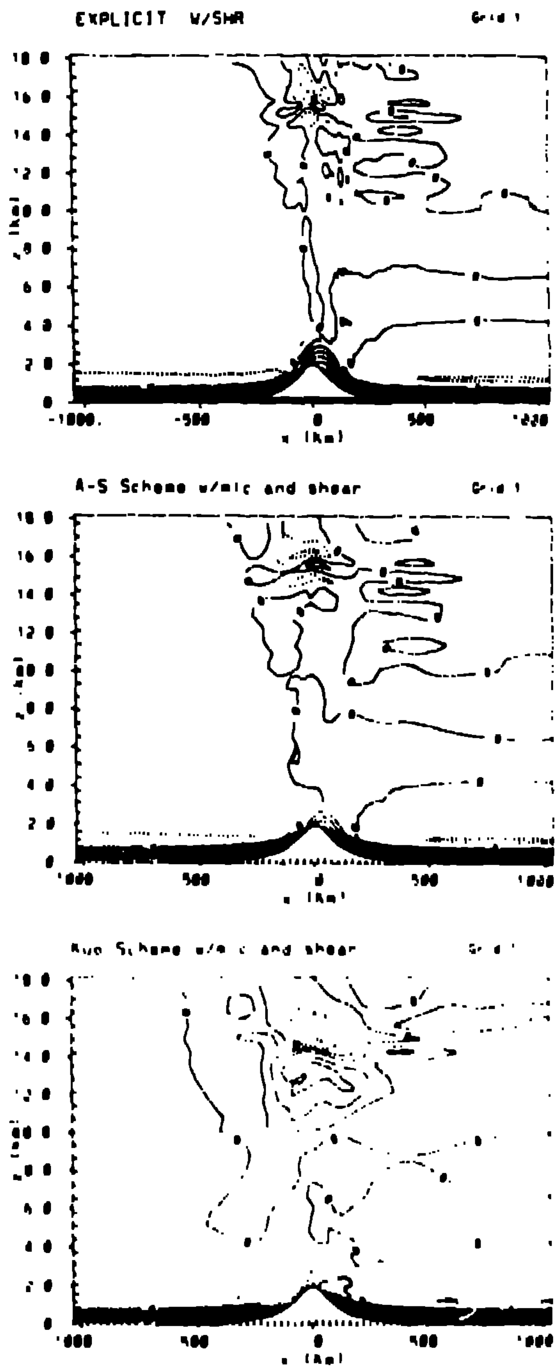


Fig. 4. Simulated potential temperature perturbation at Hour 3: (a) explicit case, (b) A-S case, and (c) Kuo case.

cooling later generated westward density current flow causing an anomalous behavior of flow evolution as will be discussed shortly. Figure 5 shows the time plots of the vertical motion for the wind-sheared case. In the explicit simulation, we can see a 3-mode structure: two stationary modes respectively at the two sides of the mountain with the lee-side one stronger; one propagating mode toward the eastern boundary which shows a very sporadic feature. The simulation with the A-S scheme also shows a 3-mode structure, however, the upwind stationary mode is much stronger than that in the explicit case. Due to the density current propagating toward the western boundary, a strong westward mode is created in the simulation with the Kuo scheme, which is not realistic.

3.2 3-D Realistic Simulations

The model topography is derived from a 5 minute global data set with a silhouette averaging scheme that preserves realistic topography heights. This height data is then interpolated to the model grid which has 0.5° horizontal resolution at the tangent point of the polar stereographic grid at 40.0°N and 112.5°W. In these experiments, we cover the geographical domain from 125.0°W to 89.0°W and 22.5°N to 47.5°N. In the vertical we use 25 levels, corresponding to a resolution of 300 meters near the surface and 1000 meters at the top of the model. The NMC 2.5° by 2.5° twice daily global analyses are used to initialize, as well as "nudge" the regional model boundaries via a Newtonian relaxation scheme. The model is initialized by the NMC analysis of July 6, 1987 for simulations of a 5 day period which had an enormous amount of convection in the western U.S. It is an extremely challenging case because the observed precipitation maxima are due to different processes: some are related to large-scale condensation; and some are purely driven by convection. For example, Iowa had continuous rainfall and accumulated more than 5 inches in this period, while North Platte, Nebraska had 1.3 inches in less than 24 hours presumably due to severe convection. Another reason for these five day tests is to establish the robustness of our parameterization design for the next generation of GCMs through RAMS.

Figure 6 shows the 24 hour precipitation areas and amounts observed within the model domain at 7:00 A.M. EST, July 7, 1987. The

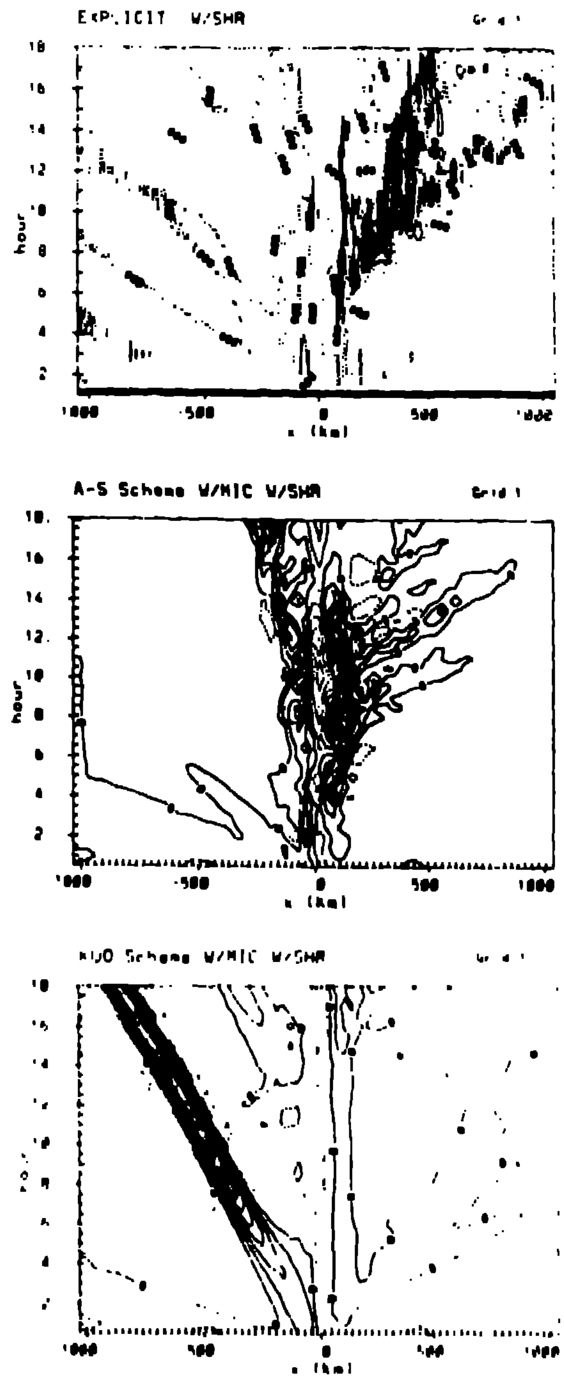


Fig. 5. Same as Fig. 4 except for the sheared cases.

primary low pressure center was located north of Winnipeg with a cold front extending to southern Colorado and warm front extending to Newfoundland. Figure 7 shows the daily precipitation simulated by the two schemes, that does not include the large-scale precipitation generated by the RAMS microphysics. Actually, the large scale precipitation occurred only in western Iowa (diagrams not shown) in both runs and continued for the next two days as observations showed. The convective precipitation produced by the A S scheme agrees fairly well with the observation in terms of both the pattern and amounts. The Kuo scheme again tends to produce a broader and less contrasted precipitation pattern as seen in the 2 D simulations. Due to the difference in the convective precipitation predicted by the two schemes, it can be anticipated that the convective heating patterns and amounts will also be different. We have found that the Kuo scheme did not simulate the 500 mb flow features as successfully as the A S scheme, perhaps because the latent heat distribution produced by the Kuo scheme is not as realistic.

4. Concluding Remarks

Simulations of a 2 D idealized convective system with RAMS provided us an opportunity to investigate the performance of two established parameterization schemes against the results produced by an explicit cloud simulation. We found that both the Arakawa Schubert and Kuo schemes are able to produce gross features similar to those revealed by the explicit cloud simulation, especially during the developing and mature stages of the convective system. The similarities include the evolution of vertical motion, surface precipitation, pressure field, temperature anomaly, and water vapor anomaly. However, in a more sophisticated case with mountain flow characteristics, we found that the downdraft effects in the Kuo scheme cooled the boundary layer much more than those in the Arakawa-Schubert scheme did and, in turn, produced convection only on the upwind side of the mountain, which proved to be unrealistic. We subsequently applied both schemes to realistic 3 D simulations over the western U.S. initialized by the NMC analysis of July 6, 1987; a case with an enormous amount of convection associated with an occluded front. It was found that the Arakawa Schubert scheme was capable

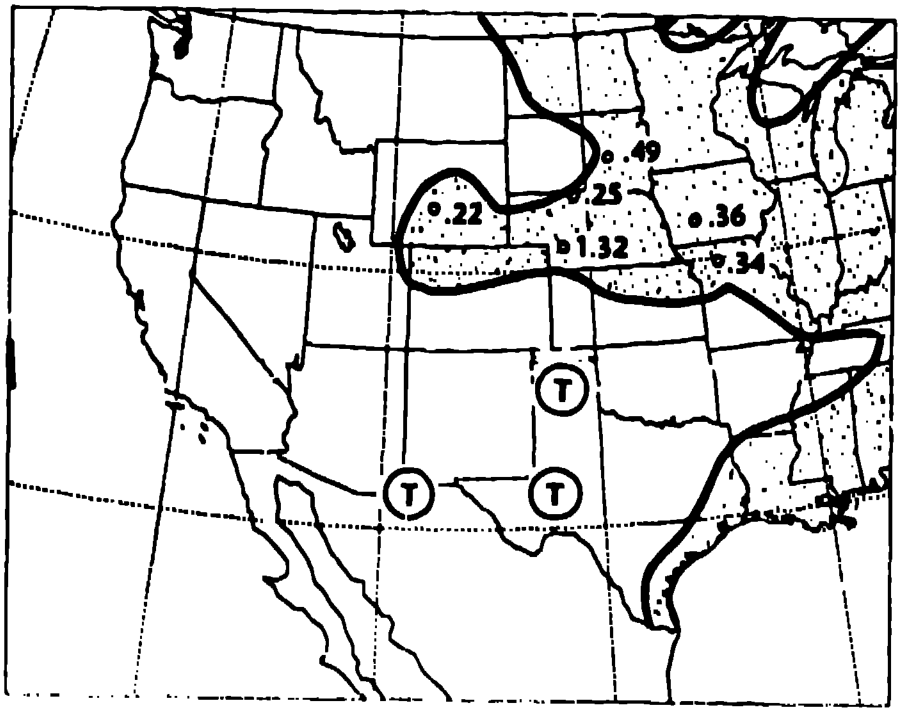
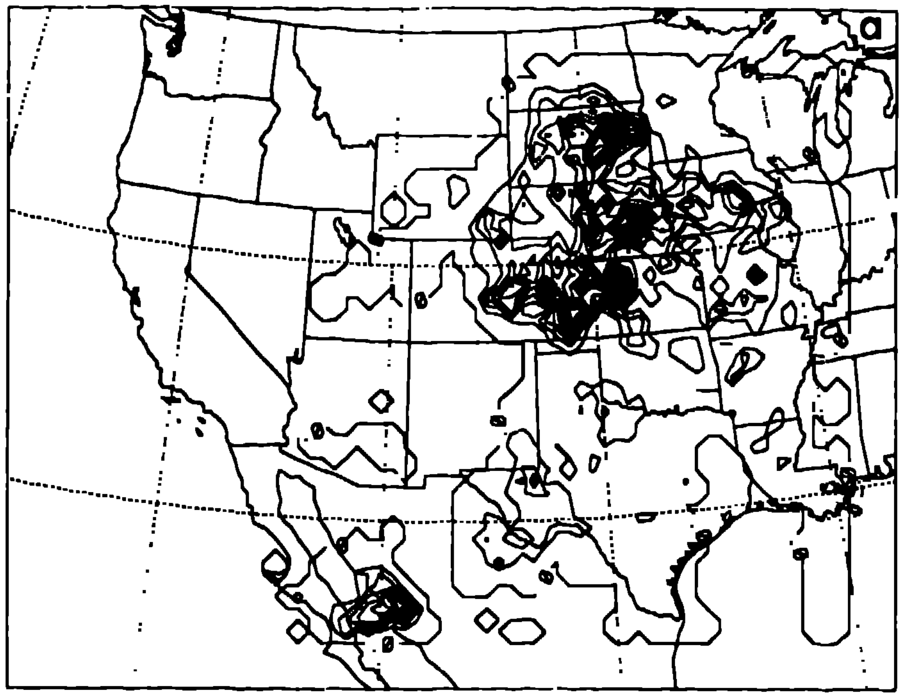


Fig. 6. Observed 24 hour precipitation areas and amounts (inches) at 7:00 A.M., July 7, 1987.



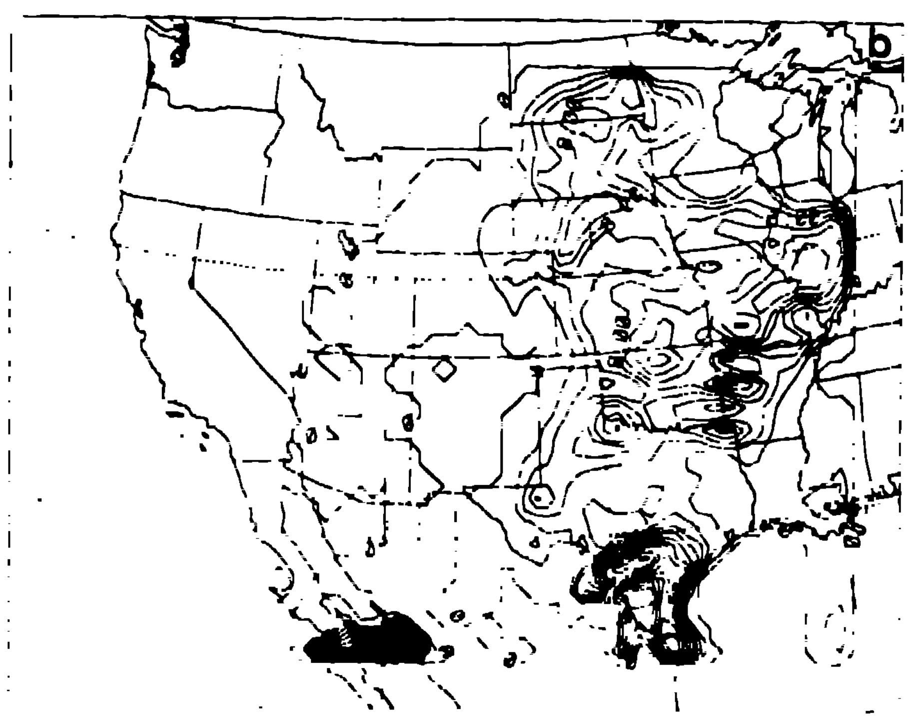


Fig. 7. Daily precipitation (mm) simulated by (a) the A S scheme and (b) the Kuo scheme.

of capturing many localized precipitation maxima whereas the Kuo scheme tended to overpredict the precipitation area and failed to depict the local extremes of precipitation. Conceivably due to the less organized latent heat distribution, the Kuo scheme did not simulate the 500 mb flow features as successfully as the Arakawa-Schubert scheme did.

Acknowledgments

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