Assimilation of June 1993 Intensive Observation Period Data and Its Use in Single-Column Climate Modeling

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Introduction

An Intensive Observation Period (IOP) of the Atmospheric Radiation Measurement (ARM) Program took place at the Southern Great Plains Cloud and Radiation Testbed (SGP CART) site from June 16-26, 1993. The National Center for Atmospheric Research (NCAR)/Penn State Mesoscale Model (MM5) has been used to simulate this period on a 60-km domain with a 20- and 6.67-km nests centered on Lamont, Oklahoma. Figure 1a shows the outer two domains, and Figure 1b shows the 20-km domain and the 6.67-km domain. The white square indicates the region extracted for the single-column modeling (SCM). Simulations are being run with data assimilation by the nudging technique (Kuo and Guo 1989, Stauffer and Seaman 1990) to incorporate upper-air and surface data from a variety of platforms. The model maintains dynamical consistency between the fields, while the data corrects for model biases that may occur during long-term simulations and provides boundary conditions. For the work reported here the Mesoscale Atmospheric Prediction System of the National Oceanic and Atmospheric Administration (MAPS/NOAA) 3-hourly analyses were used to drive the 60-km domain, while the inner domains were either unforced or nudged with observations. A continuous 10-day period was simulated.

Overview

One goal of the ARM Program is to improve general circulation models (GCMs) by obtaining detailed meteorological information in limited areas of order 200-km square and comparing GCM parameterizations with the mean radiative and convective properties in such areas. Typical GCM grid boxes are 100- to 200-km square, but there is in reality much structure at smaller scales that is represented by their parameterizations. Meteorological observations alone cannot represent this structure, so we use a full-physics mesoscale model forced by large-scale tendencies to give as complete a picture of the sub-200-km scale structures as possible. This allows us to produce a full four-dimensional characterization of the atmosphere that, given sufficiently complete physics in the model and sufficiently good data, will provide a representation of the actual state of the atmosphere.

Single-column climate models were designed to test physics parameterizations in isolation from dynamical feedbacks. To succeed, they need reliable forcing data that maintain good mass, heat, and moisture balances. Our approach is to use a full-physics high-resolution mesoscale model to provide the forcing.

The MM5 Model

The model features and options used in this study are as follows. Equations are for nonhydrostatic, compressible motion, in terrain-following coordinates with a polar-stereographic map projection. Prognostic equations exist for wind components, vertical velocity, pressure perturbation, temperature, water vapor, ground temperature, and micro-physical water and ice content variables. It has an upper radiative boundary condition, relaxation lateral boundary conditions, and interactive two-way nesting. The model

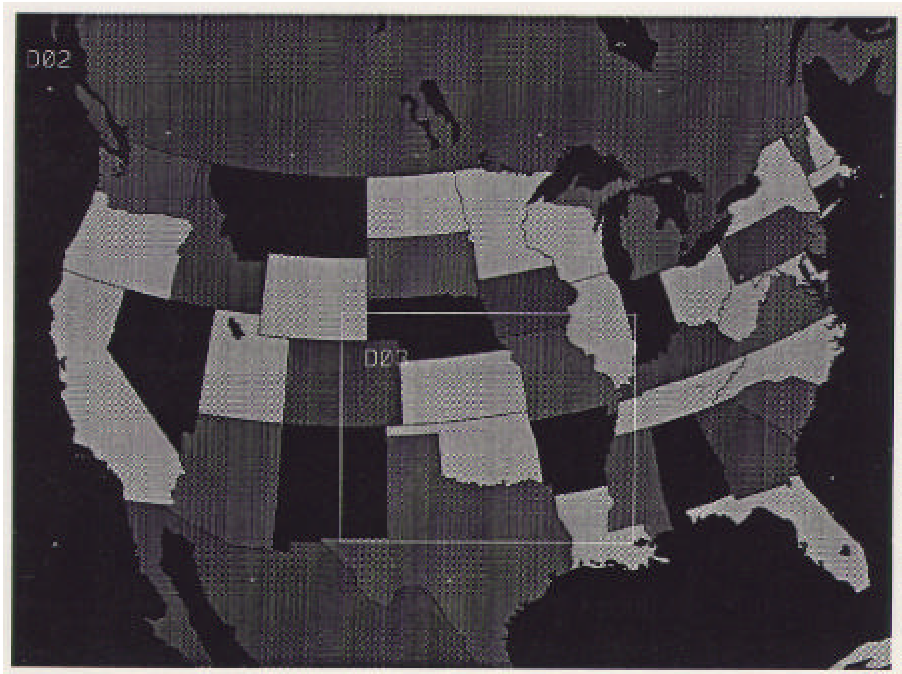

Figure 1a. 60-km domain showing 20-km domain in box.

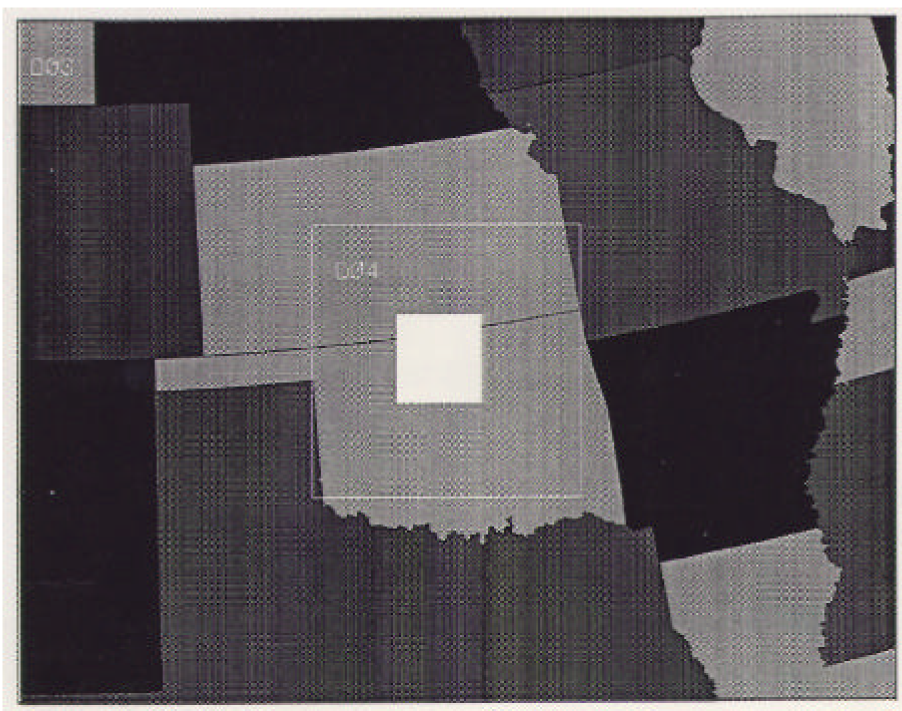

Figure 1b. 20-km domain showing 6.67-km domain outline and SCM area in white box.

includes microphysics with cloud, rain, snow/graupel, ice processes on all domains' resolved scales. The Grell cumulus parameterization scheme is adopted only on the 20-km and coarser domains. The Blackadar high-resolution planetary boundary-layer and a surface energy budget calculation are used. There is also an atmospheric longwave and shortwave radiation scheme interacting with model clouds and land surface.

Pros and Cons of Mesoscale Model SCM Forcing

The mesoscale model provides a complete budget of quantities including unobservable ones such as hydrometeor contents. These are in balance dynamically (mass, geostrophic, thermal wind, gradient wind) and physically (thermodynamic). The MM5 model has sufficiently complete physics to provide a realistic atmosphere to the SCM; furthermore, it is much more temporally and spatially complete than observations alone could provide. By applying the model at 6.67-km grid size, scales of cloud features are resolved that are parameterized in GCMs, and the need for cloud-fraction assumptions is avoided. This allows us to evaluate the cloud-fraction assumptions in GCM radiative and microphysical schemes against the "truth" of the mesoscale model. Similarly, deep convection is resolved without the need for cumulus parameterization in the mesoscale model.

On the other hand, convection is not resolved well by 6.67-km grids, and further nesting to 2.22 km would be better for convective events. The boundary-layer parameterization in the mesoscale model affects the data, and so the SCM should not be used to evaluate boundary-layer parameterizations, as this simply amounts to a comparison between the mesoscale and GCM parameterization.

The primary use of the mesoscale model in these studies is as a stepping stone to link the GCM scale with the features on scales that it cannot resolve (nor can most observed data). The mesoscale model can give representative mean properties within a GCM grid box by resolving the primary convective and radiative processes contributing to the GCM sub-grid scale.

Experiment Design

The mesoscale model was run for 10 days. Data from a 200-km square in the innermost 6.67-km domain were extracted for two purposes: 1) to examine the time evolution of the mean properties within this region, particularly heat and moisture budgets, and 2) to provide boundary conditions to a single-column version of the Community Climate Model (CCM3).

The mesoscale model data were output hourly for the ten days. Knowledge of the winds, moisture, and temperature, as well as hydrometeors, at the boundaries of the box is used to calculate the fluxes through the box sides. At the surface, it is also possible to provide the fluxes or to leave the SCM to derive its own from its surface parameterization. The latter approach was chosen here. The mesoscale model's mean values in the box then serve as verification for the SCM. The mean vertical motion is required by the SCM to be consistent with the lateral mass convergence profile imposed.

Mean Properties Within the SCM Box

Budget Equations

Before running the SCM with the data extracted from the mesoscale model, it is interesting to use the data to infer some mean properties. Of particular interest are the budgets of heat and moisture (Q_1 and Q_2, see below). These represent primarily the effects of diabatic processes (e.g., latent and radiative heating) and the vertical eddy fluxes, which are not resolved by the mean vertical motion. The equations below can be divided into three terms each.

- T the time derivative of the mean
- H the mean horizontal term
- V the mean vertical term.

In the plots, the mean horizontal term will represent the horizontal advection in the box estimated from the lateral boundary fluxes, and the vertical term uses the mean vertical velocity and vertical gradients.

$$Q_1 = \frac{\partial \overline{T}}{\partial t} + \overline{v \bullet \nabla T} + \frac{g\overline{w}}{c_p}$$

$$Q_2 = \frac{L_v}{c_p}\left(\frac{\partial \overline{q}}{\partial t} + \overline{v \bullet \nabla q}\right)$$

Results from Model Budgets in the 200-km Area

Figures 2a and 2b show the apparent heat source and moisture sink (expressed in K/day) over the 10-day period. Both show high temporal frequency behavior. For Q_1 the most noticeable result is that the bottom two panels of the four representing the mean vertical flux and the total are strongly correlated and much larger than the top two panels (note different contour intervals). This is consistent with findings in the tropics that mean temperature changes are small compared with the forcing by vertical motion. There is fairly good cancellation between vertical motion and latent heating. The cold frontal passages on 19 and 24 June were fairly weak, but stronger fronts would have a more significant mean time derivative than here. For Q_2, it can be seen that all four panels have equal magnitudes (same contour interval), but there is strong cancellation between the top two representing the time mean and the horizontal advection. The vertical advection is the primary component of Q_2, but the agreement between the two is less exact.

Implications for SCMs

Because parameterization schemes in SCMs attempt to represent Q_1 and Q_2 and require lateral fluxes to drive them and the time-dependent mean to verify them, it is particularly important in the moisture budget to have an

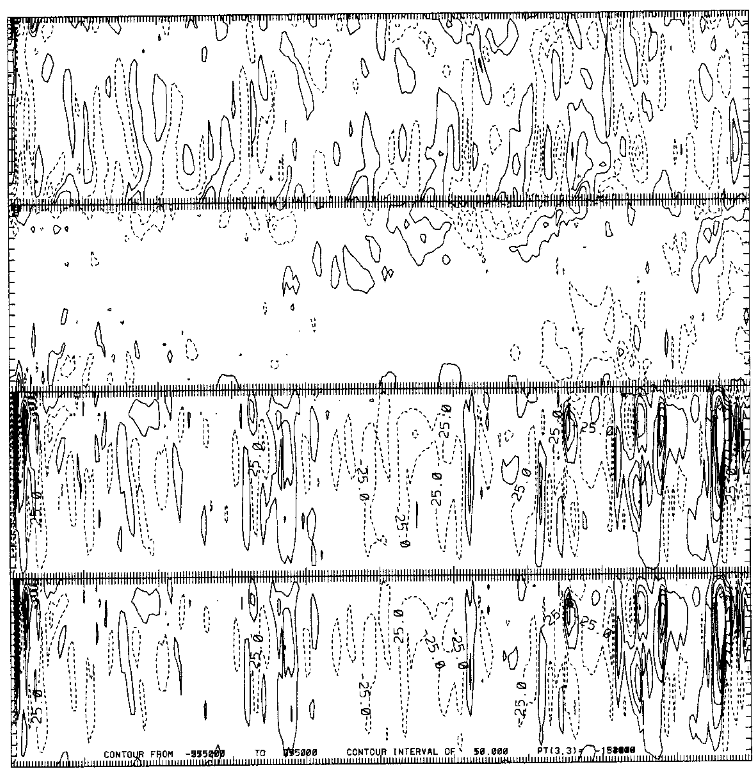

Figure 2a. Time versus pressure plot of Q_1, apparent heat source components. Time derivative, contour interval 10 K/day (top), mean horizontal term, contour interval 10 K/day (second), mean vertical term, contour interval 50 K/day (third), and total Q_1, contour interval 50 K/day (bottom). All plots are 100 to 1000 hPa, and cover ten days.

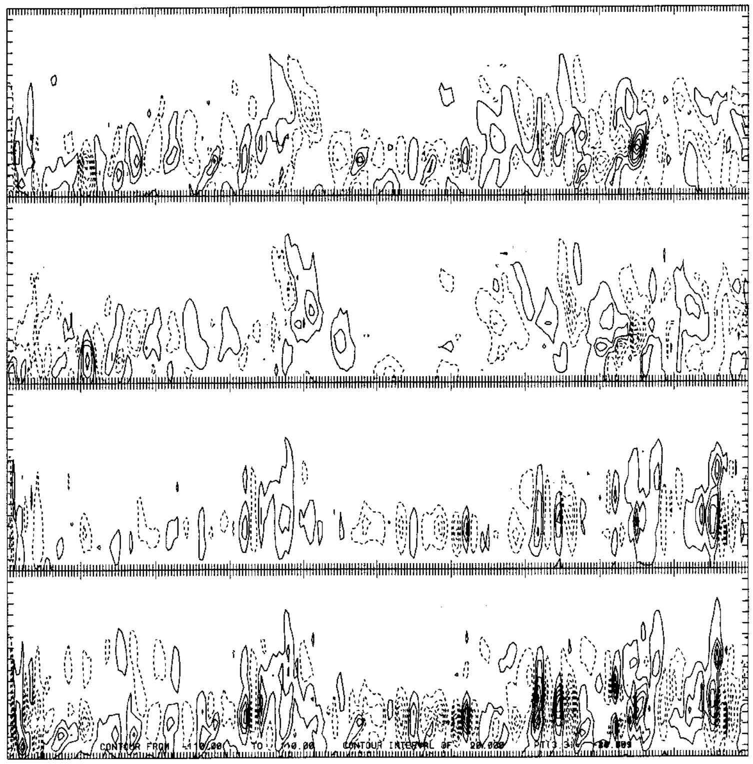

Figure 2b. Time versus pressure plot of Q_2, apparent moisture sink components. Time derivative, contour interval 20 K/day (top), mean horizontal term, contour interval 20 K/day (second), mean vertical term, contour interval 20 K/day (third), and total Q_2, contour interval 20 K/day (bottom). All plots are 100 to 1000 hPa, and cover ten days.

accurate estimate of the lateral moisture flux and mean time dependence. The temporal scales of the forcing could be severely aliased by a low observation frequency.

Single-Column Model

SCM Forcing

The CCM3 single-column model was run forced by the MM5 data described earlier. Of particular interest here is the effect of the imposed hydrometeor flux on the SCM results. Figure 3a shows the hydrometeor forcing and Figure 3b shows the water vapor forcing. It can be seen that, particularly in the upper troposphere, variations in hydrometeor content can be comparable with those in water vapor.

SCM Results

Figures 4a and 4b show that introducing hydrometeors through the lateral boundaries has an impact on the resolved cloud prediction and, hence, on radiation, precipitation, and other SCM-predicted fields. Applying the hydrometeor forcing to the water vapor forcing instead of directly to hydrometeors has a similar impact. The effect is particularly seen around day 1 and day 8. The hydrometeor distribution in the mesoscale model (not shown) is somewhat more extensive vertically because, whereas the mesoscale model resolves all clouds, the SCM parameterizes deep convection, so that, particularly in the lower troposphere, significant differences appear in mean hydrometeor content.

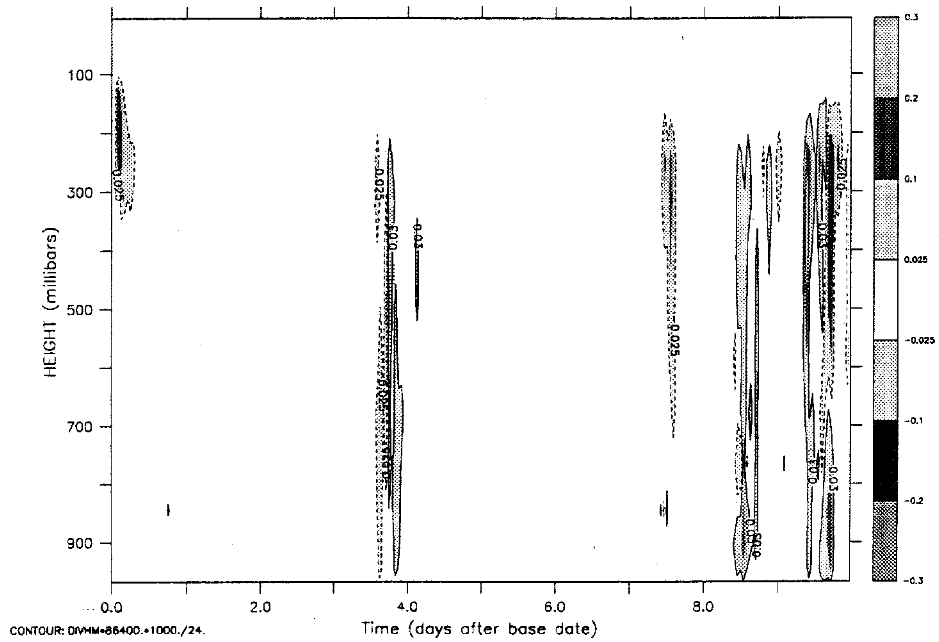

Figure 3a. Horizontal divergence of hydrometeor mixing ratio (g/kg/hr). Pressure from 100 to 1000 hPa vertically, time from days 0 to 10 horizontally.

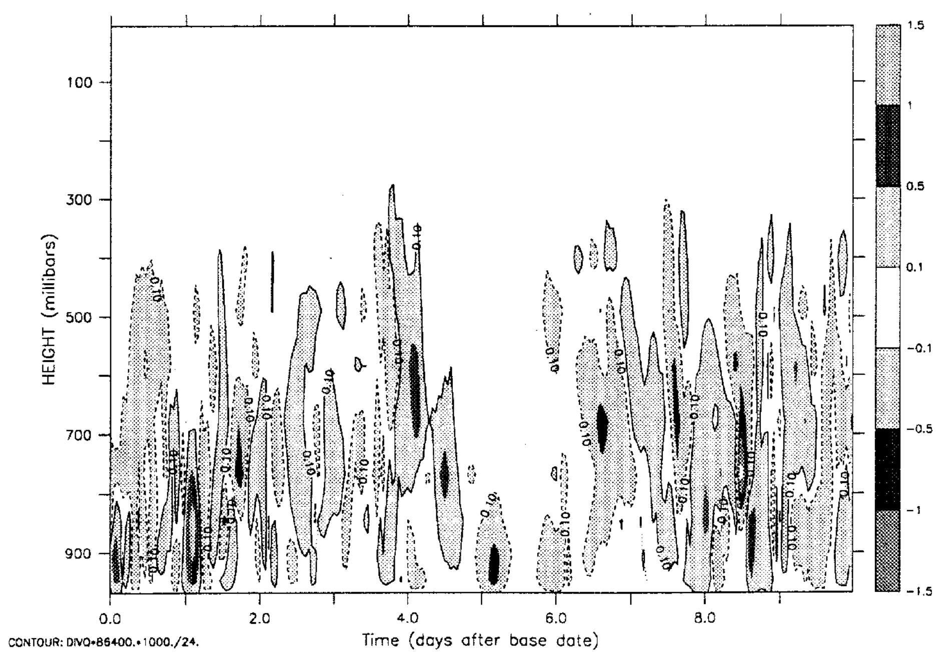

Figure 3b. Horizontal divergence of water vapor mixing ratio (g/kg/hr). Pressure from 100 to 1000 hPa vertically, time from days 0 to 10 horizontally.

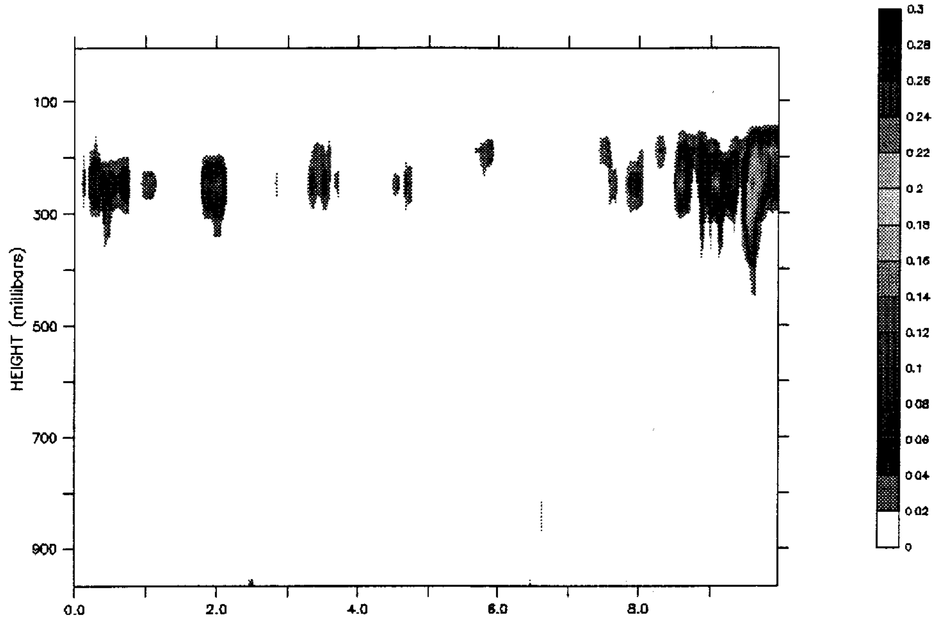

Figure 4a. SCM-predicted resolved cloud without hydrometeor forcing (g/kg).

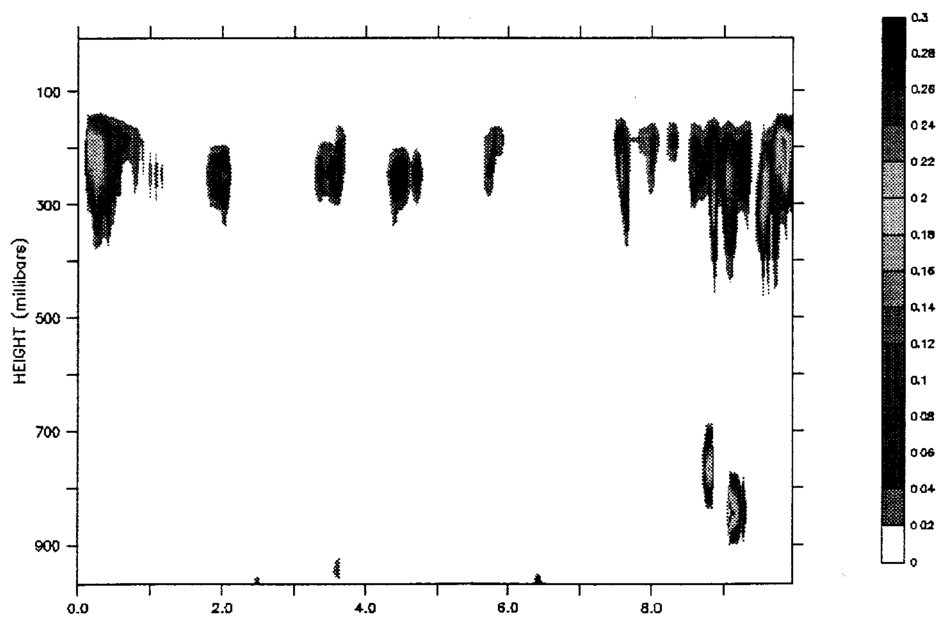

Figure 4b. SCM-predicted resolved cloud with hydrometeor forcing (g/kg).

Concluding Remarks

The use of a mesoscale model to provide data at high temporal and spatial resolution has been demonstrated. The model provides balanced fields and can make use of data assimilation to maintain closeness to the observed atmosphere. Studies presented at previous Science Team meetings have verified the model's ability to simulate soundings taken during the IOP and have shown a 12-hour cloud-resolving simulation (2.22 km) of cold-frontal convection on 24 June 1993. Here the model was run for 10 days at 6.67-km grid size centered on the SGP CART site. The data for a 200-km square were extracted and mean properties determined. These give an indication of the variability of the real atmosphere and show the need for good moisture boundary conditions if an SCM is to be forced realistically. The preliminary SCM study has shown that hydrometeor forcing has an impact. Normally this would be very difficult to obtain from observations. There are probably events where such forcing is even more important than in the period studied here (stratiform cloud or high cirrus advection through the domain).

References

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Stauffer, D. R., and N. L. Seaman, 1990: Use of four-dimensional data assimilation in a limited-area mesoscale model. Part I: Experiments with synoptic-scale data. *Mon. Wea. Rev*., **118**, 1250-1277.