Evaluation of a Stratiform Cloud Parameterization for General Circulation Models

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One of the requirements of a cloud parameterization is that it represent the full lifecycle of clouds: their formation, persistence, and decay. For clouds forming under strongly advective conditions, the domain traversed by a cloud during its lifecycle can be thousands of kilometers, much larger than that of a single grid cell of a General Circulation Model (GCM). Evaluation of a cloud parameterization under such conditions can only be achieved by a model spanning a domain much larger than that of a Single Column Model (SCM); otherwise the lateral boundary conditions for the cloud variables will control the simulation of the cloud. Thus, even if the Atmospheric Radiation Measurement (ARM) Program could measure the cloud variables on the lateral sides of the Cloud and Radiation Testbed (CART) site, the evaluation of cloud parameterizations would, under strongly advective conditions, be compromised by the lateral boundary conditions for the cloud variables.

To evaluate the relative importance of horizontal advection of cloud versus cloud formation within the grid cell of an SCM, we have performed a series of simulations with our SCM driven by a fixed vertical velocity (1 cm s^{-1}, characteristic of 250-km resolution models; Sasamori 1975) and various rates of horizontal advection. Horizontal advection is treated assuming no clouds are transported into the SCM grid cell (for lack of observations of clouds), but clouds formed within the grid cell can be transported out. The simple upstream scheme is used to treat advection, which for constant flow across a grid cell of width Δx reduces to

$$(V \bullet \nabla r)_i = \upsilon_{i+½} \frac{r_{i+1} - r_i}{\Delta x} \qquad (1)$$

where $\upsilon_{i+½}$ is the velocity on the upwind side of the grid cell, r_i is the cloud variable simulated by the SCM, and r_{i+1} is the cloud variable upwind from the grid cell, assumed to be zero (or r_v in the case of advection of total water r_w) for lack of cloud observations. The grid size is fixed at 200 km, but the horizontal wind speed varies from zero to 15 m s^{-1}. The case with zero wind speed corresponds to the assumption that clouds outside the SCM domain are the same as clouds within. Figure 1 shows the column cloud water as a function of time for different values of horizontal wind speed. The difference between the treatment assuming homogeneous conditions (zero wind) and the treatment assuming no clouds are transported into the domain increases monotonically with increasing wind speed (roughly 20%, 35%, and 50% for wind speeds of 5, 20, and 15 m s^{-1}, respectively). This indicates that the results can be quite sensitive to the assumed cloud distribution along the lateral boundaries. We therefore conclude that an SCM is not a viable testbed for evaluating cloud parameterizations, except under conditions of weak wind speeds, which in our simulation case are less than 5 m s^{-1}.

As an alternative to the use of SCMs as a testbed for evaluating cloud parameterizations, we are using a multi-dimensional Regional Circulation Model (RCM). The model generates cloud variables both within and outside the CART measurement domain, but only the clouds simulated within the CART domain are compared with observations. It is important to note that the same cloud parameterization used within the CART domain is also used outside the domain so that, in contrast to simulations by an SCM driven by boundary conditions from a Four-Dimensional Data

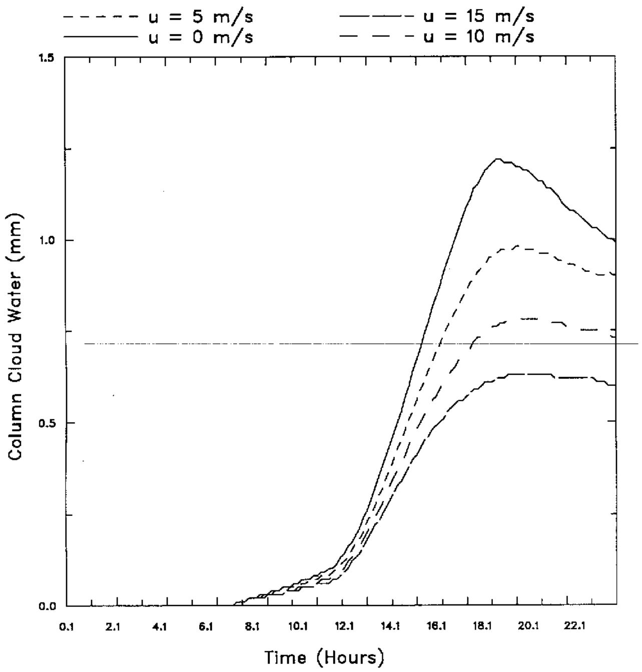

Figure 1. Simulations of column cloud water by the single column model with different horizontal wind speeds. The model was initialized with relative humidity that decreases from 90% to 60% from the surface to 6 km, and is driven by a fixed vertical velocity of 1 cm s^{-1}.

Analysis (FDDA) system, there will be no ambiguity about whether cloud simulation errors are due to the cloud parameterization inside or outside the CART domain. The simulation period is at least a few days to allow the clouds to form with little dependence on the poorly known initial specific humidity. Four-dimensional data assimilation is used to constrain the simulation toward the observed winds throughout the simulation. The domain of the RCM is chosen to be large enough that the lateral boundary conditions for the cloud variables do not significantly influence the clouds simulated within the CART domain. Experience with the First International Satellite Cloud Climatology Project Regional Experiment (FIRE) Cirrus experiments (Westphal and Toon 1990) suggests a domain of several thousand kilometers is required. The horizontal resolution of the model is consistent with that of GCMs (i.e., 100-200 km, so that cloud parameterizations can be evaluated at the appropriate resolution).

As a proof of principle, we offer the following comparison between simulated and observed outgoing shortwave radiance for a model run with simple nudging. The MM5 prototype MMZIGGY, running with our cloud parameterization (Ghan and Easter 1992), was used to simulate the development of a frontal system on the lee side of the Rocky Mountains from November 6 through November 8, 1987. Calculations were performed on a 40 x 45 gridded domain centered at 34.5°N and 99.0°W, with a grid spacing of 60 km. Two model integrations were completed. For the first, boundary conditions obtained from the European Centre for Medium-Range Weather Forecasts-gridded analysis were used, and no data assimilation was performed. For the second, the same boundary conditions were employed, and in the interior of the domain, the model temperature and horizontal winds were nudged toward values obtained from the gridded analysis, using nudging coefficients of 2.5 x 10^{-4} s^{-1}. In Figure 2a Geostationary Operational Environmental Satellite (GOES) shortwave image is compared to the output from both model runs 44 hours into the model simulations, at 20 GMT, November 7. Figure 2a shows a GOES visible image from 19:31 GMT; Figure 2b shows the model-calculated outgoing shortwave radiation from the nudged run; and Figure 2c shows the model-calculated outgoing shortwave radiation from the run with no nudging. The developing cold front can be easily discerned in the nudged simulation as it crosses the CART site in Oklahoma. It is clear that the simulation of the large-scale features of the system has been improved with the inclusion of wind and temperature nudging.

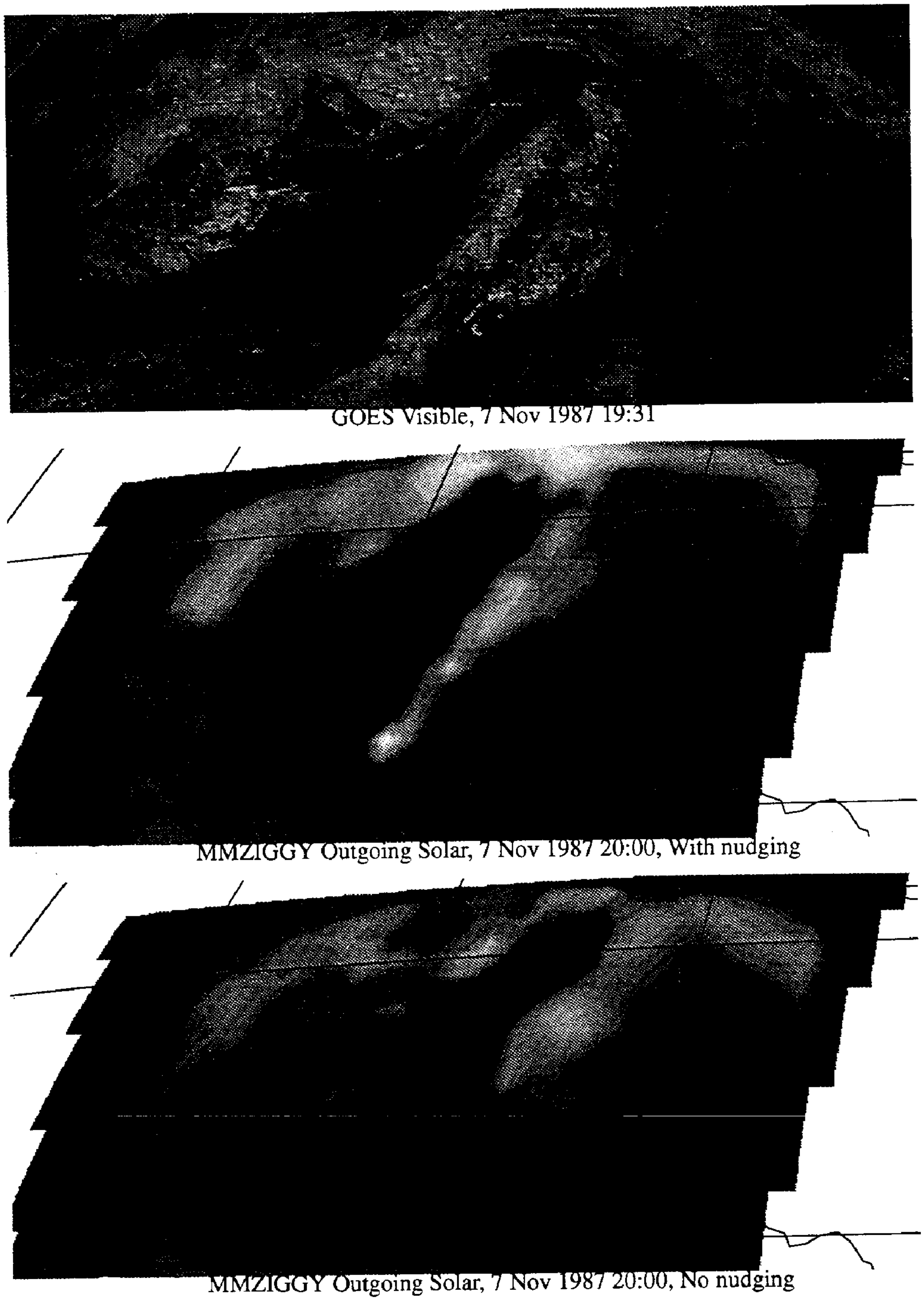

Figure 2. Simulated and observed outgoing solar radiation for a domain centered over the ARM Southern Great Plains CART site: (a) GOES visible image at 19:31 GMT, November 7, 1987; (b) Outgoing solar radiation simulated at 20 GMT, November 7, 1987, after initialization at 00 GMT, November 6, 1987, and 44 hours of simulation with data assimilation; and (c) As in (b), but without data assimilation.

References

Ghan, S. J., and R. C. Easter. 1992. Computationally efficient approximations to stratiform cloud microphysics parameterization, *Mon. Wea. Rev.*, **120**, 1572-1582.

Sasamori, T. 1975. A statistical model for stationary atmospheric cloudiness, liquid water content, and rate of precipitation, *Mon. Wea. Rev.*, **103**, 1037-1049.

Westphal, D. L., and O. B. Toon. 1990. Simulations of the large-scale environment during the FIRE Cirrus IFO. In *Proceedings of the Seventh Conference on Atmospheric Radiation*, American Meteorological Society, July 23-27, 1990, San Francisco, California. American Meteorological Society, Boston, Massachusetts.