# Interactions Between Deep Convection and Upper Tropospheric Cloudiness

D. A. Randall
K. Xu
Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523

The role of clouds has been identified as a key uncertainty in studies of global climate change (e.g., Cess et al. 1990). Among the most important clouds for climate are the cirrus, cirrostratus, and "anvil" clouds found in the upper troposphere. These clouds are often produced by the detrainment outflow from deep cumulus convection, but can also be forced by flow over orography and a variety of other mechanisms. They absorb much of the infrared radiation upwelling from below and re-emit it at much lower temperatures, thus producing a strong net radiative warming in the infrared part of the spectrum. Their tendency to cool the Earth by increasing its albedo is also important, but infrared warming typically dominates.

In support of the Atmospheric Radiation Measurement (ARM) program, we are developing an improved parameterization of upper tropospheric cloudiness, with emphasis on cloud formation, maintenance, and destruction (as opposed to cloud optical effects) by

- following the semi-empirical approach similar to that used by Xu and Krueger (hereafter XK) (1991)
- following, in parallel, a physically based approach based on the use of prognostic liquid/ice and variables, and an approach similar to that outlined by Randall (1989), together with an improved parameterization of moist convection
- conducting preliminary tests of the new parameterizations in a one-dimensional version of the Colorado State University (CSU) general circulation model (GCM), including tests in which the one-dimensional model is "forced" with observations (e.g., of large-scale vertical motion) collected at ARM sites
- using the UCLA cumulus ensemble model (CEM) to perform further tests of the parameterization, in part by simulating observations collected during ARM, and to suggest model-development strategies
- performing climate simulations with the full three-dimensional version of the CSU GCM
- making the improved parameterizations available and adaptable for use in other models, through use of suitable design strategies and also through ARM's Cloud and Radiation Testbed (CART).

The Colorado State University GCM is descended from the UCLA GCM. It includes advanced parameterizations of cumulus convection and boundary-layer clouds, as well as highly sophisticated numerical schemes (e.g., Randall et al. 1989). Cloud and radiation results produced by the model have been extensively compared with observations (e.g., Randall et al. 1985; Harshvardhan et al. 1989; Randall and Tjemkes 1991). Several model development efforts are currently under way at CSU, including coupling with an ocean model and incorporating a land-surface vegetation model with an explicit representation of photosynthesis.

The GCM can be run as a one-dimensional (1-D) model that represents a single vertical column in the GCM. The 1-D model includes all of the physical parameterizations of the GCM, including cloud formation. It is not based on a copy of the GCM; instead, the 1-D model is the GCM itself, simply recompiled and with appropriate input data. Provisions have been made to include the effects of prescribed large-scale divergence, pressure-gradient forces, and horizontal advection terms. As a result, the 1-D model is a convenient testbed for new parameterizations that are intended for use in the global model. It can also be used to isolate particular physical processes.

Randall et al. (1991) have published an example of an application of the 1-D model. The 1-D model was used to show that direct radiative-convective interactions can produce daily variability of the precipitation and other variables, with phase and amplitude similar to those observed over the tropical oceans. Randall et al. (1991) concluded that the stabilization due to absorption of solar radiation, primarily by clouds, tends to suppress convection during the afternoon, relative to the period before sunrise, and that this mechanism alone can account qualitatively for the observed diurnal cycle of precipitation over the oceans.

The UCLA cumulus ensemble model (CEM) is a two-dimensional cloud model that can be used to simulate the formation of an ensemble of clouds under a given large-scale condition (Krueger 1985, 1988; Xu and Krueger 1991; Xu 1991). The CEM includes a third-moment turbulence closure, a three-phase microphysical parameterization, and the Coriolis force. Radiative heating is currently prescribed as a function of height only; no cloud-radiation interaction occurs in the current version of the CEM. The CEM is being run at CSU and has been extensively and creatively used in studies of both cumulus convection (Xu 1991) and large-scale cloudiness (Xu and Krueger 1991).

The CEM has been used to perform numerical simulations with prescribed large-scale conditions (i.e., horizontally uniform large-scale vertical velocity and/or destabilizing and moistening rates, as well as large-scale pressure gradient forces) and underlying surface conditions. The horizontal domain is 512 km wide with a 2-km grid size.

The depth of the CEM domain is typically 19 km, with a stretched coordinate and 33 layers. Near the surface the grid interval is 100 m, while near the model top, it is 1000 m. The upper and lower boundaries are rigid. The lateral boundary conditions are cyclic. The initial thermodynamic conditions in any simulation are usually horizontally uniform. Clouds are initiated by introducing small, random temperature perturbations into the lowest model layer (centered at 47 m) after the first 30 minutes of integration so that their location and intensity are not pre-determined. Each simulation was run for five days or longer to generate a large dataset for statistical analyses.

The study of Xu and Krueger demonstrates that the CEM is a useful tool for cloud parameterization studies. Xu and Krueger evaluated the diagnostic cloudiness parameterizations used in large-scale numerical models or climate models. By analyzing the CEM-generated data, they showed that the total cloud amount can best be represented as the sum of separate estimates of stratiform and convective cloud amounts, based on different large-scale variables. This approach was shown to be superior to an estimate of the total (convective plus stratiform) cloud amount using any single large-scale variable. The stratiform cloud amount is best predicted on the basis of the relative humidity. The convective cloud amount, on the other hand, is best diagnosed by using the cumulus mass flux. Xu and Krueger showed that neither set of diagnostic relations depends significantly on the simulated cloud regime or horizontal averaging distance.

Xu and Krueger found statistically significant relations between large-scale cloudiness and several predictors, including large-scale relative humidity and large-scale vertical motion. We plan to pursue this approach by adding the prognostic cloud water variables as predictors. Preliminary results suggest that large-scale relative humidity and the large-scale average cloud water mixing ratio together serve as excellent predictors of cloud amount.

We plan to force both the 1-D GCM and the CEM with ARM data. This will allow a three-way intercomparison among the observations, the 1-D version of the GCM, and the CEM.

Three types of data are needed for use with the 1-D GCM and the CEM: initial conditions for the prognostic variables; boundary conditions, including forcing functions such as the large-scale divergence; and data for comparison with the model results. A list of the necessary data has been compiled but is omitted here for brevity.

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