Modeling of Clouds and Radiation for Development of Parameterizations for General Circulation Models

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Introduction

Atmospheric Radiation Measurement (ARM) Program research at NASA Ames Research Center (ARC) includes radiative transfer modeling, cirrus cloud microphysics, and stratus cloud modeling. These efforts are designed to provide the basis for improving cloud and radiation parameterizations in our main effort: mesoscale cloud modeling. Radiative transfer modeling is described by Kinne et al. (this meeting); stratus and cirrus cloud modeling efforts are described by Toon et al. (this meeting); and mesoscale modeling is described in this abstract.

Cloud Models for ARM

The range of non-convective cloud models used by the ARM modeling community can be crudely categorized based on the number of predicted hydrometers (Table 1). The simplest model has no predicted hydrometers and diagnoses the presence of clouds based on the predicted relative humidity. This scheme is used in many general circulation models (GCMs) and in numerical weather prediction (NWP) models. Some GCMs now include a single predictive equation for clouds.

The vast majority of cloud models have two or more predictive bulk hydrometers such as cloud water, ice water, rain, snow, graupel, etc. This method provides coarse size resolution by assigning a zero fall velocity to some species (cloud and ice) and non-zero fall velocities to other species. The assigned fall velocity depends on the density of the category, so that snow and graupel (with low density) fall more slowly than rain. Additionally, some models predict ice number concentration, from which a mean or effective particle radius can be calculated from the ice water concentration. This is valuable for calculating optical properties. The last class of model listed in the table is called size-resolving because each hydrometer category is subdivided into different bins, each with a different size. This subdivision allows the explicit calculation of hydrodynamical processes for each size, such as particle fall speeds or coalescence rates.

The Penn State/NCAR (National Center for Atmospheric Research) mesoscale model has been adapted at ARC to use several of the cloud schemes listed in Table 1. These include the relative humidity (RH), the bulk water (BW), and the size-resolving (SR) schemes. The implementation of the BW scheme uses only two species ($n = 2$): cloud/ice and rain/snow. The phase of the specie is determined by the grid box temperature. The SR model allows for twenty different sizes of ice nuclei, cloud droplets, and ice crystals, ranging from 0.01 to 600.0 micrometers, equivalent volume radius.

Our modeling approach allows us to intercompare the results of the various cloud schemes within the same dynamical framework, and the use of the PSU/NCAR mesoscale model allows us to compare our results with observations, instead of climate statistics.

The complexity of the BW and SR models is justified by the well-known sensitivity of cloud optical properties to particle size. The RH and simpler BW ($n = 1$ or 2) models use prescribed particle size when calculating optical properties. These prescriptions assume some dependence on temperature or altitude or phase. These assumptions may not be valid for both the tropics and mid-latitudes and polar regions, for multi-layer clouds, clouds in both the developing and dissipating stages, or for both the current and the future perturbed climate. The need to develop a general cloud model, valid for all cloud types and for all climates, demands that process models such as the BW (with $n =$ many) or SR be used.

Table 1. Explicit cloud models.

n[(a)]	Description	Application
0	Relative humidity model	GCM, NWP
	Bulk water cloud model	GCM
2-8	Bulk water model of cloud, ice, snow, graupel, etc. (minimal size, shape, and density resolution)	Mesoscales, cloud-scale future GCM
100	Size-resolving model: aerosol(r), cloud(r), ice(r), etc.	Mesoscales, cloud-scale

(a) n - number of predicted hydrometer variables.

We suggest that a GCM capable of answering the outstanding questions about climate change will be either an SR type or a BW type with more than several hydrometer classes. Accompanying this increase in cloud resolution, the grid resolution must increase in order to model the large-scale dynamical forcing of the cloud fields. Hence, we suggest that our modeling system using the BW scheme (with n greater than 5) or the SR scheme, on a grid of 100 kilometers or less, is a likely prototype of the GCM required to answer our questions about climate change and, at the same time, to allow direct comparison with Cloud and Radiation Testbed (CART) and other observations.

Initial Conditions

Using a limited-area modeling system to simulate observations requires accurate initial and boundary conditions. The National Oceanic and Atmospheric Administration (NOAA) Mesoscale Analysis and Prediction System (MAPS) analyses for the United States have been shown to be statistically more accurate than other National Weather Service (NWS) products, such as the Nested Grid Model (NGM), and are available every 3 hours. The analyses are a combination of current synoptic and asynoptic observations and the previous 3-hour forecast. The analysis does not directly include clouds so our model must generate its own clouds from the initial cloud-free condition.

For a particular case during NASA's First ISCCP[(a)] Regional Experiment (FIRE)-II program, we have found that this spin-up time can be greater than 12 hours. Specifically, by comparing the 11 micrometer blackbody temperature at the initial time with that derived by Minnis (NASA/LaRC) from satellite data, we find that the observed cloud field is much more widespread.

Later in the simulation, at 12 hours, when clouds were observed by radar and lidar at Coffeyville, the model shows no cloud, despite significant dynamical forcing (vertical velocities in excess of 6 cm/s). Although other explanations exist, one possibility is that the initial conditions of the upper level moisture field were too dry. The quality of the initial conditions will be investigated using the satellite analyses, lidar, and radar, as well as conventional data.

Cirrus Modeling With the Size-Resolving Model

Studies by Jensen et al. (1993a, 1993b) show that the one-dimensional SR model is capable of reproducing much of the structure of cirrus clouds. The model was used to study the sensitivity of simulated cirrus microphysical and radiative properties to poorly known model parameters, poorly

(a) International Satellite Cloud Climatology Project.

understood physical processes, and environmental conditions. The investigated parameters and processes included nucleation rate, mode of nucleation, ice crystal shape, and coagulation. The leading sources of uncertainty in the model were the phase change energy barrier, which dominates the homogeneous freezing nucleation rate, and the coagulation sticking efficiency at low temperatures, which controls the production of large ice crystals (radii greater than 100 micrometers). Jensen et al. found that the number of ice crystals that nucleates depended more on the slope of the cloud nuclei distribution at larger sizes than on the total number of cloud nuclei. Observed features such as an increase in ice concentration, a decrease in effective radius, and a decrease in ice water content with increasing cloud height were simulated.

While the microphysics of the SR model are capable of producing realistic clouds, the hydrostatic, 60-kilometer version of the PSU/NCAR Mesoscale Model 4 (MM4) does not produce the range of supersaturations that the SR model needs to drive the nucleation processes. For example, in a simulation for FIRE-II, the SR version of the model does not produce clouds over Coffeyville; whereas, the BW model does. The supersaturations were only a few percent and were too small for homogeneous nucleation to occur, but were sufficient to initiate the simpler BW nucleation scheme. This shortcoming can be corrected by using a finer scale model, such as the non-hydrostatic version of the PSU/NCAR model, or by parameterizing the subgrid-scale fluctuations in supersaturation using probability distribution functions related to the large-scale (hydrostatic) variables. We will pursue both approaches.

Cirrus Modeling With the Bulk-Water Model

The implementation of the BW model in the PSU/NCAR model has two predictive hydrometers: cloud/ice and rain/snow. The grid box temperature is used to determine whether the hydrometer is in a liquid or a solid state. This form of the BW model does not allow for mixed-phase clouds, a shortcoming that is not too restrictive when studying mid-latitude wintertime cirrus. This BW model also lacks a predictive equation for ice number concentration, which prevents a direct calculation of effective or mean particle size from the predicted ice mixing ratio. Hence, this BW model is not as general a model as we expect will be necessary for modeling the diverse range of clouds that influences climate. We plan to add a predictive equation for ice number concentration, but in the meantime, must specify the particle radii when calculating the optical depth.

To date, we have used several different values for the cloud, ice, rain, and snow particle radii. We have used 7 to 30 micrometers for water clouds and 100 to 300 micrometers for ice clouds. For rain and snow, we integrate over the size distributions implied in the BW scheme to determine effective radii ranging from 30 to 1000 micrometers. (The SR model, of course, explicitly predicts the size distribution so that the optical properties are directly calculated without assumptions as to the effective radius.)

A comparison of optical depths predicted by the model for the FIRE-II case shows that the larger specified values of cloud and ice effective radii are required to yield reasonable agreement with the optical depths calculated by Minnis et al. Differences may also be due to errors in the predicted mixing ratios of the hydrometers. We are now conducting a more thorough comparison between the BW and SR simulations and lidar, radar, and satellite data from FIRE-II.

Verification of the Model Simulations With CART Data

Our modeling must be validated on scales larger than the immediate CART site since small errors in the initial conditions outside the site could lead to errors over the CART site at the validation time. The need for multi-dimensional datasets when validating the predictions of mesoscale models cannot be overstressed, although a complete three-dimensional dataset for validating the model would require measurements beyond the scope of the CART.

More practically, we verify the model outside the CART site using conventional measurements such as sea level pressure, 500 millibar heights, and rainfall amounts. A more thorough validation inside and outside the CART site can now be carried out with the MAPS analyses and satellite analyses of visible and infrared cloud optical depth, cloud top height, blackbody temperature, visible cloud albedo, etc.

Aircraft measurements and or vertical profiling technologies such as lidar and radar and combinations of lidar and radar data will be needed within the CART site to validate the details of the cloud predictions. For example, the NOAA lidar and radar data have been combined to produce time- and cross-sections of effective radius during FIRE-II, and the University of Wisconsin VIL lidar is capable of determining a two-dimensional time-section of the cloud distribution of thin clouds. Some of these data sources are included in the CART design; we hope that others can be added in the future, at least during intensive observing periods (IOPs).

References

Jensen, E. J., O. B. Toon, D. L. Westphal, S. Kinne, and A. J. Heymsfield. 1993a. Microphysical modeling of cirrus. Part I: Comparison with 1986 FIRE IFO measurements. Accepted for publication by *J. Geophys. Res.*

Jensen, E. J., O. B. Toon, D. L. Westphal, S. Kinne, and A. J. Heymsfield. 1993b. Microphysical modeling of cirrus. Part II: Sensitivity studies. Accepted for publication by *J. Geophys. Res.*