A Stratiform Cloud Parameterization for General Circulation Models

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The crude treatment of clouds in general circulation models (GCMs) is widely recognized as a major limitation in applying these models to predictions of global climate change. The purpose of this project is to develop in GCMs a stratiform cloud parameterization that expresses clouds in terms of bulk microphysical properties and their subgrid variability.

Figure 1 summarizes the various cloud variables and their interactions. Precipitating cloud species are distinguished from non-precipitating species, and the liquid phase is distinguished from the ice phase. The size of the non-precipitating cloud particles (which influences both the cloud radiative properties and the conversion of non-precipitating cloud species to precipitating species) is determined by predicting both the mass and number concentrations of each species.

Cloud Microphysics

The cumulus cloud modeling community has developed several bulk cloud microphysics parameterizations that could, in principle, be applied to stratiform clouds in GCMs. However, because the time step required by such parameterizations is typically 10 seconds, direct application of current cloud microphysics parameterizations to GCMs is computationally impractical.

We have introduced two approximations (Ghan and Easter 1992) that together permit a tenfold increase in the permissible time step of a bulk cloud microphysics parameterization originally developed for mesoscale cloud models (Tripoli and Cotton 1980, Cotton et al. 1982 and 1986, Meyers et al. 1992). These approximations are

- assume precipitating particles fall so fast that the tendency term can be neglected and the concentration diagnosed from the balance between the source/sink terms and the divergence of the fallout
- assume snow melts instantaneously after falling below the freezing level.

The errors resulting from the approximations and the increase in time step are typically 15% for column cloud water and cloud ice. The resulting increase in efficiency permits application of the bulk parameterization to stratiform clouds in a GCM without greatly increasing the computational demands of the model. For example, when applied to the Pacific Northwest Laboratory's (PNL) version of the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM), the bulk cloud microphysics parameterization increases the computational time by about a factor of two.

The Colorado State University (CSU) bulk cloud microphysics parameterization offers most of the features of the desired treatment of cloud microphysics, but not all. In particular, droplet number concentration is prescribed rather than predicted in the CSU parameterization. To predict droplet number concentration, we are in the process of introducing the droplet number as a prognostic variable.

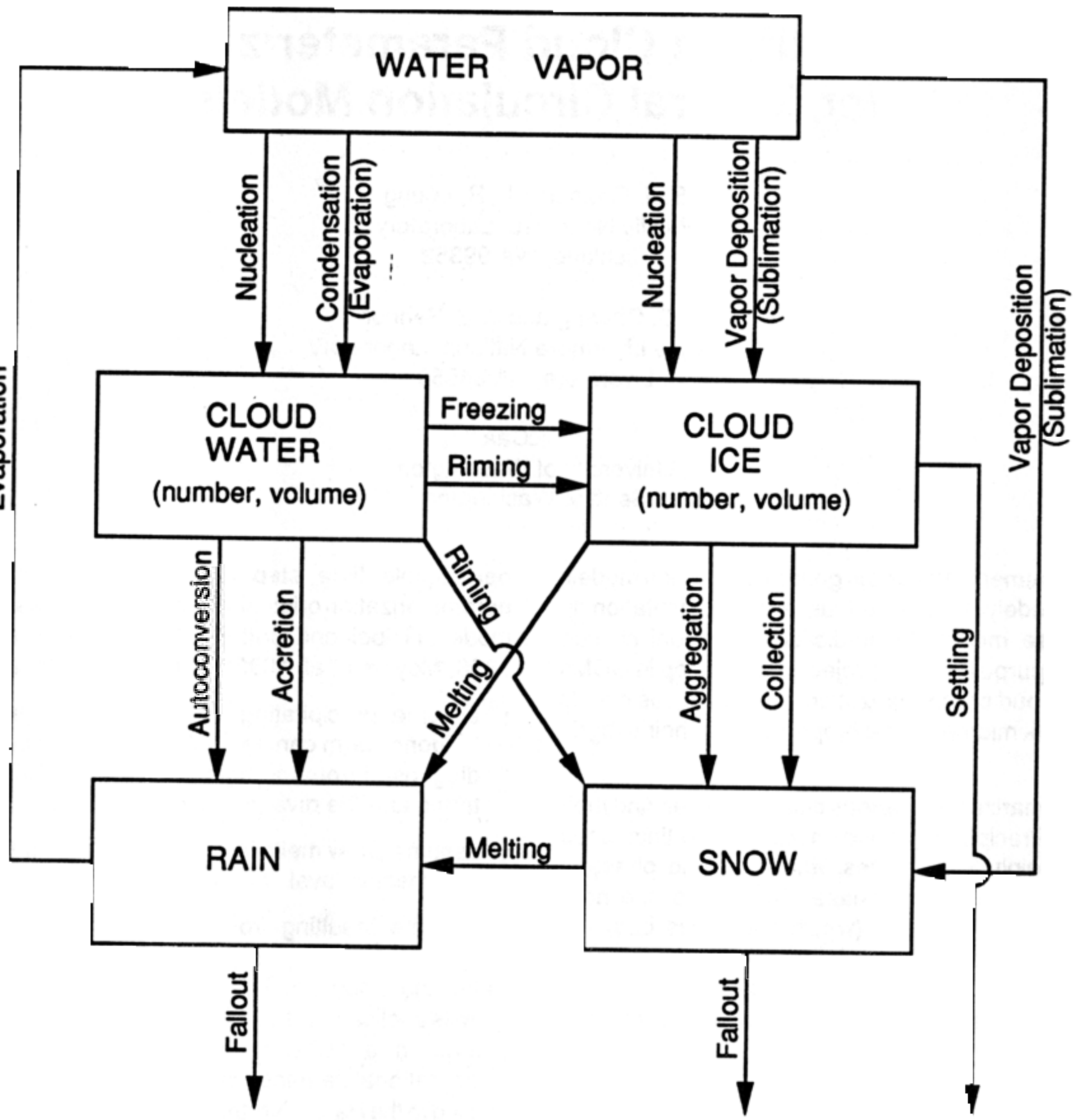

Figure 1. Cloud variables and microphysical processes represented in the stratiform cloud parameterization.

The sink terms in the droplet number balance follow from the sink terms in the cloud water mass concentration, assuming the sink processes affect the cloud water mass and number concentration, but not the average droplet mass. The droplet source reflects the nucleation of cloud droplets near the cloud boundaries and must be parameterized.

To parameterize the droplet nucleation process, we relate the number concentration of droplets nucleated, N_n, to the vertical velocity w and the aerosol number concentration, N_a, according to the simple expression

$$N_n = w N_a / (w + c N_a) \tag{1}$$

where c is a coefficient that depends on the temperature, pressure, aerosol composition, and the mode radius and standard deviation of the aerosol size distribution (Ghan et al., in press). The relationship shown in Equation (1) can be derived analytically from a number of approximations, including

- The aerosol size distribution is log-normal.
- Particle growth is due entirely to diffusion of water vapor.
- The droplet radius at maximum supersaturation can be approximated by the radius at the maximum of the Kohler curve for the aerosol.

The number nucleated according to Equation (1) has been compared with that simulated by a detailed size-resolving nucleation model (Edwards and Penner 1988) (see Figure 2). The number nucleated agrees to within 50% for vertical velocities ranging from 1 to 500 cm/s and aerosol number concentrations ranging from 50 to 5000/cm^3.

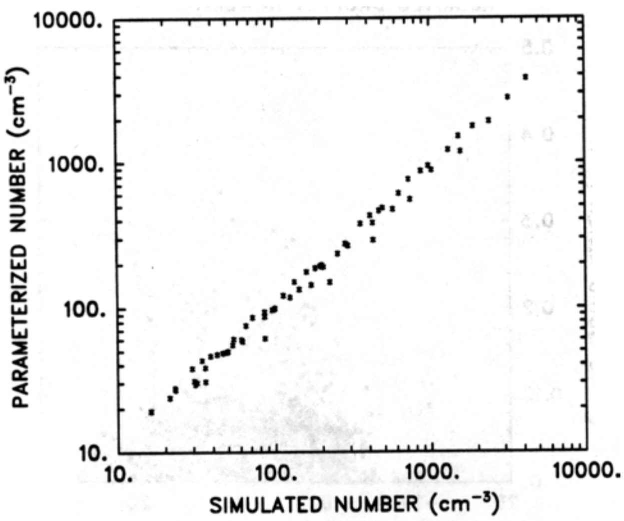

Figure 2. Droplet number concentration as parameterized versus simulated by a detailed size-resolving droplet nucleation model, for vertical velocities ranging from 1 to 500 cm/s and aerosol number concentrations ranging from 50 to 5000/cm^3.

Sub-Grid Cloud Parameterization

Sub-grid scale variations in cloud microphysical processes must be accounted for in GCMs because cloud processes are highly nonlinear and are poorly resolved by the coarse grid size of GCMs. We have initiated the development of a statistical formalism that expresses sub-grid scale variations in cloud microphysical properties in terms of idealized probability distributions. Joint probability distributions have been introduced to treat the dependence of many cloud microphysical processes on combinations of cloud variables. The Mathematica software is being used to analytically relate the parameters of joint probability distributions to the moments of the cloud variables.

Column Cloud Model

An essential task in developing cloud parameterization is its verification. Although some aspects of verification will be achieved using climatological simulations with a GCM, more control is possible by applying the cloud parameterization to forecast experiments in the field. This project will use the Atmospheric Radiation Measurement (ARM) Cloud and Radiation Testbed (CART) facilities to provide boundary conditions to drive a one-dimensional column cloud model and to provide cloud and radiation observations for model verification. The column model has been constructed and was used to develop the cloud microphysics parameterization. The same parameterizations of radiative transfer and cumulus convection used in the PNL version of the NCAR Community Climate Model (CCM1) have also been applied to the column model.

Application to a GCM

To apply the bulk cloud microphysics parameterization to a GCM, we have replaced the usual prognostic variables temperature T and water vapor mixing ratio r_v with the condensation-conserved variables

$$T_{cld} = T - L/c_p \, r_c$$

and

$r_w = r_v + r_c$

where L is the latent heat of condensation.

Temperature, water vapor, and the cloud water mixing ratio r_c can be diagnosed from T_{cld} and r_w by assuming condensation instantaneously eliminates supersaturations with respect to liquid water. Advection of cloud water is implicitly treated in the advection of T_{cld} and r_w, and therefore need not be treated explicitly, thus eliminating problems associated with advecting a field with frequent zeroes. This treatment of cloud water and cloud microphysics has been applied to the PNL version of the NCAR CCM1. A semi-Lagrangian scheme is used to advect total water, cloud ice, ice number, and cloud droplet number.

We have performed two short simulations with the GCM, one with and the other without the prognostic droplet number. Figure 3 shows a scatterplot of instantaneous cloud water concentration versus temperature for the simulation with a fixed droplet number (100/cm^3). At temperatures above freezing, a distinct threshold is evident, which reflects the autoconversion of cloud water to rain when the cloud droplet radius exceeds 10 microns. Some supercooled cloud droplets are present at temperatures as cold as -16°C.

Figure 4 shows the same scatterplot as Figure 3, but for a simulation with predicted droplet number. The number nucleated at cloud base is prescribed at 100/cm^3 rather than parameterized according to Equation (1) because sub-grid scale variations in vertical velocity have not yet been parameterized. The simulated droplet number concentration ranges from 100/cm^3 for a new cloud to much smaller concentrations for old cloud layers. Consequently, the threshold radius for autoconversion does not translate to a single threshold liquid water concentration. Cloud water concentrations are generally lower than for the fixed droplet number because the simulated droplet number concentrations are generally lower than the fixed number concentration.

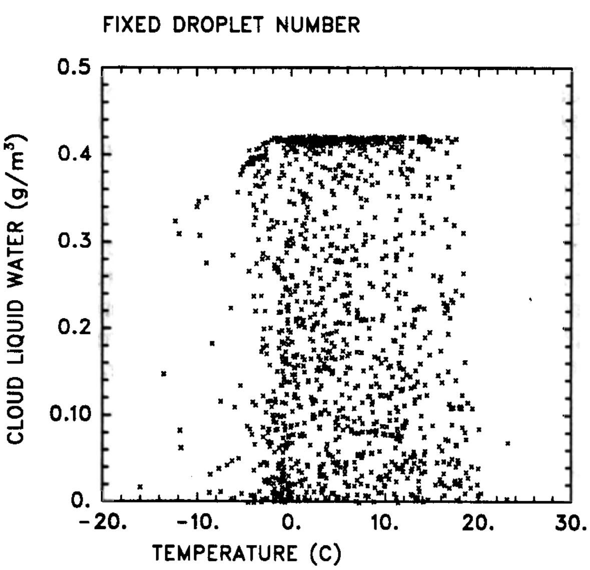

Figure 3. Instantaneous cloud water concentration versus temperature simulated by the PNL version of the NCAR CCM1 with bulk cloud microphysics and droplet number fixed at 100/cm^3.

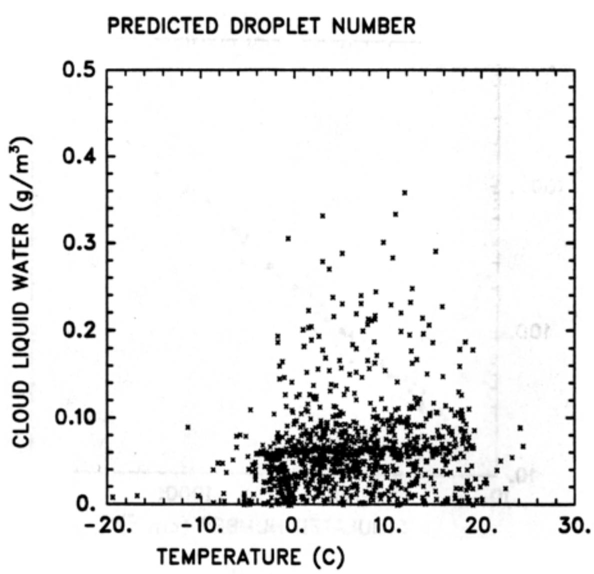

Figure 4. As in Figure 3, but for a simulation with predicted droplet number.

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