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Mixed-Phase Cloud Microphysics for Global Climate Models

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Summary

Mixed-phase clouds are composed of a mixture of cloud droplets and ice crystals. The partitioning of condensed water into liquid droplets and ice crystals in clouds varies throughout the life cycle of clouds, with droplets forming initially but crystals dominating later as ice forms first by crystal nucleation and then by vapor deposition. This report documents an ice nucleation parameterization and a vapor deposition scheme that together provide a physically-consistent treatment of mixed-phase clouds in global climate models. The ice nucleation parameterization accounts for homogeneous ice nucleation on sulfate aerosol and heterogeneous immersion nucleation on soot particles and deposition/condensation and contact mechanisms on dust particles. The vapor deposition scheme treats growth of ice crystals at the expense of cloud droplets. These schemes have been implemented in the National Center for Atmospheric Research (NCAR) Community Atmospheric Model Version 3 (CAM3) and tested for its functionality.

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1. Introduction

Mixed-phase clouds are composed of a mixture of cloud droplets and ice crystals. The partitioning of condensed water into liquid droplets and ice crystals in most climate models is specified as a function of temperature, but in nature the partitioning varies with time, with cloud water forming initially but cloud ice eventually dominating as ice crystals nucleate and grow at the expense of cloud water. This two-stage (nucleation and growth) process of ice formation in clouds has been known to be important since the early work of Bergeron (1935) and Findeisen (1938). As ice develops in clouds it influences all major cloud characteristics including precipitation formation (Tao and Simpson 1993; Tao 2003), interactions with radiation (Ackerman et al. 1998; Ackerman 1988; Martin et al. 2001; Liu et al. 2003; Toon et al. 1989), latent heat release and cloud dynamics (Willoughby et al. 1985; Simpson et al. 1967; Lord and Lord 1988), and water vapor content (Schiller et al. 1999; Gierens et al. 1999; Heymsfield et al. 1998).

Ice crystal nucleation involves a variety of mechanisms, each of which involves aerosol particles. There are two main classes of mechanisms: homogeneous and heterogeneous. Homogeneous nucleation involves homogeneous freezing of supercooled cloud or haze droplets. Heterogeneous nucleation involves aerosol particles that serve as some kind of substrate that matches the crystalline structure of ice. Heterogeneous mechanisms include direct deposition from vapor to ice on a suitable nucleus (deposition nucleation) and freezing of previously condensed supercooled cloud or haze droplets, with the freezing initiated either by contact of a nuclei with the cloud or haze droplet (contact nucleation) or by a nuclei immersed within the cloud or haze droplet (immersion nucleation).

While the influence of aerosols on cloud droplet nucleation has received considerable attention from the climate research community, the connection between aerosols and cold clouds is presently considered to be too uncertain to even speculate on whether it would be a positive or negative radiative climate forcing (Penner et al. 2001). Furthermore, because tropospheric air enters the stratosphere predominantly in the tropics by upward transport, the formation of tropical cirrus layers influences the stratospheric water vapor content (e.g., Danielsen 1993; Potter and Holton 1995). Recent indications that stratospheric water vapor concentrations are increasing (Rosenlof et al., 2001; Oltmans et al., 2000) have intensified the urgency of understanding the processes controlling water vapor in the tropical tropopause layer.

This report documents the ice nucleation parameterization and the water vapor deposition schemes that have both been implemented in to the NCAR Community Atmosphere Model, Version 3 (CAM3) and together provide a physically-consistent treatment of mixed-phase clouds in CAM3.

2. Parameterization Description

2.1 Ice Nucleation

Most aspects of the ice nucleation treatment that has been applied to CAM3 are based on the Liu and Penner (2005) ice nucleation parameterization, which was developed to determine the number of ice crystals (N_{nuc}) formed through homogeneous ice nucleation on sulfate aerosol and heterogeneous immersion nucleation on soot particles in cold clouds. In the Liu and Penner (2005) parameterization, ice number N_i depends on temperature, updraft velocity, sulfate and immersion IN (e.g., soot) number concentrations and was derived by fitting the results from a large set of cloud parcel model calculations covering different conditions in the upper troposphere. Our cloud parcel model was part of the Cirrus Parcel Model Comparison Project (CPMC) of the GEWEX (Global Energy and Water Experiment) Cloud System Study (GCSS) Working group on Cirrus Cloud Systems (WG2) (Lin et al. 2002).

The threshold relative humidity with respect to water (RH_w, in units of %) for homogeneous ice formation was fitted as a function of the temperature at which freezing commences (T, in units of °C) and the updraft velocity (w, in units of m s^{-1})

$$RH_w = A\,T^2 + B\,T + C, \tag{1}$$

where $A = 6\times10^{-4} \ln w + 6.6\times10^{-3}$, $B = 6\times10^{-2} \ln w + 1.052$, and $C = 1.68 \ln w + 129.35$. For higher T and lower w (the fast-growth regime), ice crystal number density $N_{i,a}$ (in units of cm^{-3}) from homogeneous freezing, as a function of T, w, and sulfate aerosol number concentration $N_{i,a}$ (in units of cm^{-3}) is given by the following power law function between $N_{i,a}$ and N_a

$$N_{i,a} = \min\left\{\exp(a_2 + b_2 T + c_2 \ln w) N_a^{\,a_1 + b_1 T + c_1 \ln w}, N_a\right\}. \tag{2}$$

For lower T and higher w (the slow-growth regime) a formula similar to Eq. (2) is obtained

$$N_{i,a} = \min\left\{\exp\left[a_2 + (b_2 + b_3 \ln w) T + c_2 \ln w\right] N_a^{\,a_1 + b_1 T + c_1 \ln w}, N_a\right\}. \tag{3}$$

The two regimes are differentiated by

$$T - 6.07 \ln w + 55.0 = 0. \quad (4)$$

Thus, when $T \geq 6.07 \ln w - 55.0$, or when $w \leq \exp[(T + 55.0)/6.07]$ the fast-growth regime is used.

The description of immersion ice nucleation in Liu and Penner (2005) is based on the classical theory (Pruppacher and Klett 1997; Fletcher 1962). The threshold RH_i for immersion nucleation is rather insensitive to the temperature and updraft velocity, and is ~120% when using a compatibility parameter m_{is} of 0.5 and ~130% when using m_{is} of 0.1). The critical soot number concentration $N_{s,c}$ (in the unit of cm^{-3}) for the heterogeneous nucleation-only regime is derived as

$$N_{s,c} > \exp\left\{\frac{12.884 \ln w - 67.69 - T}{1.4938 \ln w + 10.41}\right\}. \quad (5)$$

The number of ice crystals formed from immersion nucleation of soot ($N_{i,s}$, cm^{-3}) in the heterogeneous nucleation regime (determined from Eq. 5) is given as

$$N_{i,s} = \min\left\{\exp\left[(a_{21} \ln w + a_{22}) + (a_{11} \ln w + a_{12})T\right] N_s^{(b_{21} \ln w + b_{22}) + (b_{11} \ln w + b_{12})T}, N_s\right\}, \quad (6)$$

and values of the coefficients in Eq. (6) are given by: $a_{11} = 0.0263$, $b_{11} = -0.008$, $a_{12} = -0.0185$, $b_{12} = -0.0468$, $a_{21} = 2.758$, $b_{21} = -0.2667$, $a_{22} = 1.3221$, $b_{22} = -1.4588$.

The Liu and Penner (2005) ice nucleation parameterization does not treat contact and deposition nucleation, so other parameterizations are applied to CAM3. In mixed-phase clouds with temperatures between -40° and -3°C, contact freezing of cloud droplets through the Brownian coagulation with insoluble IN is considered (Young 1974). The change in ice number concentration is

$$J_{frz,cnt} = 4\pi r_v N_d N_{cnt} D_{cnt} / \rho_0, \quad (7)$$

where r_v is the volume mean droplet radius, N_d is the number concentration of cloud droplets with values prescribed in the standard CAM3, ρ_0 is the air density, D_{cnt} is the Brownian aerosol diffusivity, and N_{cnt} is the concentration of contact IN which is parameterized by

$$N_{cnt} = N_{a0} (270.16 - T)^{1.3}, \quad (8)$$

with N_{a0} the number of active ice nuclei at 269.16 K. Here we assume that all contact IN are mineral dust (Lohmann 2002), and N_{a0} is then given by the number concentration of dust particles. The Brownian aerosol diffusivity is given by

$$D_{cnt} = \frac{k_B T C_c}{6\pi\mu r_{cnt}}, \tag{9}$$

where k_B is the Boltzmann constant, μ is the viscosity of air, r_{cnt} is the aerosol number mean radius, and C_c is the Cunningham correction factor.

We assume that mineral dust can act as deposition/condensation IN (DeMott et al. 2003; Sassen 2005) as described by the Meyers et al. (1992) parameterization:

$$N_{i,d} = \exp\{a+b[100(RH_i-1)]\}, \tag{10}$$

where $N_{i,d}$ (l^{-1}) is the number of ice crystals predicted due to deposition nucleation, a = -0.639, and b = 0.1296.

2.2 Ice Depositional Growth

In most current global climate models (including NCAR CAM3) the liquid and ice are repartitioned according to a temperature-dependent fraction of ice in total water (linear temperature interpolation between -40° and -10°C) after advection. In this way models avoid the representation of a variety of processes (e.g., the Bergeron-Findersen process, contact nucleation, splintering, evaporation, energy transitions, etc.) in mixed-phase clouds.

In order to describe the ice formation process more realistically, we added the Rotstayn et al. (2000) scheme to represent vapor deposition on ice crystals, which accounts for the dependence of vapor deposition on crystal size and reduces time truncation errors. The total amount of cloud ice water that is converted from water vapor in a time step Δt in the grid box is given by

$$\Delta q_i = \min\left[q_v, \left(\frac{2}{3} c_{vd}^s \Delta t + q_{i0}^{2/3} \right)^{3/2} - q_i \right], \tag{11}$$

where $q_{i0} = \max(m_{i0}Ni/\rho_0, q_i)$ and q_i is the grid average cloud-ice mixing ratio prior to the vapor deposition calculation, m_{i0} is the initial mass of ice crystals (=10^{-12} kg). The rate constant c_{vd}^s in (11) is given by

$$c_{vd}^{s} = 7.8 \frac{(N_i / \rho_0)^{2/3} (RH_i - 1)}{\rho_i^{1/3} (A'' + B'')}, \quad (12)$$

where

$$A'' = \frac{L_s}{K_a T} \left(\frac{L_s}{R_v T} - 1 \right) \quad (13)$$

and $B'' = R_v T / \chi e_{si}$ are terms representing heat conduction and vapor diffusion, respectively. Here χ is the diffusivity of water vapor in air, which varies inversely with pressure p as χ =2.21/p in SI units, L_s is the latent heat of sublimation of water, R_v is the specific gas constant for water vapor, K_a is the thermal conductivity of air, e_{si} is the saturation vapor pressure with respective to ice, and ρ_i is the ice crystal density. The vapor deposition, combined with a treatment of riming of droplets on ice crystals, permits explicit treatment of the Bergeron-Findeisen process (in which crystals grow at the expense of evaporating or collected cloud droplets), rather than simply diagnosing the condensate phase from temperature.

3. Testing

The new scheme has been successfully compiled and tested in the CAM3 climate model and found to be functional. Few tests were performed to confirm the functionality of the new scheme. It is concluded that the scheme is ready for further testing and evaluation.

4. Results

In this report, the Liu and Penner (2005) ice nucleation scheme accounting for the homogeneous nucleation on sulfate and heterogeneous nucleation on soot particles is documented as implemented in the NCAR climate model, CAM3. Parameterizations for contact freezing of cloud droplets and deposition/condensation nucleation on mineral dust which are important in mix-phase clouds are also presented. A scheme for vapor deposition on ice crystals (Rotstayn et al. 2000) is introduced to provide a realistic representation of crystal growth and droplet evaporation in the mixed-phase clouds. Implementations of both parameterizations in the CAM3 were found to be functional.

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