CAM Microphysics Task Group
Strategy/Roadmap/Design Template
December 2005

Purpose: This document outlines the scientific basis, requirements and implementation for advancing the microphysical processes in the NCAR Community Atmosphere Model (CAM). This document is intended to serve as a guideline for microphysics development of CAM over the next few years. It was developed as part of a workshop of the CAM Microphysics Task Group, held from 8—10 November, 2005 in Boulder, CO.

Outline: There are 3 sections: I. Processes and Methods, II. More detailed requirements and code descriptions, and III. Implementation. The processes and methods section describes the critical processes, and possible approaches used or proposed for global models. The requirements and code description section provide information about fields required by the microphysics from CAM to produce a reasonable parameterization and fields required by CAM of the microphysics. The implementation section describes how the approaches are to be applied to the model. More information and updates will also be available on the web at http://www.cgd.ucar.edu/cms/meetings/microphys.

INTRODUCTION: Science Goals

There are several important science drivers which are pushing development of the representation of microphysics in global models, and specifically in the Community Atmosphere Model (CAM3). This is an important background to the development process. These science drivers should also guide the development process of the model, by helping define and prioritize 'critical processes' One view might be that complexity in the model (as represented by computational cost) should only be added when it can assist or affect one of the science drivers listed below.

Aerosol Indirect Effects (AIE) or aerosol-cloud coupling is probably the most important driver for improving the representation of cloud microphysics. Aerosol indirect effects rely on modifications to particle sizes, and nucleation of cloud particles may be strongly dependent upon the distribution of aerosols. Thus attempting to (1) explicitly treat the distribution of droplets/crystals in clouds, (2) appropriately nucleate, grow, and precipitate clouds, and (3) treat the radiative fluxes of emission and absorption associated with these clouds is critical. Since indirect effects may have important implications for anthropogenic forcing of climate, this is a tremendously important problem.

Shortwave cloud forcing and feedbacks are a significant uncertainty for estimating the global climate sensitivity. Low level stratiform clouds form over large regions of the earth's surface, and have a strong cooling effect, reflecting shortwave (solar) radiation. How the brightness and area of these clouds will respond to climate change is an important issue, and the microphysics of these clouds may affect their feedback on climate.

Aerosol and Chemical Processing in Clouds is potentially important for indirect effects as well as the transport and lifetime of many important atmospheric trace species. Chemical effects within clouds and cloud particles may significantly modify the distribution of aerosols and their composition. Soluble species may undergo chemical transformations or scavenging within clouds, with important potential impacts on atmospheric chemistry.

Reduction of biases in the representation of climate should also be a key component of any modifications to the existing parameterizations. There are significant biases in the current representation of the climate system in CAM. Changes to parameterization suites that reduce the biases relative to observations are important. In addition, new parameterization suites which better represent a process must not adversely affect the sum of those processes in the system. Some examples of important biases include the overestimate of liquid water path in mid-latitude storm tracks or the lack of appropriate spatial and temporal variability in tropical convection and precipitation.

Practically, in 2-3 years candidate parameterizations will be evaluated as part of the atmospheric model, and as part of the coupled CCSM system. Parameterizations that increase run time without introducing important feedbacks or increasing the accuracy of the simulation relative to observations are unlikely to be used in the next model release. Further discussion of this point is listed under requirements in section II below.

SECTION I: Processes and Methods

(1) What are the critical processes?

1.1 Turbulence & subgridscale motions.

Subgridscale turbulence and cloud processes drive the vertical transport of cloud and chemical species and the activation of aerosol species to form cloud droplets and ice crystals. This can affect drop circulation, in-cloud residence time and the efficiency with which clouds generate precipitation. They are also important inputs to statistical cloud schemes (Tompkins, 2002; Klein et al., 2005). Ideally CAM would have a unified treatment of turbulence and cloud mass flux (Lappen and Randall, 2001a,b,c).

The current microphysical parameterization does not require this information. Future parameterizations will require statements about the mean vertical velocity of a model cell, the subgridscale velocity inhomogenieties within the cell, and possibly a statement about the rate of mixing within the cell, (e.g. the rate at which in-cloud inhomogenieties mix with each other and the rate at which the clouds and environment mix. This kind of conceptual framework is present in the early Tiedtke cloud scheme. The inhomogenieties probably differ in stratiform and convective situations.

There are several ways of getting information on sub grid scale velocity perturbations. These perturbations can be derived from the turbulence, particularly in the boundary layer. There is little diagnosed turbulence in the free troposphere. Information about sub grid scale vertical motions is also contained in the vertical diffusion, shallow convection, deep convection, and gravity wave parameterizations. It is hoped that these various sources can be used to generate a reasonable sub grid vertical velocity distribution, probably as a single standard deviation for each grid cell. This should be sufficient to drive a detailed microphysical scheme. Any parameterization should be checked against aircraft observations of vertical velocity.

1.2 Sub-grid scale humidity distributions

The subgrid statistical distribution of total humidity drives much of the subgrid variability in clouds and cloud microphysics. Relative humidity variations can be driven by specific humidity (water vapor) fluctuations or by subgrid fluctuations in temperature, though the two are often not coupled. A statistical cloud scheme (Tompkins, 2002; Klein et al., 2005) would use turbulence, vertical velocity, and precipitation to diagnose the parameters of an idealized distribution of total humidity. For warm clouds, the statistical distribution of cloud water can be diagnosed from the statistical distribution of total humidity by assuming supersaturation with respect to liquid water is small (Smith, 1990). The same assumption can be applied to cloud water in cold clouds as well, but the distribution of cloud ice concentration must be subtracted from the total water. The statistical distribution of cloud ice should not be diagnosed because the supersaturation with respect to ice depends on the cloud life cycle; the distribution should be predicted by applying the statistical distribution of supersaturation to ice nucleation and vapor deposition.

There are several conceptual complications with integrating a ‘sub grid’ humidity scheme with detailed microphysics. Detailed microphysical schemes generally assume homogeneity across the domain. They know nothing about the ‘sub grid’ or about a ‘cloud fraction’. It is possible to integrate microphysical expressions over statistical distributions of the cloud variables (Pincus and Klein, 2000; Ovtchinnikov and Ghan, 2005). However, such analytic integrations are not feasible for many processes and statistical distributions, and numerical integrations may be too computationally expensive. Initially it may be possible to simply have an ‘in-cloud’ water amount diagnosed from the grid average and some knowledge of ‘cloud fraction’. Ideally, the cloud fraction may need to be re-diagnosed after modification of clouds by a microphysical scheme. Further conceptual development of these ideas will be necessary.

Measurements of humidity distributions at the ‘sub-grid’ scale in the troposphere and lower stratosphere are available from in-situ aircraft observations (e.g. Korolev and Isaac 2005). Distributions for various flight campaigns can be combined into sample PDFs by location and level.

1.3 Distribution of clouds

Given the distribution of humidity, the liquid cloud fraction within each layer can be diagnosed by assuming liquid water condenses for relative humidity exceeding 100%

(Smith, 1990). The ice cloud fraction requires consideration of ice nucleation and vapor deposition. Cloud fraction can be combined with cloud mass flux to diagnose cloud updraft velocity. Cloud overlap specifications are needed for both radiation (including photolysis calculations) and microphysics (droplet nucleation and droplet collection by precipitation). It should be a requirement that the particular overlap assumptions be treated consistently within the radiation and cloud microphysics. Two methods have been used in GCMs in the past: 1) an analytic expression for the overlap, and explicit solution techniques that depend on that overlap assumption; 2) a separate parameterization that maps from the analytic overlap expression to an independent pixel approximation (e.g. a division of each column into a set of homogeneous subcolumns, see Jakob and Klein, 1999). It is probable that the radiation codes for CAM will be moving to an Independent Column Approximation (ICA) for consistency. The statistics of the ensemble of subcolumns agree with the original statistical statement of overlap. Improvements to the maximum/random overlap scheme have been recently developed by P Raisanen (2005, in press).

Observations of cloud distributions can be compiled from geosyncronous or polar orbiting nadir looking IR sensors, at least to get top level cloud. Lidar (ground based or satellite such as CALIPSO) and cloud radars (again, ground based and possible satellites like TRMM and CLOUDSAT) can be used to get cloud structure information. A combination of methods and sensors will be necessary to develop a good sub-grid scale distribution of clouds. Measurements will also vary by region: stratocumulus regions will need different measurements than deep convective regions.

1.4 Cloud microphysics

As a minimum, cloud properties must be represented in terms of cloud droplets, ice crystals, rain drops, and snow. Number as well as mass must be determined for cloud droplets and ice crystals. Rain and snow can be diagnosed rather than predicted from their mass balance by neglecting their tendency terms. Most detailed schemes do use prognostic equations for precipitation. It may be desirable to actually carry 2 moments (mass and number) for rain to allow a proper treatment of evaporation.

Several two-moment bulk schemes have been developed that could be used (Ghan et al., 1997a,b; Morrison et al., 2005); the challenge will be to integrate them with the statistical framework and with cloud fraction parameterizations discussed above. Other two-moment schemes, include Seifert and Beheng (2001, 2005), Milbrandt and Yau (2005), Meyers et al. (1997), Feingold et al. (1998)

In addition, more complete “size resolved” or “bin microphysics” treatments (Toon et al., 1988; Jensen et al., 1994; Jacobson, 2003) could be used for reference simulations, provided they use the same subgrid humidity and updraft information used by the bulk schemes. At lease one of these schemes (CARMA, Toon et al 1998) is currently being implemented in the CAM framework. Ice particle shape must somehow be determined so that its impact on vapor deposition, sedimentation and radiation can be represented.

Cloud microphysical processes involve exchanges between different particle types and between particle types and water vapor. Essential processes are listed below. Four processes were thought to be most important: Autoconversion, contact nucleation, condensation nucleation and vapor deposition

Droplet nucleation or activation. A physically-based treatment requires information about the aerosol properties (see 1.7), cloud fraction/overlap, and cloud updraft velocity. Subgrid variability in updraft velocity may be important. Abdul-Razzak and Ghan (2000, 2004) and Fountoukis and Nenes (2005) parameterize the nucleation process. Integration over the cloud updraft velocity and cloud fraction can be treated following Ghan et al. (1997b) and Ovtchinnikov and Ghan (2005). Size-resolved schemes may not be suitable for this process in global models because they require explicit prediction of supersaturation.

Crystal nucleation. A variety of mechanisms (homogeneous and heterogeneous) may be involved. A physically-based treatment also requires information about aerosol properties and updraft velocity, plus the supersaturation with respect to ice. Subgrid variability in updraft velocity and supersaturation may both be important. Lohmann (2002a,b), Lohmann and Karcher (2002), Karcher and Lohmann (2003), Lohmann et al. (2004), and Liu and Penner (2005) have developed treatments of both homogeneous and heterogeneous nucleation. Sub grid vertical velocities can be derived as discussed in Section 1.1. Supersaturation for ice will ideally be diagnosed directly rather than specified. Clearly, homogenous nucleation (or homogenous freezing) is the place to start. The theory for homogenous freezing is fairly well established. Heterogeneous nucleation theory is advancing rapidly.

Droplet condensation/evaporation. It is reasonable to assume condensation bounds relative humidity with respect to liquid water at 100% (Kessler, 1969). The treatment must be integrated with the statistical distribution of total water (Smith, 1990). It is not clear whether droplet number is depleted by evaporation in proportion to cloud liquid water or liquid cloud fraction. Previous treatments have assumed the latter.

Vapor deposition/sublimation for ice crystals. Ice nuclei concentrations are too low to assume vapor deposition bounds relative humidity with respect to ice. An explicit (or semi-analytic: Rotstayn et al., 2000) treatment of deposition/sublimation is required. It should be integrated with the statistical distribution of total water.

Evaporation for rain. The current formulation of evaporation follows Kessler, and Sundqvist. It is probably overly simplistic, and alternate forms should be considered. Schlesinger et al. (1988) (one-moment scheme) and Feingold (1993) (two moment scheme) are candidates.

Condensation on rain can be neglected because excess water can be assumed to condense on droplets. However, the cloud overlap issue is important for this term.

Vapor deposition/sublimation for snow. An explicit treatment following Byers (1965) should account for cloud overlap.

Autoconversion of droplets to rain. The treatment should depend on droplet number as well as cloud water. Recent work by Khairoutdinov and Kogan (2000), Liu and Daum (2004), Liu et al. (2004, 2005) and by Wood (2005) looks promising. The impact on droplet number could be approximated by assuming autoconversion decreases droplet number in proportion to cloud water (i.e., the droplet size distribution does not change), but in some schemes (Khairoutdinov and Kogan, 2000) the droplet size distribution shifts and droplet number decreases before cloud water does. Additional multimoment schemes include Seifert and Beheng (2001), Feingold et al. (1998). A table lookup method may be most efficient.

Conversion of ice to snow. At the very least, the treatment should distinguish between the ice and clear fraction of the grid cell. The current formulation follows formulations of Cotton et al. (1986) and Lin et al. (1983). Newer treatments are possible.

Sedimentation of ice, snow, rain. The dependence on crystal shape and of course particle size distribution should be treated. The settling velocity within precipitating core is required. Treatments by Locatelli and Hobbs (1974), Lin et al. (1983), Cotton et al. (1986), Mitchell (1996), Ivanova et al. (2001), and Mitchell and Heymsfield (2005) are available. Sedimentation for bulk moment schemes can be formulated quite accurately by using a-priori bin truncations, applying bin fall velocities, and resumming moments at the end of the operation (Feingold et al. 1998).

Collection of cloud water by ice, snow, rain. Collection is proportional to the product of the cloud water and the concentration of the precipitating species, so integration over the joint statistical distribution is required. Cloud overlap is critical here (Jakob and Klein, 2000). Microphysical formulations are available from Tripoli and Cotton (1980), Cotton et al. (1986), and Lin et al. (1983).

Collection of cloud ice by snow. Can probably be treated the same as for cloud water.

Freezing. Droplet freezing is probably covered by homogeneous ice nucleation.

Melting of ice and snow. Thermodynamic equilibrium is often assumed, but may not be valid.

Optical properties. Optical properties for each distinct water species are required (see below). The necessary optics should include sufficient information to calculate photolysis rates for simulations which include chemistry. New developers should plan to provide information on the longwave and shortwave radiative properties for each type of cloud condensate. The level of sophistication of the statement of optical properties can vary, for example some developers may prefer to provide single values of optical properties (e.g. single scattering albedo in the shortwave). Others may prefer spectrally resolved values. What will be the fundamental optical properties we will use?
The radiation group strongly recommends instead that the cloud and aerosol developers specify a method for computing cloud and aerosol optical properties as a function of model state and diagnostic variables for input to the radiation computation. All optical properties should be traceable to the original assumptions regarding microphysical and chemical properties. I.e. the optics must be reproducible and adaptable to arbitrary spectral discritization.

1.4.1 Observations of Microphysics

Measurements will be necessary for evaluating cloud microphysical schemes. Some of these processes are somewhat ‘ad-hoc’ (autoconversion) and do not have direct analogues. Size distributions of cloud particles in various cloud types and their evolution will be necessary to evaluate the integrity of the microphysical schemes proposed. Ice and liquid water contents are basic important measurements. Shape information of cloud particles may also be necessary. Observations of updraft velocity, relative humidity and aerosol distributions will be critical for understanding nucleation and particle growth processes. Some in-situ data sets from field campaigns have been analyzed for this purpose.

Recent measurements of the ice particle size distribution in frontal and cirrus clouds indicates that it is bimodal, with the small particle mode having particle lengths less than 100 μm and peak concentrations often 2 orders of magnitude greater than the large mode. The small mode comprises roughly 10-35% of the total IWC in mid-latitude cirrus (Ivanova et al. 2001) and 30-60% in tropical anvil cirrus (McFarquhar and Heymsfield 1997). A test of any ice cloud microphysics scheme would be to predict the observed temperature dependent ratios of number concentration, mean size and IWC between these two modes, as well as the mean length for the small mode, which for mid-latitude cirrus is quite stable at about 27 μm ± 3 μm. Observations indicate that the temperature dependence of the small mode-large mode interrelationship is reversed for mid-latitude cirrus relative to tropical anvil cirrus clouds. These considerations are important since the observations indicate that the small mode can often dominate the radiative properties in tropical anvil cirrus clouds.

There is a need for more laboratory studies of the ice processes and their interactions. Most of the parameters which are currently used in formulation of ice processes have been obtained from 1-2 studies done 40-50 years ago. We need to know parameters of ice processes with accuracy comparable to those of the warm rain processes. Currently our knowledge of ice processes is unsatisfactory for development of reliable models of ice particles formation and growth.

1.5 Convection

This topic is intimately tied to section 1.1. The distinction occurs because vertical motions are sufficiently rapid that even smaller cloud particles cannot be viewed as residing within a grid volume during a typical model timestep. Cloud microphysics plays an important role in convective as well as stratiform clouds. If the most important role of convective clouds is to transport moisture and chemical species upward, cloud microphysics governs the efficiency of that transport. Ideally the treatment of convective clouds would be integrated with the statistical cloud framework. Assuming that does not happen in the near term, some effort should be devoted to improving the treatment of cloud microphysics in a cumulus convection scheme (Zhang et al., 2005). This is a challenging task, because the equilibrium framework requires integration upward to determine the precipitation formed by autoconversion, and integration downward to determine the collection of cloud water by precipitation. Since cloud water is involved in both integrations, the problem may be ill-posed. Considering cloud overlap makes the problem even more difficult. A prognostic framework may be more tractable, but may also prove to be impractical.

To date only one candidate convective parameterization attempts to include significant microphysics (Donner). Ideally, the microphysics represented in convective clouds should be the same as, or at least consistent with the microphysics for stratiform clouds, which in the context of this document we refer to generically as ‘microphysics’ or the microphysical parameterization. In order to actually derive any microphysics from the convection, it will need to supply a vertical velocity or a spectrum of vertical velocities. It is hoped that a key subset of the most important microphysical processes could be incorporated into the convective parameterization. A vertical velocity is also important because from a mass flux, mass of detrained condensate AND vertical velocity an area fraction of convective cloud can be consistently determined. The issue of convective cloud fraction is ill posed without a vertical velocity. Vertical velocities may also allow a better representation of detrained condensate (see below).

Another key role and interaction of convection is to detrain cloud condensate, water vapor and aerosols. These species will probably be input into the microphysics scheme for determination of convective ‘anvil’ properties and evolution. It is critical that the output from the convection be sufficient to drive the microphysics. Mass detrained may not be enough, and some representation of number concentration or size will be important. The critical aspect from the microphysics is simply that with the input from convection the cloud + detrained mass will be substantially different (mass of condensate, phase, size distribution and aerosols) than that in an in situ stratiform or cirrus cloud formed or maintained in the absence of convection.

Detailed measurements of convective cloud properties (including cloud distributions) and microphysical information described above (hydrometeor size distributions, aerosol populations, ice and liquid water content) are necessary. In addition, to help evaluate and constrain cloud mass fluxes, transport tracers (such as Radon gas [222Rn]) would be valuable. NOx (produced by lightning) is another useful tracer.

1.6 Aerosol-cloud interactions

One motivation for improving the treatment of cloud microphysics in CAM is to facilitate the treatment of cloud-aerosol interactions. In order to begin the estimation of microphysical rates, information on the number of activated drops is necessary. This calculation is likely to be an intermediate step between the aerosols and cloud microphysics in the model. Several possibilities exist for treating this process (see below). In addition, the cloud processes will have to scavenge aerosol mass as drops precipitate, and will have to also consider what happens to the aerosol if a cloud evaporates before precipitating (see resuspension below). An aerosol size distribution in the form of a few size bins is currently available in CAM, and testing of detailed bin aerosols (up to 30 bins) is also ongoing.

The treatments of droplet and crystal nucleation discussed above address the influence of aerosols on clouds. Clouds influence aerosols through several different mechanisms.

Activation. This process determines how which aerosol particles enter the cloud phase. Once the supersaturation in cloud updrafts has been determined from a parameterization, the size distribution of the activated aerosols can be easily diagnosed (Abdul-Razzak and Ghan, 2000; Fountoukis and Nenes, 2005). This process is much more important for droplets than crystals because so few particles are ice nuclei. Some models keep track of dissolved aerosol inside of drops. This enables local resuspension of aerosol upon complete evaporation, as well as coalescence scavenging (process whereby aerosol decreases in number due to drop coalescence), and scavenging by rain. Candidates include Flossmann et al. (1985), Toon et al. (1988), Feingold et al. (1996).

Vertical transport. The mass flux framework of cumulus parameterizations can be applied to both interstitial and cloud-phase species.

Impacts on chemistry. Aqueous chemistry is an important source of sulfate mass and depends on cloud water mass and cloud fraction as well as concentrations of SO_2 and oxidants. Barth et al. (2000). In addition, cloud microphysics affects the formation of aerosols through its impact on photolysis rates and through the washout of soluble chemical species.

Resuspension. Activated aerosol particles are resuspended when droplets evaporate completely. This depends on the treatment of droplet evaporation. This is less important for precipitation (as the number of precipitating drops is likely small relative to total aerosol, see below), but is likely quite important to treat properly for cloud particle evaporation. While number of aerosol may not be conserved (due to coagulation for example), mass should be conserved.

Nucleation scavenging. Activated particles are scavenged from the atmosphere if the cloud precipitates and the precipitation reaches the ground. Unless the particles are carried in the rain phase it will be necessary to assume that particles are scavenged from the atmosphere when the cloud precipitates. This introduces a bias only if rain drops evaporate completely before reaching the surface. If the cloud-phase particles are not predicted separately from the aerosol phase (Jones et al., 2001; Easter et al., 2004), it will be necessary to diagnose the cloud-phase. Several methods are available, including prescribing the cloud-phase fraction when clouds are present (Barth et al., 2000; Tie et al., 2001; Iversen and Seland, 2002; Stier et al., 2005) or diagnosing the cloud-phase from a prescribed supersaturation (Adams and Seinfeld, 20002) or threshold size for activation (Spracklen et al. 2005).

Impaction scavenging. All aerosols can be scavenged by impaction by precipitating rain and snow, though some are scavenged more efficiently than others. Dana and Hales (1974) and Slinn (1984) describe widely used methods. It will be necessary to know the precipitating fraction of the grid cell to treat this properly. This process also depends on the size distribution of aerosol and raindrops.

Detailed measurements of aerosol size distributions and composition are necessary for understanding this problem. Again, these should be available from in-situ aircraft. Bulk aerosol properties may also be available from satellite sensors, ranging from nadir views of extinction to detailed vertical structure information from cloud and space based lidar measurements. Nucleation and activation will require evaluation against laboratory and chamber studies.

1.7 Aerosol specific properties

To provide an aerosol context for the treatment of cloud microphysics, the representation and composition of aerosol properties should be clarified. The composition of aerosols depends on the emissions, transport and chemical transformation of aerosol precursors. The formation of sulfate depends on the oxidation of DMS (by OH or NO_3) and of sulfur dioxide by OH, or H_2O_2 or ozone in cloud droplets. The composition of inorganic aerosols further depends on the atmospheric ammonia cycle, and odd nitrogen cycle (through the concentration of HNO_3) and is further modified through interactions with dust (see for example Tang et al., 2004). Ideally the internally mixed aerosol composition should be diagnosed using a thermodynamics module for calculating gas-particle equilibrium concentrations among aerosol ions and their gaseous precursors (e.g., SCAPE: Simulating Composition of Atmospheric Particles at Equilibrium). In addition, secondary organic aerosol formation requires simulating the oxidation of higher order organic molecules.

To treat the effects of aerosol on both droplet number and crystal number, aerosol properties should be expressed in terms of composition and size distribution rather than CCN or IN concentration. Size distribution can be expressed in terms of either a small number of modes (typically log-normal) or a modest number (up to twelve) of sections (Toon et al., 1988; Adams and Seinfeld, 2002; Colarco et al., 2002; Jacobson, 2002). The mass concentration of each important component of the CCN and IN concentration (sulfate, seasalt, soil dust, black carbon, and organic carbon as a minimum) should be predicted for each mode or section, and number concentration should also be predicted, particularly for the modal representation (Easter et al., 2004). The width of the modes or sections can be prescribed. It may be necessary to predict both the cloud-phase and the aerosol-phase particles, though it should not be necessary to advect the cloud-phase particles (Koch et al., 2005). For each component the hygroscopicity (and refractive index) must be specified so that the bulk hygroscopicity (refractive index) of each mode or section can be determined. For organic carbon, the dependence of its surface tension on its concentration should be specified (Li et al., 1998; Abdul-Razzak and Ghan, 2004).

As noted above, measurements of detailed aerosol size distributions and composition will be necessary to understand aerosol properties. Laboratory measurements of aerosol properties will also be necessary to fill in details.

Aerosol optical properties should also come in here – e.g., the semi-direct effect.

1.8 Cloud-radiation interactions

Cloud radiative properties (optical depth, single-scatter albedo, asymmetry factor) can be expressed in terms of cloud microphysical properties using any of several schemes available for droplets and crystals. Requirements are that the schemes account for the dependence on liquid and ice water content, particle number concentration or mean size, particle shape, chemical composition, and the width of the size distribution and be sufficiently general to account for the photolysis of chemical species. For a statistical cloud scheme it may be necessary to integrate across the distribution of liquid and ice water path, though a pure independent pixel approximation may be preferable Accounting for cloud overlap within this context may be particularly challenging, and may require an approximate sampling technique such as that proposed by Pincus et al. (2003).

In the case of ice clouds, the shape or bimodality of the size distribution becomes a factor since representing the size distribution with an "effective diameter" (D_e) to obtain cloud radiative properties works well only for monomodal size distributions (Mitchell 2002). Errors from using D_e increase as the small mode mean size decreases. Indirect aerosol effects will likely manifest through the small mode primarily, and it is not clear how sensitive a D_e approach would be to indirect aerosol effects.

The microphysics should be prepared to supply a detailed interpretation from the cloud properties to optical properties which can be efficiently parameterized upon model initialization (e.g. through a lookup table). In addition it is hoped that this treatment can be based on first principles (Mie calculations) rather than field data if possible. It is also desirable that the optical properties be specified for arbitrary spectral resolution to allow the radiation flexibility on this point.

Laboratory and atmospheric measurements of radiative properties are available from ground based sites and in-situ measurements, which will have to be carefully combined.

2. **Microphysical Methods**

Suitable treatments for individual processes have been described for most of the above processes. Some labor savings might be possible if there are any integrated packages already available. Although there are packages that treat the set of desired cloud microphysics processes efficiently, and there are packages that treat subgrid variability in some aspects of clouds, there are no packages that treat subgrid variability in microphysics processes. Here we list microphysics packages that with some effort might be integrated with a statistical representation of clouds.

Two important general questions arise from the context of a global model with resolutions expected to be on the scale of 10's to 100's of kilometers (practically 50-250km). The first is to consider the appropriate timescales that can be represented, with a typical model time step of 20-30 minutes. Time splitting for faster processes is possible, but expensive. Second is to recognize the spatial scales involved and to develop a strategy for size resolution of hydrometeors and aerosols given the bulk nature of the global model grid box.

The first step is to decide on a strategy for size resolution of hydrometeors (and aerosols). A moment approach or bin approach, or perhaps some combination (e.g., multiple moments in individual bins; Tzivion et al. 1987). Another option is the quadrature method of moments (e.g., McGraw, 1997), which does not require basis functions. Whatever approach is taken it would be nice to be able to modify as computation time increases. Issues for discussion: equivalence between number of moments and number of bins; basis functions; sensitivity to high order moments. These issues are discussed in more detail under section (3) the discussion of hierarchy of approaches. In general a moment scheme is thought to be most appropriate for the scales of interest. Making the scheme flexible and extensible is desirable, so that additional moments could be added, or individual processes can be parameterized in different ways, or even turned off all together if they are not found to significantly impact global simulations.

With all of these schemes, most large-scale treatments must have some sort of explicit closure. This complication, which is not generally present in mesoscale or LES models arises because there is usually fractional condensation (cloudiness) in a large (order 100km grid cell), and there are other processes as well which contribute to condensation (such as detrainment from moist convection).

With respect to implementation of these schemes, high resolution LES models with bin resolving/spectral microphysics are a good tool for parameterization development. Observations are important as a source for verification of such models; however, they rarely contain integrated and comprehensive data needed for parameterization development of the processes listed.

Verification of such models is, therefore, also of primary importance. We need to raise the bar for what constitutes a robust verification of a model used for parameterization development. It is not enough to compare, e.g., "average drop spectrum" in the model with some average spectrum from observations. Instead emphasis should be on the ability of a model to match statistical distributions of a *set of drop spectrum parameters*. For instance, a comparison should be made between *histograms* of the modeled and observed set containing 5-moments of the DSD, such as: concentration, mean radius, liquid water content, precipitation flux, radar reflectivity.

Parameterization development would be significantly accelerated if a community model with explicit microphysics will be available.

2.1 Detailed model approaches/parameterizations.

These detailed schemes cover quite a range, and use bin microphysics or variations on bin microphysics calculations, such as parameterizations based on ‘bin microphysics’ calculations. These schemes include the detailed CARMA code (Toon et al., 1988, Jensen et al., 1994). Also the model of Jacobson (2003). There are a series of multi-moment bin methods covering both warm and cold cloud microphysics by Feingold et al. (1994, 1996) and Reisin et al. (1996) Adams and Seinfeld (2002) have a detailed scheme which is based on the Feingold and Reisin work. In addition there are detailed schemes by Kogan (1991) and Ovtchinnikov and Kogan (2000).

None of these schemes may be suitable for droplet nucleation in CAM because they require extremely short timesteps (less than 10 s) and an explicit treatment of condensation in updrafts to predict supersaturation.

An additional problem arises in integrating these schemes with fractional cloudiness. They can operate just on the cloudy portion of the grid box, but this requires some sort of closure assumption (which typically comes from diagnosing humidity or supersaturation rather than prediction). Using a series of independent columns or a sample of independent columns is one way around this problem.

2.2 Bulk or two-moment schemes

There are also several available bulk or two moment schemes which may be suitable. These include Milbrandt and Yau (2005), Meyers et al. (1997) and Feingold et al. (1998). Ghan et al. (1997a,b) has implemented a microphysical scheme in CAM already, which may be useful to explore. This scheme also has nice extensions to activation of existing CAM aerosols. Morrison et al. (2005) have developed a two moment microphysical scheme which has been applied to mesoscale models. The treatment may be suitable for climate models as well.

For ice nucleation there are several schemes designed for global models by Lohmann et al. (1999, 2002, 2004). Liu and Penner (2005) have developed a suite of ice nucleation schemes that is currently being tested in CAM. There is also a scheme by Seifert and Beheng (2001, 2005), but the later may not be suitable for CAM because it requires explicit prediction of supersaturation.

2.3 Aerosol physics

The details of the aerosol physics are somewhat exogenous to the treatment of microphysics. As noted in section (1) we really only need to state what we require as input from the aerosol microphysics. It is likely that the microphysics will work with a module or parameterization that activates droplets and passes them and the aerosol composition and mass to the microphysics, which will take care of the growth, evaporation and sedimentation. Some possible aerosol physics schemes include those of Easter et al. (2004), Herzog et al. (2004), Liu et al. (2005) and Binkowski and Roselle (2003)

One advantage of this approach is that the microphysics can be designed to work with a detailed aerosol package if people want to implement and run it. The required level of detail for aerosol composition will depend on the process. For droplet activation, Ervens et al. (2005) suggests that composition effects on activation are much less important than previous studies have suggested. For direct and semi-direct radiative forcing, composition information may be more important. The microphysics should be able to conserve, scavenge, and resuspend aerosol mass.

3. Hierarchy

A tool such as CAM is used for a wide variety of applications, and is also being applied across a wide range of scales. The issue naturally arises whether there should be a range of levels of sophistication for both clouds and aerosol microphysics. It is likely that we will not be able to run climate simulations with a detailed ‘bin’ microphysical or aerosol scheme, but these schemes may be very useful for testing.

Overall, the time and space scales of the model should dictate the appropriate hierarchy. Given the 20-200km possible range of CAM resolutions for the lifetime of a microphysics code (10 years or so), and more importantly, given timesteps of 20-30 minutes, a detailed bin approach is probably not feasible. Two-moment schemes that carry number and mass of condensate are probably sufficient. Implementation of such a scheme will require some further information (vertical velocities) as well as some conceptual changes. It is also likely beyond the available CCSM resources to support more than one microphysics code.

However, it is likely that a hierarchy will develop within a supported framework. For example, individual processes and components listed under section 1.4 for microphysical tendencies can be used differently by different researchers. It is likely that some of the terms which never dominate the tendencies may be dropped in a 'supported' scheme, but others can add them.

Is this a time to try to build a scalable scheme that can expand to more bins/moments as computation power increases? The option of broad bins with multiple moments in a bin may also be worth considering (e.g. Tzivion et al. 1987). In this conception, a 'bin' is simply a constituent, such as cloud ice, which can have additional moments (a size distribution). Adding another 'bin' and moments would be simply making the distribution multi-modal. In the case of ice crystals, adding a second bin for 'small crystals' would make the distribution bimodal. Such flexibility would be desirable.

Also desirable would be flexibility for implementing different microphysical schemes from smaller scale models. The Weather Research and Forecast model (WRF) is an example of a source for detailed microphysical schemes. There is significant interest from several quarters in possibly adapting WRF microphysical schemes to CAM. In addition, there is a nascent effort to produce a unified multi-scale model framework integrating WRF and CAM, and commonality to the microphysics would be useful. To accomplish this goal, an 'interpretive' module for WRF microphysics might be developed, that would allow a scheme designed for WRF to function in CAM. Practically it appears that there are few software barriers to this (both models have similar engineering frameworks). There are a few conceptual issues, particularly related to the stability of schemes at CAM timesteps (order 20-30 minutes), and to the representation of 'cloud fraction' or sub grid heterogeneity generally. Some treatments like vertical velocity variations are treated, but many are not. Schemes must also conserve mass and energy (most do explicitly conserve mass, moist static energy might not be conserved to CAM standards). Allowing sub-stepping in time is also a possible option for detailed schemes. These issues are worth resolving to enable flexibility.

SECTION II: REQUIREMENTS/CODE DESCRIPTION DOCUMENT

Design of the requirements needs to refer back to the science questions in the introduction. The major questions we seek to answer include aerosol indirect effects, cloud radiative forcing and feedback, chemistry and bias reduction. The requirements for each piece of the code should flow from these requirements and the necessary complexity and interactions in the code. This section will describe the basic 'requirements' in terms of science, software design, numerics and evaluation. It will then describe some of the key input and output issues, and develop a schematic template based on the discussion in section I.

1. Requirements

The framework of a global general circulation model of the atmosphere which is coupled to other component models of the earth system imposes a number of restrictions on the conceptualizing and implementation of a detailed microphysical scheme. The microphysics naturally interacts with transport, dynamics and heating terms, and has a strong impact on radiation. These science requirements, detailed below, have lead to the design of a standard programming interface for CAM, which is described in brief, and is described in detail in an on-line document. These software requirements and science requirements lead to certain numerical requirements, and requirements for testing. A suggested evaluation strategy is described for candidate parameterizations that are used by model developers at NCAR, but is freely available for others.

1.1 Science Requirements

The fundamental science requirement of any candidate physics parameterization is the *conservation of mass & energy.* There are strict tests for such conservation in the model, and these must be adhered to. The fundamental nature of this requirement flows directly from the science interest in simulating global climate over long periods of time. Loss of mass or energy would be of the same magnitude or larger than the signals being sought (in CO2, in heating or cooling, etc).

Note that this requirement means that models designed to understand climate have as their highest priority, consistent treatment of the energy balance and radiation. Hence in CAM the radiation is last physical processes calculated each time step, while in many cloud and mesoscale models the microphysics is calculated last, since the most important processes are precipitation and the latent heating associated with condensation, and radiative processes are secondary. This becomes important since many detailed microphysical schemes do not strictly conserve moist static energy.

Conservation of mass is also fundamental. The atmospheric mass must remain stable, and all trace species (including water) must be conserved, since molecules are not created or destroyed through (most) physical processes. Chemical processes may modify the mass of trace species. In particular, it is required that water substance as the sum of all phases be conserved. This is critical for the moist static energy balance, and it is also critical for properly treating aqueous chemistry, including aerosols, chemical processing and isotope of water.

A second science requirement is that microphysics codes must scale: they should be able to run anywhere on the planet, and be stable (see below under numerical requirements for a more detailed discussion of stability) under all conditions and cases. Thus a common framework must work for condensation and precipitation in warm marine boundary layers, in cirrus, in frontal and arctic conditions. Such schemes must also be stable for condensation in extreme atmospheric conditions, or expressly not run for those conditions, such as polar stratospheric clouds, and polar mesospheric clouds.

The global nature of the simulations means that schemes should find a way to deal with sub grid variability of many of the input fields. This starts with the probability that the model will separate cloud and environmental fields in some way: either by estimating 'in cloud' and 'clear sky' fractions of the grid box, or by creating independent columns as described in section I. These concepts bring along a host of complexities which may need to be considered. These include most importantly the subgrid distribution of vertical velocity and water substance in all three phases. It also includes treating the complication of assuming how overlap between cloud layers is treated, particularly for precipitation.

Furthermore, the science drivers are pushing us towards schemes that can in some way treat the size distribution of cloud particles and aerosol, and the composition of aerosol. Current treatments (single effective diameter) are probably not sufficient.

1.2 Software design requirements

For implementing a microphysics scheme, we will rely on standard CAM physics interfaces, described in the "Interface to column physics and chemistry packages" (http://www.ccsm.ucar.edu/models/atm-cam/docs/phys-interface/) for CAM4. This document describes a generic FORTRAN90 'interface' that makes it easier to bring any new parameterization into the framework of CAM. The coding standards for CAM are very similar to those of WRF for example, which should conceptually make it straightforward to do any software engineering for a microphysics scheme from WRF to be adapted to CAM.

We describe the basics of the interface briefly here. Essentially the interface requires a register of fields, an initialization component, and a run time component, constructed in a module. It needs to meet several detailed standards for interfacing with the rest of the code. These standards are designed so that a parameterization can be independent of the model gridding, parallelization and underlying dynamics and transport.

1. At run time the physics parameterizations will input the model state and the state of all fields in 'state' and 'physics' buffers. A parameterization works on randomly positioned columns and will pass tendencies back to the code, which will update the physics buffer.

1.3 Numerical requirements

Time steps: The global model also enforces requirements on the numerical implementation of any scheme. As has been noted before, model time steps are many minutes, typically 20-30 minutes. This may require time splitting for some processes, but it is desirable to avoid such time splitting if possible. More important is that the scheme remain stable in this range of time steps. That may be a problem for some fast prognostic processes, such as rain.

Unit tests: In addition, it would be very advantageous to be able to design unit tests for the microphysics code. A 'unit test' is a problem with a known (often analytical) solution that can be used for testing whether a parameterization is behaving as it should. Conservation of mass is an example of a type of unit tests. These unit tests are built into the model, especially for energy conservation, as well as for water vapor tracers.

Convergence: any scheme should converge with respect to horizontal and vertical resolution as the model is run. As resolution increases, it would be desirable that the answer should converge. This may be problematic for processes that rely on 'sub grid' variations, or in-cloud and out of cloud distinctions.

Error growth: the scheme should be stable for small perturbations to parameters. A small change in the location on phase space should not lead to wildly different solutions. This may be difficult to achieve with schemes that are inherently non-linear (autoconversion is an example, saturation is another example), but the scheme can be designed to be slightly smoother.

1.4 Evaluation of simulations

Another important requirement is evaluation of simulation performance. This should occur against benchmarks as development proceeds. The two types of benchmarks commonly used are 'control' simulations and observations. The discussion of processes contains some information on observations that can be used for evaluating parameterizations.

Control simulations should also be documented, to the extent that the control simulation performance must also be evaluated. These simulations are usually existing model runs that have already been evaluated. Evaluation should also recognize that common standards of model performance must be maintained relative to observations, and 'biases' relative to observations should not be made substantially worse without reason. For example: top of atmosphere energy balance is critical for steady state simulations.

A comprehensive, flexible and extensible evaluation package has been developed at NCAR for use with CAM. The package is described at: http://www.cgd.ucar.edu/cms/mstevens/diagnostics/ . It uses NCL (NCAR Command Language) to generate graphics from CAM output and archived datasets, creating as output a compressed archive of web pages that can be unpacked on a web server. The diagnostic can run as a difference between two model runs, or comparing a model run to observations. The observational data is also available.

Ideally evaluation should be performed as changes are made to the simulations, and the evaluations archived (the simple all in one web site facilitates this). That way a record of model changes can be constructed, with the contribution of incremental changes to model performance. It also allows a more complete metric, if some particular bias or change results which was not anticipated, the evolution of that bias or change can be quickly evaluated.

2. Input/Output variables and their interactions

The processes and requirements of the global model environment allow a detailed conceptual model to be developed. This section described what each package or parameterization might do (which piece of the science problem it is addressing). It discusses some of the interaction among processes, and then proceeds to a discussion of a model framework and expected input and output variables. This framework is a conceptual piece, which is a work in progress.

2.1 Some considerations between processes

Likely processes we will have to consider for interactions with microphysics and science drivers are: Microphysics, Aerosols, Cloud and Humidity distributions, Convection, Radiation, and possibly Chemistry.

Cloud fluxes and transport. Cloud schemes will have to have explicit 3D transport, and may need to be consistent with sub-grid cloud fraction schemes and a humidity distribution. A humidity distribution at the sub grid scale (even if it is just cloud and no cloud), will be supplied to a cloud scheme.

Aerosols and microphysics/condensation. The aerosols should supply to the large scale condensation scheme a size distribution (number, size, mass: enough to reproduce it) and composition information, even if this must be specified or taken from climatology. In reverse, microphysics/condensation can modify and scavenge the aerosols, changing the aerosol distribution. What should be the parameters for an aerosol size distribution? (Number, mass, dispersion, composition, others?)

Aerosols and radiation. Aerosol distribution should be passed to the radiation scheme, so that absorption and scattering can be performed.

Aerosols and chemistry. Aerosol size and composition should be supplied to the chemistry scheme for possible evolution. Chemistry need do nothing with this information and leave aerosols untransformed, or chemical processing can take place. Photolysis (photochemistry) will also likely happen here. This likely will happen after radiation.

Cloud microphysics and radiation. Cloud particle size distributions should be passed to the radiation scheme.

Cloud microphysics and deep convective parameterization. Microphysics should be consistent between deep convection and large scale condensation. How will this work? Does the same microphysics happen twice? Does convection happen first?

2.2 What tasks are the responsibility of each 'package'?

Referring back to section I: we have various different parameterizations that act on processes. In designing an integrated set of physics (and not just a single parameterization), it is necessary to divide responsibilities and determine up front which parameterizations will handle which processes. Packages can take on more than one subset of processes. A partial set of such requirements has been described. At a minimum, the parameterization should specify some value for a parameter listed as a required output. In CAM3 for example, there is no specification of a size distribution, but a particle size ‘distribution’ or at least a number concentration, can be calculated from the total condensate and the specified single particle size.

This is only one such possible set, and is related to the input and output variables described below. The responsibilities detailed below are described in Figure 1, accompanying this document.

Microphysics: The microphysics will handle particle size distributions. It has also been proposed that the initialization of the microphysics also describe the optical properties of all possible particle size distributions. The microphysics will calculate precipitation terms, and will determine the final values of condensation and evaporation of cloud water. It will also need to specify the transformation of aerosols: scavenging in precipitation and resuspension by evaporation. It is expected that the microphysics will be passed information on droplet and crystal number and mass. This will include the detrained mass from convection. The microphysics will also need a subgrid vertical velocity. It will also have to work in the context of some ‘fractional’ cloud cover, and may work on subcolumns. There may be an ‘interpreter’ for the microphysics which would handle some of the sub-grid issues, and possibly condensation closure to facilitate the integration of detailed codes into the model.

Aerosols: The aerosol package or a separate code will be ‘required’ to provide activated droplets (mass and number) to the microphysics scheme. This ‘activator’ will need information on model state and subgrid vertical velocity distributions. The ‘activator’ could be driven by either specified or prognostic aerosols, and should be able to handle convective detrainment as well. The aerosols themselves will be transformed by the microphysics, and mass will be ‘resuspended’

Vertical velocities: vertical velocities will need to be described for aerosols, microphysics and within convection. Simple empirical relations could be used, but ideally information from 'sub grid dynamics' such as turbulence, diffusion and gravity waves, should be used to determine vertical velocity spectra.

Radiation: The radiation package as mentioned in section I will need a coherent and physical description of the optical properties of the assumed cloud size distributions.

Convection: ideally needs to not just have a mass flux, but some idea of vertical velocities. From a mass, a mass flux and a vertical velocity, the area fraction of convection can be determined. Convection should provide some information on not just mass, but number concentration of aerosols as well. If the conceptual implementation of the scheme does not permit this, it is likely that some sort of transport module or 'convective detrainer' may be necessary. This is important for aerosol activation as well.

Cloud distributions: a scheme that determines the fractional cloudiness must make sure that it is consistent with the condensate. Such a scheme should determine a provisional value for condensation and evaporation. Fractional cloudiness may need to be recalculated after the microphysics is called as well to make sure that microphysical processes have not emptied clouds of water. Some cloud overlap assumptions must be made, and the treatment be acceptable for the microphysics. It may be possible to use some form of the independent column approximation with a limited number of columns. Conceptually this scheme must be integrated with the microphysics.

2.3 What are the input and output variables?

Based on the science drivers, processes and the interactions above, several specific output variables will be 'required'. These requirements are based on (1) science drivers directly and (2) input variables for other processes necessary for trying to meet the science drivers. For example: we want to know the size distribution of cloud particles for all clouds in order to use this information in the radiation code, and simulate aerosol indirect effects.

Not every variable is listed, only variables not currently in the state or physics buffers in the model (e.g.: water mixing ratios, temperature, winds). These variables are also listed in Figure 1.

Turbulence:

Input: turbulence kinetic energy, gravity waves (orographic, non-orographic) at present time step (or previous if not yet available).

Output: subgrid vertical velocity, or simply a variance of vertical velocity

Aerosol or 'Aerosol Activator'

Input: cloud fraction, updraft velocity, composition and size distribution of aerosol

Output: number of activated droplets and crystals, number and mass of activated aerosol

Convection:

Input: model state, aerosols

Output: transport terms, mass flux, vertical velocity, area fraction, detrained condensate (mass and number)

Radiation:

Output: heating rates (from previous time step)

Input: from microphysics, size distributions to handle optical properties

Microphysics:

Input: cloud condensate (ice and liquid) mass and number with a cloud fraction, or simply the 'in-cloud' content., rain and snow mass and number

Output: Tendencies for aerosol, precipitation (rain mass and number, snow mass), tendencies for state variables (temperature, water vapor) and cloud condensate.

2.4 Conceptual scheme for detailed microphysics

The accompanying diagram takes the interactions and required inputs and outputs, and attempts to describe a self-consistent microphysics scheme implementation and its integration with other expected model components. The basics of the scheme are discussed above with the detailed inputs and outputs. The diagram in figure 1 and description below assume a fairly detailed 2-moment cloud microphysics scheme, carrying number and mass for liquid and ice. Rain and snow are assumed in this case to be diagnostic (not prognostic), with mass and number for rain, and just mass for snow. Radiation is assumed to use an independent column approximation.

The microphysics will be passed information on condensed species from convection or an interpreter for convection, and a spectrum of activated droplets and crystals from the aerosol scheme or a set of activation codes. The aerosol activation and microphysics will need subgrid vertical velocities, which can be generated from sub-grid scale dynamics such as turbulence and gravity wave schemes.

The microphysics scheme will also have to be integrated conceptually with the representation of sub grid processes. In the current formulation of CAM, this is achieved through a cloud fraction scheme, which provides a fractional cloud cover. Future schemes may also diagnose condensate, which can either be used as a closure for the microphysics, or be used as an initialization, with a final value updated at the end of a timestep. There may be some information as well on the distribution of humidity within a grid cell. Assumptions about cloud overlap will also have to be made. Alternative treatments of sub-grid cloud would divide the grid box up into independent columns with uniform characteristics (cloudy, not-cloudy by column and level). Radiation will likely use independent columns.

Ideally, some or all of the interface issues described above could be placed in a macro-micro physics interaction module. This would facilitate using other microphysical frameworks (bin treatments, or simply additional bins. The goal would be to move the closure assumptions of the interaction piece if possible

For outputs, the microphysics must do appropriate 'bookkeeping' for aerosols, returning the mass and number, converted to cloud-phase, depleted by precipitation, and resuspended. It will return tendencies for temperature and all the water species, including rain and snow. There will also be an optics 'package' to translate size distributions into optical properties for use by the radiation code as discussed under processes in section I.

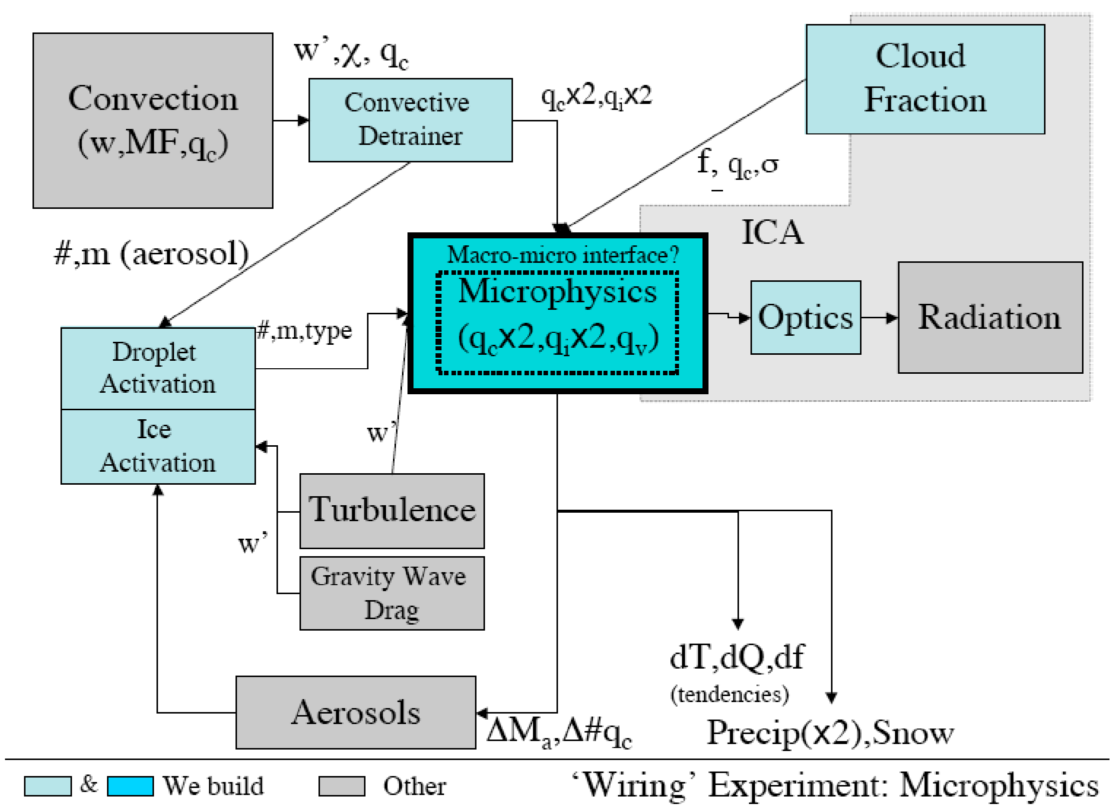

Figure 1: Conceptual framework proposed for new CAM microphysics

SECTION III: IMPLEMENTATION

(1) Entrepreneurial microphysical and aerosol efforts in CAM

A series of various projects is underway of interest to CAM community. This is a partial list of contributed projects.

Leo Donner (GFDL) discussed cloud scale vertical velocities in the GFDL GCM and the Donner convection scheme.

Ben Johnson (NCAR) discussed the implementation of a PDF cloud scheme in CAM. He described progress to date, as well as some of the conceptual issues.

Steve Ghan (PNNL) discussed prediction of droplet number in CAM and incorporation of aerosol indirect effects. One result appears to be the reduction of Liquid Water Path in the model, which is a known bias.

Jon Egill Kristjansson, (University of Oslo) detailed a new prognostic cloud droplet number parameterization for NCAR CAM, and coupling to a detailed aerosol model. Total indirect forcing was about -0.5W/m2 in the Oslo version. An intercomparison of GCM's with aerosol indirect effects was described as well.

Rob Wood (U Washington) discussed evaluating parameterizations of precipitation microphysics in warm clouds and some possible diagnostic relationships in observations, such as number v. rain rate, and some of the details of representing autoconversion processes.

Paul Field (NCAR), discussed a new compositing analysis of extra tropical cyclones as a possible diagnostic of model representations of storms and the microphysical processes within them.

Jimy Dudhia (NCAR) discussed a new ice-cloud treatment for single moment microphysics schemes in WRF.

Alexei Korolev (Met Service, Canada), described a detailed database of cold cloud observations (mostly in midlatitudes) from aircraft, which can be used to better understand the statistics of crystals in cold clouds and their environment.

Xiaohong Liu, (Univ of Michigan) discussed the implementation of a scheme for prediction of ice crystal number in CAM, and some early results of investigations of the indirect effect applied to cirrus. A detailed treatment of supersaturation is necessary for an explicit treatment.

Jean Francois Lamarque (NCAR) described the development of a detailed bin aerosol model for CAM and some initial results showing that it can start to represent aerosol climatologies at different locations.

David Mitchell (Desert Research Institute) discussed the potential for indirect aerosol effects for cirrus clouds and implications for GCMs. He detailed experiments adding a small particle mode to ice clouds, and showed potentially significant changes to cloud forcing in CAM.

Eric Jensen (NASA Ames) described the integration of the CARMA microphysical model with CAM.

Greg Thompson (NCAR) discussed bulk microphysics packages in mesoscale models (MM5, WRF, and RUC) and showed detailed evaluations using case studies. The focus of the case studies was getting icing conditions right.

(2) Expertise in the CAM microphysics group

The members of the CAM microphysics development group have each identified their areas of interest and expertise, (table 1 below). There is a wide variety of expertise and potential intellectual resources to draw upon in this effort. Experience ranges from global model schemes to detailed bin microphysical models, and with aerosols, microphysics and convection.

(3) Commitments and timelines

Following is an initial approach and timeline for implementation of scheme described in section II and illustrated in figure 1.

A small NCAR group (Gettelman, Morrison, Neale) will attempt to implement the detailed microphysical scheme of Morrison et al (2005) into CAM. The choice of this scheme is based on: (1) applicability of a comprehensive 2-moment scheme designed for mesoscale models and (2) willingness of Morrison to assist with implementation in CAM.

The effort will start with a basic ‘scoping’ study implementing the scheme in the single column version of CAM. The goals will be (1) to examine the conceptual interaction with the macrophysics (cloud fraction), (2) to identify timing and cost issues and (3) other conceptual problems that may limit the applicability of this scheme or detailed moment schemes in general. Integration with the macro component will involve a collaboration with Ben Johnson. As part of goal (3), the group will report on the potential applicability for any detailed mesoscale model scheme (i.e.WRF). The group will issue a preliminary report to the AMWG co-chairs in Feb 2006 on the applicability of such schemes and the Morrison et al (2005) scheme in CAM in particular. A further discussion of the next steps of this effort is expected for the AMWG meeting in March.

A second option for pursuit if the above work is not initially successful (Plan B) would be to work with modifications to the existing framework to treat aerosol indirect effects. This would involve using the approach developed by Ghan et al (1997) for aerosol extensions to CAM3 microphysics, and adding marginal improvements with existing CAM microphysics framework, updating the individual process parameterizations (e.g. autoconversion and others) without modifying the overall structure of the current Rasch and Kristjansson (1998) parameterization.

The overall goal is to have something ‘working’ in CAM that can achieve the science goals identified (indirect effects, stratiform cloud forcing) a year from now so that detailed testing with other components of the model can proceed over the next 2 years.

(4) Project Next steps

The microphysics group will assess progress at the CCSM atmospheric model working group (AMWG) meeting in March 2006. At this time it is hoped that the feasibility of the Morrison et al (2005) scheme can be determined, and the issues of how to proceed can be assessed.

At this point (March 2006) we hope to begin a discussion of the various component processes within and around the microphysical scheme. It is likely that we will think about the addition, subtraction and modification of individual process parameterizations, and on the other related components of the microphysical scheme implementation outlined in Figure 1.

Droplet and crystal activation are important pieces of the puzzle, and are available from the Morrison et al (2005) scheme. In addition, there is a liquid drop nucleation formulation for CAM developed by Ghan et al (1997). An ice nucleation formulation has been developed by Liu and Penner (2005). We would also like in March to revisit the merits of each individual component of the scheme for cost/complexity tradeoffs.

In addition, the other model components in Figure 1 will also need development. Developments in these areas will be revisited in March 2006 when the pathway for microphysics development is a bit clearer. These areas are listed below:

1. Convection and microphysics (Rasch, Donner)

The development of a ‘convective detrainment’ module or the appropriate microphysics output for convection is an important piece of evaluating alternative formulations of the convection scheme for CAM. There are several candidate schemes, and this piece will be evaluated in the course of selecting a new convective parameterization for the model. Phil Rasch and Leo Donner, who are working on the convective schemes, will oversee this aspect of the development.

2. Radiation and microphysics (Optics) (Mitchell)

David Mitchell will assist the CAM microphysics group in developing the interface between the microphysics and the radiation scheme. This effort will be in conjunction with Bill Collins, who is overseeing development of the radiation code for CAM.

3. Vertical velocity (TBD)

Sub-grid vertical velocities are vital for aerosol nucleation and microphysics. These can be specified, or information from other model components will be used. It is hoped that this critical development piece will be picked up soon. A new hire in the climate modeling section has some expertise in this area, and may be of assistance. The issue will be revisited in March 2006.

4. Cloud Fraction (Gettelman/Johnson/Neale)

The development of fractional cloudiness will have to be integrated with any changes to the microphysics scheme. Ben Johnson is investigating the implementation of a PDF based statistical cloudiness scheme similar to that of Tompkins (2001) in CAM, and has also modified the current Slingo (1987) scheme to be more self-consistent. It is hoped that these methods will be integrated with the microphysics

Name	Affiliation	Phase	Experience	Favorites	Processes	Comments
Andrew Gettelman	NCAR/CGD	ice	some GCM, simple models	cirrus	supersaturation	Interested in ice and supersaturation, also whole picture: putting model together
Phil Rasch	NCAR/CGD	Ice, liquid, aerosols	microphysics, aerosols in current CAM	cirrus, stratiform, convection	ice processes, convective mass fluxes, tracer transport and aerosol	AMWG Co-Chair
Leo Donner	GFDL	ice,liquid	GFDL GCM convection	convection	convection, vertical velocity, double moment microphysics, mesoscale component	AMWG Co-Chair
Graham Feingold	NOAA	warm	bin & bulk, no GCM	boundary layer clouds	autoconversion, growth, collision coalescence, evaporation of precipitation for GCMs	Developed bin and bulk schemes
Steven Ghan	PNNL	ice, liquid, aerosols	GCM aerosols & microphysics		Nucleation/Activation Parameterization, aerosols in CAM2, CCM3. PDF of updraft velocity, Sud grid autoconversion, Radiation	interested in sharing schemes in CAM, getting indirect effects going
Richard Neale	NCAR/CGD		convection	convection	convection	Atmospheric Model Liason, expects to work on convection
Chris Bretherton	UW-Seattle	warm	GCM parameterization	PBL, shallow cumulus	turbulence, boundary layer, shallow cumulus	crude microphysics in schemes, want more.
Jón Egill Kristjánsson	U Oslo	aerosols, water/ice	CAM prognostic water, CAM aerosol package	aerosols	aerosol indirect effects, ice clouds	developed current scheme with Rasch, interested in helping with next scheme
Xiaohong Liu	U Michigan	ice	CAM ice/aerosols	cirrus, ice, aerosols	ice nucleation & # concetnration, homogenous nucleation, mixed phase cloud.	developing scheme to do ice indirect effects, working on tying to radiation
Eric Jensen	NASA Ames	ice	Bin microphysics	cirrus, convection	Bin microphysical model into CAM	Putting CARMA into CAM, happy to help with comparisons
Andrew Heymsfield	NCAR/MMM	ice	Bin,Bulk microphysics and GCM	cirrus	sedimentation velocity, ice processes and indirect effects, small ice particles	interested in continuing paramerization work for sedimentation
Alexei Korloev	Met Service Canada	ice, liquid	Observations, in-situ measurements	frontal, mid-lat, stratiform clouds	collection of in-situ observations of re v. T, IWC v. T, pdfs, LWP, supersaturation	Can provide 'parameterizations' based on large numbers of in-situ observations.
Hugh Morrison	NCAR/ASP	ice, liquid	moment microphysics for mesoscale models	stratiform	nucleation processes, reconcile nucleation theory	Has a 2 moment scheme for MM5, working on WRF and CRM implementations with MMM, interested in CAM application.
Greg Thompson	NCAR/RAL	ice, liquid	MM5 microphysics	wintertime midlat	autoconversion, snow->graupel, case study simulations, collection ice/snow	Mostly single moment scheme with double moment ice.
Bill Hall	NCAR/RAL	ice, liquid	MM5, WRF microphysics		4 autoconversion parameterizations, multiple levels of consistency	has a good way to put stuff into WRF, working with Thompson, Morrison, Rassmusen
Paul Field	NCAR/MMM	liquid	mesoscale processes	midlat cyclones	precipitation, cloud structure	with Rob Wood: database of composite midlatitude cyclones to apply to CAM. Interested in helping with evaluation
Chuck Bardeen	CU	ice, liquid	bin microphysics	aerosols	bin microphyiscs, aerosols	working with Jensen on CARMA in CAM
Rob Wood	UW-Seattle	warm	obs, warm rain parameterization	rain	warm rain, autoconversion, scavenging, metrics and diagnostics, aerosol scavenging	metrics with Paul Field, has a parameterization, working now on aerosols
Jamie Smith	CU	ice, convection	LES, CRM	deep convection	isotopes in LES and CRM models. Tinkering with CAM and bin Microphysics	
Ben Johnson	NCAR/UKMO	liquid	PDF scheme for water	cloud fraction	PDF cloud fraction scheme for CAM, modified slingo cloud fraction scheme	will be leaving soon for UKMO to do something else
Catherine Chuang	LLNL	aerosols	bin aerosol in chem models	aerosols	aerosol bin model into cam, cloud drop nucleation, optical properties	working on aerosol cloud interactions in NWP mode
David Mitchell	DRI	ice	obs, ice parameterization	cirrus, ice	midlat and tropical cirrus, bimodal. analytic framework for: supersaturation, aggregation, nucleation, advection	has 3 different schemes at various levels, also working on optical properties. Link aerosol indirect effects to cirrus drop freezing
Peter Hess	NCAR/ACD	aerosols	chemical models	aerosols	chemistry in climate models, aerosols	Climate-Chem WG co-chair. Working on aersols and chemistry in CAM
OTHERS: Smith, Barth, Dudhia, Lamarque						

Table 1: List of CAM Microphysics group members expertise.

References

Abdul-Razzak, H., and S. J. Ghan, 2000: A parameterization of aerosol activation. Part 2: Multiple aerosol types. *J. Geophys. Res.*, 105, 6837-6844.

Abdul-Razzak, H., and S. J. Ghan, 2004: Parameterization of the influence of organic surfactants on aerosol activation. *J. Geophys. Res.*, *109*, 10.1029/2003JD004043.

Adams, P. J., and Seinfeld, J. H.: Predicting global aerosol size distributions in general circulation models, *J. Geophys. Res.*, *107*, 4370, doi: 10.1029/2001JD001010, 2002.

Binkowski, F.S., and S. J. Roselle, 2003: Models-3 Community Multiscale Air Quality (CMAQ) model aerosol component 1. Model description., *J. Geophys. Res.*, *108,* 4183, doi:10.1029/2001JD001409.

Byers, H. R., 1965: *Elements of Cloud Physics*, University of Chicago Press, 191 pp.

Fountoukis, C., and A. Nenes, 2005: Continued development of a cloud droplet formation parameterization for global climate models. *J. Geophys. Res.*, *110,* doi:10.1029/2004JD005591.

Colarco, P., O. Toon, O. Torres, and P. Rasch, 2002: Determining the UV imaginary index of refraction of Saharan dust particles from Total Ozone Mapping Spectrometer data using a three-dimensional model of dust transport, J. Geophys. Res., 107(D16), 4289, doi:10.1029/2001JD000903.

Cotton, W. R., G. J. Tripoli, R. M . Rauber, and E. A. Mulvihill, 1986: Numerical simulation of the effects of varying ice crystal nucleation rats and aggregation processes on orographic snowfall. *J. Clim. Appl. Meteorol.*, *25*, 1658-1680.

Dana, T. M., and J. M. Hales, 1974: Statistical aspects of the washout of polydisperse aerosols. *Atmos. Environ.*, *10*, 45-50.

Easter, R. C., S. J. Ghan, Y. Zhang, R. D. Saylor, E. G. Chapman, N. S. Laulainen, H. Abdul-Razzak, L. R. Leung, X Bian and R. A. Zaveri, 2004: MIRAGE: Model description and evaluation of aerosols and trace gases, *J. Geophys. Res.*, *109*, doi: 10.1029/2004JD004571.

Ervens, B., G. Feingold, and S. M. Kreidenweis, 2005: The influence of water-soluble organic carbon on cloud drop number concentration. *J. Geophys. Res.*, 110, D18211, doi:10.1029/2004JD005634.

Feingold, G., B. Stevens, W. R. Cotton, and R. L. Walko, 1994: An explicit cloud microphysical/LES model designed to simulate the Twomey effect, *Atmos. Res.*, 33, 207–233.

Feingold, G., 1993: A parameterization of rainfall evaporation for use in general circulation models. J. Atmos. Sci., 50, 3454--3467.

Feingold, G., S. M. Kreidenweis, B. Stevens, and W. R. Cotton, 1996: Numerical simulation of stratocumulus processing of cloud condensation nuclei through collision-coalescence. J. Geophys. Res, 101, 21,391--21,402.

Feingold, G., B. Stevens, W. R. Cotton, and A. S. Frisch, 1996: On the relationship between drop in-cloud residence time and drizzle production in stratocumulus clouds. J. Atmos. Sci., 53, 1108-1122.

Feingold, G., R. L. Walko, B. Stevens, and W. R. Cotton 1998: Simulations of marine stratocumulus using a new microphysical parameterization scheme. Atmos. Res.,47--48, 505--528.

Ferrier, B.S., A double-moment multiple-phase four-class bulk ice scheme. Part I: description, *J. Atmos. Sci., 51*, 249- 280, 1994.

Flossman, A.I., W.D. Hall, and H.R. Pruppacher, A theoretical study of the wet removal of atmospheric pollutants. Part I: The redistribution of aerosol particlescaptured through nucleation and impaction scavenging by cloud droplets, *J. Atmos. Sci., 42*, 582-606, 1985.

Ghan, S. J., L. R. Leung, and Q. Hu, 1997: Application of cloud microphysics to NCAR CCM2. *J. Geophys. Res.*, *102*, 16,507-16,528.

Ghan, S. J., L. R. Leung, R. C. Easter, and H. Abdul-Razzak, 1997: Prediction of droplet number in a general circulation model. *J. Geophys. Res.*, *102*, 21,777-21,794.

Gong, S. L., Barrie, L. A., Blanchet, J.-P., von Salzen, K., Lohmann, U., Lesins, G.,

Spacek, L., Zhang, L. M., Girard, E., Lin, H., Leaitch, R., Leighton, H., Chylek, P.,

and Huang, P.: Canadian Aerosol Module: A size-segregated simulation of atmospheric aerosol processes for climate and air quality models: 1. Module developments, *J. Geophys. Res.*, *108*(D1), 4007, doi:10.1029/2001JD002002, 2003.

Herzog, M., D. K. Weisenstein, J. E. Penner, 2004: A dynamic aerosol module for global chemical transport models: Model description. *J. Geophys. Res.*, *109*, D18202, doi:10.1029/2003JD004405,

Ivanova, D., D.L. Mitchell, W.P. Arnott, C. Schmit and M. Poellot, 2001: A GCM parameterization for bimodal size spectra and ice mass removal rates in mid-latitude cirrus clouds. *Atmos. Res.*, 59-60, 89-113.

Iversen, T., and Seland, O.: A scheme for process-tagged SO4 and BC aerosols in NCAR-CCM3 validation and sensitivity to cloud processes, *J. Geophys. Res.*, *107*, doi:10.1029/2001JD000885, 2002.

Jacobson, M. Z., 2002: Analysis of aerosol interactions with numerical techniques for solving coagulation, nucleation, condensation, dissolution, and reversible chemistry among multiple size distributions, *J. Geophys. Res.*, *107*(D19), 4366, 10.1029/2001JD002044.

Jacobson, M. Z., 2003: Development of mixed-phase clouds from multiple aerosol size distributions and the effect of the clouds on aerosol removal *J. Geophys. Res.*, *108,* 4245, doi:10.1029/2002JD002691,

Jakob, C., and S. A. Klein, 2000: A parametrization of the effects of cloud and precipitation overlap for use in general-circulation models. *Quart. J. Roy. Meteorol. Soc.*, *126*, 2525-2544.

Jensen, E. J., O. B. Toon, D. L. Westphal, S. Kinne, A. J. Heymsfield, 1994: Microphysical modeling of cirrus 1. Comparison with 1986 FIRE IFO measurements *J. Geophys. Res.* **99**, 10421-10442.

Jones, A., Roberts, D. L., Woodage, M. J., and Johnson, C. E.: Indirect sulphate aerosol forcing in a climate model with an interactive sulphur cycle, *J. Geophys. Res.*, *106*, 20293-20310, 2001.

Karcher, B., and U. Lohmann, 2003: A parameterization of cirrus cloud formation: Heterogeneous freezing, J. Geophys. Res., 108(D14), 4402, doi:10.1029/2002JD003220.

Khairoutdinov, M., and Y. L. Kogan, 2000: A new cloud physics parameterization in a large-eddy simulation model of marine stratocumulus, *Mon. Weather Rev.*, *128*, 229–243.

Klein, S. A., R. Pincus, C. Hannay, and K.-M. Xu, 2005: How might a statistical cloud scheme be coupled to a mass-flux convection scheme? *J. Geophys. Res.*, *110*, doi:10.1029/2004JD005017.

Koch, D., Schmidt, G. A. and Field, C.: Sulfur, sea salt and radionuclide aerosols in GISS ModelE, *J. Geophys. Res.*, submitted, 2005.

Kogan, Y. L. (1991), The simulation of a convective cloud in a 3-D model with explicit microphysics, J. Atmos. Sci., 48, 1160–1189.

Korolev, A. and G. Isaac, 2005: Relative humidity in liquid, mixed phase and ice clouds. Conditionally accepted in JAS.

Lappen, C-L., and D. A. Randall, 2001a: Toward a unified parameterization of the boundary layer and moist convection. Part I: A new type of mass-flux model. *J. Atmos. Sci.*, *58,* 2021–2036.

Lappen, C-L., and D. A. Randall, 2001b: Toward a unified parameterization of the boundary layer and moist convection. Part II: Lateral mass exchanges and subplume-scale fluxes. *J. Atmos. Sci.*, *58*, 2037–2051.

Lappen, C-L., and D. A. Randall, 2001c: Toward a unified parameterization of the boundary layer and moist convection. Part III: Simulations of Clear and Cloudy Convection. *J. Atmos. Sci.*, *58,* 5052-2072.

Li, Z., A. L. Williams, and M. J. Rood, 1998: Influence of soluble surfactant properties on the activation of aerosol particles containing inorganic solute, J. Atmos. Sci., 55, 1859– 1866.

Lin, Y.-L., R. R. Farley, and H. D. Orville, 1983: Bulk parameterization of the snow field in a cloud model, *J. Clim. Appl. Meteorol.*, *22*, 1065–1092.

Liu, X., and J. E. Penner, 2005: Ice nucleation parameterization for a global model. *Meteorol. Z.*, *14*, 499-514.

Liu, X., Penner, J.E., and Herzog, M., 2005: Global modeling of aerosol dynamics: Model description, evaluation and interactions between sulfate and non-sulfate aerosols, *J. Geophy. Res.*, Vol. 110, No. D18, D18206, 10.1029/2004JD005674

Liu, Y., and P. H. Daum, 2004: On the parameterization of the autoconversion process. part I: Analytical formulation of the Kessler-type parameterizations, *J. Atmos. Sci.*, *61*, 1539-1548.

Liu, Y., P. H. Daum, and R. McGraw, 2004: An analytical expression for predicting the critical radius in the autoconversion parameterization, *Geophys. Res. Lett.*, *31*, L06121, doi:10.1029/2003GL019117.

Liu, Y., P. H. Daum and R. McGraw, 2005: Size truncation effect, threshold behavior, and a new type of autoconversion parameterization. *Geophys. Res. Lett.*, *32*, doi:10.1029/2005GL022636.

Locatelli, J. D., and P. V. Hobbs, 1974: Fall speeds and masses of solid precipitation particles, *J. Geophys. Res.*, *79*, 2185–2197.

Lohmann, U., J. Feichter, C. C. Chuang, and J. E. Penner, 1999: Prediction of the number of cloud droplets in the ECHAM GCM, J. Geophys. Res., 104, 9169– 9198.

Lohmann, U. , 2002a: A glaciation indirect aerosol effect caused by soot aerosols, *Geophys. Res. Lett., 29*, 10.1029/2001GL014357.

Lohmann, U. , 2002b: Possible aerosol effects on ice clouds via contact nucleation, *J. Atmos. Sci., 59*, 647-656.

Lohmann, U., and B. Karcher, 2002: First interactive simulations of cirrus clouds formed by homogeneous freezing in the ECHAM GCM, J. Geophys. Res., 107(D10), 4105, doi:10.1029/2001JD000767.

Lohmann, U., B. Karcher, and J. Hendricks, 2004: Sensitivity studies of cirrus clouds formed by heterogeneous freezing in the ECHAM GCM, *J. Geophys. Res.*, *109*, D16204, doi:10.1029/2003JD004443.

McFarquhar, G.M. and A.J. Heymsfield, 1997: Parameterization of tropical cirrus ice crystal size distributions and implications for radiative transfer: Results from CEPEX. J. Atmos. Sci., 54, 2187-2200.

McGraw, R., Description of aerosol dynamics by the quadrature method of moments. *Aerosol Sci. and Tech., 27*, 255-265, 1997.

Menon, S., J. Hansen, L. Nazarenko, and Y. Luo, Climate effects of black carbon aerosol in China and India, *Science*, *297*, 2250-2253, 2002.

Meyers, M.P., R.L. Walko, J.Y. Harrington, and W.R. Cotton, New RAMS cloud microphysics prameterization. Part II: The two-moment scheme, *Atmos. Res.*, *45*, 3-39, 1997.

Milbrandt, J., and M.K. Yau, 2005: A multi-moment bulk microphysics parameterization. Part I: Analysis of the role of the shape parameter, *J. Atmos. Sci.*, Vol. 62, No. 9, 3051–3064.

Milbrandt, J., and M.K. Yau, 2005: A multi-moment bulk microphysics parameterization. Part II: A proposed three-moment closure and scheme description, *J. Atmos. Sci.*, Vol. 62, No. 9, 3065–3081.

Mitchell, D.L., 1996: Use of mass- and area-dimensional power laws for determining precipitation particle terminal velocities. *J. Atmos. Sci.*, 53, 1710-1723.

Mitchell, D.L., 2002: Effective diameter in radiation transfer: General definition, applications and limitations. *J. Atmos. Sci.*, 59, 2330-2346.

Mitchell, D.L., and A.J. Heymsfield, 2005: Refinements in the treatment of ice particle terminal velocities, highlighting aggregates. J. Atmos. Sci., 62, 1637-1644.

Morrison, H., J. A. Curry, and V. I. Khvorostyanov, 2005: A new double-moment microphysics parameterization, Part I: Description, *J. Atmos. Sci.*, 62, 1665-1677.

Ovtchinnikov, M., and S. J. Ghan, 2005: Parallel simulations of aerosol influence on clouds using a cloud-resolving model and a single column model. *J. Geophys. Res.*, *110*, doi:10.1029/2004JD005088.

Ovtchinnikov, M., and Y. L. Kogan (2000), An investigation of ice production mechanisms in small cumuliform clouds using a 3D model with explicit microphysics. part I: Model description, *J. Atmos. Sci.*, *57*, 2989– 3003.

Pinucs, R., and S. A. Klein, 2000: Unresolved spatial variability and microphysical process rates in large-scale models. *J. Geophys. Res. 105,* 27,059-27,065.

Pincus, R., H. W. Barker, and J.-J. Morcrette, 2003: A fast, flexible, approximate technique for computing radiative transfer in inhomogeneous cloud fields. *J. Geophys. Res. 108,* 4376, doi:10.1029/2002JD003322,

Rasch, P. J. and J. E. Kristjánsson, 1998, A Comparison of the CCM3 Model Climate Using Diagnosed and Predicted Condensate Parameterizations, J. Climate., 11:1587-1613

Reisin, T., Z. Levin, and S. Tzivion, , Rain production in convective clouds as simulated in an axisymmetric model with detailed microphysics. Part II: effects of varying drops and ice nucleation, *J. Atmos. Sci., 53*, 1815-1837, 1996b.

Reisner, J., R. M. Rasmussen, and R. T. Bruintjes, Explicit forecasting of supercooled water in winter storms using the MM5 mesoscale model, *Quart. J. Roy. Meteorol. Soc., 124*, 1071-1107, 1998.

Rotstayn, L. D., B. F. Ryan, and J. J. Katzfey, 2000: A scheme for calculation of the liquid fraction in mixed-phase stratiform clouds in large-scale models. *Mon. Wea. Rev.*, *128*, 1070-1088.

Saleeby, S.M., and W.R. Cotton, A large-droplet mode and prognostic number concentration of cloud droplets in the Colorado State University Regional Atmospheric Modeling System (RAMS). Part I: Module descriptions and supercell test simulations, *J. Appl. Meteorol.*, *43*, 182-195, 2004.

Schlesinger, M. E., J. H. Oh, and D. Rosenfeld, 1988: A parameterization of the evaporation of rainfall. *Mon. Weather Rev*., 116, 1887-1895.

Seifert , A., K. D. Beheng, 2001: A double-moment parameterization for simulating autoconversion, accretion and self collection. Atmospheric Research 59–60, 265– 281.

Seifert , A., K. D. Beheng, 2005: A two-moment cloud microphysics parameterization for mixed-phase clouds. Part 1. Model description. *Meteorology and Atmospheric Physics*, in review.

Seifert, A. and K.D.Beheng, (2005b): A two-moment cloud microphysics parameterization for mixed-phase clouds. Part II : Maritime vs. continental deep convective storms, *Meteorology and Atmosperic Physics*, In press, 2005b.
Slinn, W. G. N. (1984), Precipitation scavenging, in *Atmospheric Science and Power Production*, edited by D. Randerson, pp. 472– 477, U.S. Dep. of Energy, Washington, D. C.

Smith, R.N.B., 1990: A scheme for predicting layer clouds and their water content in a general circulation model. *Q. J. R. Meteorol. Soc., 116*, 435-460.

Spracklen, D. V., Pringle, K. J., Carslaw, K. S., Chipperfield, M. P., and Mann, G.W.: A global off-line model of size-resolved aerosol microphysics: I. Model development and prediction of aerosol properties. *Atmos. Chem. Phys.*, *5*, 2227–2252, 2005.

Stier, P., Feichter, J., Kinne, S., Kloster, S., Vignati, E., Wilson, J., Ganzeveld, L., Tegen, I., Werner, M., Balkanski, Y., Schulz, M., Boucher, O., Minikin, A., and Petzold, A.: The aerosol-climate model ECHAM5-HAM. Atmos. Chem. Phys., 5, 1125–1156, 2005.

Sundqvist, H., 1988: Parameterization of condensation and associated clouds in models for weather prediction and general circulation simulation, in *Physically-based Modeling and Simulation of Climate and Climate Change*, Vol. 1, edited by M. E. Schlesinger, 433–461, Kluwer Academic.

Tie, X., G. Brasseur, L. Emmons, L. Horowitz, and D. Kinnison, 2001:

Effects of aerosols on tropospheric oxidants: A global model study, *J. Geophys. Res.*, *106*, 2931– 2964.

Tompkins, A. M., 2002: A prognostic parameterization for the subgridscale variability of water vapor and clouds in large-scale models and its use to diagnose cloud cover, *J. Atmos. Sci.*, *59*, 1917– 1942.

Toon, O.B., Turco, R.P., Westphal, D., Malone, R., Liu, M.S., 1988. A multidimensional model for aerosols: Description of computational analogs. J. Atm. Sci 45 (15), 2124–2143.

Tripoli, G. J., and W. R. Cotton, A numerical investigation of several factors contributing to the observed variable intensity of deep convection over south Florida, *J. Appl. Meteorol.*, *19*, 1037–1063, 1980.

Tzivion, S., G. Feingold and Z. Levin, 1987: An efficient numerical solution to the stochastic collection equation. J. Atmos. Sci., 44, 3139--3149.

Wood, R., 2005: Drizzle in stratiform boundary layer clouds. Part II: Microphysical aspects. *J. Atmos. Sci.,* 62, 3034-3050, 2005.

Zhang, J., U. Lohmann, and P. Stier, 2005: A microphysical parameterization for convective clouds in the ECHAM5 climate model: Single-column model results evaluated at the Oklahoma Atmospheric Radiation Measurement Program site. *J. Geophys. Res. 110,* D15S07, doi:10.1029/2004JD005128.