Purpose: This document is intended as a framework for discussion at our workshop. The ‘final’ document will be made available to the CAM community in early 2006 and serve as a guideline for microphysics development of CAM over the next few years.

Outline: There are 3 sections: I. Processes and Methods, II. More detailed requirements and code descriptions, and III. Implementation. Processes and methods attempt to describe 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.

At this point, we would like (1) to make sure we have covered the important topics, (2) produced a picture of what people are doing and planning and (3) to think about details for candidate approaches. So far section II is not detailed and will need significant discussion, and section III needs your additional input. Everything is open for discussion.

Accordingly:
- Please rank the importance of processes in section I.
- Please indicate if we are missing any processes or candidate schemes in section I (with references).
- Provide some brief information on your plans (a paragraph or two) for section III.
- Provide any other comments you wish on the document.

We would like to receive any comments you might have before the workshop, and will send out a revised version incorporating these comments about 1 week before the meeting. This will also serve as a template for the workshop agenda.

SECTION I: Processes and Methods

(1) What are the critical processes?

For each process we would like to describe: (A) description of key issues, (B) what is known, (C) potential parameterizations, and (D) measurements for evaluation.

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. 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).
A reasonable microphysical parameterization will probably require information about the vertical velocity. The current microphysical parameterization does not require this information. Future parameterizations will probably require statements about the mean vertical velocity of a model cell, the subgridscale velocity inhomogenieties in the cell, and possibly a statement about the rate of mixing within the cell, (eg 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. We need to deal with this.

Measurements of Turbulence and Cloud Mass Flux?

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. 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.

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 and microphysics (droplet nucleation and droplet collection by precipitation); ideally, the particular overlap assumptions can 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 (eg a division of each column into a set
of homogeneous subcolumns. The statistics of the ensemble of subcolumns agree with
the original statistical statement of overlap. Can the maximum/random overlap scheme
be improved upon?

Observations:
Cloud distributions can be compiled from geosynchronous 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. 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. In addition, more
complete “size resolved” 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. 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 as follows.

**Droplet nucleation.** 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.
Droplet condensation/evaporation. It is reasonable to assume condensation bounds relative humidity with respect to liquid water at 100%. 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. 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.

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.

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. Same as for cloud water.

Freezing. Droplet freezing is covered by homogeneous ice nucleation. [Lets not make judgements yet]

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). 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?

1.4.1 Observations

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.

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.

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. 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.

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

*Aqueous-phase chemistry.* This important source of sulfate mass depends on cloud water mass and cloud fraction as well as concentrations of SO$_2$ and oxidants. Barth et al. (2000).

*Resuspension.* Activated aerosol particles are resuspended when droplets evaporate completely. This depends on the treatment of droplet evaporation.

*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.

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 of the aerosol properties should be clarified. 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.

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, and the width of the size distribution. For a statistical cloud scheme it may be necessary to integrate across the distribution of liquid and ice water path. 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.

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

Can we prioritize key processes?
What is most important in 1.1-1.8?
Please Pick 5 from 1.1-1.8 and rank them

(2) What are candidate cloud microphysics packages for global models for (1.1-1.8)?
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.

2.1 Detailed model approaches/parameterizations.
CARMA (Toon et al., 1988, Jensen et al., 1994)
Feingold et al. (1994) (warm clouds only)

Question: None of these schemes may be suitable for droplet nucleation in CAM because they require explicit prediction of supersaturation, which requires explicit resolution of cloud-scale vertical motion.

2.2 Bulk or two-moment schemes
2.2.1 Cloud microphysics
Morrison et al. (2005)
Ghan et al. (1997a,b)
Seifert and Beheng (2001, 2005) (may not be suitable for CAM because it requires explicit prediction of supersaturation).

2.2.2 Aerosol physics

We do not intend to spend much time considering this topic. If we focus on microphysics, we really only need to state what we require as input from the aerosol microphysics. For example, are mean and standard deviation of different modes enough? How detailed do we need size resolution? How detailed do we need composition information? Do we need to know about internal vs. external mixing?

Some possible aerosol physics schemes include:
Easter et al. (2004)
Herzog et al. (2004), Liu et al. (2005)
Binkowski and Roselle (2003)

What level of sophistication will we make possible with the microphysics? Can we design a microphysics scheme to work with a detailed aerosol package if people would like to run it.

(3) Should we have a range of levels of sophistication for both clouds and aerosol microphysics? It is likely that we will not be able to run for climate simulation a detailed scheme.

What is the appropriate hierarchy?

3.1 'Bulk' or 'computational efficiency' approach
What can we afford to run for 100 years?
How many tracers?

3.2 'Kitchen sink' approach: detailed model
“Spectral” or size resolved treatment possible. Can we do this with the same set of inputs (‘hooks’, ‘variables’) as 3.1 so the code does not need re-engineering?
What are the minimum required inputs and outputs for a detailed scheme? Also see section II below
Does NCAR support a detailed scheme, or just a ‘climate’ scheme?

SECTION II: REQUIREMENTS/CODE DESCRIPTION DOCUMENT

Given the above discussion, how do we describe a code with the right inputs and outputs?
(AKA: APPLICATION PROGRAMMING INTERFACE)

1) What are the ‘requirements’ to represent these processes?
1.1 Requirements (examples, or list for each process):
separate cloud and environmental fields?
conservation of mass & energy
size distribution of cloud particles
subgrid distribution of water substance
dependence of processes on distribution of water
treatment of cloud overlap effects
updraft velocity distribution within clouds
aerosol: number, size, composition
time step of minutes or longer

(2) Interactions

2.1 Templates for a useful programming paradigm
parameterizations work on sets of columns
1. call initialize(list of constants for parameterization, eg, gravity, heat
capacity of liquid water, etc,)
sets internal constants
2. call step forward (list of input variables, time step to produce new
simulations over,
list of output variables (diagnostics and tendencies)

2.2 what are the input and output variables?
2.3 what tasks are the responsibility of each 'package'?
Packages can take on more than one subset of processes

2.4 Some considerations between processes

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, size, 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.
Phytolysis (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?

SECTION III: IMPLEMENTATION

(1) Who is working on what? Entrepreneurial efforts in CAM
For each Group (A) PI, CO-I's, contact info (B) primary science goal (C) process(es) being treated (D) methodology/algorithm (E) funding source (F) progress and expected timeline.

Then: What are we missing that we need to get from elsewhere or need to encourage efforts on?

(2) Commitments and timelines
What are the candidate approaches from Sec. I, 1 & 2?
How can this interact with (3) in Section I?
Who will help integrate them with the model (refer to Sec. III)?

References


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


