Aerosol Effects on Clouds, Energy & Hydrologic Cycle

Steven Ghan, Trond Iversen, Jon Egill Kristjansson, Athanasios Nenes, Joyce Penner

Scientific advances to be accomplished within this project

Anthropogenic aerosol particles can influence clouds and the cycles of water and energy through two very different mechanisms: (a) scattering, absorbing, and emitting solar and infrared radiation, and (b) nucleating cloud droplets and ice crystals. The former mechanism produces a direct influence on the energy cycle and a “semi-direct” effect by suppressing cloud formation due to absorption of solar radiation in the atmosphere. Aerosols may also cause melting of snow and ice when absorbing particles are deposited on the surface. Aerosol absorption of solar radiation in the atmosphere slows the hydrological cycle by reducing the evaporation needed to balance the solar energy absorbed at the surface. In the latter mechanism (“indirect effect”) aerosol particles form the nuclei for cloud droplets and ice crystals. In liquid water clouds, the enhanced droplet nucleation reduces cloud particle size and increases cloud water path, which in turn increases cloud albedo. The reduction in cloud particle size also suppresses precipitation and may increase cloud coverage. The increased cloud albedo and cloud cover decrease solar insolation at the surface and may also slow the hydrological cycle. In mixed-phase clouds, the reduced cloud droplet size may suppress glaciation. On the other hand, the small fraction of anthropogenic aerosols that can serve as ice nuclei, e.g., soot, will promote glaciation, which would tend to enhance precipitation locally. Depending on microphysical sources and sinks of cloud droplets and ice crystals, the ratio between liquid water and ice in a grid box may deviate significantly from a simple temperature-ice fraction relationship. Since aqueous chemistry in clouds is a primary source of hygroscopic aerosol mass and precipitation is a primary scavenging mechanism for aerosol, the feedback of the hydrological cycle on the global aerosol is an important aspect of indirect effects. This project will use a fairly complete representation of the aerosol to explore the competing and complementing mechanisms by which natural and anthropogenic aerosols influence clouds and the cycles of water and energy. The end product will be more confident estimates of the influence of aerosols on the climate system than available by today’s models.

Necessary model capability

A fairly complete representation of the aerosol is required in order to treat the competition between multiple aerosol types for water in cloud updrafts. All important components of cloud condensation and ice nuclei must be treated, both in terms of number and surface area (because, e.g., coarse sea salt can dominate particle surface area). The cloud nucleating properties of particles in clouds and the water uptake properties of particles in clear air should be treated in a consistent manner, i.e., in terms of hygroscopicity and surface tension. Both internal and external mixtures of particles must be accommodated. Radiative properties of particles must depend on both composition and wet size. Particle mass and particle number must be predicted independently to distinguish between processes that influence mass only from those that influence number only. Droplet number and crystal number must be predicted, with a proper treatment of microphysical sources and sinks. Ice nuclei concentration must be expressed in terms of the predicted aerosol properties. Droplet and crystal effective radius must be related to droplet number and crystal number, and this must be done consistently in the condensation and radiation schemes of the model. A realistic treatment of the subgrid dependence of droplet autoconversion on droplet number is required. Snow and ice albedo must be related to deposition of absorbing aerosol.

Current status of models / model development. Key scientific personnel.

CAM presently only predicts mass for about ten externally mixed aerosol types. Droplet number is prescribed independently of a prescribed droplet radius. Ice crystal radius is prescribed. Aerosol radiative properties are prescribed functions of relative humidity.

To get where we need to be, the aerosol representation needs to be generalized to treat a modest number of aerosol modes, each composed of an internal mixture of multiple aerosol components, with the mass of each component and the total number of each mode predicted (X. Liu, R. Easter, T. Iversen / A. Kirkevåg / Ø. Seland). This will require the addition of nitrate and ammonium to the suite of aerosols with an accurate treatment of the limitation of mass transport to larger sized particles (J. Penner), as well as treatments of particle nucleation (R. Easter), coagulation (code from F. Binkowski), and “renaming” (R. Easter). Droplet (S. Ghan, T. Storelvmo, J.E. Kristjansson) and crystal (X. Liu, J. Penner, T. Storelvmo, J. E. Kristjansson) number must be introduced as prognostic cloud variables, with the parameterized nucleation expressed in terms of full set of aerosol properties and a subgrid representation of updraft velocity (S. Ghan, A. Nenes, J. Penner, and X. Liu). Autoconversion of cloud water to rain needs to be expressed in terms of particle number (Y. Liu, R. Wood, and A. Nenes), accounting for subgrid variability in cloud parameters such as liquid water content (S.Ghan). For ice clouds, autoconversion formulations need to be replaced by fallspeed relations. Droplet and crystal effective radius need to be expressed in terms of droplet and crystal number, respectively (S. Ghan, D. Mitchell and J. E. Kristjansson). The shape of the ice crystals, which may depend on the ice nuclei present, needs to be taken into account (D. Mitchell, J. E. Kristjansson). Aerosol radiative properties should be expressed in terms of the mean wet size and bulk refractive index of the aerosol, as well as relative humidity (S. Ghan, A. Kirkevåg, T. Iversen). Snow and ice albedo need to be expressed in terms of surface soot concentration (M. Flanner).

Funding for S. Ghan and X. Liu (for ice nucleation) will be by DOE ARM. Funding for R. Easter and X. Liu (for aerosol dynamics) depends on DOE SciDAC renewal. Y. Liu is funded by ARM and DOE ASP. T. Storelvmo, Ø. Seland and A. Kirkevåg are presently funded by the Norwegian Research Council, some future funding has been obtained through EU FP6 and more is being sought from the Norwegian Research Council. J. Penner and A. Nenes are funded by N.S.F. and NASA.

Performance metrics

To provide a target for model development, we have identified several metrics of performance that should be met before the added complexity of the CCSM physics is acceptable. These include the following:

1. The simulated spatial/temporal distribution of top-of-atmosphere energy balance (shortwave and longwave) for the CAM-only present-day configuration must be either unchanged or improved by the added physics. This is an absolute requirement.
2. The simulated spatial/temporal distribution of precipitation for the CAM-only present-day configuration must be either unchanged or improved by the added physics.
3. The simulated spatial/temporal distribution of sulfate, black carbon, and organic carbon aerosol mass concentration should agree with in situ measurements to within a factor of 1.5 (i.e., the rms difference should be less than 50% of the global mean).
4. The simulated spatial/temporal distribution of accumulation mode number concentration should agree with in situ measurements to with a factor of 1.5.
5. The simulated spatial/temporal distribution of CCN concentration at a supersaturation of 0.1% should agree with in situ measurements to with a factor of 1.5.
6. The simulated spatial/temporal distribution of aerosol optical depth should agree with satellite and surface retrievals to within a factor of 1.5.
7. The simulated spatial/temporal distribution of column droplet number should agree with satellite retrievals to within a factor of 2.
8. The simulated spatial/temporal distribution of liquid and ice water paths should agree with satellite retrievals to within a factor of 2.
9. The simulated correlation between cloud albedo and effective radius for optically thin and thick clouds over land and ocean should be within a factor of 2 of satellite estimates.
10. The simulated distribution of the variation of droplet effective radius with aerosol optical depth $\frac{\partial \ln r_e}{\partial \ln \tau}$ should be within a factor of 2 of observations.

What types of CCSM simulations are needed?

Simulations with preindustrial and present day emissions of aerosols, precursor gases, and oxidants. Validation for present day by comparison with aircraft measurements of size distribution and CCN spectra, surface measurements of aerosol PM 2.5 mass concentrations, and satellite measurements of aerosol, cloud optical depth, effective radius and liquid water path. Sensitivity experiments with and without scattering and absorbing aerosols and indirect effects. Sensitivity will also be investigated with regard to uncertain parameters in the aerosol parameterizations.

Time frame

Allow two-three years for model development. Another year for experiments.

Computing resources needed

These changes could triple the CAM run time compared with prescribed aerosol. Note that the accurate treatment of nitrate in aerosol could increase run times by a factor of ten.