

Regional Effects of Aerosols on the Atmospheric Radiative Balance

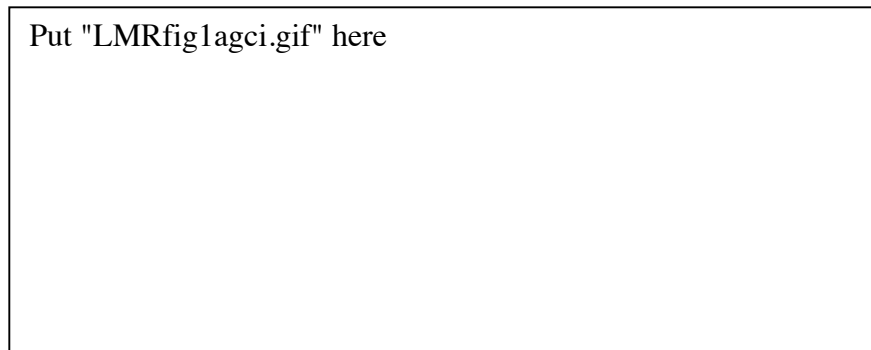
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Aerosols represent one of the greatest uncertainties in quantifying atmospheric sources of climate change. The role of aerosol particles in providing nucleation sites for cloud droplets is complex: this so-called “indirect effect” incorporates unsolved problems in atmospheric chemistry, thermodynamics, and fluid mechanics. Much of this uncertainty lies in our inability to describe the processes that control the evolution of particles in a chemically accurate and computationally efficient way. Even the simplest atmospheric scenarios of pristine marine conditions in remote areas involve significant challenges in understanding theoretically how different processes change aerosol particles, in describing numerically their impacts on climate, and in devising technical improvements to measure the variables needed to test our predictions.

While the principle that aerosol particles serve as nuclei on which cloud droplets form is widely accepted, the ability to predict which particles will activate to droplets in supersaturated conditions is one of the largest uncertainties remaining in quantifying the radiation budget in the atmosphere. A central uncertainty in this problem is the computational cost of a sufficiently detailed, internally- and externally-mixed aerosol microphysics model capable of predicting accurate particle growth. Russell and Seinfeld (1998) combines the dual-moment approach with a multiple population capability, resulting in detailed tracking of aerosol particles from individual sources. This last feature makes this new algorithm capable of addressing complex aerosol-cloud interaction questions, such as the role of ship emissions in producing so-called “ship tracks” in the sub-visible reflectance signatures of cloud layers.

The strength of this detailed model is that it can be compared directly to in situ measurements collected as part of field projects. For looking at the impact of aerosols on cloud radiative properties, one of the most complete aircraft-based data sets is provided by the Monterey Area Ship Track (MAST) Experiment in June of 1994. Ship tracks provide an excellent example of aerosol-induced changes of cloud properties, since their satellite signature shows enhanced reflectance in the $3.7 \mu\text{m}$ channel of AVHRR satellites. This signature is illustrated in Fig. 1, where the higher reflectance results from a decreased average cloud droplet size in the track (Ferek et al., 1998).

Figure 1. AVHRR $3.7 \mu\text{m}$ image of one ship track measured in clean marine conditions during the MAST project. The ship position is shown with white dots on the satellite image and with gray dots and labeled position times on the magnified inset. The inset also shows the flight track of the University of



Washington C131-A aircraft as a black line with gray dots where the track was sampled. Times labeling dashed gray lines indicate the approximate age of the track measured from the time of emission to the sampling point. Solid gray lines show the observed track location at the indicated satellite overpass times (image from Russell et al., 1999.)

The MAST field measurements are described by Durkee et al. (2000a), with two detailed case studies investigated by Noone et al. (2000a,b). Russell et al. (2000a) showed the presence of hydrophobic combustion organic species in cloud droplets, suggesting that less soluble species may also be present in particles that serve as cloud condensation nuclei. Hobbs et al. (2000) have used the MAST measurement set to infer the relative cloud-droplet-forming potential of particles collected from several different ships.

In Russell et al. (1999), this unique MAST data set was used to compare measured cloud droplet distributions to the predictions of the chemically detailed microphysical aerosol model. This work includes explicit comparisons of this detailed aerosol cloud model to comprehensive in-situ measurements. These model results show that the effect of anthropogenic pollution (such as ship emissions) is strongly dependent on the degree of background pollution (from continental sources) in preexisting clouds. The impact of ship emissions on pristine marine clouds significantly changes the maximum supersaturation reached in cloud, thus altering the cloud's radiative characteristics. The change in cloud properties in continentally-influenced clouds is much less pronounced. In fact, the effect of additional aerosol on already-polluted clouds can be quite small. A summary of the effect of aerosol particles on cloud properties under clean marine and continentally-influenced conditions is shown in Table 1.

Table 1. Summary of the effect of aerosol particles on cloud properties under clean marine and continentally-influenced conditions.

<i>Parameter</i>	Clean Marine	Anthropogenically-Influenced
<i>Background</i>		
Effective radius	10.8 μm	5.7 μm
Liquid water content	0.19 g m^{-3}	0.22 g m^{-3}
Maximum supersaturation	0.68%	0.26%
Droplet number	53 cm^{-3}	293 cm^{-3}
<i>Track</i>		
Effective radius	3.4 μm	4.1 μm
Liquid water content	0.20 g m^{-3}	0.22 g m^{-3}
Maximum supersaturation	0.18%	0.15%
Droplet number	2130 cm^{-3}	985 cm^{-3}

Erlick et al. (2000) used a detailed Mie scattering routine to calculate the clean marine cloud characteristics corresponding to changes in the Earth's overall reflectance (albedo) that could result in a significant cooling effect. The magnitude of that effect varies strongly with the assumptions used. Figure 2 compares several different approaches to predicting the indirect effect of aerosol particles on cloud albedo. The Twomey approach (Twomey et al., 1984) predicts a much smaller relative change than either the correlations currently included in GCM simulations (Jones et al., 1994; Feichter et al., 1997) or the explicit chemical and microphysical calculations of Erlick et al. (2000).

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Figure 2. Comparison of the albedo predicted for the clean marine and anthropogenically-influenced ship track cases (data from Erlick et al., 2000).

The range of indirect effects predicted here illustrates the importance of the approach and underlying assumptions used in calculating the aerosol indirect effect. The chemical composition of particles will control which particles in a given size range can activate to form cloud droplets, and the number of such particles that exist in the "background" (or unpolluted) cloud at a given supersaturation will determine whether the effect of additional aerosol is significant.

The predicted changes in cloud reflectance will increase the cloud albedo, producing a shortwave forcing effect of cooling (for low-lying stratocumulus clouds). In addition, particles may cause significant feedback effects on cloud lifetime, precipitation, cloud cover, and other cloud-related processes. These meteorological elements of the climate response may have equally (or more) important effects on the radiative balance of the Earth's atmosphere than the forcing itself. Since neither the magnitude nor the sign of the albedo change relates linearly to the resulting changes in surface temperature, GCM calculations that incorporate these feedbacks are needed to assess the climate impact of aerosols.

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