Interactions Between Aerosols and Clouds

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The albedo of marine stratus clouds can be altered by the addition of aerosols to the marine boundary layer. (Twomey 1977, Charlson et al. 1987, Coakley et al. 1987). As the number of cloud condensation nuclei increases, the number of cloud droplets increases, the size of the cloud droplets declines, the drizzle rate declines, and the liquid water increases (Twomey 1977, Radke et al. 1989, Albrecht 1989). The result of these changes is to increase the optical depth of the cloud, causing its visible albedo to rise.

A number of studies have subsequently suggested that anthropogenic increases in aerosol production will alter the earth's climate. The change is due not only to the direct effect of the aerosols on the earth's radiation budget, but also about equally to the indirect effects of aerosols on clouds (Penner et al. 1992, Charlson et al. 1992). During the past few years we have been systematically examining the relations between changes in aerosol abundance and cloud properties in the hopes of eventually quantifying these interactions. We find that not all types of clouds respond in the same manner to changes in aerosol concentrations and that some hypotheses in the literature about the relations between aerosols and clouds may be incorrect.

The microphysical studies we have been conducting are based upon versions of the microphysical model discussed by Toon et al. (1988). We have coupled a radiative transfer model to the cloud model (Toon et al. 1989) and have developed a one-dimensional turbulent transport model to represent boundary-layer dynamical processes. The model has been further developed and applied to the marine boundary layer by Ackerman et al. (1992, 1993) and to cirrus clouds by Jensen et al. (1993a, 1993b). These two versions primarily differ by having ice physical processes active in the cirrus model. The basic microphysical model has also been embedded in the Penn State/National Center for Atmospheric Research (NCAR) mesoscale dynamical model and used to simulated cirrus clouds during the First ISCCP(a) Regional Experiment (FIRE) project.

One of our goals in performing one-dimensional studies is to develop the microphysics for these three-dimensional simulations. However, since the microphysics itself is computationally very demanding, the one-dimensional simulations are often useful for cloud simulations of microphysics in situations in which dynamics either is not important or can be parameterized. Here we discuss only one-dimensional simulations.

Marine stratus are the only clouds for which there are significant data showing effects of aerosols on cloud properties. We have simulated ship tracks with our model using particle injection rates based upon observations (Radke et al. 1989).

In the simulations, we first model the development of a stratus cloud having properties similar to those observed in the region in which ship tracks were studied by Radke et al. (1989). Then we inject particles and follow the subsequent evolution of the cloud albedo, liquid water content, particle size, and so forth for several days.

We find that the modeled cloud responds in a similar manner to that observed. The simulated cloud albedo increases from about 50% to about 60%; the mean droplet size declines from about 11 to about 9 µm; and the liquid water content changes from 0.4 to about 0.5 g m^{-3} as the particle concentration increases from about 50 to 120 cm^{-3}. The longevity of the ship tracks in our simulations exceeds 24 hours, as is sometimes observed for actual ship tracks.

(a) International Satellite Cloud Climatology Project.

The simulations show that it is not necessary to hypothesize unusual dynamical processes or gas-to-particle conversion extending over long time periods in order to account for the observed properties and longevity of ship tracks. Of course, gas-to-particle conversion almost certainly does occur at least near the ship stack, and the alteration of the cloud properties in a confined area probably does induce dynamical motions near the ship track.

Our one-dimensional simulations cannot reproduce the three-dimensional dynamics of the marine boundary layer. However, we believe the presence of ship tracks requires a boundary layer in which relatively little vertical shear is present to avoid dispersing the aerosols over a wide region. This requirement may account for the relative rarity of ship tracks.

Another issue regarding marine stratus that we investigated is the relation between particle production rates and resulting particle concentrations. Baker and Charlson (1990) suggested that this relationship has only two discontinuous solutions: for small production rates, cloud particle numbers are limited to small values (order 50 cm^{-1}) by drizzle; for larger production rates, drizzle is suppressed, leading to much higher particle concentrations.

While our simulations agree that the number of particles is a rapidly increasing function of the particle production rate, we find a continuous relationship between particle concentrations and particle production rate. Our results suggest that the functional form Baker and Charlson (1990) assumed for the loss of particles due to coalescence of cloud drops was overly simplified. In addition, we examined the lifetimes of particles in marine stratus clouds. We find that several days can be required for clouds to come to equilibrium with a new particle production rate and that the residence time of the aerosol mass is much longer than the residence time of the particle number. The different lifetimes occur because mass must be removed at the surface, but numbers are also reduced by coalescence. Hence, the distance that particles drift downwind from their source can be overestimated if mass residence times are used.

We have also examined the sensitivity of cirrus cloud properties to aerosol concentrations. Changes in cirrus cloud optical depth will have a lesser impact on the earth's radiation budget than equivalent changes in optical depth of a stratus cloud because cirrus clouds impact both solar and infrared radiation in an opposing manner. That is, as cirrus clouds become more optically thick, they reflect more sunlight to space, but they also become better infrared absorbers and thereby prevent infrared loss to space.

More importantly, cirrus clouds are not very responsive to changes in aerosol concentrations because they require a substantial supersaturation with respect to ice to lead to nucleation. Therefore, once nucleation occurs and ice crystals begin to grow, they quickly drop the supersaturation below the level at which new particles can nucleate. For this reason, the number of cirrus cloud particles is not very sensitive to the number of aerosols. In short, the clouds control the number of ice crystals. The largest impact on cirrus occurs when the number of large or easily activated aerosols changes because then the number that can be activated at a given supersaturation varies (Jensen and Toon 1992). Even then, however, the effects are much less dramatic than for stratus for the reasons mentioned above.

We have not yet examined the sensitivity of continental stratus or of convective clouds to aerosols. Continental stratus usually form where many cloud condensation nuclei are present. Additional aerosols are observed to change cloud albedo by smaller amounts as the aerosol populations increase, so the continental stratus would be expected to be much less sensitive than marine stratus to aerosol concentrations.

In general, the impact of anthropogenic aerosols on clouds needs to be carefully evaluated since the effects of aerosols on clouds depend considerably upon the type of cloud being considered. In addition, for the marine boundary layer, the aerosol residence time by mass considerably exceeds the residence time by number so the area downwind of the source affected by aerosols can be incorrectly estimated unless the relevant residence time is used.

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