Effect of Cloud Condensation Nuclei on the Optical Properties of a Layer Cloud: Numerical Simulation with a Cloud-Microphysical Model

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The influence of aerosols on the atmospheric radiative budget, as seen in the effect of cloud condensation nuclei (CCN) on the optical properties of clouds, for example, is one of the key issues in understanding and predicting global climate change.

To study quantitatively the effect of CCN on the optical properties of low-level layer clouds, we developed a cloud microphysical adiabatic parcel model. The model relates the size distribution of cloud droplets both to the updraft velocity in a cloud and to the size distribution and constituents of CCN.

The growth of cloud droplets by condensation is calculated, with emphasis on avoiding numerical diffusion of the droplet spectrum. Near the cloud base, the activation of CCN and the subsequent growth of cloud droplets are calculated in a Lagrangian framework to accurately model the effect of CCN on the droplet's growth by condensation. In the middle and upper parts of the cloud, the cloud droplet size distribution is partitioned into fixed bins of cloud droplet radii in an Eulerian framework to estimate the growth by coalescence. In the middle and upper parts of the cloud, the growth by condensation is calculated using an advection algorithm, and the growth by coalescence is calculated using a flux method. Using simulated vertical profiles of droplet size distribution, the radiative properties (reflectance, transmittance and absorptance) of the cloud (for short-wavelength radiation) are computed by solving the radiative transfer equation using a discrete ordinate method without parameterization.

The absorptance of a cloud is controlled primarily by the integrated liquid water content (ILWC). Reflectance and transmittance depend on both the ILWC and the concentration (or effective radius) of cloud droplets. Our results show that the concentration of cloud droplets is not uniquely determined by the ILWC, but depends on both the updraft velocity and the size distribution and constituent of CCN. Although the concentration of cloud droplets increases as the concentration

of CCN of whole size range increases, the concentration of cloud droplets approaches a limiting value that is a function of the updraft velocity. Therefore, reflectance increases and transmittance decreases as the concentration of CCN increases. Furthermore, both transmittance and reflectance approach limiting values that depend on the updraft velocity. The rate of change due to an increase in CCN concentration is large when the ILWC is small. For a given updraft velocity, the effect of the constituents of the CCN on the optical properties decreases as the concentration of CCN increases.

The addition of Aitken-sized CCN effectively increases the number of cloud droplets and the reflectance of a cloud. The rate of increase is larger in maritime air masses than in continental air masses, especially when the updraft velocity is large. On the other hand, the addition of giant CCN only slightly affects reflectance, because the addition of giant CCN only slightly decreases the concentration of cloud droplets.

The optical properties of clouds have traditionally been estimated as a function of the ILWC, under the assumption that the microphysical properties of clouds are controlled primarily by the ILWC. Our results show, however, that the optical properties are related not only to the ILWC but also to both CCN and updraft velocity. The size distributions of both the original CCN and of added aerosols that can work as CCN are important when estimating the effect on indirect radiative forcing of anthropogenic aerosols.

The sensitivity of the layer clouds' optical properties to anthropogenic aerosols decreases as CCN concentration increases, especially for cases with low updraft velocity near the cloud base. The relationship between cloud droplet concentration and CCN concentration shown in our study is not derived from Twomey's (1959) equation approximating cloud droplet concentration. The difference in the sensitivity of the optical properties of layer clouds to anthropogenic aerosols among different air masses can be detected from the long-term global observations using remote sensing technology.

Our results show that the addition of anthropogenic aerosols increases the reflectance of clouds in a clean air mass, but absorptance is not sensitive to CCN concentration. This result suggests that indirect radiative forcing of anthropogenic aerosols causes cooling, when changes in the "dirtiness" of a cloud and cloud amount can be neglected. However this radiative forcing of anthropogenic aerosols would not be dominant in an air mass rich in CCN.

This study is described in Kuba *et al.* (2001) in detail.

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