J1.1 AEROSOL EFFECTS ON THE LIFETIME OF SHALLOW CUMULUS

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1. INTRODUCTION

The frequent reference in the literature to aerosol effects on the lifetime of clouds is in stark contrast to the absence of observations of this effect. In the realm of climate modelling, the "lifetime effect" is used synonymously with the "second indirect effect" (e.g., IPCC, 2007) where it is suggested that an increase in aerosol reduces precipitation, enhances cloud liquid water and increases lifetime (Albrecht 1989). Climate models that investigate the "cloud lifetime effect" usually do so by modifying the parameterization of autoconversion of cloud water to rain water. The effect of aerosol on cloud lifetime is not resolved because convection is not resolved. At much smaller scales, cloud modellers have examined the effect of aerosol on the lifetime of single clouds (e.g. Khain et al. 2005; Teller and Levin 2006). Although such exercises are illuminating, the response of the lifetime of an individual cloud to changes in aerosol is not statistically robust, particularly when the cloud is initialized by a warm bubble. Recent studies have begun to study ensembles of clouds in the model domain. These large eddy simulations (LES) resolve the eddies that are responsible for convection. They are initialized by random temperature perturbations, allowing turbulence to develop in a more natural manner, and a population of clouds to evolve. Individual clouds are tagged and tracked (e.g., Zhao and Austin 2005) and the effect of aerosol on cloud sizes (Xue and Feingold 2006) and lifetimes (Jiang et al. 2006) can be calculated in a statistical manner. In Jiang et al. (2006) we show that aerosol effects on the lifetime of a population of clouds is small, and much smaller than the variability in lifetime at any given aerosol concentration. The following is a summary of those results.
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2. MODELS AND CASE DESCRIPTIONS

Three different models and four soundings are applied. Two of the models are large eddy models; the first is based on the Regional Atmospheric Modeling System (RAMS, version 4.3, Cotton et al., 2003) coupled to a microphysical model described by Feingold et al., (2005). The model includes coupling between microphysics, dynamics, aerosol, radiation and a land surface model. Aerosol and drops are size-resolved and prognostic equations are solved for each bin. The domain size is 6.4 km x 6.4 km x 5 km with $\Delta x = \Delta y = 100$ m and $\Delta z = 50$ m. The time step is 2 s. The second LES is the University of California Los Angeles model, UCLA-LES Stevens et al. (1999). It is similar to RAMS but uses simplified treatment of radiation and surface forcing. It too includes size-resolved treatment of drop size distributions (Xue and Feingold 2006). It is applied to simulation of marine trade cumulus clouds where surface forcing is assumed constant. Both models are initiated with instantaneous pseudo-random temperature perturbations in the lowest model levels. Turbulence and subsequent cloud development typically occur after 1-2 hours. A field of clouds develops, enabling statistical assessment of aerosol effects on clouds. Periodic boundary conditions are applied.

The Tel Aviv University two-dimensional (TAU-2D), non-hydrostatic, slab-symmetric cloud model (Yin et al., 2000) that has been widely applied to aerosol-cloud studies. Because it only simulates single clouds it provides a rather limited view of cloud response to aerosol but it is very useful for elucidating physical processes. The model does not include radiation or surface forcing but for the short simulations performed here this is unimportant. TAU-2D is initiated with a warm bubble by applying a brief, localized temperature perturbation at the surface for anywhere between 2 s and 120 s, depending on the initial profile.

All the models use a bin representation of the drop size distribution and associated growth processes Tzivion et al. (1987) which solves for two moments (mass and number) in each of 33 size bins. The processes of activation, condensation, collision-coalescence, breakup, and sedimentation are represented. Aerosol particles are assumed to be lognormally distributed and composed of an inorganic salt. Size distribution differences between models are negligible compared to the contrast between clean and polluted conditions.

Four different soundings have been chosen, each generating clouds of different sizes, depths and precipitation: (i) The Barbados Oceanographic and Meteorology Experiment (BOMEX) is a well-studied trade cumulus case (e.g., Siebesma et al., 2003). The sounding develops shallow cumulus clouds with depths ranging from a few 100 m to 1 km. Cloud fractions (CF) are ~10 - 15%. At low aerosol concentrations (N_a ~ 25 cm^{-3}) clouds produce small amounts of drizzle (cloud-averaged rainrate ~ 0.1 mm d^{-1}; (ii) A continental convective case from the Smoke, Aerosols, Clouds, Rainfall, and Climate (SMOCC) experiment as simulated in Jiang and Feingold (2006). This surface-forced case generates somewhat deeper clouds ranging from a few 100 m to 3 km and CF of ~ 20%. Clouds with small aerosol concentrations N_a ~ 100 cm^{-3}) produce local precipitation rates of up to 100 mm d^{-1}; (iii) A Mediterranean sounding (MED) adapted from measurements in the Central Mediterranean Sea develops shallow cumulus clouds with depths and horizontal dimensions of about 500 m ; (iv) A sounding adapted from Kogan (1991) which produces convective clouds with a depth of about 2000 m, and horizontal dimensions of about 1500 m, i.e., significantly larger than clouds in the other soundings. The mean subcloud potential temperature gradient indicates that the Kogan sounding is the most unstable, SMOCC is the most stable, and MED and BOMEX lie in-between. The high subcloud relative humidity RH in Kogan also contributes to deeper and larger clouds.

3. SIMULATION RESULTS

A brief summary of results is given here; details and figures will be furnished at the conference.

Based on analysis of hundreds of individual clouds, the LES results suggest that aerosol has a negligible effect on cloud lifetimes, despite the negative correlation between aerosol concentrations and precipitation manifested in the simulations. The variability in cloud lifetime at any given aerosol concentration is much larger than the effect of a change in aerosol concentration over the range 25 cm^{-3} to 2000 cm^{-3}. This result is in accord with the results of Jiang and Feingold (2006) and Xue and Feingold (2006) who showed that for warm convective clouds, fields such as LWP and cloud fraction have an inherent variability at any given aerosol concentration that is much larger than aerosol effects on these fields.

When considering aerosol effects on cloud lifetime for individual clouds generated by the TAU-2D model, it will be shown that an increase in aerosol from 100 cm^{-3} to 2000 cm^{-3} results in a decrease in cloud lifetime of 10% for the MED sounding and 40% for the Kogan sounding. This decrease appears to be inversely proportional to the magnitude of free tropospheric RH, in agreement with Ackerman et al. (2004), albeit for a different cloud type (cumulus vs. stratocumulus). For the BOMEX sounding the TAU-2D model shows no effect of aerosol on cloud lifetime, in agreement with the LES results.

An analysis of the results suggests that two processes with opposing effects are acting on these clouds. As aerosol concentration increases, precipitation decreases, which acts to increase cloud water. On the other hand, the increase in aerosol concentration decreases cloud droplet size and enhances evaporation rates (Squires, 1952; Wang et al. 2003; Xue and Feingold 2006). For the weakly precipitating clouds studied here the effect of enhanced evaporation rates appears to dominate. Wang et al. showed that an increase in drop concentration results in higher entrainment rates near the tops of a stratocumulus cloud. The total water flux near the cloud top is higher and therefore cloud top LWC is reduced. Xue and Feingold (2006) and Jiang et al. (2006) show that the vortical circulation around the core of a cumulus cloud is strengthened by the enhanced evaporation rates associated with smaller droplets. Entrainment rates increase with increasing aerosol, resulting in a decrease in the size and lifetime of small cumulus.

4. SUMMARY

Analysis of hundreds of shallow cumulus clouds generated by large eddy simulations suggests that the effect of aerosol on the lifetime of these clouds is negligible, and much smaller than the variability in cloud lifetime associated with clouds at any given aerosol concentration. Individual clouds, as simulated in a two-dimensional single cloud model show a reduction in cloud lifetime with increasing aerosol. It is suggested that evaporation-entrainment feedbacks discussed by Wang et al. (2003), Xue and Feingold (2006), and Jiang et al. (2006) may be responsible for this unexpected result. Higher aerosol concentrations result in higher evaporation rates that tend to increase the vortical circulation around the core of a cumulus cloud and enhance entrainment. This hypothesis will need to be tested against detailed simulations using PDF methods (e.g. Jeffery and Reisner, 2006) and observations.

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