A Modeling Study of Aerosol Effects on Cloud Radiative Property and Precipitation

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Abstract

The two-moment warm cloud parameterization of Chen and Liu (2004) is incorporated into a regional model to study the effects of aerosol concentration on cloud radiative property and precipitation. Using a prescribed tri-modal lognormal aerosol size distribution, the aerosol numbers are calculated from prognostic aerosol masses, for which advection, diffusion, and cloud drop activation/deactivation are considered. The sensitivity of cloud and raindrops to aerosol numbers, and its subsequent effects on precipitation is examined.

The aerosol indirect effect, more aerosols increase the cloud condensate nucleus (CCNs), leading to an increase in cloud albedo and a decrease in precipitation, is simulated. Simulations of a cold front passed through northern Taiwan during May 16-17, 2003, with different initial conditions for continental and maritime aerosol numbers were conducted. It is found that more aerosols result in more but smaller cloud drops and more cloud water, leading to an increase in albedo. The effects on rains are complex: smaller cloud drops has less efficient coagulation for raindrop to form (autoconversion), leading to fewer raindrop numbers and less rainwater; while more cloud water enhances the accretion for raindrop growth. Nevertheless, for the whole cloud system, the impact of increasing aerosols inhibits precipitation.

Key word: Cloud microphysics, aerosol

1. Introduction

Aerosols play a key role in cloud life cycle, serving as cloud condensate nucleus (CCNs) to initiate cloud formation, determining the cloud radiative properties and thus the radiative heating/cooling, and participating in the precipitation process. More aerosols result in more but smaller cloud drops, enhancing cloud albedo (Towmey, 1977; Coakley et al., 1987; Twohy et al., 1995; Ackerman et al., 2000), reducing cloud drop coagulation and drizzling formation, and perhaps extending cloud lifetime (Albrecht, 1989; Rosenfeld, 2000). Ackerman et al. (2004) recently demonstrate that, for boundary layer stratocumulus, the environment (humidity and droplet concentration of overlying air) also plays an important role. Although progress are being made in recent years in cloud schemes to allow aerosol-cloud interaction, for instance: Kogan (1991), Ackerman et al., (1995 and 2004), Flossmann (1998), and Khain et al. (2001) explicitly resolved size spectrums of water condensates; Ghan et al. (1997 and 2001), Lohmann et al. (1999), Khairoutdinov and Kogan, (2000), and Chen and Liu (2004) calculated moments of condensate drops; and Lohmann and Roeckner (1996), and Menon et al. (2002) diagnosed cloud drop numbers depending on aerosol concentrations, continued researches are needed not only on aerosol impacts on clouds and radiation, but also its effect on precipitation.

In this study, the scheme recently developed by Chen and Liu (2004; C&L scheme hereafter) for "warm clouds" is incorporated into the Mesoscale Model version 5.3 (MM5) of Pennsylvania State University-National Center for Atmospheric Research (NCAR). This two-moment cloud scheme explicitly considers the masses and drop numbers of water condensates (clouds and rains) as prognostic variables. For the numerical experiments, we pick the case of a cold front passed through northern Taiwan during 16-17 May 2003 and triggered deep convection. Because of the lack of aerosol information, sensitivity of precipitation to aerosol is examined using a range of values for both continental and maritime aerosols. The simulations used four nested domains with horizontal resolution of 3, 9, and 27 km and the inner most domain located in northern Taiwan (120.7-122.2°E;

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24.5-25.5°N) where hourly station precipitation data are available.

2. Treatment of Cloud-Aerosol Interaction

When a proper aerosol treatment is incorporated with, C&L scheme can perform cloud-aerosol interaction: aerosols become CCNs to initialize the condensation growth of cloud and rain droplets, while the evaporation of cloud drops results in the increase of aerosol numbers. In the present study, we followed the approach of Chen and Liu (2004) to calculate the number of activated CCNs and their sizes: assuming ammonium sulfate aerosols with a tri-modal lognormal size distribution. All aerosols larger than the critical radius of the Köhler-curve, depending on super-saturation and the aerosol composition, are activated as cloud (radius less than 10 μm) or rain drops (radius greater than 10 μm). Once the CCN activation is processed, the critical radius becomes the cutoff radius which separates the aerosol size distribution into two parts: available and unavailable for CCN activation. Thereafter, the critical radius has to be smaller than the cutoff radius to allow more CCN be activated later. Otherwise, no more CCN is activated no matter the air is supersaturated or not.

Furthermore, to decide the aerosol size distribution when its advection has to be calculated in our three dimensional model, we simply assume that the shape of the tri-modal lognormal distribution remains unchanged and only the total number (or mass) varies with time. In this treatment, the total number and the cutoff radius of aerosols are two parameters need to be solved from two additional prognostic variables. In this study we choose the mass of aerosols contained in the water condensates (wet aerosol) and the mass of aerosols not activated yet (dry aerosol) as these two additional variables, whose prognostic equations consider the processes of advection, diffusion, CCN activation, and cloud drop deactivation.

Because the numbers of water condensates and the masses of aerosols are highly discontinuous at cloud boundary, a more accurate and stable advection scheme is needed. Therefore, the total variance diminishing scheme (Hirsch, 1988; Allen, 1991; and Bott, 1992), a second order advection scheme, is introduced in MM5 to calculate the advection of cloud and aerosol particles. We also apply a horizontally homogeneous aerosol concentration as initial condition along with a constant value below 850 hPa or at the lowest three σ levels, and decreases exponentially in the vertical with a scale height of 3.57 km. Aerosols at the surface are initialized with clean continental and maritime aerosols with the number density of 1800 and 200 cm^{-3} respectively (Whitby, 1978; and Jaenicke, 1993), which are used as the background cases. To test the sensitivity of the simulation results to different aerosol initial conditions, experiments were conducted with the aerosol initial number density 10, 5, 0.2 and 0.1 times the background values. We show the simulation results of the continental background case, and the two cases of a factor 10 larger and smaller to bracket the range. In addition, we focus our discussion on the continental aerosols because similar characteristics were obtained from simulations with maritime aerosols. An additional experiment utilizing Hsie warm cloud scheme (Hsie and Anthes, 1984) was also conducted for comparison purpose.

3. Simulation Results

Figure 1 shows the model simulated total cloud/rain water and numbers averaged over the inner most domain for the continental aerosols. It is quite clear that more aerosols produce more cloud water and numbers, while the opposite is simulated for rainwater and numbers. However, the changes in rainwater are not as distinct as that of cloud water. Three peaks, which will be shown below, coincide with the three precipitation events. In addition, increases in cloud drop numbers outpace the increases in cloud water, thus yielding a smaller cloud drop size, as reflected in a smaller effective radius illustrated in the same figure. We have also used NCAR community climate model version 3 radiation scheme to calculate, off-line, the albedo. The increased albedo is due to increased opacity associated with increases in cloud water and numbers, as well as a decrease in the cloud effective radius. Note that no albedo was calculated during the night (hour 18-30).

The above characteristics are a result of the autoconversion when drop numbers of aerosols and cloud/rain drops are explicitly considered in the microphysics. Autoconversion accounts for the cloud drop self-collection for which larger drops have larger coagulation coefficients, and then turning those coalesced drops exceeding the size threshold into raindrops. Therefore, more aerosols yield more cloud drop numbers but smaller size can result in less efficient autoconversion, leading to fewer raindrops and less rainwater. However, the raindrop accretion process, the major rainwater source favorable in the environment of more cloud water, would mitigate the response of autoconversion, which explains the small difference in rainwater among the different aerosol cases. Another aspect concerning rainfall is that larger raindrop sizes will have faster fall speeds; the latter are explicitly calculated using the C&L diagnostic equations. Consequently, the net change in precipitation rate will depend on the two competing factors, decreasing rainwater and faster rain fall speed, which is in sharp contrast with the explicit moist schemes that consider no droplet size variation. For the latter, threshold of cloud water content basically dominates the autoconversion and rainwater content decides the fall speed of raindrops; therefore, more cloud water usually results in more rainwater through autoconversion process with subsequent faster raindrop falling speeds and precipitation rate.

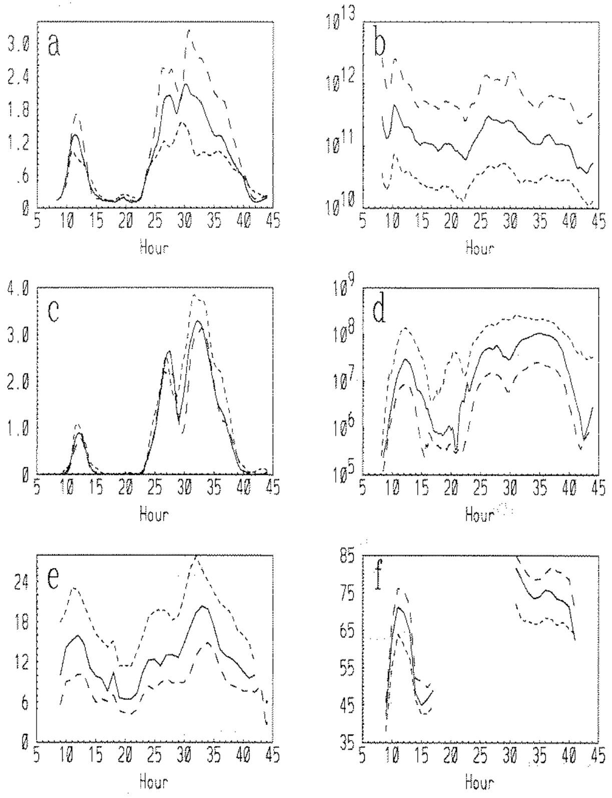

Figure 1. Model simulated cloud/rain properties averaged over the inner most domain (99×135 km^2 with 3 km resolution): (a) column cloud water (kg/m^2), (b) column cloud drop numbers (m^{-2}), (c) column rain water (kg/m^2), (d) column rain drop numbers (m^{-2}), (e) effective cloud drop radius (μm), and (f) albedo (%). The x-axis is the local time in Taiwan starting at 0500 LT, 16 May 2003. The simulations were run for the clean continental aerosols (solid line) as the background, and a factor of ten larger (dashed line) and smaller (dotted line) of the background value.

Comparison of simulated precipitation with observation, averaged over the four available stations (Tanshui, Anpu, Chutzehu, and Keelung) over Northern Taiwan, is shown in Fig. 2. Note that the model results are also the mean values of the four grid points next to the respective stations. The observations indicate three rainfall events, each lasted for over three hours with intensity larger than 2.5 mm/hour; in particular the second event is quite intense, nearly 20 mm fell during 1700 to 2000 LT. Because of no aerosol information is available, we conduct the comparison using the ten simulations (five each for continental and maritime aerosols) to illustrate the range. The model also simulates three rainfall events, with the first and third in better agreement with observation than the second, which is off in both the timing and intensity. [We have specifically examined the second event by conducting additional experiments using other cloud schemes available in the model version, including also the mixed liquid/ice phase schemes. They all failed to simulate this heavy precipitation mainly because of the absence of moisture convergence simulated in the model.] Nevertheless, C&L scheme demonstrates that, in addition to explicitly allowing the aerosol-cloud/rain drop interaction, improvement in simulating precipitation is also achieved when compared with Hsie scheme.

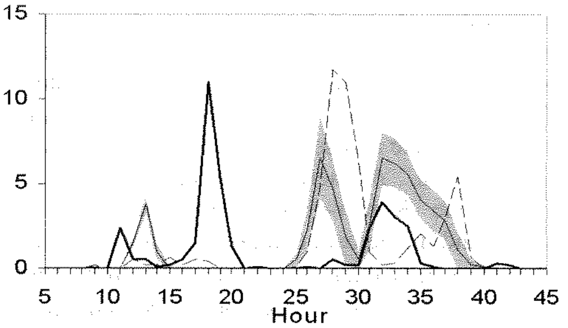

Figure 2. Comparison of model simulated and observed surface precipitation rate (mm/hr). Thick solid line is the mean of four observation stations (see text) while the simulations are the means over the four-grid points closest to the stations. The thin solid line is the mean value of the 10-simulations (in shading) for both the continental and marine aerosols using C&L scheme. Dashed line is the simulation using Hsie scheme.

4. Discussion

The present study demonstrates that cloud radiative properties and the precipitation are sensitive to aerosol number density. Although the net changes in precipitation rate is subject to the competing factors of less rainwater and faster terminal velocity, nevertheless the surface precipitation is most likely to decrease when considering the whole cloud systems. The results of the convective cloud simulations are consistent with other findings from boundary layer stratocumulus studies (Albrecht, 1989; Ackerman et al., 1995; and Rosenfeld, 2000) that increasing aerosol concentration would lead to increasing cloud water, drop numbers, and albedo but inhibiting rainfall. Note however that the effect of giant CCNs, which can increase the precipitation (Feingold et al., 1999), is not fully accounted in our study due to the prescribed size distribution that has a negligible number of giant CCNs and also the heavy precipitation type of this simulation is not favor for showing the giant CCN effect.

In addition to the simplified aerosol treatments, another relevant issue in the present study is the use of a warm cloud parameterization for the deep convection clouds, in which a mixed liquid/ice cloud particles might present. It is worthwhile to compare our simulations with those of Rosenfeld and Woodley (2000) who identified cases of deep convection clouds over Texas. In that study, the observed supercooled liquid water can be as large as 1.8 g/m^3, median volume radius ~8.5μm, and drop number ranges 100-1000 cm^{-3}, while the corresponding area averaged values in our most polluted simulations are 0.5 g/m^3, 9μm, and 100 cm^{-3} respectively. In addition, we have also conducted an experiment using Reisner mixed phase cloud scheme including graupel, which uses the same warm cloud microphysics of Hsie scheme, the results indicate similar temporal precipitation variation (to Hsie scheme) although its intensity becomes smaller. In any case, the effect of aerosols on mixed phase microphysics remains to be studied, and we are currently in the processes of developing a "cold" cloud parameterization, which will be more appropriate to address the issue. Furthermore, the study by Ackerman et al. (2004) of marine stratiform clouds suggests the importance of humidity above the clouds, which may even affect the sign of aerosol effect on precipitation. Nevertheless, it is quite clear that the cloud parameterization in climate models needs to explicitly consider the interaction between aerosols and cloud/rain drops as well as the environment where the cloud system is embedded.

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