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Simulation of the effects of increasing cloud condensation nuclei on mixed-phase clouds and precipitation of a front system

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Increasing cloud condensation nuclei (CCN) concentration usually leads to increasing cloud albedo and decreasing precipitation for warm clouds but its effect on the precipitation of mixed-phase clouds is less clear. Here, a bulk-formula semi-two-moment mixed-phase cloud scheme is incorporated with a regional model to study this aspect on a front system associated with convection. Although this cloud scheme is comparably simpler than most detailed bin-resolving cloud schemes used in cloud resolving models, certain features of CCN effects are reasonably simulated. Results show that both the first and the second indirect effects are simulated and that ice-phase precipitation effectively removes cloud water from the upper troposphere, leading to weaker first indirect effects. Sensitivity simulations show that although increasing CCN number results in more cloud drops and ice, its effect on surface precipitation depends on the interplay between the decreased warm-rain production and the decreased/increased ice-phase precipitation. The increase in cloud drops consequently enhances the diffusional growth of ice particles in water-subsaturated environments but inhibit it in water-supersaturated environments. Moreover, the change in riming depends on the balance between the enhancement due to more cloud drops and the suppression due to smaller cloud drops. For the case studied here, the precipitation responds nonlinearly to CCN number change, causing precipitation decrease in high CCN concentration environments but showing no clear tendency in low CCN concentration environments.

1. Introduction

Aerosol can serve as CCN to initiate cloud drops and regulate drop number, thus determining cloud radiative properties and affecting precipitation development. Many aerosol–cloud interaction studies (e.g. Kogan, 1991; Flossmann, 1998; Menon et al., 2002) have shown similar effects on warm cloud properties: more aerosol results in more but smaller cloud drops, increasing cloud albedo (Twomey, 1977; Coakley et al., 1987; Ackerman et al., 2000), an effect known as the first indirect effect. In addition, the smaller cloud drops can reduce the efficiencies of cloud drop coagulation and raindrop formation and thereby prolong cloud lifetime (Albrecht, 1989; Rosenfeld, 2000), an effect termed as the second indirect effect. It is also shown in some studies (Ackerman et al, 2004; Jiang et al., 2006) that the second indirect effect may be overestimated or even does not exist when the feedback from dynamics and dry environments are included. Hereafter, the consequences of changing the CCN number is referred to the CCN effect and the effect of giant CCN is insignificant in this study due to the limited amount of giant CCN. Note that the giant CCN, with radii greater than 5 μm, can quickly become rain embryo after activation to enhance precipitation (Feingold et al., 1999).

In warm clouds, because the majority of vapor condenses on cloud drops rather than on raindrops, the CCN effect on precipitation is significant and simply dominated by coalescence between liquid drops to convert cloud drops into raindrops.

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However, when ice-phase microphysics participates, the CCN effect on precipitation, involving rain, snow and graupel, becomes much more complex (Rosenfeld et al., 2008). Through freezing, similar to its effect on warm clouds, increasing CCN number may result in number increase and size decrease for cloud ice, thus enhancing the thickness and lifetime of outflow anvils (Chen et al., 1997). Different from warm clouds, in addition to the collision between droplets, the vapor deposition on ice-phase hydrometeors is another important source of ice-phase precipitation. For example, in an orographic precipitation case study by Colle et al. (2005), while liquid clouds consumed 73% of vapor condensation, snow can claim 24% of vapor condensation, an amount more than twice the sum of its development through both the autoconversion from and the accretion with cloud ice.

It is plausible that increasing CCN number may enhances/suppresses ice-phase hydrometeor formation by changing the number, size, and the evaporation/condensation rate of cloud drops. As CCN number increases, the associated increases in cloud drops and cloud water would increase their evaporation in water-subsaturated environments, enhancing the Bergeron–Findeisen process to feed the ice-phase hydrometeors. On the other hand, more cloud drops tend to consume more vapor in water-supersaturated environments, thus suppressing the supersaturation and subsequently weakening the diffusional growth of ice-phase hydrometeors. High water-supersaturation can be found in regions either with strong vertical motions (such as in deep convection) or with low cloud drop count. The increase in cloud water and cloud drop number not only affects the Bergeron–Findeisen process, it also affects the riming process, another dominant process for ice-phase precipitation growth in mixed-phase clouds. Riming, the process of cloud drops collected by ice-phase hydrometeors, can be strengthened by increasing cloud drops and weakened by the decreasing cloud drop sizes. In Lohmann (2004), the smaller cloud drops due to increasing anthropogenic aerosols may decrease the riming rate in stratiform clouds when a size-dependent collection efficiency is introduced to the riming calculation. Therefore, in order to understand the net effect on precipitation, it is pertinent to examine the various roles of CCN in ice-phase microphysics.

In this study, a bulk-formula semi-two-moment mixed-phase cloud scheme, which activates CCN to start cloud and raindrop development in water-supersaturated environments, is incorporated within the fifth generation Pennsylvania State University National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5) to investigate the effects of CCN on clouds, radiation, and precipitation in a convection system. It is called a "semi-two-moment" scheme because there are two moments for cloud drops, raindrops and cloud ice but only one moment for snow and for graupel. The considered prognostic variables include the mixing ratios and number concentrations of cloud drops, cloud ice, and raindrops; and the mixing ratios of snow, and graupel. The bulk-formula two-moment cloud schemes can save computational time and are more practical to apply to global models and regional climate models, and although they cannot simulate the changes in the size distributions nor perform more precise collision calculations as in the bin-resolving cloud schemes, the performance of the bulk-formula two-moment cloud schemes is quite good. For instance, in Morrison and Grabowski (2007), the comparison of the cloud properties simulated by the bin and the two-moment warm-rain microphysical schemes in a kinematic framework indicates that the features of the indirect effects can be well simulated although the magnitudes of indirect effects may be different.

In the following discussion, ice-phase precipitation includes snow and graupel, and ice-phase hydrometeors refer to cloud ice, snow, and graupel. Because the grid size of the model used in this study is larger than a few kilometers, it is better to simulate cloud systems horizontally extending more than a few tens of kilometers. More model details, the semi-two-moment cloud scheme, and the experiment design are described in Section 2. Section 3 presents the simulation results and the discussion and conclusion are given in Section 4.

2. Model, the mixed-phase cloud scheme, and experiments

2.1. Model

The same model used in Cheng et al. (2007), which is based on MM5 with an improved second-order advection scheme and the warm cloud scheme of Chen and Liu (2004, hereafter as the "CL scheme") for the simulations of CCN effects on stratiform warm clouds, is used in this study. The CL scheme is a two-moment bulk water warm cloud scheme, explicitly predicting the mass and the drop number of cloud drops and raindrops. All processes in the CL scheme are listed in Appendix A. Besides the cloud–aerosol interaction in the cloud scheme, advection, diffusion, and vertical mixing of prognostic hydrometeors and aerosol variables are also calculated in the model.

In the model, aerosol is assumed to be ammonium sulfate with a tri-modal lognormal size distribution and the prognostic aerosol mass is used to calculate the size distributions of dry aerosol. For CCN activation, the minimum size of dry aerosol to be activated depends on supersaturation according to Köhler equation. To simulate CCN activation and cloud diffusional growth, higher temporal resolution is needed because the supersaturation can change drastically. Therefore, we used time splitting integration in a Lagrangian framework (Cheng et al., 2007), treating each grid box as an ascending/descending air parcel, to resolve the changes in CCN and thermodynamical fields caused by activation and diffusional growth. In this way, the maximum supersaturation can be explicitly resolved and the number of activated cloud drops can be more accurately simulated. The remaining microphysical processes are calculated in an Eulerian framework after CCN activation and diffusional growth of hydrometeors are accounted for.

To simulate the first indirect effect on radiation, the radiation scheme of NCAR-CCM3 is added to the model and calculated every 30-min. In the model, the radiation scheme is fully coupled with the cloud microphysical properties: the cloud liquid water path and cloud ice path are calculated from predicted cloud water and cloud ice, the effective radii of liquid drops are calculated by the diagnostic formula of the CL scheme, and the effective radii of cloud ice are represented by the mean volume radii of ice particles. In addition, the masses of aerosol contained within cloud drops and raindrops are carried as two extra prognostic variables to account for aerosol recycling from drop evaporations. For the control case in this study, the tri-lognormal distribution at the surface is assigned