Atmospheric Research 145–146 (2014) 112–129

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmos

A modeling study of the aerosol effects on ice microphysics in convective cloud and precipitation development under different thermodynamic conditions

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ARTICLE INFO

Article history:
Received 28 November 2013
Received in revised form 14 March 2014
Accepted 28 March 2014
Available online 5 April 2014

Keywords:
Cloud model
Aerosol effects
Ice microphysics
Cloud invigoration

ABSTRACT

An improved approach for cloud droplet activation process parameterization is proposed that can utilize the empirically determined hygroscopicity information and practically limit the sizes of newly activated droplets. With the implementation of the improved approach in a cloud model, the aerosol effects on ice microphysics in convective cloud and precipitation development under different thermodynamic conditions is investigated. The model is run for four different thermodynamic soundings and three different aerosol types, maritime (M), continental (C) and polluted (P). Warm rain suppression by increased aerosol (i.e., CCN) is clearly demonstrated when weakly convective warm clouds are generated but the results are mixed when relatively stronger convective warm clouds are generated. For one of the two soundings that generate strong convective cold clouds, the accumulated precipitation amount is larger for C and P than for M, demonstrating the precipitation enhancement by increased CCN. For the maritime cloud, precipitation is initiated by the warm rain processes but ice hydrometeor particles form fast, which leads to early but weak cloud invigoration. Another stronger cloud invigoration occurs later for M but it is still weaker than that for C and P. It is the delayed accumulation of more water drops and ice particles for a burst of riming process and the latent heat release during the depositional growth of rimed ice particles that invigorate the cloud strongly for C and P. For the other sounding where freezing level is low, ice particles form fast for all three aerosol types and therefore warm rain suppression is not clearly shown. However, there still is more precipitation for C and P than for M until the accumulated precipitation amount becomes larger for M than for C near to the end of the model run. The results demonstrate that the precipitation response to aerosols indeed depends on the environmental conditions.

1. Introduction

Aerosols and clouds play important roles in climate change. IPCC (2007) reported that aerosol indirect effects could exert a significant impact on climate change. In conjunction with this issue, many scientists have studied the changes of microphysical properties of clouds and their impact on precipitation due to aerosols. Nonetheless, it can be said that there is no clear agreement among the results of different studies with regard to quantitative and even qualitative evaluation of the aerosol effects on precipitation. Some of these studies showed that an increase of aerosol number concentration led to an increase in cloud lifetime and a decrease in precipitation (e.g., Rosenfeld, 1999; Andreae et al., 2004; Hudson and Yum, 2001). Unlike these studies, however, in some other observational and numerical studies

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http://dx.doi.org/10.1016/j.atmosres.2014.03.022
0169-8095/

aerosol induced precipitation enhancement was reported, especially when ice processes were involved (Lin et al., 2006; Fan et al., 2007; Rosenfeld et al., 2008; Lee et al., 2008, 2009).

One thing certain seems to be that the aerosol effects on precipitation depend on the environment conditions under which the clouds form and on the cloud types (e.g., Khain, 2009). Recently reviewing many studies on this issue, Tao et al. (2012) summarized the physical processes behind the aerosol effects on convective precipitation development. Basically it is the precipitation enhancement for high CCN concentration due to cloud invigoration (Rosenfeld et al., 2008) through the latent heat-dynamic effect caused by suppression of warm rain and thus retaining more liquid water in the cloud to be frozen at upper level (e.g., Wang, 2005; Khain et al., 2005) and/or through the evaporative cooling effect: stronger evaporative cooling due to more but smaller cloud drops under high CCN concentration conditions could induce more vigorous convection, ultimately leading to enhanced surface precipitation (Lee et al., 2008, 2009).

This study attempts to reveal more insight on the issue of the aerosol effects on convective cloud and precipitation developments, especially when ice microphysics is involved. Takahashi's cloud model with bin microphysics (Takahashi, 1976a; Takahashi and Kawano, 1998; Yang and Yum, 2007) is employed, and cloud and precipitation development under various thermodynamic conditions is examined for different aerosol conditions. Considering the intrinsic limitation of bulk microphysics models in describing detailed microphysical evolution of hydrometeors, having bin microphysics scheme in the Takahashi cloud model is advantageous. However, this model has its own limitation in the calculation of cloud droplet activation process: the newly activated cloud droplets are assumed to take a prescribed size distribution shape, which only depends on the given air mass types, maritime and continental. This should not be true in real clouds where aerosol distribution and supersaturation condition interactively determine the newly activated droplet concentrations and their sizes. Realistic treatment of this process is critical since it crucially affects further development of cloud and precipitation. The latent heat release during condensation, freezing and deposition, which are the main energy sources of convective clouds, is eventually affected by this process. In model experiments performed under the same environmental conditions, the onset time of precipitation and its amount can be varied depending on how the cloud droplet activation process (not only the determination of newly activated droplet concentration but also the sizes of these droplets) is handled in the model.

So in this study a major improvement is made for the Takahashi cloud model in the way to calculate the cloud droplet activation process. Among the several approaches that are available these days, Kogan's (1991) approach is found to be physically sound and can successfully limit the newly activated droplet sizes to a realistic value. Therefore Kogan's approach is adopted in the Takahashi cloud model but with an important modification. Kogan (1991) assumed a single chemical composition of known inorganic salt (i.e., NaCl) for input aerosol distribution. Here we propose a way to incorporate the hygroscopicity information of ambient aerosols that can be significantly different from that of NaCl or $(NH_4)_2SO_4$, which is known and thus frequently assumed in modeling studies as in Kogan (1991).

With the implementation of the improved cloud droplet activation process parameterization into the model, we investigate the aerosol effects on convective cloud and precipitation development under four different thermodynamic conditions. The convective available potential energy (CAPE) is small for two of the four thermodynamic soundings and therefore only warm clouds can be formed under these thermodynamic conditions. The main focus is on the other two thermodynamic soundings that have large CAPE and therefore suitable for developing strongly convective clouds with mixed phase hydrometeors, which can illustrate the aerosol effects on ice microphysics in these strongly convective clouds. Here the model runs are done only for 120 min to investigate the aerosol effects in detail up to the precipitation development stage.

This paper is organized as follows: Section 2 describes the model, experimental setup, and a detailed explanation of the droplet activation process; in Section 3 the aerosol effects on convective cloud and precipitation development under different thermodynamic conditions are compared, with the emphasis on ice microphysics; discussion, and summary and conclusions are given Sections 4 and 5.

2. The model

2.1. Model description and experimental setup

The cloud model we used is a two-dimensional model developed by Takahashi (1976a). This is a nonhydrostatic and anelastic model with spectral bin microphysics that can simulate deep convection of both warm and cold clouds. In the Takahashi cloud model, four categories of hydrometeor species are considered: spherically shaped water drop, graupel and dense graupel (equivalently hail), and disk-shaped ice crystal (snowflake). Each of water drop, graupel and dense graupel species is divided into 36 bins with mass doubling in each consecutive bin (covering the radius range of 1 μm to 3.25 mm), and 23 categories in radius (from 10 μm to 2.05 cm) and 5 in thickness (from 10 μm to 4.1 cm) for ice crystals. In this study water drops of radii greater than 320 μm are considered as raindrops. The following values were assumed for density: water drops, 1 g cm^{-3} at any temperature; ice crystals, 0.1 g cm^{-3}; graupel, 0.3 g cm^{-3}; and dense graupel, 0.9 g cm^{-3}.

The domain size is 100 km × 12 km with $\Delta x = 400$ m and $\Delta z = 200$ m. A smaller grid interval of 200 m in the x axis produced no significant differences in results from 400 m (Takahashi and Kawano, 1998). Both the dynamics and the microphysical processes are calculated with 1 s time step except the collision process with 20 s time step. Ogura and Takahashi (1973) tested smaller time steps such as 10 s and 5 s, and the results were not significantly different. In this study the collision efficiency data for collision of graupels and dense graupels with water drops are modified according to Khain et al. (2001) to take into account the smaller density of ice hydrometeors than that of water drops, which resulted in slower formation of precipitation particles (Lee and Yum, 2012). Open boundary conditions are used on both sides of the model domain. The upper and lower boundaries are rigid with free slip condition. Basic equations and numerical schemes are