Atmospheric Research 206 (2018) 1–12

Contents lists available at ScienceDirect

Atmospheric Research

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

The effect of ice nuclei on a deep convective cloud in South China

Xin Deng, Huiwen Xue*, Zhiyong Meng

Department of Atmospheric and Oceanic Sciences, School of Physics, Peking University, Beijing, China

ARTICLE INFO

Keywords:
Ice nuclei
Deep convective cloud
Vertical transport
Ice nucleation
Homogeneous freezing
Heterogeneous nucleation

ABSTRACT

This study uses the Weather Research and Forecasting Model to simulate a deep convective cloud under a relatively polluted condition in South China. Ice nuclei (IN) aerosols near the surface are effectively transported upwards to above the 0 °C level by the strong updrafts in the convective cloud. Four cases with initial surface IN aerosol concentrations of 1, 10, 100, and 1000 L^{-1} are simulated. All simulations can well reproduce the major characteristics of the deep convective cloud in terms of the evolution, spatial distribution, and its track. IN aerosols have little effect on these macrophysical characteristics but can significantly affect ice formation. When IN concentration is increased, all heterogeneous nucleation modes are significantly enhanced, whereas the homogeneous freezing of cloud droplets is unchanged or weakened depending on the IN concentration and the development stages of the deep convective cloud. The homogeneous freezing of haze particles is generally not affected by increased IN but is slightly weakened in the extremely high IN case. As IN concentration is increased by 10 and 100 times, the enhanced heterogeneous nucleation is still not strong enough to compete with homogeneous freezing. Ice formation is hence still dominated by the homogenous freezing of cloud droplets and haze particles in the layer of 9–14 km, where most of the ice crystals are produced. The microphysical properties are generally unaffected in all the stages of cloud evolution. As IN concentration is increased by 1000 times and heterogeneous nucleation is further enhanced, the homogeneous freezing of cloud droplets and haze particles dominates only in the mature and dissipating stages, leading to unaffected ice number mixing ratio in the anvil region (approximately above 9 km) for these two stages. However, in the developing stage, when the supply of cloud droplets is limited, the homogeneous freezing of cloud droplets is weakened or even suppressed due to the very strong competition for liquid water with heterogeneous nucleation, leading to significantly lower ice number mixing ratio in the anvil regions. In addition, the microphysical properties in the convective core regions below the cloud anvil (approximately below 9 km) are also affected in the case of 1000 L^{-1}. The enhanced heterogeneous nucleation produces more ice crystals below 9 km, leading to a stronger conversion from ice crystals to snow particles, and hence higher number and mass mixing ratios of snow. The IN effect on the spatial distributions and temporal evolutions of the surface precipitation and updraft velocity is generally insignificant.

1. Introduction

Aerosols can serve as ice nuclei (IN) to facilitate ice formation at temperatures warmer than the homogeneous ice nucleation temperature (Pruppacher and Klett, 1997, p287). IN are traditionally thought to be solid, insoluble particles with crystalline structures similar to the hexagonal lattice of ice (Lamb and Verlinde, 2011, pp308). Such particles include dust, soot, and volcanic ash from either natural or anthropogenic sources (e.g., DeMott, 1990; Fornea et al., 2009). However, over the past decade, laboratory experiments showed that some organic and biological particles can also serve as IN, although without the crystalline structures similar to ice crystals (e.g., Wang et al., 2012; Hoose and Möhler, 2012; Murray et al., 2012).

Field projects such as CRYSTAL-FACE (Cirrus Regional Study of Tropical Anvils and Cirrus Layers-Florida Area Cirrus Experiment) and NAMMA (NASA African Monsoon Multidisciplinary Analyses) showed the wide existence of ice-nucleating aerosols inside ice crystals in cloud anvil of deep convective clouds. Insoluble particles (soot, organic carbon, dust, and metals) account for 51–55% on average in the number of residual nuclei collected from anvil clouds over Florida during CRYSTAL-FACE, and the ratio of insoluble to soluble (salts and sulfate) particles in small residual nuclei increases as the anvil environmental temperature increases (Twohy and Poellot, 2005). This indicates that insoluble particles play an important role in triggering ice formation at warmer temperatures in cirrus anvil. Twohy (2015) found that dust is the dominant residual particle type sampled in ice crystals

* Corresponding author at: Department of Atmospheric and Oceanic Sciences, School of Physics, Peking University, Room 518 North, Physics Building, 209 Chengfu Road, Beijing 100871, China.
E-mail address: hxue@pku.edu.cn (H. Xue).

https://doi.org/10.1016/j.atmosres.2018.02.013
Received 18 November 2017; Received in revised form 15 February 2018; Accepted 15 February 2018
Available online 17 February 2018

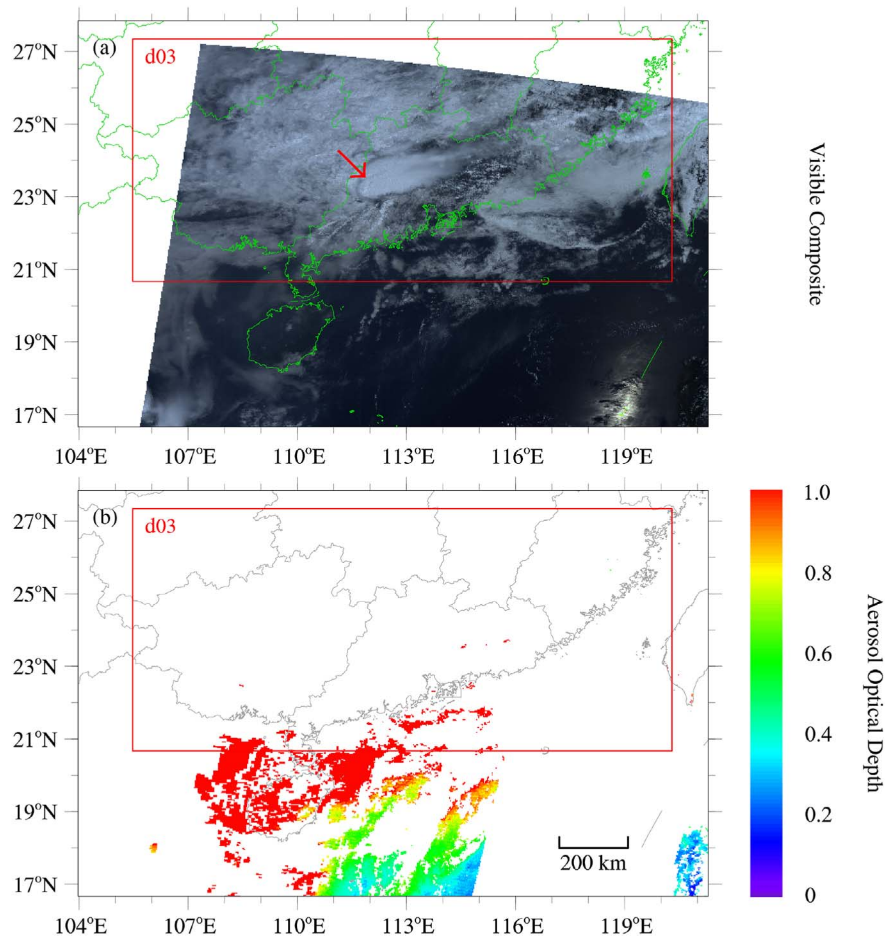

Fig. 1. MODIS images of (a) visible composite and, (b) aerosol optical depth at local time 10:50 on 17 April 2011. The red boxes indicate the location of innermost domain (d03). The red arrow in (a) indicates the location of the deep convective cloud. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

from anvil outflow of tropical Eastern Atlantic Ocean during NAMMA, which is downwind of the Saharan dust source.

Results from some numerical simulations indicate that increasing IN concentration can increase cloud ice amount in deep convective clouds. For example, van den Heever et al. (2006) showed that high IN concentration in the dust layer leads to higher proportion of vertically integrated ice water in the total condensate (liquid and ice) in a CRYSTAL-FACE case using the Regional Atmospheric Modeling System (RAMS). Similar results were also found in a large eddy simulation (LES) (Carrió et al., 2007). Fan et al. (2010) employed a 3-dimensional cloud resolving model to simulate the IN effect on two deep convective clouds over Tiwi Islands, northern Australia. They found that both ice number concentration and ice water content increase dramatically when multiplying the IN concentration by a factor of 2.5 either in the mid-troposphere only or in the whole vertical extent of the troposphere.

Increasing IN concentration can sometimes decrease the ice water content. In a LES study of the IN effect on a deep convective cloud over Tiwi Islands (Connolly et al., 2006), the number concentration of the total ice particles (ice, snow and graupel) increases when enhancing heterogeneous ice nucleation by five times, but decreases when enhancing by ten times. However, in a Weather Research and Forecasting (WRF) model simulation of a deep convective cloud over tropical western Pacific (Phillips et al., 2007), it was found that the cloud is hardly affected when IN concentration is increased by 10 times but significantly affected when IN concentration is increased by 1000 times. In the extremely high IN case, ice concentration is increased by up to half an order of magnitude at lower altitude (below −20 °C level) due to the enhanced heterogeneous nucleation, while reduced by up to one order of magnitude at higher altitude because homogeneous freezing of cloud droplets is suppressed by the decreased liquid water.

The IN impact on the updrafts and precipitation of deep convections is largely uncertain, with regard to both the magnitude and the sign. Some studies suggested that more IN result in more latent heat release during glaciation and therefore stronger updrafts. More ice particles can also produce more precipitation through stronger depositional growth and collection of cloud droplets (Ekman et al., 2007; Hazra et al., 2016). But van den Heever et al. (2006) demonstrated a decrease of the 12-h accumulated precipitation with increasing IN, although the precipitation in the initial stage (first 6 h) increases with IN concentration. Some investigations argued that the effect of IN on the strength and surface precipitation of deep convections are limited (Connolly et al., 2006; Fan et al., 2010). The reason is that cloud ice is not enough and mainly exists at high altitudes, thus the latent heat released by the increased ice mass mainly heats the upper level and is less important than other microphysical processes (Fan et al., 2010).

IN can nucleate ice crystals via four ice nucleation modes: deposition nucleation, condensation freezing, contact freezing, and immersion freezing (Lamb and Verlinde, 2011, pp312). Sensitivity experiments with RAMS showed that deposition-nucleation/condensation-freezing is an important mechanism of ice formation only when temperature is colder than −10 °C, while contact freezing is efficient only when temperature is warmer than −15 °C (Cotton et al., 1986). Hiron and Flossmann (2015) used a 1.5-dimensional dynamic framework coupled with bin-resolved microphysics to study the role of different ice nucleation modes in convective clouds. They found that homogenous freezing and immersion freezing dominate ice formation in convective clouds. Condensation freezing also plays an important role. On the contrary, deposition nucleation and contact freezing are much less