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Role of mineral dust, soot, and bacteria in cloud and precipitation formation processes over Indian subcontinent using an atmospheric general circulation model

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A B S T R A C T

An aerosol-type specific heterogeneous nucleation parameterization that based on the classical nucleation theory has been implemented into the atmospheric general circulation model (AGCM), ECHAM5. The microphysical responses in precipitation formation to the variation of ice nuclei (IN) species over Indian subcontinent were analyzed using AGCM, considering the immersion freezing nucleation from mineral dust, dust with ammonium sulfate coating, soot and bacteria species. Immersion freezing by bacteria species is found to be dominating in October–December, whereas dust with ammonium sulfate produces more cloud ice in January–March. There are very little differences in cloud ice formation during April–May and June–September among various IN species. There is also a geographic dependence in the role of different IN species in precipitation formation, like bacteria is important in Southern Peninsula and dust particles play a significant role in central India. In nature the emission of ice nucleating active bacteria and non-biological dust, soot into the atmosphere is important and highly dependent on temperature, and precipitation. So it is the worthy of investigation on the role of different kind of aerosols on the microphysics and precipitation processes, the biosphere–atmosphere interaction and climatic research.

1. Introduction

Ice processes in clouds are important to cloud radiative properties and precipitation formation processes. More than 50% of the mid-latitude precipitation is produced via cold-cloud (involving ice) processes, whereas this proportion in tropical region is about 30% (Lau and Wu 2003). Below −38 °C, cloud ice formation occurs by homogeneous freezing process. But at temperatures between 0 °C and −38 °C, aerosol particles that act as ice nuclei (IN) are required to initiate cloud ice. These ice nuclei can lower the energy barriers of ice nucleation so that ice particles can be produced heterogeneously in relatively warm environments. They can initiate cloud ice through the deposition mode, condensation–freezing mode, contact freezing mode or the immersion-freezing mode (cf. Pruppacher and Klett, 1997, p. 309).

Recently a major field experiment called Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX) in India (conducted by Indian Institute of Tropical Meteorology, IITM) has been done during the period May–September 2009 (http://www.tropmet.res.in/~caipeex/). The experiment reveals the presence of ice nuclei (IN) over Indian subcontinent (Prabha et al. 2012) and most of them are dust and soot origin (Padmakumari et al. 2012). This actually opens up the possibility of heterogeneous ice nucleation where ice nuclei (IN) play a crucial role in mixed-phase processes that do not develop high enough to reach the homogeneous freezing levels. Recently, Waliser et al. (2009) have shown that the representation of cloud ice in general circulation model (GCM) is inadequate. They have analyzed many satellite data and pointed out that even though parameterization in GCMs accounting for cloud ice processes have, still is not sufficient. So, this is an ongoing challenge in rectifying these shortcomings and motivates for this present study to improve the bias in the cloud hydrometeor production. Thus the role of various IN species (e.g., mineral dust, soot and bacteria) that can modulate cloud ice formation through their different nucleation ability and manifest in the cloud and precipitation formation has been taken as great interest using a general circulation model (GCM).

The origin of atmospheric ice nuclei has been of scientific interest for decades. Originally, this interest was due to the discovery in the 1940s that precipitation could be induced via the seeding of clouds with ice nuclei. More recently, it has been suggested that ice nuclei may have an important climatological effect due to their role in cloud microstructure and radiative properties (Carrió et al. 2007). Natural IN that has been identified to be abundant and important in the atmosphere includes wind-blown dust and biogenic aerosols (hereafter called bio-aerosols). Mineral dust particles mainly originate from the deserts, semi-arid areas and to a lesser extent, grass lands, cultivated lands, sandy seashores and river banks. The dust particles from the arid regions of the Asiatic continent have been implicated as

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possible heterogeneous IN since more than 50 years ago (Isono et al. 1959). Other studies also suggested that mineral dusts are highly variable in space and time. The concentration of mineral dust particles in the atmosphere can be very low over remote oceans, and may reach well above several thousand per cubic centimeter near the desert area in Northern China during the dust-storm active season of Spring (Fratini et al. 2007).

Ice nucleation by mineral dust have been shown by deposition (Salam et al. 2006), immersion freezing (Zuberi et al. 2002) and contact (Svensson et al. 2009) mode. Most mineral dust aerosols tend to have mixed chemical composition, including variety of inorganic and organic species. As for example Zuberi et al. (2002) and Hung et al. (2002) showed freezing of ammonium sulfate solution with mineral dust as the center. Experimental data on ice formation in concentrated aqueous particles containing mineral dusts is crucial for improving models. Under the scenarios of global climate change, one may expect mineral dust and bacteria concentration in the air to vary in response to changes in soil moisture and ecosystem. But the magnitude of such changes and how they affect clouds and precipitation formation remain largely unexplored.

Bio-aerosols include whole organisms (e.g. bacteria, fungi and phytoplankton), reproductive materials (e.g. pollen) and fragments (e.g. plant wax). Matthias-Maser et al. (2000) suggest that the proportion of biological material in remote continental, polluted continental and remote maritime environments is respectively 28%, 22% and 10%. Among various bio-aerosols, bacteria are considered a major type of natural IN because of their efficient ice-nucleating ability and large quantity. Worldwide availability of such nuclei was established by finding ice-forming nuclei in plant litters collected in different climatic zones (Schnell and Vali, 1973).

Soot is the name given to all of the solid primary, carbonaceous products from incomplete combustion, and may be of natural or anthropogenic origin. CCN (cloud condensation nuclei) and ice nucleating activity of soot particles (DeMott, 1990) are significant to the general understanding of human influence on clouds and precipitation. If soot acts as ice nuclei, then an increase in soot emission due to fossil fuel combustion may lead to an increase of IN concentration in the troposphere. Thus, it is important to evaluate the ice-forming activity of soot particles. Therefore, a greater understanding of ice nucleation by various IN species is required to improve our ability to simulate cloud formation processes.

To perform a realistic model simulation, one needs to know not only microphysical mechanisms involved but also the properties (i.e. ice nucleation capabilities) of IN species. In most cloud models the number of ice nuclei which are available to initiate the formation of primary ice particles in supercooled liquid clouds are calculated with simple equations mainly as function of the temperature and/or the ice supersaturation that serve as surrogates for explicitly resolving deposition and freezing nucleation mechanisms. Earlier work partially based on measurements of atmospheric ice nuclei using a static filter approach (Fletcher, 1962; Huffman, 1973). Yet, these measurements cannot differentiate the types of IN, so the empirical formulas obtained from them are not suitable for the study of a particular type of IN. It is one of the major challenges of cloud physics field to improve the formulation of ice formation in cloud models. More sophisticated laboratory experiments (DeMott, 1990, Möhler et al., 2006; Hung et al., 2002; Levin et al., 1987, Hazra et al., 2004) have been designed toward measuring the ice nucleation efficiency of specific types of IN (e.g., mineral dust, sea salt, soot, bacteria, spores, fungi, algae and pollen), and their results are crucial to the numerical study. Chen et al. (2008) reanalyzed several of these experimental results to provide physically-based parameterization formulas of heterogeneous ice nucleation from several types of IN.

In nature, dust in the atmosphere usually mixed with ammonium sulfate. When dust and ammonium sulfate becomes ice germ, the ice nucleation rate of dust and ammonium sulfate changes with two mixing mode (external mixing or internal mixing). The nucleation rate of pure mineral dust (kaolinite), dust coated with ammonium sulfate, which is internally mixed are considered in this present study. So, in this paper we apply the experimentally determined nucleation rate formulas for bacteria (BAC), dust (kaolinite) (KAD), mineral dust coated with ammonium sulfate (internal mixing) (ASD) and soot (SOOT) into a microphysical scheme of the atmospheric general circulation model (ECHAM5) to assess the potential impacts of natural and anthropogenic ice nuclei on cloud properties and precipitation. This is the first time where the effect of different IN species (mineral dust to anthropogenic aerosol like soot and biological, bacteria) are examined using GCM for cloud and precipitation formation processes. Although there are other freezing processes for heterogeneous nucleation but immersion freezing nucleation is very common in the atmosphere. Hence in this present study only immersion freezing nucleation are considered to see how the cloud ice production improved using this particular freezing process with different species. Section 2 will describe about the model used for this particular sensitivity studies. The results and conclusions are presented in Sections 3 and 4, respectively.

2. Model and experimental design

2.1. General description

The fifth-generation atmospheric general circulation model (ECHAM5) developed at the Max Planck Institute for Meteorology (MPIM) has been used for this present study. The model is a spectral model, which we ran at T106 resolution with 19 levels in the vertical. A comprehensive model description of ECHAM5 is given in

Table 1
List of four sensitivity experiments for different IN species (e.g., dust coated with ammonium sulfate (ASD), kalolinite dust (KAD), soot (BAC), *Pesudomonas syrinage* bacteria (BAC)) along with control (CTL).

Sensitivity experiments	Contact angle (θ in deg.)	Activation energy ($x\ 10^{-20}$ J)	Details
ASD (r_N=0.075 μm)	57.9	4.55	The immersion freezing nucleation rate formulation by dust with ammonium sulfate based on Chen et al. (2008) replacing Biggs (1953) formulation
KAD (r_N=0.75 μm)	29.9	16.0	The immersion freezing nucleation rate formulation by dust (kaolonite) based on Chen et al. (2008) replacing Biggs (1953) formulation
SOOT (r_N=0.04 μm)	32.2	13.8	The immersion freezing nucleation rate formulation by soot based on Chen et al. (2008) replacing Biggs (1953) formulation.
BAC (r_N=0.5 μm)	12.5	12.8	The immersion freezing nucleation rate formulation by bacteria (*Pseudomonas syrinage*) based on Chen et al. (2008) replacing Biggs (1953) formulation
CTL			This is the control experiment where, ice initiation takes place considering original formulation by Biggs (1953) immersion freezing formulation