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The effect of mineral dust and soot aerosols on ice microphysics near the foothills of the Himalayas: A numerical investigation

Anupam Hazra [a,*], B. Padmakumari [a], R.S. Maheskumar [a], Jen-Ping Chen [b]

[a] Indian Institute of Tropical Meteorology, Pune 411 008, India
[b] Department of Atmospheric Sciences, National Taiwan University, Taipei 10673, Taiwan

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ABSTRACT

This study investigates the influence of different ice nuclei (IN) species and their number concentrations on cloud ice production. The numerical simulation with different species of ice nuclei is investigated using an explicit bulk-water microphysical scheme in a Mesoscale Meteorological Model version 5 (MM5). The species dependent ice nucleation parameterization that is based on the classical nucleation theory has been implemented into the model. The IN species considered include dust and soot with two different concentrations (Low and High). The simulated cloud microphysical properties like droplet number concentration and droplet effective radii as well as macro-properties (equivalent potential temperature and relative humidity) are comparable with aircraft observations. When higher dust IN concentrations are considered, the simulation results showed good agreement with the cloud ice and cloud water mixing ratio from aircraft measurements during Cloud Aerosol Interactions and Precipitation Enhancement Experiment (CAIPEEX) and Modern Era Retrospective Analysis for Research and Applications (MERRA) reanalysis. Relative importance of IN species is shown as compared to the homogeneous freezing nucleation process. The tendency of cloud ice production rates is also analyzed and found that dust IN is more efficient in producing cloud ice when compared to soot IN. The dust IN with high concentration can produce more surface precipitation than soot IN at the same concentration. This study highlights the need to improve the ice nucleation parameterization in numerical models.

1. Introduction

Aerosols are one of the key components of the climate system and the hydrological cycle (Ramanathan et al., 2001). It is well documented that the cloud radiative feedback and effect of aerosol are the major sources of uncertainty in the climate models (Ramaswamy et al., 2001). There are numerous important studies on aerosol direct effect over South Asia as well as Indian summer monsoon (Ji et al., 2011, 2015). Aerosol indirect effects are similarly important for cloud and precipitation studies (Rosenfeld et al., 2008; Fan et al., 2012; Hazra et al., 2013b). Water soluble aerosols that act as cloud condensation nuclei (CCN) for droplet formation are usually quite abundant in the troposphere, so an increase in their concentration can lead to smaller cloud droplets thus reducing the chances of coalescence to form raindrops. While many recent studies focused on the effect of increasing CCN, the effect of ice nuclei (IN) has received less attention. As ice nucleation is dependent on specific aerosol types, the impact of natural and anthropogenic sources of ice nucleation can lead to change in the hydrological cycle (Denman et al., 2007). Heterogeneous ice nucleation activated by particles that have surface properties favorable to lowering the energy barrier for crystallization, triggers at warmer temperatures as compared to homogeneous nucleation (below −40 °C).

The origin of atmospheric ice nuclei has been of scientific interest for decades and it has strong impact on the pathways for ice and mixed-phase cloud formation and precipitation (Fan et al., 2010; Kulkarni et al., 2012a, 2012b; Teller et al., 2012). It has also 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). Recently Zeng and Coauthors (2011) had also shown that the ice crystal enhancement factor that is related to the number concentration of IN (N_{IN}) for tropical clouds is important for quantifying the contribution of changes of IN to global warming (Zeng and Coauthors, 2009a). The IN concentrations strongly impact upper-tropospheric ice water content and are also important in quantifying the effect of IN variability (Zeng and Coauthors, 2009b).

Natural IN has been identified as abundant and important in the atmosphere. The most common atmospheric IN are mineral dust particles which originate from the deserts, semi-arid areas and to a lesser extent from grass lands, cultivated lands, sandy seashores and river banks.

* Corresponding author at: Indian Institute of Tropical Meteorology, Dr. Homi Bhabha Road, Pashan, Pune 411 008, India. Tel.: +91 20 2590 4475.
E-mail address: hazra@tropmet.res.in (A. Hazra).

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Mineral dust particles from the arid regions of the Asiatic continent have been implicated as possible heterogeneous IN (Lohmann and Diehl, 2006; Kulkarni et al., 2012a, 2012b; Teller et al., 2012; Wang et al., 2012), which is highly variable in space and time (DeMott et al., 2010). The concentration of mineral dust particles in the atmosphere can be very low over remote oceans, and may well exceed several thousand per cubic centimeter near the desert area in Northern China during the dust-storm active season of spring (Fratini et al., 2007). Even at several thousand kilometers downwind of the source region, the concentration may still reach a few tens of particles per cubic centimeter during a relatively strong dust storm event (Chun et al., 2001). The majority of the mineral dust particles transported from continental areas to marine region have a wide size range from 0.5 μm to 75 μm diameters (Maring et al., 2000, 2003). Recent in-situ observations during Cloud Aerosol Interactions and Precipitation Enhancement Experiment (CAIPEEX) conducted over India in 2009, near the Himalayan foothills showed the presence of transported dust from the west (Padmakumari et al., 2013a, 2013b). The typical IN concentration is found to be 0–5 per liter over different parts of India (Patade et al., 2014). Hazra et al. (2013a) showed that dust IN of such concentrations can affect cloud and precipitation formation processes during south-west monsoon over the Indian subcontinent.

Similar to the mineral dust, soot particles can also act as ice nuclei (DeMott, 1990; Chen et al., 2008). Soot particles are basically carbonaceous products from incomplete combustion, and may be of natural or anthropogenic origin. Using samples of different hygroscopicity and surface porosity, an extensive comparison of IN and CCN activity of black carbon (BC) containing aerosol were reported by Köhler et al. (2009). It has been pointed out that freshly emitted fossil-fuel pollution does not nucleate ice heterogeneously to any appreciable extent (e.g. Köhler et al., 2009). Again, as pointed out by Phillips et al. (2013), biomass-burning pollution displays copious IN. Because of their large global emission, it is important to evaluate the ice-forming activity of soot particles. Recent in-situ observations showed the presence of dust as well as anthropogenic aerosols such as biomass burning over the foothills of the Himalayas (Padmakumari et al., 2013a). They also reported ice phase above 6 km at temperatures lower than −14 °C which is much higher than −40 °C for cloud ice formation. Besides the species-dependent ice nucleation capability, cloud ice production also depends on N_{IN} (Zeng and Coauthors, 2009b).

Thus, the present study addresses

(a) The relative role of mineral dust and soot particles (species type) acting as ice nuclei in cloud microphysical and precipitation processes.

(b) The role of number concentration of dust ice nuclei in modifying the cloud microphysical properties and precipitation.

The formation of ice in clouds is of great importance, as ice nucleation is one of the key processes initiating precipitation. The precipitation formation dominantly depends on the characteristics of clouds through the mechanism of freezing, deposition, condensation, melting and evaporation (Waliser and Coauthors, 2009; Hazra et al., 2015a, 2015b; Halder et al., 2015). Errors in predicting vertical structure of cloud ice hydrometeors lead to larger biases in precipitation processes through feedback mechanisms (Waliser and Coauthors, 2009; DeMott et al., 2010; Fan et al., 2012). Biases in representation of clouds in cloud resolving models (CRMs) and general circulation models (GCMs) arise largely from inadequate representation of ice and liquid water content profiles (Waliser and Coauthors, 2009; Phillips et al., 2008; DeMott et al., 2010). Based on analysis of many satellite data they pointed out that existing parameterization schemes in GCMs that account for cloud ice processes are inadequate (Waliser and Coauthors, 2009). Given recent attention to the role of ice phase in cloud and precipitation formation processes, there also exists a gap in our understanding of heterogeneous ice nucleation process and hence is one of the key limitations in both CRMs and GCMs. Therefore, rectification of these shortcomings is a major challenge and also motivation for this present study. Furthermore, realizing the biases in ice number concentrations and its role in ice-phase microphysics, we propose modified formulations to diagnose cloud ice. Thus, an ice nucleation parameterization based on classical nucleation theory (CNT), with aerosol-specific parameters derived from experiments, has been implemented into a CRM.

In this paper we apply the experimentally determined nucleation rate formulae for dust into a sophisticated microphysical scheme of the Mesoscale Meteorological Model Version 5 (MM5) to assess qualitatively the potential impacts of natural ice nuclei on cloud properties and precipitation.

2. Data

The Modern Era Retrospective Analysis for Research and Applications (MERRA) data product has been used to compare the vertical structure of cloud ice and cloud water with model simulations. Detailed description of data set is available in recent work (Rienecker and Coauthors, 2011). During CAIPEEX-2009, a twin engine Piper Cheyenne research aircraft equipped with standard instrumentation was used (for more details about the experiment and the instrumentation see Kulkarni et al., 2012a, 2012b). The measurements were made near the foothills of the Himalayas from the base of Pathankot (32.2° N, 75.63° E) during 23 to 28 May 2009. In the present study the aircraft data obtained on 24 and 28 May 2009 are utilized. On these days high aerosol concentrations were measured up to 4 km using a Passive Cavity Aerosol Spectrophotometer Probe (PCASP) and clouds were observed in the vicinity of haze (Padmakumari et al., 2013a, 2013b). A cloud droplet probe (CDP) was used to measure the drop size distribution in the range of 2–50 μm and concentration. The Cloud Imaging Probe (CIP), measuring in the size range of 25–1550 μm, was also used to obtain hydrometeor images. Ice nuclei concentrations were inferred from the CIP measurements. Data is collected at an interval of 1 s (flight speed ~ 100 m/s).

Radiosonde observations were conducted from the base station, Pathankot, during the aircraft operations. During this period, the surface average temperatures were about 40 °C and relative humidity (RH) varied from 10% to 20%. Hence, dry weather prevailed over the region. Westerly and northwesterly winds are dominant during this period bringing in desert dust from the western countries. Initially weak convection prevailed but by late afternoon convective clouds was observed. Aircraft sampling was done mostly on fresh growing cumulus towers. Multiple horizontal level penetrations were made at different altitudes on the 24th and the 28th of May. Each cloud penetration was made for a minimum of 5 s and a maximum of 60 s on a level flight, so that convective cores of the clouds were also sampled. Cloud droplet number concentration (CDNC) and cloud droplet effective radii (CDER) are averaged along each horizontal penetration. The theta and RH profiles derived from the aircraft as well as radiosondes launched at the time of the flight are also used in this study.

3. Model framework

3.1. Model general description

At present, numerical simulation using a detailed cloud microphysics scheme is probably one of the most effective ways of understanding the role of various IN species in precipitation formation, as the whole picture of precipitation formation cannot be easily reproduced in the