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Study of cloud microphysical properties over India during CAIPEEX using a mesoscale model with new cloud microphysical scheme—Part I

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ABSTRACT

Incorporation of aerosol interaction in cloud microphysics is being the central issue now a day. In the present study, an improved and modified cloud microphysical scheme comprising bulk-formula two-moment mixed-phase cloud scheme has been incorporated with a regional model to study the cloud–aerosol interaction in the mixed-phase cloud system. The paper intends to sensitivity study as to what extent this new microphysical scheme can capture the observed cloud microphysical properties. The observed cloud microphysical hydrometeors are evaluated from MODIS (Moderate Resolution Imaging Spectrometer) and CAIPEEX (Cloud Aerosol Interaction and Precipitation Enhancement EXperiment) data set over the Indian peninsular region. Surface accumulated precipitation is collected from TRMM-3B42 data sets. One active convection (case study 1) and two suppressed convection events (case study 2 and case study 3) during Indian south west monsoon are simulated over three different locations of the Indian peninsular region with the help of a multi nested mesoscale model based on microphysical modification. The cloud microphysical properties such as cloud water path from satellite data retrieval and cloud drop number concentration, cloud droplet radius from CAIPEEX, are reproduced well by the modified microphysical scheme. The rainfall is also reasonably well simulated during active monsoon convection event (6th July, 2009) as well as suppressed monsoon convection events (15th June and 19th August, 2009). Moreover, another sensitivity experiment is done to include natural aerosols, like dust as a representation of heterogeneous ice nucleation. The inclusion of mineral dust effect as ice nuclei provides realistic cloud microphysical properties during present case studies successfully. So it is a worthy investigation of the role of different kinds of aerosols on the microphysics and precipitation processes.

1. Introduction

Aerosol is one of the key components of the climate system and the hydrological system (Ramanathan et al., 2001). Recently, Krishnamurti et al. (2010) had shown that the western Asian desert air incursions toward central India, leads to the formation of a blockage over west Asia. Water soluble aerosols that act as condensation nuclei for cloud drop formation are usually quite abundant in the troposphere. So an increase of aerosol usually leads to smaller cloud drops and thus reduces the chances of coalescence to form raindrops. The situation may be different when ice-phase processes are involved. Many studies have shown that an increase in cloud condensation nuclei (CCN) may actually result in more precipitation by enhancing mixed-phase precipitation formation (Lin et al., 2006) or by altering cloud dynamics as a result of either enhanced latent heat release (Goswami et al., 2006; Rosenfeld, 2000) or by stronger rain evaporation and formation of surface cold-air dome in a squall line system (Tao et al., 2007). Recently a major field experiment called Cloud Aerosol Interaction and Precipitation Enhancement EXperiment (CAIPEEX) in India has been conducted by Indian Institute of Tropical Meteorology, (IITM) during the period of May–September 2009 (http://www.tropmet.res.in/~caipeex/). In this CAIPEEX-Phase I experiment attempts have been taken to identify and to understand the pathways through which aerosols may influence in cloud and precipitation formation. Experimental details and analysis of microphysical structure has already been documented (Thara et al., 2011; Kulkarni et al., 2012). The aircraft measurement during CAIPEEX provides us a good quality of aerosol and cloud microphysical data like, the aerosol number concentration, cloud drop number concentration as well as cloud drop effective radius for different cloud systems in different parts

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of India (Thara et al., 2011; Kulkarni et al., 2012; Nair et al., 2012). During CRYSTAL-FACE the entrainment of midlevel aerosols into a rapid cumulonimbus updrafts were observed and were found to be critical in the generation of anvil ice particles simulated by Fridlind and Coauthors (2004) in the 3D cloud model using spectral microphysics. Heymsfield et al. (2005) argued that cloud liquid evaporates without homogeneous freezing if convective updrafts become weak. These actually open up the possibility of heterogeneous ice nucleation and play a crucial role of ice nuclei (IN) in mixed-phase processes for clouds that do not develop high enough to reach the homogeneous freezing heights. The dust particles from the arid regions of the Asiatic continent have been reported as possible heterogeneous IN, more than 40 years ago (Isono et al., 1959). Hung et al. (2002) showed freezing of ammonium sulfate solution with mineral dust as the center. Therefore, a greater understanding of ice nucleation mechanisms of mineral dust is required to improve the ability of heterogeneous ice nucleation process in the model. It will definitely improve the understanding of cloud aerosol interaction and hence cloud microphysical parameterization of model physics. In recent decades many researchers (e.g., Kaskautis et al., 2009; Badarinath et al., 2010 and Manoj et al., 2011) have demonstrated the importance of cloud–aerosol–radiation interactions in understanding the dynamics and thermodynamics of climate. The study by Rajeevan et al. (2010) also proposed the area of uncertainty according to the impact of aerosol chemistry and the composition of heterogeneous ice and droplet nucleation by using WRF model. In spite of no aerosol effect, Chakravarty et al. (2011) successfully simulate active monsoon convection event but their model WRF could not simulate the suppressed monsoon convection event. Further modification in cloud parameterization schemes is essential to capture suppressed monsoon convection event. Authors have utilized a new microphysical scheme coupled with aerosol-scheme and have explored the research to simulate suppressed monsoon convection event.

CAIPEEX-Phase I *in situ* measurement revealed that the maximum concentration of aerosols was in the range of 1000–2000 cm^{-3} in June at Hyderabad (17.2N, 79.2E), was very few ($<1000\ cm^{-3}$) in July at Bangalore (13.1N, 77.6E) and was high ($>2000\ cm^{-3}$) in August at Bareilly (28.4N, 79.4E) (Thara et al., 2011; Kulkarni et al., 2012). Therefore, they have proposed that any numerical model aimed at the prediction of precipitation during monsoon period should keep the aerosol effects into account. In the present study, authors have utilized a new microphysical scheme in the mesoscale model (MM5) to see the microphysical structure of different types of clouds while contrasting large-scale environments associated during CAIPEEX study over different regions (e.g., Hyderabad, Bengaluru and Bareilly).

In this present endeavor, first cloud properties will be analyzed by moderate resolution imaging spectrometer (MODIS) data. The main objective of this present study is to validate a detailed cloud microphysics scheme in numerical model simulation. It is probably one of the most effective ways of understanding the role of aerosols in cloud and precipitation formation. Three cloud systems (one active as well as two non active) in three different geographical locations are chosen to enrich the sensitivity of the experiment. It can be remembered that proper simulation of a shallow cloud is one of the challenging jobs in the field of cloud physics. The microphysical properties and precipitation and are compared with satellite and CAIPEEX observations to make the experiment robust.

The data, model used and design of experiments are described in Section 2 and the results are described in Section 3. Microphysical tendencies are documented in Section 3.5. Results of atmospheric dust inclusion as ice nuclei (IN) for the heterogeneous immersion freezing nucleation are presented in Section 3.6. The main conclusions are summarized in Section 4.

2. Data and model framework

2.1. Satellite and CAIPEEX data

The daily data of cloud parameters from Level-3 MODIS (http://gdata1.sci.gsfc.nasa.gov) satellite, namely cloud water path (CWP) for both liquid and ice have been used here (King et al., 2003). Next we use CAIPEEX phase-I observation, which is conducted over different parts of the country from May to September 2009 to collect dataset (cloud microphysical parameters) like cloud drop number concentration (CDNC) and cloud drop effective radius (CDR) for studying various aspects of aerosol–cloud interaction over the region (Kulkarni et al., 2012). The Tropical rainfall measuring mission (TRMM) generated products namely 3B42 daily rainfall dataset are also utilized for the study. Finally these satellite and CAIPEEX observation data are used to validate the model simulations with modified microphysical scheme. Description of modified microphysical scheme is discussed in the next sub-section.

2.2. General description of microphysical mechanisms

A non-hydrostratic mesoscale meteorological model version 5 (MM5) with a new explicit microphysical scheme is applied to examine the effects of aerosol for contrasting events during south west monsoon period. The microphysical processes in the model have been sophisticated and detailed with the two-moment warm-cloud microphysical process of Chen and Liu (2004)(called the CL scheme hereafter) to include the effect of cloud condensation nuclei (CCN). The one-moment microphysical scheme is unsuitable for investigation of the aerosol effects on clouds because it only predicts the mass of cloud droplets but fails to represent the number concentration of cloud droplets. In the two-moment microphysical scheme, both the mass and the total number concentration of cloud droplets are predicted. It is able to predict explicitly the mass and number of cloud drops and raindrops.

The CL scheme consists of a series of empirical bulk formulas for masses (the third moment) and number concentrations (the zero-th moment) of liquid water condensates. These formulae are derived based on statistical analyses of a parcel model simulation using the detailed cloud microphysics of Chen and Lamb (1994). In addition, the CL scheme also provides diagnostic equations to calculate the terminal velocities and the effective radius of condensates, which are critical to precipitation process and radiation heating/cooling, respectively. This scheme requires description of CCN, which is assumed to be composed of ammonium sulphate and maintain a tri-modal lognormal size distribution; and their activation into cloud drops follows the Köhler theory. In the last step at the model the Köhler-curve critical radius, which depends on the degree of supersaturation, is retrieved from prognostic dry aerosol and total aerosol masses. When the Köhler-curve critical radius of the present time step is smaller than that of the previous time step, CCN with radius values in between are activated. In addition, the masses of aerosols inside the clouds and inside the precipitation are two new prognostic variables to account for the aerosols recycled from the evaporation of cloud drops. The CL scheme also considers the creation of raindrops directly from giant CCN. The scheme has other mechanism of warm-rain production along with auto-conversion mechanism.