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Impact of elevated aerosol layer on the cloud macrophysical properties prior to monsoon onset

S. Dipu [a,*], Thara V. Prabha [a], G. Pandithurai [a], J. Dudhia [b], G. Pfister [b], K. Rajesh [c], B.N. Goswami [a]

[a] *Indian Institute of Tropical Meteorology, Pune, India*
[b] *National Center for Atmospheric Research, Boulder, USA*
[c] *Aryabhatta Research Institute of Observational Sciences, Nainital, India*

HIGHLIGHTS

- ► Elevated aerosol layer (2–5 km) was caused by increased dust emission from Thar Desert.
- ► Interaction of aerosol via radiation parameterization is investigated with WRF-Chem.
- ► Enhanced dust emission leads to increased heating in the elevated aerosol layers.
- ► Enhanced dust emissions may influence cloud distribution and precipitation patterns.

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ABSTRACT

Atmospheric aerosols alter the radiation balance by absorption/scattering of solar radiation, and indirectly by modifying the cloud microphysical properties. Observations during the Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX) provide a unique opportunity to investigate the aerosol–cloud interaction in a dry to wet transition phase prior to the onset of southwest monsoon. It is observed that aerosol loading increased over the central Indian region in spite of the increase in surface rainfall. This aerosol loading was observed mainly in the 2–5 km level above surface. The origin and influence of elevated aerosol layer have been investigated with the help of WRF-Chem simulations by conducting sensitivity experiments for dust emissions, modified based on the satellite observations. To enhance the dust emissions, the erodible fraction over the Thar Desert region is enhanced to an average factor of 1.7 based on TOMS aerosol index (AI) and USGS land use category, which contributed to enhanced dust emissions by a factor of 1.25 over the study region. This enhancement of dust emission from Thar Desert can result in an increased radiative heating due to elevated aerosol layers, which leads to an increase in the ice mixing ratio and ice water content in the regions of dry to wet transition. It is shown that even natural dust emissions (without changes in anthropogenic emissions) may also influence the spatial and temporal distribution of cloud and precipitation and the hydrological cycle.

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1. Introduction

The effect of aerosol on the clouds and precipitation is multifold due to the interaction between the microphysical, radiative, dynamical interactions, large-scale aerosol transport, and water budget (Menon et al., 2002; Ramanathan et al., 2005; Feingold et al., 2005; Lau et al., 2006). Mineral dust aerosol from desert region constitutes a major fraction of the aerosol burden over the globe (Andreae, 1995) and it contributes at least 80% of the total dust budget (Forster et al., 2007). Mineral dust and carbonaceous aerosol are two major absorbing aerosols in the atmosphere (Wang et al., 2009). Lau et al. (2006) demonstrated that the absorbing aerosols can act as an elevated heat pump over the Tibetan region and may increase the summer monsoon rainfall over northern India through forced ascend and enhanced convection during the early part of monsoon season. The mechanism behind the formation of elevated aerosol layers during pre-monsoon season could be primarily due to advection of dust, mixed with fine-mode aerosol particles by the strong northwesterly winds above the Himalayan ridges (Brun et al., 2011). Anomalous aerosol build-up in the month of May has been suggested to delay the onset of monsoon rainfall

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* Corresponding author.
E-mail address: dipuss@gmail.com (S. Dipu).

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due to the aerosol semi-direct effect (Bollasina and Nigam, 2009; Lau and Kim, 2010). The main source of the absorbing aerosol during the pre-monsoon season over northern India are desert dust (Pandithurai et al., 2008; Chinnam et al., 2006; Prasad and Singh, 2007), and biomass burning (Kumar et al., 2011a), whereas the south Indian regions are significantly influenced by anthropogenic aerosol (Vinoj et al., 2009). The temporal and spatial variability of physical and chemical properties of aerosol is higher over northern region (Chung et al., 2005; Moorthy et al., 2008; Ramachandran and Cherian, 2008) during pre-monsoon.

Breon (2002) demonstrated that anthropogenic aerosol emissions might increase the cloud cover by up to 5%, resulting in a substantial net cooling of the Earth's atmosphere. It is also found that for a range of conditions, increase in aerosol loading are associated with the local intensification of rain rates detected by the Tropical Rainfall Measuring Mission (TRMM) data-set (Koren et al., 2012). The pre-monsoon high aerosol loading over the Indian region was studied with the help of a general circulation model, which simulates the emissions, transport, and radiative impact of aerosols (Menon et al., 2002; Lau et al., 2006; Ramanathan et al., 2005). These studies investigate the effect of absorbing aerosol on regional climate and hydrological cycle. It may also be noted that the model simulated aerosol optical properties exhibit large uncertainties over the Indian region (Verma et al., 2008; Adhikary et al., 2007). Panicker et al. (2010) investigated the effect of aerosol on the cloud microphysics over the Indian region and reported that the Twomey effect is dominant over the Indian region during below normal monsoon rainfall years while the anti-Twomey effect (The cloud droplet size increases with increase aerosol concentration, under constant liquid water content) was found for normal and above normal monsoon rainfall years. These results indicated that the Aerosol Indirect Effect (AIE)/ Twomey effect (The cloud droplet size decreases with increase aerosol concentration, under constant liquid water content) depends on the transport of aerosol from different source regions in association with large-scale circulation patterns.

There is mounting evidence that the boundary layer is a reservoir for aerosol and elevated aerosol layers exist over the Indian Ocean (Ramanathan et al., 2007) and continental India (Raj et al., 2008; Satheesh et al., 2008; Prabha et al., 2012). The entrainment from elevated aerosol polluted layers into the planetary boundary layer (PBL) and *vice versa* holds the key for changes in the PBL turbulence and the cloud properties. Heating of the air above the inversion layer can lead to a lower entrainment rate and a shallower, moist PBL (Feingold et al., 2005). However, the dynamics that drive such effects through entrainment is less understood.

The main aim of the present study is to investigate the role of elevated aerosol layer and entrainment of aerosol into this layer on the developing convection over the peninsular Indian region and over the Bay of Bengal (BoB). Elevated aerosols layers mainly observed in the lower troposphere, which is influenced by vertical advection and wind speed. The study has the following objectives a) to simulate the dust emissions from Thar desert in contributing to the elevated aerosol layers observed during the first phase of CAIPEEX pre-monsoon monsoon transition, b) to investigate the role of heating rate differences between the Thar desert and over the dry to wet transition region in modulating convection and c) to investigate the impact on the cloud macrophysics.

Data and methodology are described in Section 2. Section 3 deals with observational evidence of elevated pollution layer using satellites and CAIPEEX aircraft observations. It also discusses the modeling study performed for understanding the aerosol entrainment in the elevated pollution layer. The radiative heating rates between the model and observation are also discussed in this section. A detailed analysis of the aerosol entrainment at the source region and over the CAIPEEX observational base is investigated in Section 4. The impact of modified dust source emissions from Thar Desert region on developing monsoon thermodynamic structure and rainfall is another aspect of present study (Section 5).

2. Data and methodology

Observational data used in this study include airborne observations with the CAIPEEX aircraft and satellite observations for identification and characterization of dust source regions.

2.1. CAIPEEX experiment

CAIPEEX is designed to identify and understand the pathways through which aerosol particles may enhance precipitation. Airborne observations of middle and low-level clouds, aerosol and the cloud condensation nuclei (CCN) were carried out during CAIPEEX. The main objective of the CAIPEEX is to understand the clouds, aerosols and their interaction during pre-monsoon and summer monsoon season. A detailed description of the above CAIPEEX project can be found at http://www.tropmet.res.in/~majfiles/thara-dipu.html and in Kulkarni et al. (2012). The experiment was conducted with the help of an instrumented aircraft with different bases over the Indian region. The aerosol measurements were carried out using an onboard Passive Cavity Aerosol Spectrometer Probe (PCASP). It is an instrument developed by Droplet Measurement Technologies (DMT Inc., Boulder, CO) for the measurement of aerosol particle size distributions (0.1–3 μm). The aerosol data presented are cloud screened with a cloud droplet number concentration threshold of 20 cm^{-3}. The Aircraft Integrated Meteorological Measurement System (AIMMS) is used to measure various meteorological parameters (winds, temperature and relative humidity) onboard the research aircraft. During the days 17 and 19 May 2009, CAIPEEX aircraft observations were conducted over the study region with single flight per day.

2.2. WRF-Chem

The chemistry version of the Weather Research and Forecasting Model (WRF-Chem (Version 3.2.1)) with the GOCART lumped aerosol scheme (Ginoux et al., 2001) that simulates trace gases and particulates simultaneously with meteorological field (Grell et al., 2005) is used in this study. Zhao et al. (2010) have shown that as compared to other schemes, the spatial distributions of dust emissions are mainly dominated by the spatial distributions of the dust source function in the GOCART scheme. For the analysis in the present study, the model is configured to cover the Indian and Saharan Desert region, extending from 1.7 °N to 34.9 °N and from 34.9 °E to 94.9 °E, with 265 grid points in east-west direction and 159 in the north-south direction, a horizontal resolution of 27 km and 50 vertical layers up to 10 hPa. Initial and boundary conditions for the meteorological variables were obtained from the Final Analysis Data (available from NCAR data repository (http://dss.ucar.edu/datasets/ds083.2/)). The WRF-Chem physical parameterization options selected for various atmospheric processes are summarized in Table 1 and the simulation period was from 12 to 22 May 2009. The time step for the model simulations is taken as 60 s and model results are output every hour.

2.3. Satellite measurements

Satellite based aerosol measurements are obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) and Total Ozone Mapping Spectrometer (TOMS) satellites for the period 11–22 May 2009. The Level 3 MODIS (AQUA and TERRA)

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