Atmospheric Environment 105 (2015) 22–31

Contents lists available at ScienceDirect

Atmospheric Environment

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

Radiative effect of dust aerosols on cloud microphysics and meso-scale dynamics during monsoon breaks over Arabian sea

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HIGHLIGHTS

- Elevated dust layer over AS caused more heating during monsoon breaks as compared to JJAS mean.
- Dust induced semi-direct effect is more pronounced in cold clouds as compared to warm clouds.
- Dust induced heating affects meso-scale environment and monsoon break.

ARTICLE INFO

Article history:
Received 5 September 2014
Received in revised form
29 November 2014
Accepted 16 January 2015
Available online 17 January 2015

Keywords:
Dust aerosol
Radiative heating
Semi-direct effect
Cloud micro and macrophysics
Monsoon breaks

ABSTRACT

During monsoon breaks (large scale rainfall below the long term normal), dry air laddened with dust aerosols intrude over central India through Arabian sea (AS) from West Asian desert regions. To understand the effect of these dust aerosols on marine clouds over AS during monsoon breaks, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) and Cloud and the Earth's Radiant Energy System (CERES) data have been analyzed for the period 2007 to 2013. The vertical profile of dust backscatter coefficient (DBS) showed an elevated layer between 2 and 5 km and the maximum heating rate observed is 9 K/Day which is higher by 3 K/day as compared to the heating observed in June to September (JJAS) mean. Semi-direct effect due to the interaction of the long range transported dust with pristine cloud environment is observed in both warm and cold clouds. Significant differences in shortwave and longwave fluxes at the top of the atmosphere (TOA), cloud micro and macrophysical parameters are observed between the clouds with and without dust. Also, the percentage differences are more in cold clouds as compared to warm clouds. Dust induced semi-direct effect is found to be more pronounced in cold clouds, while indirect effect in warm clouds. Zonal anomalies of dynamical parameters due to dust induced heating, affect the circulation patterns in the immediate meso-scale environment, which strengthen/extend the monsoon break situation.

1. Introduction

Dust aerosols play an important role in global and regional climate. They have direct forcing on climate through absorption and scattering the incoming solar radiation (Kaufman et al., 2002). High concentrations of dust act as cloud condensation nuclei in water clouds (DeMott et al., 2003; Kaufman and Fraser, 1997; Levin et al., 1996) and ice nuclei in cold clouds (Isono et al., 1959; DeMott et al., 2003; Mohler et al., 2003). Subsequently, aerosols have indirect forcing on climate by modifying cloud properties through increasing cloud albedo and suppressing precipitation (Albrecht, 1989; Twomey, 1977). Indirect effects due to dust over both warm and cold clouds were shown in different studies (Li et al., 2010; Min et al., 2009). In addition to the above two effects, dust is also responsible for semi direct effects, which is associated with the changes in cloud properties due to the presence of absorbing aerosols. Highly absorbing aerosols can generate local heating that in turn changes the relative humidity and the stability of the troposphere and thereby influence cloud formation and lifetime. Therefore, they induce an increase or a reduction of cloud cover and cloud albedo, depending upon the vertical distribution of aerosols below, within or above the clouds (Koch and Del Genio, 2010). Studies on semi-direct effect of dust aerosols showed suppression in the growth of cloud thickness (Huang et al., 2006a, 2006b; Su et al., 2008; Yorks et al., 2009).

During Asian summer monsoon (June to September), desert

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http://dx.doi.org/10.1016/j.atmosenv.2015.01.037
1352-2310/

dust is the most frequently occurring aerosol type over AS and Indian sub-continent, and most of it is mainly due to the long range transport from the desert regions of Africa and West Asia (Rahul et al., 2008; Prijith et al., 2013; Kaskaoutis et al., 2014a). The source and advection of dust aerosols depends up on the weather conditions and the strength of the monsoon circulation (Rahul et al., 2008; Manoj et al., 2011; Kaskaoutis et al., 2014b). The spatial and vertical variability of aerosol optical depths (AOD) over AS was studied during monsoon and found largest in the month of July (Prijith et al., 2013). Dust aerosols can change the radiative balance both at the surface and top of the atmosphere (TOA) significantly. According to global climate model simulations, dust-induced heating of the atmosphere over North Africa and West Asia rapidly modulate monsoon rainfall over central India (Vinoj et al., 2014 and references therein).

Over the marine region, the warming due to dust aerosols may perturb the monsoon circulation. There are periods during monsoon season, when there is striking reduction of rainfall over most parts of India and increase near Himalayas and parts of north east and south east peninsular India. Such periods are termed as 'Monsoon breaks' (Rao, 1976). Breaks are permanent features of monsoon intra seasonal oscillations. Dust induced heating during monsoon breaks may cause significant changes in local/regional scale processes in the absence of large scale processes. In the present study, satellite data from different sources has been combined to investigate the interaction of dust aerosols with clouds and radiation and their possible effect on meso-scale dynamics during monsoon breaks over AS.

2. Synoptic conditions during monsoon breaks

Indian summer monsoon is an important component in the global climate system. Strong westerlies generated by North–South temperature gradient in the surface and lower tropospheric levels bring abundant amount of moisture and cloudiness to the land, which eventually produce large amount of rainfall during monsoon season over the Indian sub-continent (Rao, 1976; Webster et al., 1998). The active and break phases of the monsoon are the manifestation of northward propagating monsoon intra-seasonal oscillations (MISO) (Goswami, 2003). The active (break) conditions are mainly associated with episodes of high (less or no) rainfall for a certain period of the season. During monsoon break situation, monsoon trough at the sea level is shifted north from its normal position to the foot hills of the Himalayas (Ramamurthy, 1969; Rao, 1976). Also, another convective zone develops over the equatorial Indian Ocean with rising motion in 0–10° N belt and sinking motion in 15–25° N belt over the Indian region (Gadgil, 2003). Multi-layer inversions exist during break days associated with the intrusion of dry and warm air from the west or north-western region at middle and higher levels (Maheskumar et al., 2013). In the present study only break days are chosen during the years from 2007 to 2013 based on the rainfall criterion (daily standardized rainfall anomaly less than −1.0) discussed in Rajeevan et al., 2010.

3. Data & methodology

The CALIPSO mission uses crucial lidar and passive sensors to obtain unique data on aerosol, cloud vertical structure and optical properties (Winker et al., 2009, 2007). CALIPSO science team developed different aerosol models for different aerosol types by combining AERONET and ground based lidar observations using Lidar Ratio as main constraint. By combining these models and Cloud-Aerosol Discrimination Algorithm, the satellite retrieved backscatter data is divided into six aerosol types (Omar et al., 2009) such as Dust, Polluted Continental, Smoke, Clean Continental, Polluted Dust and Clean Marine. In the present study CALIPSO Version 3.01 Level 2 Aerosol Layer Products of 5 km horizontal resolution has been used.

CERES instruments on Aqua ad Terra satellites measure the radiation fluxes at the TOA. The data cover three spectral regions, shortwave (0.2–5 μm), window (8–12 μm) and total (0.2–100 μm) at a spatial resolution of 20 km at nadir. The longwave radiative flux (LWF) is calculated by subtracting the shortwave radiative flux (SWF) from the total radiative flux. In the present study, CERES Aqua Edition 3A Single Scanner Footprint (SSF) data set is used, which is a combination of CERES radiation, MODerate Resolution Imaging Spectroradiometer (MODIS) cloud microphysical retrievals and ancillary meteorological fields (Huang et al., 2006b). The parameters used are cloud effective temperature (T_e), liquid effective radius (R_e), ice effective diameter (I_d), ice water path (IWP), liquid water path (LWP), cloud optical depth (COD), cloud top height (C_h), cloud top temperature (CTT), SWF and LWF.

Aerosol Index (AI) calculated from Ozone Monitoring Instrument (OMI) onboard the NASA Aura satellite has been used to obtain UV-absorbing aerosols such as desert dust particles as well as carbonaceous aerosols (Torres et al., 2013). HYSPLIT transport and dispersion model of NOAA Air Resources Laboratory (ARL) is used to derive the airmass back trajectories at three atmospheric levels such as 2000, 3000 and 4000 m above the ground ending at 8 UTC over a coastal station Mumbai. Mean sea level pressure (MSLP), geopotential height at 700 hPa (Z700), vertical velocity, vorticity and divergence at different height levels are obtained from National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis data at $2.5° \times 2.5°$ resolution (Kalnay et al., 1996). For the above parameters, anomalies were computed from the long term mean (1981–2010) and are used to understand the synoptic patterns and changes in the vertical structure of the atmosphere and the convection processes associated with aerosol heating during monsoon breaks.

The radiative heating due to dust aerosol is estimated by using SBDART (Santa Barbara DISORT Atmospheric Radiative Transfer) Model (Ricchiazzi et al., 1998). This model is extensively used to estimate aerosol radiative forcing over different regions in India (Das et al., 2013; Sinha et al., 2013 and references there in). In this model temperature and relative humidity profiles were considered for the standard tropical atmosphere and surface properties are considered for ocean atmosphere. The mean dust AOD profile retrieved from CALIPSO measurements was used to estimate the realistic dust impacts. The vertical resolution of the atmosphere was set to 0.5 Km up to lower levels, which is compatible with vertically gridded CALIPSO dust profiles.

The monsoon intensity, duration, precipitation amount, and aerosol loading show large interannual variability. This variability also affects the active and break (dry) spells (Manoj et al., 2011) as well as the dust activity and aerosol loading over India (Gautam et al., 2009; Kaskaoutis et al., 2012; Vinoj et al., 2014). The present study investigates the changes in cloud properties and meso-scale dynamics due to dust induced heating during monsoon breaks over AS using the above mentioned data sets.

4. Analysis

The geographical area selected for the present study is 0–25° N and 60–75° E over the AS. A total of 12 monsoon break days are considered for the analysis which satisfied the criterion that the CALIPSO track is over AS, and dust is the major aerosol component present (based on the images of CALIPSO aerosol types) as compared to other aerosols in the selected region. These 12 days are not equally distributed along the years. To detect dust induced cloud modifications, the present data analysis is segregated into