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Dust aerosol characterization and transport features based on combined ground-based, satellite and model-simulated data

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ABSTRACT

In this paper, we study aerosol characteristics over an urban station in Western India, during a dust event that occurred between 19 and 26 March 2012, with the help of ground-based and satellite measurements and model simulation data. The aerosol parameters are found to change significantly during dust events and they suggest dominance of coarse mode aerosols. The fine mode fraction, size distribution and single scattering albedo reveal that dust (natural) aerosols dominate the anthropogenic aerosols over the study region. Ground-based measurements show drastic reduction in visibility on the dust-laden day (22 March 2012). Additionally, HYSPLIT model and satellite daily data have been used to trace the source, path and spatial extent of dust storm events. Most of the dust aerosols, during the study period, travel from west-to-east pathway from source-to-sink region. Furthermore, aerosol vertical profiles from CALIPSO and synoptic meteorological parameters from ECMWF re-analysis data reveal a layer of thick dust extending from surface to an altitude of about 4 km, and decrease in temperature and increase in specific humidity, respectively. The aerosol radiative forcing calculations indicate more cooling at the surface and warming in the atmosphere during dust event. The results of satellite observations are found to have good consistency with ground-based air quality measurements. Synthesis of satellite data integrated with ground-based observations, supplemented by model analysis, is found to be a promising technique for improved understanding of dust storm phenomenon and its impact on regional climate.

1. Introduction

Dust is a global phenomenon, and it impacts regional/global climate and the biogeochemistry of land and oceans. The Arabian Peninsula is one of the most difficult environments to characterize, monitor and model as it is the largest confluences of dust and anthropogenic emissions in the world. Frequent dust storms and high pollution levels are main features of the region. The peak of dust storm activity occurs usually during the day time, when intense solar heating of the ground generates turbulence and local pressure gradients (Middleton, 1986a,b). The role of dust aerosols in climate system, such as effects on visibility, atmospheric circulation, radiation-energy balance of the earth–atmosphere system, human health (Nastos et al., 2011), atmospheric heating and stability (Alpert et al., 2004), and also cause serious biological and ecological effects (Falkowski et al., 1998), is among the hottest topics in atmospheric and climate research. Dust is considered to be one of the major sources of tropospheric aerosol loading, and constitutes an important key parameter in climate aerosol-forcing studies (Huang et al., 2006; Slingo et al., 2006). Widely prevalent in the tropics (Prospero, 1999), dust aerosols are effective in reflecting solar energy back to space thereby "cooling" the earth's surface (Tegen et al., 1996; Myhre et al., 2003). Direct scattering of solar radiation by dust aerosol particles may cause a change in the vertical temperature profile, cloud properties and precipitation. Several studies using satellite and surface observations (Husar et al., 1997, 2001; Prospero, 1999; Prospero et al., 2002; Washington et al., 2003; Dumka et al., 2015) have shown that the global sources of the atmospheric dust are the arid and semiarid desert regions contributing to the long-range transport of dust particles lifted by strong surface winds (>5 ms^{-1}). Once these particles enter the upper troposphere (above ~8 km), can be transported around the earth in a latitudinal belt in a week or two. Dust aerosols are generally removed from the atmosphere by dry and wet deposition, with dry deposition removing larger particles near the source regions and wet deposition dominating during long-range transport over the oceanic regions.

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The Inter-governmental Panel on Climate Change (IPCC) and the World Meteorological Organization (WMO) recognize dust as a major component of atmospheric aerosol, which is an essential climatic variable to study. According to Kinne et al. (2006), dust accounts for about 75% of the global aerosol mass load and 25% of the global aerosol optical depth (AOD). The main source of the dust around the globe is African continent, especially northern part (Sahara desert), Saudi Arabian regions and Asian continent (eastern areas) (Marticorena et al., 1997; Prospero et al., 2002; Engelstaedter and Washington, 2007; Liu et al., 2008a,b). Different techniques have been developed to identify dust hotspots and pathways. Numerical modeling, trajectory analysis, remote sensing and satellite imagery, dust observations and meteorological data analysis, mineral tracers and geological models can be applied as the principal tools to research dust events (Gerivani et al., 2003; Draxler et al., 2001; Xuan, 2005; Wang and Fang, 2006; Alam et al., 2011).

Long-range transport of dust aerosols from Arabian Sea has been the subject of intense investigation due to potential impact of such pollutants on the global radiative budget (Badarinath et al., 2010; Dumka and Kaskaoutis, 2014). These aerosols transport over long distances from the source region and represent an important process of land-atmospheric interaction (Ginoux et al., 2001; Vijayakumar et al., 2014). Because dust can be transported over thousands of kilometers, it can have an influence at great distances from its original source by wind currents (Middleton and Goudie, 2001). The frequency of the dust-storm occurrence in Arabian Peninsula is at a maximum during the pre-monsoon (March–May) season, when dust aerosols are transported by southwesterly winds from the arid and semi-arid regions around the Arabian Sea (Kalapureddy et al., 2009). The meteorological parameters and soil conditions should be quite special in order to support the lifting and transport of the dense dust. The dominance of the dust aerosols over central and northern parts of the Arabian Sea was revealed from ship-cruise campaigns (ARMEX, ICARB) during the pre-monsoon (Kalapureddy et al., 2009) and monsoon (Moorthy et al., 2005) seasons. The strong influence from dust events, indicate that they are mainly limited to local scales (Bayat et al., 2011). Moreover, dust particles are non-spherical, which affect the accuracy of the retrieval of the aerosol optical properties (Mishchenko et al., 1995) and aerosol radiative forcing (Sharma et al., 2012). During the pre-monsoon season, they mainly influence the rainfall distribution. Dust aerosols alter precipitation both by acting as cloud and ice nuclei (comprising the indirect aerosol effect), and through the effect of aerosol radiative forcing upon the dynamics and thermodynamics of the atmospheric and ocean circulation (Charlson and Heintzenberg, 1995; Hansen et al., 1997). Changes in radiative forcing have an effect on the monsoonal circulation and such changes induced by dust storms can have a major influence on the strength of the monsoon (Miller and Tegen, 1998; Ramanathan et al., 2001).

Since the ground-based observations of dust are limited in space and time, and dust also transported over longer distances from source regions, monitoring of a dust storm is possible through satellite observations along with model simulations. Once dust is raised, its direction of transport depends on prevailing wind direction and speed. Thus, the transport of dust aerosols plays an important role in the regional and global radiative balance both at the surface and the top of the atmosphere. Therefore, dust monitoring can better be achieved by the combined use of the satellite and ground-based observations, and model simulations provide further understanding and prediction capabilities. In this paper, we report the results of the analysis of dust aerosol plume that originated over the Arabian Sea during 18–20 March 2012, persistent over Pune, India from 21 to 25 March 2012. The radiative forcing exerted by these aerosols at bottom of the atmosphere (BOA), atmosphere (ATM) and top of the atmosphere (TOA) during the period of the dust event is also presented. In the present communication, we first provide a brief description of the experimental site, instrumentation and methods followed to analyze the dust event over the study region. Then, the results obtained from the ground-based measurements are presented and discussed in conjunction with dust model estimations and satellite observations. Finally we present the conclusions drawn from the study.

2. Experimental site

The study was performed over Pune urban area (18.53°N, 73.8°E, 559 m amsl), located at about 100 km inland from the west coast of India and is located on the Leeward side of the Western Ghats. During pre-monsoon (Mar–May), weather is very hot with the maximum temperature of about 40 °C. The air flow in the lower troposphere is predominantly westerly during pre-monsoon season when there is an influx of mineral dust from the Arabian Sea. The type of environment in and around the station and the possible aerosol type present over the station is a combination of pollution. Dust generation due to surface heating and strong winds contribute to aerosol loading in pre-monsoon season (Vijayakumar et al., 2012). Other sources of aerosols over the site are derived mainly from main highways, road dust, industrial and vehicular emissions. This indicates the spatio-temporal variation in aerosol characteristics can be generally attributed to the naturally occurring dust particles and contribution of anthropogenic activities in pre-monsoon season.

3. Data sets and methodology

The source and characteristics of data sets, archived from ground-based, space-borne experiments and model evaluations are discussed in this section. The details are also furnished in Table 1.

3.1. Ground-based observations

The aerosol optical and microphysical properties of the total atmospheric column are from the standard CIMEL radiometer (Model CE-318, Cimel Electronique, France) setup at IITM, Pune, India, as a part of the AERONET global network since October 2004. In the present study, the retrieved Aerosol Optical Depth (AOD), Ångström Exponent (AE), Radiative Forcing (RF), Single Scattering Albedo (SSA), and Aerosol volume Size Distribution (ASD) from 0.05 to 15 μm in particle radius from level 2.0, Fine mode AOD (FM AOD), Coarse Mode AOD (CM AOD), and fine mode fraction (FMF) from level 1.5 data have been used. The details of AERONET instrument and its performance at Pune can be found in Holben et al. (1998) and Sumit et al. (2011).

The integrating Nephelometer used in the present study is a multiple wavelength instrument capable of providing information on total scatter as well as backscatter coefficients at 450, 525 and 635 nm (Devara et al., 2013). A detailed description of the instrument is available in Müller et al. (2011). In this study, we used visual range values during dust event period. It is calculated from following Koschmieder's Formula

$$L_v = 3.912/\sigma_{ext} \quad (1)$$

where L_v = visual range, σ_{ext} = extinction coefficient. In this formula, we used extinction coefficient values, measured at 525 nm wavelength as this wavelength interacts strongly throughout the human range of visibility.