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Investigation of aerosol optical, physical, and radiative characteristics of a severe dust storm observed over UAE

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ABSTRACT

This work presents a detailed study of the dynamical processes triggering the occurrence of the two heavy dust storms which occurred between 18 and 22 March 2012 over the Middle East. The dynamics of this event are related to the coupling of subtropical jet and polar jet over the Saudi Arabia region, resulting in massive dust storm generation and dust transport through Rub' al Khali and the Persian Gulf to the UAE region. AOD and PM_{10} values showed a fourfold increase during the event reaching a maximum of 1.8 and 1653 μg/m^3 respectively. The spatial extent of the dust storm is evident from high values of MODIS AOD (~1.5) and OMI aerosol index (4.5) covering the entire Middle East. The total attenuated backscatter at 550 nm from CALLIPSO showed the vertical extent of dust up to 8 km. In addition, surface temperature showed a decrease of almost 15 °C during the event signifying the intensity of the dust storm. Aerosol radiative forcing estimates during the dust storm showed a cooling at the surface and warming in the atmosphere, with a maximum forcing value reaching up to ~−210 Wm^{-2} (185 Wm^{-2}). Hence, it is evident from the present study that the dust layer caused an additional warming of ~150 Wm^{-2} in the atmosphere over this region. The present event showcases the importance of dust storm induced aerosol optical and physical processes, and associated atmospheric dynamics over UAE as well as other affected regions.

1. Introduction

Dust storms are very common phenomena in the Middle East owing to the large scale desertification. They often disrupt the daily life by reducing visibility and imposing severe environmental and health risks. For instance, a fierce sandstorm lashed the Middle East on the 11 February 2015, forcing the closure of the Suez Canal in Egypt and grounding flights in a number of airports in the region as reported by the Japan News 2015 (http://www.the-japan-news.com/news/article/0001927611). These dust storms also inject dust into the air, causing air pollution, respiratory diseases, ecological disasters, and low visibility affecting transportation and aviation. Dust storms are generally accompanied by strong winds causing desertification by wearing away the soil-surface, causing huge economic loss by damaging the structure of the top soil. Most importantly, the dust deposited on the ground can significantly lower grain productivity by affecting photosynthesis process (Farmer, 1993). Very few studies have focused on studying wind characteristics in the Middle East (see Ouarda et al., 2015), and therefore the involved dynamics related to dust storms are not properly understood.

The dominant sources of dust are desert, arid regions, terrains with loose soil and uncultivated lands (Lim & Chun, 2006). Dust storms are generated when strong surface wind lifts fine grained dust particles into the air and strong turbulence or convection diffuses the dust to cover large areas. The strong wind contributes to long range transport of the dust thereby affecting distant regions as well (Shao, 2008 and references therein). Windblown dust, particularly during the dust storm has an enormous impact on the aerosol optical properties of the atmosphere (Du et al., 2008; Xin, Wang, Li, & Wang, 2007; Zakey, Solmon, & Giorgi, 2006). The airborne dust has both direct and indirect effects on the climate system. The direct impact is caused by altering the Earth's radiation budget through scattering and absorption of radiation (Bangert et al., 2012; Harrison, Kohfeld, Roelandt, & Claquin, 2001; Haywood & Boucher, 2000; Jayaraman, Song, Vetrivel, Shankar, & Verkman, 2001; Satheesh & Ramanathan, 2000; Sokolik et al., 2001; Tegen et al., 1997). The indirect effect is caused by affecting atmospheric cloud nucleation and optical properties (Bangert et al., 2012; Levin, Ganor, & Gladstein, 1996; Nakajima, Higurashi, Kawamoto, & Penner, 2001; Penner et al., 1998; Wurzler, Reisin, & Levin, 2000). These processes modify the physical and optical properties of the dust, thereby altering the dust radiative properties. Dust storms modify the atmospheric dynamics in the source regions as well as having a large impact on regional and global scales due to long-range transport.

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Different parts of the Middle East, especially the United Arab Emirates (UAE) are affected by dust storms (horizontal visibility lies between 0 and 1 km) for almost 30% of the time during various seasons. The frequency of occurrence of dust storms peaks during the premonsoon season (March–May) when dust aerosols are transported by southwesterly winds from the arid and semi-arid regions around the Arabian Peninsula (Ackerman & Cox, 1982; Middleton, 1986; Aher, Pawar, Gupta, & Devara, 2014; Prakash, Stenchikov, Kalenderski, Osipov, & Bangalath, 2015; Saeed, Al-Dashti, & Spyron, 2014).

Several investigators in the past studied different aspects of desert dust in the Middle East and Arabian Peninsula using ground based and satellite observations to characterize the large-scale dust loading of the atmosphere (e.g. Aher et al., 2014; Alharbi & Moied, 2005; Badrinath et al., 2010; Miller et al., 2008; Notaro, Alkolibi, Fadda, & Bakhrjy, 2013; Pease, Tchakerian, & Tindale, 1998; Prakash et al., 2015; Saeed et al., 2014; Smirnov et al., 2002). However, very few studies to date have been carried out to understand the dynamics and the effect of these dust storms on meteorological parameters. During 18–22 March, 2012 a heavy dust storm occurred in the Arabian Peninsula, largely affecting the UAE, Oman regions and the dust storm extended for a long period (~4 days) (Aher et al., 2014; Prakash et al., 2015). Prakash et al. (2015) simulated the March 2012 dust storm by using the WRF-Chem model. The simulation results compared well with the ground based and satellite borne observations such as AOD and related parameters. Although previous studies focused on a number of aspects of dust storms, an overall comprehensive analysis which deals with aerosol physical and dynamical properties is limited. The present study aims to investigate these aspects extensively by making use of wide range of data sources such as surface measurements; aerosol robotic network (AERONET) data; radiosonde observations; satellite data from moderate resolution imaging spectrometer (MODIS), ozone monitoring instrument (OMI) and the cloud-aerosol lidar and infrared pathfinder satellite observation (CALIPSO)); Barcelona Dust Forecast Center (BDFC) parameters; and ERA-Interim reanalysis data sets during March, 2012. This analysis aims to provide an insight into the origin, transport pathways and related atmospheric dynamics of the dust storm.

2. Data base

2.1. Surface observations

Hourly observations of horizontal visibility (HV) (km), temperature (°C), relative humidity (%), wind speed (m/s), wind direction (deg) and weather phenomena (WP) are obtained from Abu Dhabi international airport weather station. According to the World Meteorological Organization (WMO) criteria, the dust episodes are categorized into dust events (HV lies between 1 to 5 km), dust storms (HV lies in 200 m to 1 km), and severe dust storms (HV 0-200 m), respectively based on WP recorded during each hour of observation. The surface observations utilized in the present study correspond to the period of 17–22 March 2012. In addition to that, radiosonde measurements are also used during the same period available over same location twice a day at 00 and 12 UTC.

2.2. AERONET data

The data used for the presented study were obtained from the AERONET global network during March 2012 to study the variability in AODs during the dust storm. The CIMEL sun-photometer used in the AERONET station measures the irradiance every 15 min at 340, 380, 440, 500, 675, 870 and 1020 nm respectively, with a FWHM of 2 nm for the 340 nm channel, 4 nm for the 380 nm channel, and 10 nm for the other channels. The direct sun measurements take 8 s to scan all wavelengths with a motor driven filter wheel positioning each filter in front of the detector. To retrieve volume size distribution from AERONET data an inversion algorithm is used in the size range from 0.05 to 15 μm together with spectrally dependent complex Refractive Index (RI), Single Scattering Albedo (SSA) and Asymmetry parameters (ASY) from spectral sun and sky radiance data (Dubovik & King, 2000). A series of papers describing the instrumentation, measurements, accuracy, and cloud screening procedure have been presented earlier (Eck et al., 1999; Holben et al., 1998, 2001; Smirnov, Holben, Dubovik, Neil, & Eck, 2000). We have used level 2 cloud screened and quality assured ground based AERONET data of the nearest possible location which is at Mezaira (23.1°N; 53.8°E; 204 m msl), during March, 2012 for the present study.

2.3. Satellite data sets

2.3.1. OMI

The OMI was launched in July 2004 on NASA's EOS Aura satellite. OMI provides UV aerosol index information on a global scale at a daily basis, passing over a certain location once or twice a day. A detailed description about the OMI instrument is given in Levelt et al. (2006). The UV aerosol index is a residual quantity that indicates the departure of the spectral dependence of the upwelling radiation from that of a pure Rayleigh atmosphere bounded by a Lambertian surface. In this study, the Aura/OMI level 3 daily global $1^\circ \times 1^\circ$ gridded near-UV Aerosol data product is utilized which is available from Giovanni web tool (http://giovanni.gsfc.nasa.gov).

2.3.2. MODIS

MODIS instrument onboard the NASA EOS (Earth 5 Observing System) Terra and Aqua satellites provides aerosol properties over both land and ocean with a near-daily global coverage (Kaufman et al., 1997; Salomonson, Barnes, Maymon, Montgomery, & Ostrow, 1989; Tanré, Kaufman, Herman, & Mattoo, 1997). The standard AOD product is retrieved using the dark-target approach at near-infrared wavelengths (2.1 and 3.8 μm) (Kaufman et al., 1997). Hence, this approach provides information about the global distribution of aerosols but may not be accurate over bright surfaces. The Deep Blue (DB) algorithm is preferable to retrieve aerosol properties over deserts (bright surfaces) because it employs two blue channels (0.412 and 0.470 μm), for which surface reflectance's is relatively small compared to 0.650 μm channel (Hsu, Tsay, King, & Herman, 2004). The uncertainties in AOD obtained with DB algorithm are 25–30% (Hsu, Tsay, King, & Herman, 2006). Shi, Zhang, Reid, Hyer, and Hsu (2013) provided a complete description of DB aerosol products retrieval biases and related uncertainties. The daily Level-3 aerosol product from Aqua (collection 5.1, MYD08) is used for the present analysis.

2.3.3. CALIPSO

The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) is the primary instrument on the CALIPSO satellite, launched on April 28, 2006 along with the cloud profiling radar system on the CloudSat satellite (Winker et al., 2006). The CALIPSO payload consists of the CALIOP, the Infrared (IR), and wide field camera. CALIOP is designed to acquire vertical profiles of elastic backscatter at two wavelengths (532 nm and 1064 nm) from a near nadir-viewing geometry during both day and night phases of the orbit. In addition to the total backscatter at the two wavelengths, CALIOP also provides profiles of linear depolarization at 532 nm. The depolarization measurements enable the discrimination between ice and water clouds, and the identification of non-spherical aerosol particles. Due to the non-availability of CALIPSO data during 16–29 March 2012, we only considered data from 20 to 22 March 2012.

2.4. BDFC

The Earth Sciences Department from the Barcelona Supercomputing Center (BSC)—Centro Nacional de Supercomputacion (CNS) maintains a dust forecast operational system with the updated version of the former