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Changes in aerosol optical properties due to dust storms in the Middle East and Southwest Asia

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ABSTRACT

Super dust storms occurred over the Middle East and southwest Asia on March 2012. These storms reduced the air quality over the Gulf Region, Iraq, Iran, and Pakistan. Airports were shut down due to poor visibility, schools were closed, and hundreds of people were hospitalized with respiratory problems. In order to better understand the effects of such dust storms we have analyzed aerosol optical and radiative properties during this event using data from the Moderate Resolution Imaging Spectroradiometer and the Aerosol Robotic Network. Maximum aerosol optical depth (AOD) values occurred on the18th of March in Kuwait, Bahrain, Qatar, and Saudi Arabia, where values of 4.9, 4.4, 4.3, and 4.9 were recorded, respectively. In Oman, the Arabian Sea, and Iran, maximum AOD values occurred on the 19th of March, reaching 4.5, 5, and 5, respectively. The dust storm then spread across Pakistan, passing through Multan, Faisalabad, and Lahore where maximum AOD values of 2.1, 2.6, and 2.7, respectively, were attained on the 20th of March. The maximum aerosol volume size distributions (VSDs) in Lahore occurred on dusty days and minimum VSDs on non-dusty days. The VSD, single scattering albedo, refractive index, and asymmetry parameter values on dusty days suggested that dust aerosols were predominant over anthropogenic aerosols in these urban environments. The shortwave aerosol radiative forcing (ARF) values (on both dusty and non-dusty days) ranged between -50 W m^{-2} and -194 W m^{-2} (average: -114 ± 40 W m^{-2}) at the earth's surface, and between -31 W m^{-2} and -105 W m^{-2} (average: -58 ± 25 W m^{-2}) at the top of the atmosphere (TOA). The longwave aerosol ARF values ranged between $+6$ W m^{-2} and $+20$ W m^{-2} (average: $+12 \pm 4$ W m^{-2}) at the earth's surface, and between $+7$ W m^{-2} and $+30$ W m^{-2} (average: $+16 \pm 7$ W m^{-2}) at the TOA. Longwave radiations therefore produced significant warming, both at the TOA and at the earth's surface.

1. Introduction

Dust storms cause significant perturbations in the radiation-energy balance of the earth's atmospheric system, in atmospheric heating and stability (Alpert, Kishcha, Shtivelman, Krichak, & Joseph, 2004), in chemical and biological ecosystems (Singh, Prasad, Kayetha, & Kafatos, 2008), and in ambient air quality and human health (Nastos, Kampanis, Giaouzaki, & Matzarakis, 2011). Different natural mineral dust particles may either absorb or scatter radiation (ultra violet, visible, and infrared), resulting in either “positive forcing”, i.e. heating, or “negative forcing”, i.e. cooling (Alpert et al., 1998; Liao & Seinfeld, 1998; Miller, Perlwitz, & Tegen, 2004; Sinha & Harries, 1997; Sokolin & Toon, 1996; Tegen, Lacis, & Fung, 1996). Mineral dust aerosols reflect shortwave (SW) radiation within the atmospheric window channel back into space resulting in cooling of the Earth's system, but longwave (LW) radiation is absorbed resulting in a warming effect (Xia and Zong, 2009). Variations in the properties, transport, and dynamics of different mineral dust aerosols have been investigated by Almeida (1987), Prospero and Carlson (1972), and Tegen and Fung (1994). Dust storms can have considerable impacts on the hydrological cycle, on climate variability, and on ambient air quality (Golitsyn & Gillette, 1993; Kaufman, Tanre', & Boucher, 2002; Miller, Tegen, & Perlwitz, 2004; Parungo et al., 1995; Prospero, Ginoux, Torres, Nicholson, & Gill, 2002; Ramanathan, Crutzen, Kiehl, & Rosenfeld, 2001; Tegen et al., 1996).

Dust particles can alter the surface radiation budget leading to changes in the temperature of the earth's surface and consequently influencing the exchange processes between the earth's surface and atmosphere, as well as atmospheric dynamics. Accurate estimation of the radiative impact of mineral dust storms is therefore important, particularly because of their broad spatial distributions and large optical depths (Mishra and Tripathi, 2008). Changes in the aerosol radiative forcing (ARF) of the troposphere due to dust storm activity over the western Sahara Desert and eastern tropical North Atlantic Ocean have previously been investigated by Alpert et al. (1998). The vertical distribution of dust aerosols has a large influence on RF, and on the climate (Forster et al., 2007;Huang et al., 2009; Zhu et al., 2007). Liao and Seinfeld (1998) reported that clear-sky long-wave RF and cloudy sky top-of-

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atmosphere (TOA) SW RF are very sensitive to the dust layer. Mineral dust has also been found to be the main factor affecting aerosol optical depth (AOD) in various arid regions of the world (Houghton et al., 2001; Tegen et al., 1997).

Dust storms originating from arid and desert areas in Africa (e.g., the Sahara Desert), the Middle East, Saudi Arabia, and India (e.g., the Thar Desert) often travel to the coastal areas of Pakistan and contribute to the total aerosol loading over various regions of Pakistan. Variations in the optical properties of dust aerosols over the Indo-Gangetic plains have been reported by Prasad et al. (Prasad and Singh, 2007; Prasad et al., 2007). Some general optical properties of dust aerosol over Lahore and Karachi have previously been analyzed by Alam, Trautmann, and Blaschke (2012) using AERONET data, and the frequency of dust storms over southwest Asia has been discussed by Husar et al. (2001) and Middleton (1986).

Dust storms result in changes to aerosol loading in the troposphere over southwest Asia during the pre-monsoon season and influence the rainfall distribution because dust aerosols alter the earth's radiative balance, either directly by extinguishing solar and Earth radiation, or indirectly by acting as, or enhancing, cloud condensation nuclei (CCN), thereby affecting the cloud albedo, cloud lifetime, precipitation rate, and hydrological cycle (Charlson & Heintzenberg, 1995; Hansen, Sato, & Ruedy, 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 & Tegen, 1998; Ramanathan et al., 2001). Ground-based observations and satellite data are very important for monitoring dust events and estimating ARF.

In this study we have used Moderate Resolution Imaging Spectroradiometer (MODIS) data to analyze aerosol properties over the Middle East and southwest Asia during dust storms that several meteorologists have characterized as super dust storm (NASA Earth Observatory Natural Hazards, 2012). We also investigated aerosol optical and radiative properties over Lahore (Pakistan) during dusty and non-dusty days on March 2012 using both Aerosol Robotic Network (AERONET) and MODIS data. The pathways and possible source regions for the dust storm events were also investigated by back-trajectory analysis using a Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model. In addition to aerosol characteristics, ARF values at the earth's surface and at the TOA were calculated for different episodes of the dust storm using the Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) model (Ricchiazzi, Yang, Gautier, & Sowle, 1998).

2. Data

Spatio-temporal variations in AOD during the strong dust storm event over the Middle East and southwest Asia were analyzed using MODIS data. It was also considered to be important to analyze the aerosol characteristics, including optical and radiative properties, during the dust storm, for which AERONET data would have been the best option. Unfortunately however, AERONET data were not available over the dust storm period for the sites in Bahrain, Saudi Arabia, and Kuwait; we therefore used data from the Lahore AERONET site.

2.1. Aerosol Robotic Network (AERONET)

The CIMEL sky radiometer is the standard AERONET instrument for measuring direct sun and diffuse sky radiances within the 340–1020 nm and 440–1020 nm spectral ranges, respectively (Holben et al., 1998). An inversion algorithm was used to retrieve aerosol volume size distributions for radii ranging from 0.05 to 15 μm, while spectrally dependent complex refractive indexes (RIs), single scattering albedos (SSAs) and asymmetry (ASY) parameters were obtained from spectral sun and sky radiance data. The detailed aerosol properties retrieved were used for calculating broad brand fluxes within the spectral range from 0.2 to 4.0 μm. The AERONET data are available at three levels – level 1.0 (unscreened), level 1.5 (cloud screened; Smirnov et al., 2000), or level 2.0 (quality assured; Holben et al., 1998) – and can be downloaded from the AERONET website (http://aeronet.gsfc.nasa.gov/). For this study we used AERONET level 2.0 data from both direct sun (AOD) and inversion products (SSA, ASY, RI) for the month of March, 2012. The uncertainty in AOD retrieval under cloud-free conditions was $<\pm 0.01$ for wavelengths >440 nm, and $<\pm 0.02$ for shorter wavelengths, which is less than the $\pm 5\%$ uncertainty for the retrieval of sky radiance measurements (Dubovik et al., 2000). The retrieval accuracy has been explained in detail by Dubovik et al. (2002).

2.2. Moderate Resolution Imaging Spectroradiometer (MODIS)

MODIS instruments are installed on the Terra and Aqua satellites which were launched in December 1999 and May 2002, respectively. They offer high radiometric sensitivity (12 bit) over 36 spectral bands with wavelengths ranging from 0.41 μm to 14.4 μm. The spatial resolution of the MODIS instrument varies with the spectral band, ranging from 250 m to 1.0 km at nadir. The MODIS instruments offer an unprecedented opportunity to examine terrestrial, atmospheric, and oceanic phenomena around the world. MODIS instruments measure the AOD with an estimated error of $\pm(0.05 + 0.15\tau)$ over land (Chu et al., 2002) and 0.03 ± 0.05 over the ocean (Remer et al., 2005). The operational MODIS aerosol retrieval algorithm has recently been improved in order to correct systematic biases in the MODIS algorithm used previously (Levy et al., 2007; Remer et al., 2005). The MOD04 AOD daily data products from Terra and Aqua Deep Blue AOD with a spatial resolution of 10×10 km from 1st March to 31st March, 2012 are utilized in this study. We have chosen this Deep Blue AOD product for the desert regions (Saudi Arabia, Persian Gulf, southeast Iran, southwest Pakistan) rather than the standard AOD product. In addition, the MODIS surface albedo product was also used. More detailed information on algorithms for the retrieval of aerosol data is available at http://modis-atmos.gsfc.nasa.gov.

2.3. Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO)

CALIPSO was launched on 28 April 2006 to study radiative effects of aerosols and clouds on climate. CALIPSO carries the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), a two wavelength polarization Lidar (532 and 1064 nm). It provides information on the vertical distribution of aerosols and clouds, cloud particle phases, and classification of aerosol size (Winker, Hunt, & McGill, 2007). Detailed discussion on CALIPSO and its instruments is provided by Hunt et al. (2009) and Winker, Pelon, and McCormick (2003).

3. Results and discussion

3.1. Formation of dust events and meteorological situation

Iraq, Saudi Arabia, and the Persian Gulf form a hot-spot region that has reported the highest occurrence of dust storms (Kutiel & Furman, 2003). Dust storms in Saudi Arabia, the Persian Gulf, Iraq, and Iran, on the Arabian Peninsula, and in southwestern Pakistan are more frequent in spring and summer than in autumn and winter. Two separate dust storms occurred over the Middle East and southwest Asia in March, 2012.

Due to a high pressure zone that formed over eastern Syria on March 17th, 2012 and a low pressure zone over northern Iraq, winds accelerated rapidly towards Iraq resulting in the development of a super dust storm that quickly spread across Iraq. High temperatures increased the likelihood of a dust storm by rendering unstable the atmospheric layers close to the ground surface. Airborne dust particles were blown towards the southeast and into Saudi Arabia, and the resulting dust