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Investigation of optical and radiative properties of aerosols during an intense dust storm: A regional climate modeling approach

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ABSTRACT

The dynamical and optical properties of aerosols during an intense dust storm event over the Arabian Sea have been studied using Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) and space borne instruments such as MODIS, MISR, CALIPSO and CERES during the period 17 to 24 March, 2012. The model captures the spatio-temporal and vertical variations of meteorological and optical parameters, however an overestimation in simulated aerosol optical parameters are observed when compared to satellite retrievals. The correlation coefficients (R) between simulated and observed AOD from MODIS and MISR are found to be 0.54 and 0.32 respectively. Model simulated AOD on dusty days (20 and 21 March 2012) increased by 2–3 times compared to non-dusty days (17 and 24 March 2012) and the single scattering albedo (SSA) and the asymmetry parameter increased from 0.96 to 0.99 and from 0.56 to 0.66, respectively. The R between simulated shortwave (SW) radiation at top of the atmosphere (TOA) and TOA SW radiation obtained from CERES is found to be 0.43, however the model simulated SW radiation at the TOA showed an underestimation with respect to CERES. The shortwave aerosol radiative forcing (SWARF) during the event over surface and TOA are ∼ -19.3 and ∼ -14.2 Wm^{-2} respectively, which is about 2–5 times higher when compared to the respective forcing values during non-dust days. Estimated net radiative forcing was in the range of −13 to −21 Wm^{-2} at TOA and −12 to −20 Wm^{-2} at the surface. The heating rate during event days within the lower atmosphere near 850 hPa is found to 0.32 − 0.4 K day^{-1} and 0.18 − 0.22 K day^{-1} on dusty and non-dusty days, respectively. Results of this study may be useful for a better modeling of atmospheric aerosols and its optical and radiative properties over oceanic region.

1. Introduction

Desert dust aerosols are the second largest source of natural aerosols (Prospero et al., 1996), that has the potential to cause significant climate feedback (DeMott et al., 2003). It can absorb and scatter shortwave (SW) and longwave (LW) radiation, influence microphysical properties of clouds (ice nuclei) (Lohmann and Diehl, 2006), change surface albedo by deposition on ice and snow (Painter et al., 2007), and fertilize phytoplankton by oceanic deposition (Prospero et al., 1996). Miller et al. (2004) suggested that dust aerosol can reduce global evaporation and precipitation by reducing surface temperature. Major sources of dust aerosol are in the arid regions of the Northern Hemisphere, which lie in a broad zone that extends from the west coast of North Africa, over the Middle East, Central and South Asia to China (Prospero et al., 2002). The source regions of extended dust belt nearby the Arabian Sea is shown in Fig. 1. Among these sources Saharan dust has been extensively studied by scientific community (Gläser et al., 2015). Similar to the transatlantic transport of Saharan dust, dust sources over Middle East during Shamal wind (Hamidi et al., 2013), transport considerable amount of dust over the Arabian Sea (AS). Gharai et al. (2013) have pointed out that frequency of dust transport over AS is more during pre-monsoon and its vertical distribution can reach up to 6 km. The absorbing and scattering nature of dust minerals can reduce the surface reach of solar radiation (solar energy) and trap radiation within the atmosphere. Such disparities of solar energy budget in atmosphere could highly influence the optical and radiative properties by give rise of aerosol optical depth and increase in aerosol radiative forcing and heating rate. Which may leads to the atmospheric warming or cooling effect. Increase of radiative forcing caused by imbalance of atmospheric energy budget make catastrophe in temperature distribution. Thus, which can modify the dynamics of

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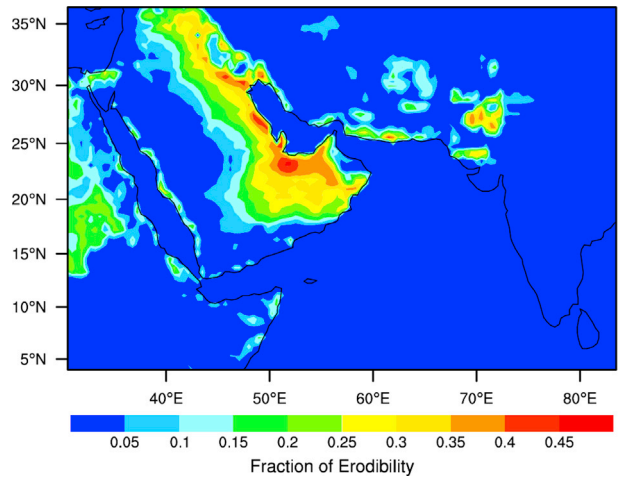

Fig. 1. Simulated fraction of dust erodibility (dimensionless) regions from GOCART emission scheme.

atmospheric circulation and significantly influence south west monsoon over the Indian region (Vinoj et al., 2014).

The present study is an approach to simulate an intense dust storm event over the AS during 17–24 March, 2012 and is also among the first studies to simulate an intense dust storm event over AS. This dust storm is one of the few events over the AS that has been critically studied in the recent years. Kunte and Aswini (2015) analyzed its source, transportation path and dissipation using back trajectory model, wind speed, direction and remote sensing methods. A decrease in sea surface temperature (SST) and an increase in chlorophyll is also reported during the post event period. Jose et al. (2016b) analyzed its impact on radiation over the AS at top of the atmosphere (TOA) using synchronous satellite observations and found a shortwave aerosol radiative forcing (SWARF) efficiency of $-39.12\,Wm^{-2}$ per unit AOD. Impact of these dust aerosols on regional atmosphere over mainland (Delhi, Jodhpur, Lahore and Karachi) have been studied by Srivastava et al. (2014) using *in-situ* observations. However, it is essential to examine the model derived optical properties, when compared to the observational limitation of satellite retrievals during the dust storm event. It will be of great interest to estimate the atmospheric heating over AS caused by an intense dust storm using Weather Research and Forecasting model coupled with Chemistry (WRF-Chem). The dust aerosol optical properties and radiative effect have been estimated and discussed using the model. A suite of remote sensing observations are also used for comparing simulated parameters.

2. Data set and methodology

2.1. Model description

The study uses the Weather Research and Forecasting model coupled with Chemistry (Fast et al., 2006) (WRF-Chem) version 3.6.1 covering a domain focused on the AS extended form 50° E to 80° E in the west-east direction and 10°N to 30°N in the south-north direction at the horizontal resolution of 50 km with 65×85 grid cells. The vertical level were composed of 29 layers with a maximum height of ~20 km from the surface, while around 18 layers are in the first 10 km of the surface. The initial and lateral boundary conditions for the meteorological fields are obtained from National Centre for Environmental Predictions, Final Analysis (NCEP/FNL) having the temporal interval of 6 h and spatial resolution was 1° x 1°. The input for dust dynamic process such as dust erosion, fraction of sand, clay and other soil properties are from United States Geological Survey (USGS). The physical and dynamical parameterization utilized in the model is summarized in Table 1.

The chemical mechanism used in this model is Model for Ozone and Related chemical Tracers (MOZART4) gas phase chemistry (Emmons et al., 2010) linked to the Model for Simulating Aerosol Interactions and Chemistry (MOSAIC) (Zaveri et al., 2008) with 4 size bins to represent the aerosol size distribution, which allow the detailed study of aerosol composition and chemical properties. The Goddard global Ozone Chemistry Aerosol Radiation and Transport (GOCART) emission scheme (Ginoux et al., 2001) is used for the dust emissions in the WRF-Chem model. The dust emission influx are calculated online during the model simulation. Dust particle size bins assumed in GOCART scheme are ranging from $0.1 - 6\ \mu$ m followed by the expression,

$$F_p = CSs_p u_{10m}^2 (u_{10m} - u_t) \quad \text{if } u > u_t$$

where, F_p represents the emission flux of aerosol size bin p, C is a dimensional factor ($1\ \mu g\ s^2\ m^{-5}$), S is the source function representing the erodibility field, u_{10m} is the horizontal wind speed at 10 m from the surface, u_t is the threshold velocity wind erosion, and s_p is the fraction of each size class of dust emitted in the atmosphere. Previous studies reported that atmospheric aerosol can be composed of a wide variety of compounds, including sulfate, nitrate, ammonium, carbonaceous materials, sea salt, and crustal species from soil dust. The new gas-particle partitioning module ASTEM (Adaptive Step Time-Split Euler Method) is coupled with the thermodynamic module MESA (Multicomponent Equilibrium Solver for Aerosols) – MTEM (Multicomponent Taylor Expansion Method) are used in this scheme. The updated MOSAIC scheme is based on new Henry's law coefficients, which is capable for the calculation of aqueous atmospheric aerosol mixing rate coefficients, solid-liquid or gas-phase state, and its composition within the aerosol particles.

The initial and lateral boundary conditions for chemical species are obtained from the output of MOZART4 with six hour interval. The chemical boundary condition for biogenic emissions of trace species are obtained from Model of Emissions of Gases and Aerosols from Nature (MEGAN) (Guenther, 2006). Emissions from open bio-mass burning are obtained to the model via the Fire Inventory from NCAR version1(FINN v1) (Wiedinmyer et al., 2011) with the addition of online plume rise

Table 1
Physical, dynamical and radiative schemes utilized for WRF-Chem simulation.

Specification	Option	Reference
Microphysics	Morriosn double moment scheme	Morrison et al. (2009)
Cumulus Parameterization	New Grell scheme (G3), improved version of Grell-Devenyi (GD).	Grell and Dévényi (2002)
Surface Layer	Revised MM5 Monin-Obukhov scheme, based on Monin-Obukhov with Carslon-Boland viscous sub-layer and standard similarity functions from look-up tables.	Jiménez et al. (2012)
Land Surface	NOAH Land Surface model, unified NCEP/NCAR/AFWA scheme with soil temperature and moisture in four layers, fractional snow cover and frozen soil physics.	Chen and Dudhia (2001)
Boundary Layer	Mellor-Yamada Nakanishi and Niino Level 2.5 (MYNN2).	Nakanishi and Niino (2006)
Short-wave Radiation	Rapid Radiative Transfer Model for General Circulation Models (RRTMG), includes the online aerosol-meteorological interaction and Monte-Carlo Independent Column Approximation (MCICA) method of random cloud overlap for major trace gases.	Iacono et al. (2008)
Long-wave Radiation	RRTMG	Iacono et al. (2008)