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High-resolution dust modelling over complex terrains in West Asia

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ABSTRACT

The present work demonstrates the impact of model resolution in dust propagation in a complex terrain region such as West Asia. For this purpose, two simulations using the NMMB/BSC-Dust model are performed and analysed, one with a high horizontal resolution (at $0.03^\circ \times 0.03^\circ$) and one with a lower horizontal resolution (at $0.33^\circ \times 0.33^\circ$). Both model experiments cover two intense dust storms that occurred on 17–20 March 2012 as a consequence of strong northwesterly Shamal winds that spanned over thousands of kilometres in West Asia. The comparison with ground-based (surface weather stations and sunphotometers) and satellite aerosol observations (Aqua/MODIS and MSG/SEVIRI) shows that despite differences in the magnitude of the simulated dust concentrations, the model is able to reproduce these two dust outbreaks. Differences between both simulations on the dust spread rise on regional dust transport areas in south-western Saudi Arabia, Yemen and Oman. The complex orography in south-western Saudi Arabia, Yemen and Oman (with peaks higher than 3000 m) has an impact on the transported dust concentration fields over mountain regions. Differences between both model configurations are mainly associated to the channelization of the dust flow through valleys and the differences in the modelled altitude of the mountains that alters the meteorology and blocks the dust fronts limiting the dust transport. These results demonstrate how the dust prediction in the vicinity of complex terrains improves using high-horizontal resolution simulations.

1. Introduction

Mineral dust represents the major contribution to the atmospheric optical thickness in many regions (Tegen et al., 1997), and evidence exists of increasing dust production in recent decades (Prospero and Lamb, 2003; Mahowald et al., 2010). Dust storms play an important role in the Earth system with important impacts on radiation (IPCC, 2014), clouds (Karyampudi and Pierce, 2002), atmospheric chemistry (Prospero et al., 1995; Cuevas, 2013), ecosystems (Fung et al., 2000; Jickells and Spokes, 2001; Mahowald et al., 2005; UNEP, 2012), biogeochemical cycles (Jickells et al., 2005; Schulz et al., 2012), human health issues such as respiratory diseases, cardiovascular diseases, infections (Thomson et al., 2006; Díaz et al., 2012; De Longueville et al., 2013; Pérez García-Pando et al., 2014), and also on ground and air transportation due to visibility reduction (Shirkhani-Ardehjani, 2012), agriculture (Stefanski and Sivakumar, 2009), energy and industry (El-Nashar, 2003; Elminir et al., 2006; Sulaiman et al., 2011; Ohde and Siegel, 2012; Kazem et al., 2014) and satellite retrievals (Merchant et al., 2006; Amiridis et al., 2013). Modelling is essential not only to have a powerful tool to predict the global or regional dust budget and its interaction in the climate-weather system, but also to complement remote sensing and in-situ observations and to understand dust processes.

In the recent years, some dust models have been developed for regional and global dust prediction such as global models like the Navy Aerosol Analysis and Prediction System (NAAPS; Westphal et al., 2009), the Met Office Unified Model (MetUM™; Woodward, 2011; Collins et al., 2011), the aerosol model at the European Centre for Medium-range Weather Forecasts (MACC-ECMWF; Morcrette et al., 2009; Benedetti et al., 2009) and NMMB/BSC-Dust (Pérez et al., 2011; Haustein et al., 2012). The above global models, together with others, are participating in the International Cooperative for Aerosol Prediction (ICAP) Initiative (Sessions et al., 2015) for aerosol forecast centers, remote sensing data providers, and to lead systems developers to share best practices and to discuss pressing issues facing the operational aerosol community. There are also several regional models that have been developed to predict the dust cycle, for example the BSC-DREAM8b model (Nickovic et al., 2001; Pérez et al., 2006a,b; Basart et al., 2012) and the CHIMERE model (Menut, 2008; Schmechtig et al., 2011).

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The models mentioned above (global and regional) are participating in the World Meteorological Organization (WMO) Sand and Dust Storm Warning Advisory and Assessment System Northern Africa, Middle East and Europe Regional Center (SDS-WAS NAMEE RC; http://sdswas.aemet.es/). The NAMEE RC seeks to achieve comprehensive, coordinated and sustained observations and modelling capabilities of sand and dust storms, to improve their monitoring state, increase the understanding of their formation processes, and enhance prediction capabilities of dust models. The studies comparing and evaluating the temporal (on annual, seasonal and daily basis) and spatial variability of desert dust load and deposition simulated by different models contribute to determining the limitations of the current models and the degree of uncertainty in estimates of dust emission, transport and deposition. They also highlight the sources of uncertainty in these estimates, and point to the key foci for future research to constrain these uncertainties. West Asia is one of the regions where the participating models in the WMO SDS-WAS NAMEE RC shows high variability (Terradellas et al., 2012). Miller et al. (2004) and Tanaka and Chiba (2006) suggest that about 15–20% of the global dust emission is from the Arabian Peninsula and Central Asia. The alluvial plains and dry deserts in south-western Asia and West Asia are important dust sources associated with a complex topography (Ginoux et al., 2012). Topography alters the meteorology of dust emission and transport in many ways. Liu and Westphal (2001) show that wind and dust simulations improve over Asia due to a better-resolved topography. Israelevich et al. (2012) observe an accumulation of desert dust in the Po Valley in front of Alps as the dust-carrying air flow from North Africa reaches them and slows down, highlighting that the terrain relief may also affect aerosol propagation.

The NMMB/BSC-Dust model has been selected as the operational model of the first WMO Regional Meteorological Center specialised in Atmospheric Sand and Dust Forecast, the Barcelona Dust Forecast Center (BDFC; http://dust.aemet.es). The present work investigates the NMMB/BSC-Dust model's ability to reproduce dust propagation in complex terrains. For this purpose, two simulations are performed, one with a high horizontal resolution (at $0.03° \times 0.03°$) and one with a lower horizontal resolution (at $0.33° \times 0.33°$), both of which covered two intense dust storms that occurred on 17–20 March 2012 that spanned over thousands of kilometres affecting the whole Arabian Peninsula. The model results are compared against ground-based (AERONET and weather stations) observations and satellite aerosol products (Aqua/MODIS and MSG/SEVIRI). Section 2 includes a geographical description of the study region, West Asia. In Section 3, the NMMB/BSC-Dust model and descriptions of the different observational datasets are introduced. Section 4 reports an overview of the entire dust event in mid-March 2012, the model evaluation and the discussion of the corresponding results. Finally, Section 5 concludes the present analysis.

2. Study region: West Asia

West Asia is a singular region characterized by a complex topography (with several peaks higher than 3000 m); a low average annual precipitation; low soil moisture content; small dust sources with erodible sediments of fine particles from areas with dry lakebeds, dry riverbeds and sand seas; and a wide variety of meteorological phenomena (e.g., Shamal winds, thermal sea breezes, thunderstorms or low-level jets) which are able to produce severe dust storms (i.e., Rezazadeh et al., 2013). Its three primary desert regions are the Rub Al-Khali ("Empty Quarter") in the south-east, An Nafud in the north-west, and the Ad Dahna sand corridor in the east, connecting the previous two deserts. Remote desert regions that can potentially serve as dust source regions to Saudi Arabia include the vast Saharan Desert to the west and Syrian and Iraqi Deserts to the north (Prospero et al., 2002; Goudie and Middleton, 2006). The seasonal variation of the dust activity in the West Asia is complex and differs for different regions. In most parts of West Asia, dust is active all year long, with minimum activity in the winter months. Dust activity increases in March and April, peaks in June and July and weakens in September (Shao, 2008).

West Asia contains large areas of mountainous terrain (Fig. 1). The Zagros Mountains are located in Iran, in areas along its border with Iraq. The Central Plateau of Iran has divided into two drainage basins: the northern basin is Dasht-e-Kavir (Great Salt Desert), and is the southern basin is Dasht-e-Lut. In Yemen, elevations exceed 3000 m in many areas, and highland areas extend north along the Red Sea coast and north into Lebanon. A fault-zone also exists along the Red Sea, with continental rifting creating trough-like topography with areas located well-below sea level. Al-Hajar mountain range is located in the east of the United Arab Emirates (UAE) and along the north coast of Oman, and reaches up to 3000 m elevation with its highest mountains in its central section, Jebel-al-Akhdar.

3. Methods

3.1. The NMMB/BSC-Dust model

The NMMB/BSC-Dust model (Pérez et al., 2011; Haustein et al., 2012) is the dust module of the NMMB/BSC-Chemical Transport Model (NMMB/BSC-CTM; Pérez et al., 2011; Jorba et al., 2012; Spada et al., 2013; Badia and Jorba, 2014; https://www.bsc.es/earth-sciences/nmmbbsc-project). The NMMB/BSC-Dust has been developed at the Earth Sciences Department of the Barcelona Supercomputing Center-Centro Nacional de Supercomputación (BSC) in collaboration with NOAA/National Centers for Environmental Prediction (NCEP), NASA Goddard Institute for Space Studies and the International Research Institute for Climate and Society (IRI). The NMMB/BSC-Dust model provides operational dust forecast over North Africa-Middle East-Europe and global regions.

The most relevant characteristic of the NMMB/BSC-Dust model is its on-line coupling with the Non-hydrostatic Multiscale Model (NMMB). This provides a unique framework to simulate/predict weather and air quality in a wide range of scales from global to mesoscale applications (from 100 to 1 km), and allows interactions among meteorology-dust-chemistry processes. The NMMB/BSC-Dust model solves the mass balance equation for dust taking into account the following processes: (1) dust generation and uplift by surface wind and turbulence (White, 1979; Marticorena and Bergametti, 1995; Marticorena et al., 1997), (2) horizontal and vertical advection (Janjic et al., 2005; Janjic and Black, 2007), (3) horizontal diffusion and vertical transport by turbulence and convection (Janjic et al., 2005; Janjic and Black, 2007) (4) dry deposition and gravitational settling (Zhang et al., 2001) and (5) wet removal which includes in-cloud and below-cloud scavenging from convective and stratiform clouds (Betts, 1986; Betts and Miller, 1986; Janjic, 1994; Ferrier et al., 2002). Transport of dust by advection and turbulent diffusion is analogous to those of moisture transport in the NMMB. The model includes eigth dust size bins (between 0.10 and 10 μm in radius) with intervals taken from Tegen and Lacis (1996) and Pérez et al. (2006b).

Grid points acting as desert dust sources are specified using arid and semiarid categories of the global USGS 1-km vegetation data set and the STATSGO-FAO soil map global soil texture data set. According to the criteria used by Tegen et al. (2002), the model uses four soil populations (i.e., clay, silt, fine-medium sand and