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Development of high-resolution dynamic dust source function - A case study with a strong dust storm in a regional model

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HIGHLIGHTS

- A high-resolution dynamic dust source has been developed.
- New dust source better resolves the complex topographic distribution.
- A case study is successfully conducted with a strong dust storm in NU-WRF.

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ABSTRACT

A high-resolution dynamic dust source has been developed in the NASA Unified-Weather Research and Forecasting (NU-WRF) model to improve the existing coarse static dust source. In the new dust source map, topographic depression is in 1-km resolution and surface bareness is derived using the Normalized Difference Vegetation Index (NDVI) data from Moderate Resolution Imaging Spectroradiometer (MODIS). The new dust source better resolves the complex topographic distribution over the Western United States where its magnitude is higher than the existing, coarser resolution static source. A case study is conducted with an extreme dust storm that occurred in Phoenix, Arizona in 02–03 UTC July 6, 2011. The NU-WRF model with the new high-resolution dynamic dust source is able to successfully capture the dust storm, which was not achieved with the old source identification. However the case study also reveals several challenges in reproducing the time evolution of the short-lived, extreme dust storm events.

1. Introduction

Dust is one of the most abundant aerosol types in the atmosphere, playing an important role in the Earth's radiation budget, cloud formation, atmospheric dynamics, and ocean biogeochemistry in various spatial and temporal scales (Husar et al., 2001; Haywood et al., 2005; Jickells et al., 2005; Forster et al., 2007; Evan et al., 2008). Mineral dust is also a major air pollutant that causes premature deaths by cardiopulmonary disease and lung cancer for the countries around the source region (Giannadaki et al., 2014; Sprigg et al., 2014; Morman and Plumlee, 2014). The impact of dust is not limited to source areas but extends to larger regional or even global scales (Carlson and Prospero, 1972; Prospero and Lamb, 2003; Kaufman et al., 2005; Chin et al., 2007; Shao et al., 2010; Yu et al., 2012).

The majority of global dust loading is concentrated near the sources in the permanent desert regions (so-called desert-belt), including North Africa, Middle East, and East Asia (Prospero et al., 2002; Chin et al., 2009; Huneeus et al., 2011; Ginoux et al., 2010, 2012). However, dust is also emitted from semi-arid regions such as the Sahel and inner Mongolia, as well as from agricultural areas. Although dust aerosol generated from semi-arid and agricultural areas is much less than that from the major deserts, its importance for air quality and human health is greater at local- and regional-

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scales due to their proximity to populated areas. Correctly identifying the dust source locations and representing the dust storm events in numerical models are keys to estimate the impacts of dust on the environment and society.

We present here the dust simulation with the NASA Unified-Weather Research and Forecast (NU-WRF) modeling system (Peters-Lidard et al., 2015). The objective of this paper is two-fold. The first goal is to describe a new, high spatial resolution (1-km) dynamic dust source ($S_{dynamic}$) for NU-WRF that represents an improvement of the existing static dust source (S_{static}) at 0.25° × 0.25° resolution (described below) currently available in the community WRF-Chem model. The second goal is to evaluate the NU-WRF model simulation of an extreme dust storm case which occurred in Phoenix, Arizona at 02–03 UTC July 6 (or 19–20 MST, July 5), 2011. While systematic observation for a severe dust storm is rare, we revisit the Phoenix dust storm which has been relatively better documented by observations from various platforms, including visual, surface radar, and surface stations (e.g., Raman et al., 2014; Vukovic et al., 2014). They also provide the meteorological background about the extreme dust storm. Through qualitative and quantitative comparisons with these direct and indirect observations, we discuss details about the simulated dust storm, meteorological conditions, dust source, and surface- and columnar intensity of the dust storm.

In section 2, the high-resolution dynamic dust source in the NU-WRF/GOCART dust emission parameterization and the model experiment setup are described. The case study of the Phoenix dust storm is presented in section 3. In section 4, we discuss the challenges in dust simulation, followed by the summary in section 5.

2. Method

2.1. Dust emission parameterization and source function

The dust emission module in NU-WRF is based on the mechanisms from the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model (Ginoux et al., 2001). Dust emission in GOCART, assuming that the soil mobilization is proportional to the horizontal wind speed at near surface, is parameterized with the 10-m wind speed, the threshold velocity of wind erosion, and the surface condition for each dust size group from 0.1 to 10 μm in radius (Ginoux et al., 2001, 2004; Chin et al., 2009). For each size group with effective radius *r*, dust emission flux *F* (μg m^{-2} s^{-1}) is expressed as:

$$F(r) = CSs(r)u_{10m}^2(u_{10m} - u_t(r, w)), \text{ if } u_{10m} > u_t \tag{1}$$

where *C* is a dimensional factor (0.4 μg s^2 m^{-5} for the current study), *S* is the dust source function or probability of dust uplifting with a value between 0 and 1, *s(r)* is the fraction of size group *r* within the soil, u_{10m} is the 10 m wind speed (m s^{-1}), and u_t is the threshold velocity of wind erosion as a function of dust density, particle diameter, and surface wetness to account for the bonding effect between water and particles (Ginoux et al., 2001, 2004). There are five mass size classes in the GOCART scheme with the respective size ranges of 0.1–1 μm, 1–1.8 μm, 1.8–3 μm, 3–6 μm, and 6–10 μm. The first group is clay that accounts for 0.1 of the total dust mass. The balanced mass is evenly distributed to the remaining 4 dust size groups that are all silt. In the optical property calculations, the clay group is further split into four groups (0.1–0.18, 0.18–0.3, 0.3–0.6, 0.6–1) with mass fractions of 0.9, 8.1, 23.4, and 67.6%, respectively (Tegen and Fung, 1994).

The topographic depression (*H*) and surface bareness (*B*) are two key parameters used in the GOCART scheme to calculate the dust source function (*S*), while other parameters such as soil temperature, surface wetness, and snow cover are also included in *S* calculation. The dimensionless topographic depression term *H* is defined as equation (2). *H* represents the probability of accumulated sediments, based on the consideration that dust sediments from surface erosion are accumulated in valleys and surface depressions (Ginoux et al., 2001; Prospero et al., 2002):

$$H = \left(\frac{z_{max} - z}{z_{max} - z_{min}}\right)^5 \tag{2}$$

where *z* is the altitude of a grid cell, and z_{max} and z_{min} are the maximum and minimum elevations of topography in the surrounding 10° × 10° search area. The fifth order power is applied to increase the topographic contrast.

In the community WRF-Chem/GOCART, *H* (0.25° × 0.25°) is generated with the GOCART scheme based on the topography and land mask from the Geophysical Fluid Dynamics Laboratory C360 High Resolution Atmospheric Model (~0.24° resolution) which are derived from the 5 min NAVY data (Ginoux et al., 2001; Putman and Lin, 2007). The bare soil surface in the community WRF-Chem/GOCART was determined based on the 8 km land-cover data from the Advanced Very High Resolution Radiometer (AVHRR) satellite (DeFries et al., 1998) and it does not resolve the temporal variations of vegetation cover.

Recently, Kim et al. (2013) have described a method of constructing a global dynamic surface bareness (*B*) in 1° × 1° spatial resolution using the 8-km spatial resolution AVHRR Normalized Difference Vegetation Index data (NDVI). Calculated from the visible (VIS) and near-infrared (NIR) radiation, NDVI reflects the state of vegetation over surface (Tucker, 1979):

$$\text{NDVI} = (\text{NIR-VIS})/(\text{NIR+VIS}) \tag{3}$$

MODIS NDVI has been applied for recent dust simulation studies either as a source masking (Vukovic et al., 2014) or as a surface vegetation fraction which is an input parameter for surface roughness estimation (Xi and Sokolik, 2015). In the present study MODIS NDVI is used to derive surface bareness following Kim et al. (2013). The surface is considered erodible when NDVI is below the threshold NDVI value (i.e., $NDVI_{thr}$). The $NDVI_{thr}$ has been set to 0.15 taking the fact that the typical NDVI values are 0.05–0.10 over bare ground and the values gets larger than 0.2 during growing season over semi-arid region such as grass or shrub land (Huete et al., 1999; Zeng et al., 2000; Miller et al., 2006; Kim et al., 2013), such that the surface bareness *B* is determined as

$$B = \begin{cases} 1, & NDVI < NDVI_{thr} \\ 0, & otherwise \end{cases} \tag{4}$$

Keeping the principles of the original dynamic dust emission parameterization, the present study has made two major improvements. First, the degree of topographic depression (*H*) has been calculated using the U.S. Geological Survey (USGS) global topography map in 30 arc-second (~1-km) resolution (GTOPO30; USGS, 1996) within a larger search area (12° × 12°). Second, the surface bareness (*B*) is constructed using daily MODIS NDVI data in 0.01° (~1-km) resolution over North America (Case et al., 2014). The high resolution topographic and source function better resolves the complex geographical variability especially over the western United States (Fig. 1a and b). The MODIS NDVI for July 2011 shows a strong spatial variation ranging from 0.1 to 0.8 (Fig. 1c). The erodible bare-ground (i.e., NDVI <0.15) appears over the western United States (Fig. 1d).