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Derivation of an observation-based map of North African dust emission

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ABSTRACT

Changes in the emission, transport and deposition of aeolian dust have profound effects on regional climate, so that characterizing the lifecycle of dust in observations and improving the representation of dust in global climate models is necessary. A fundamental aspect of characterizing the dust cycle is quantifying surface dust fluxes, yet no spatially explicit estimates of this flux exist for the World's major source regions. Here we present a novel technique for creating a map of the annual mean emitted dust flux for North Africa based on retrievals of dust storm frequency from the Meteosat Second Generation Spinning Enhanced Visible and InfraRed Imager (SEVIRI) and the relationship between dust storm frequency and emitted mass flux derived from the output of five models that simulate dust. Our results suggest that 64 (±16)% of all dust emitted from North Africa is from the Bodélé depression, and that 13 (±3)% of the North African dust flux is from a depression lying in the lee of the Aïr and Hoggar Mountains, making this area the second most important region of emission within North Africa.

1. Introduction

By mass, aeolian dust is the most pervasive aerosol on the planet, and the largest fraction of all global dust emission is in North Africa (e.g. Engelstaedter et al., 2006; Ginoux et al., 2006). African dust emission and transport is both affected by—and affects—the climate. For example, previous work has shown there is an increase in dust emission and transport over the Atlantic during periods of Sahelian drought (Prospero and Lamb, 2003) due to a decrease in soil moisture over the Sahel (Cowie et al., 2013), increased surface wind speeds over the Sahara (Ridley et al., 2014), or some combination of the two (Doherty et al., 2014). Once transported over the Atlantic, direct radiative forcing by dust both warms the atmosphere and cools the surface (Evan and Mukhopadhyay 2010), contributing interannual to decadal scale variability of tropical Atlantic sea surface temperatures (Evan et al., 2012) and exciting coupled modes of equatorial variability (Evan et al., 2009, 2011).

The influence of these aerosols on the climate system extends well beyond the direct radiative effect. Recent work has shown that African dust may influence clouds as far away as the west coast of the United States, providing ice nuclei required for precipitation in so-called atmospheric rivers (Creamean et al., 2013). Aeolian dust contains nitrogen, phosphorus and iron, all of which are required for primary productivity in oceanic and terrestrial ecosystems, and there is a large body of work demonstrating the importance of the atmospheric input of these elements via dust transported from western Africa (Das et al., 2013; Okin et al., 2011; Mahowald et al., 2010).

In order to improve understanding of dust-climate effects it is necessary to elucidate surface and atmospheric processes governing emission. However, the vast majority of North African dust emission occurs within largely uninhabited regions and thus there is a paucity of both meteorological and surface observations in these locations, particularly homogeneous measurements of each that span time scales of years to decades. As a result, numerical models play a crucial role in this field of study, yet there are relatively few observational data sets against which model output can be validated, and as a result model output is often validated against surface visibility observations and retrievals of aerosol optical depth from satellites and ground-based instrumentation—none of which are direct measures of dust—and surface concentrations from a limited number of sampling stations (e.g., Ginoux et al.,

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2001; Huneeus et al., 2010; Tegen and Miller, 1998; Todd et al., 2008).

Given the lack of observations it is not surprising that recent studies have identified issues with the representation of the dust cycle in models. Kok (2011) evaluated the emitted size distribution of dust within several climate models, finding that all of the models underestimated the number of large particles emitted and thus the emitted mass flux, in agreement with earlier findings by Cakmur et al. (2006). Evan et al. (2014) examined dust in Climate Model Intercomparison Project Phase 5 (CMIP5) models, corroborating the findings of Kok (2011) and finding that, when forced by observed sea surface temperatures, models cannot reproduce historical year-to-year variability in cross-Atlantic dust transport, as determined by satellite data and paleo-proxy data. Furthermore, considering soil characteristics, Kok et al. (2014) found that a majority of models underestimate dust emissions sensitivity to the soil erodibility, i.e. the ability of the soil to emit dust for a given above-threshold friction velocity (definition following Kok et al., 2014; Zender et al., 2003).

In the present paper we attempt to address the need for more observational records against which models can be evaluated by creating a spatially explicit map of annual dust emission using data from the Meteosat Second Generation Spinning Enhanced Visible and InfraRed Imager (SEVIRI). The remainder of this paper is organized as follows. In Section 2 we describe the models and satellite data used in this study. In Section 3 we compare the spatial structure of emission amount and emission frequency among the models, and define a statistical relationship between the two. In Section 4 we use this statistical relationship to derive the new observational climatology of dust emission amounts. We conclude in Section 5 with a summary of the main results of the paper.

2. Models and satellite data

In this paper we examine dust emission amount and frequency of events using one year of output from four regional models centered over North Africa and one global climate model. A summary of the models considered here and some of their relevant features can be found in Table 1.

2.1. Satellite data

15-min IR dust index images calculated from brightness temperatures at 8.7 μm, 10.8 μm and 12.0 μm observed by SEVIRI MSG satellite are used inferring dust source activation frequencies over North Africa for the period March 2006–February 2010 (Schepanski et al., 2007, 2012). As the images are available throughout day and night, dust source activation events were identified at sub-daily (hourly) resolution and geo-located by tracking back dust plumes individually to their point of origin, which is assumed to be the dust source and recorded on a 1 × 1 map. It is noted that no dust sources can be spotted under optical thick clouds or dust plumes. Due to the 15-min resolution of the native dust index images information on the diurnal cycle of dust source activation events can be retrieved, allowing for a relatively precise location of dust sources (Schepanski et al., 2012). Compared to an automated detection of dust plumes (Ashpole and Washington 2013), the manual identification by Schepanski et al. (2009) is likely less prone to systematic errors. Furthermore, the results from Ashpole and Washington do not cover all of North Africa, which is required for this study. The Schepanski et al. data set has been used for mapping dust sources (Schepanski et al., 2007), identifying the diurnal cycle of dust emission onset over Western Africa and associated meteorological conditions driving dust uplift (Schepanski et al., 2009), and model validation (e.g., Johnson et al., 2011). The dust source activation data set compares well with the spatio-temporal distribution of dust sources identified from surface visibility observations at weather stations (Laurent et al., 2010).

2.2. Models

In this study we examine the output from two dust simulations (Zhao et al., 2010, 2013) made with the Weather Research and Forecasting with Chemistry (WRF-Chem) model (Grell et al., 2005; Skamarock and Klemp, 2008). WRF-Chem simulates trace gases and particulates with the meteorological fields and simulates a variety of coupled physical and chemical processes such as transport, deposition, emission, chemical transformation, and radiation, and includes online coupling of chemistry and meteorology. WRF-Chem has been widely used to simulate the dust life cycle and climatic impact at the global scale (e.g., Zhao et al., 2013) and the regional scale over West Africa (Zhao et al., 2010, 2011), Saudi Arabia (Kalenderski et al., 2012), North America (Zhao et al., 2012), and East Asia (Chen et al., 2013). The simulations are conducted at one-degree horizontal resolution throughout the domain. Two dust emission schemes, one based on Ginoux et al. (2001) and the other on Kok et al. (2014), both coupled with a modal aerosol model, are used in this study. The emission scheme from Ginoux et al. (2001) (hereafter referred to as WRF-GOCART) calculates the dust emission flux as a function of horizontal wind speed at 10 m, the threshold 10 m wind speed below which dust emission does not occur, and a prescribed source function that defines the potential dust source regions and comprises surface factors, such as vegetation and snow cover. The dust emission scheme developed by Kok et al. (2014) (hereafter referred to as WRF-KOK) is derived from a physically based theory that uses the concept that dust emission is a threshold effect without an explicitly prescribed

Table 1
Overview of model characteristics. Shown here are models' dust emission scheme types and number of bins, meteorological forcing at model boundaries, horizontal resolution, and model output data time resolution. All dust output fields are instantaneous.

Model	Dust emission	Boundaries	Horiz. resolution	Output
TEGEN	Offline, 3 bins Tegen et al. (2002)	ERA-Interim forecasts Dee et al. (2011)	Western Africa 1 × 1 degree res	3-Hourly
WRF-GOCART	Online, 3 mode Zhao et al. (2013)	Forced everywhere with NCAR/NCEP reanalysis	60°S–70°N and all longitudes 1 × 1 degree res	3-Hourly
WRF-Kok	Online, 3 mode Kok et al. (2014)		60°S–70°N and all longitudes 1 × 1 degree res	3-Hourly
CESM	Online, 3 bins Mahowald et al. (2006)	N/A	Global 0.94° × 1.24° res	30-Minute
CHIMERE	Online, 9 bins (0.039–40 μm), saltation and sandblasting, Menut et al. (2013)	N/A	Global 1 × 1 degree res	Hourly