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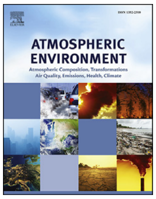

Role of surface wind and vegetation cover in multi-decadal variations of dust emission in the Sahara and Sahel

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HIGHLIGHTS

- Vegetation modulates bareness over Sahel and is anti-correlated with emission.
- Surface wind drives the inter-annual variation of Saharan/Sahelian dust emission.
- The Sahara and Sahel account for 82% and 17% of North Africa dust emission.

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ABSTRACT

North Africa, the world's largest dust source, is non-uniform, consisting of a permanently arid region (Sahara), a semi-arid region (Sahel), and a relatively moist vegetated region (Savanna), each with very different rainfall patterns and surface conditions. This study aims to better understand the controlling factors that determine the variation of dust emission in North Africa over a 27-year period from 1982 to 2008, using observational data and model simulations. The results show that the model-derived Saharan dust emission is only correlated with the 10-m winds (W10m) obtained from reanalysis data, but the model-derived Sahel dust emission is correlated with both W10m and the Normalized Difference Vegetation Index (NDVI) that is obtained from satellite. While the Saharan dust accounts for 82% of the continental North Africa dust emission (1340–1570 Tg year^{-1}) in the 27-year average, the Sahel accounts for 17% with a larger seasonal and inter-annual variation (230–380 Tg year^{-1}), contributing about a quarter of the transatlantic dust transported to the northern part of South America. The decreasing dust emission trend over the 27-year period is highly correlated with W10m over the Sahara ($R = 0.92$). Over the Sahel, the dust emission is correlated with W10m ($R = 0.69$) but is also anti-correlated with the trend of NDVI ($R = -0.65$). W10m is decreasing over both the Sahara and the Sahel between 1982 and 2008, and the trends are correlated ($R = 0.53$), suggesting that Saharan/Sahelian surface winds are a coupled system, driving the inter-annual variation of dust emission.

1. Introduction

Dust plays an important role in global climate by interacting with solar and terrestrial radiation, altering cloud amount and radiative properties (Haywood et al., 2003; Forster et al., 2007; Evan et al., 2008; Kim et al., 2010). Dust is also important to biogeochemical cycles by fertilizing land and ocean and modulating carbon uptake (Jickells et al., 2005; Maher et al., 2010; Yu et al., 2015a). North Africa is the world's largest dust source accounting for about one half of the global dust mass loading in the atmosphere (Kinne et al., 2006; Chin et al., 2009), and its impact can go well beyond the source region extending to hemispheric or even

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global scales (Carlson and Prospero, 1972; Kaufman et al., 2005; Prospero et al., 2014; Yu et al., 2015b). Mineral dust is also an air pollutant that causes premature deaths by cardiopulmonary disease and lung cancer (Giannadaki et al., 2014).

North Africa is known to be the largest dust source area in the world, but the dust sources are not homogeneously distributed (Ginoux et al., 2001, 2012; Formenti et al., 2011). For example, the Köppen-Geiger climate classifies North Africa into three regions with the Sahara desert in the north, the Savanna in the south, and the Sahel, a semi-arid transition zone, between the two (Kottek et al., 2006). Although the Saharan desert is considered to be the major dust source in North Africa, a number of previous observational and modeling studies have found that the dust sources in Sahel plays an important role in the North African climate system (Charney, 1975; Tegen et al., 2004; Yoshioka et al., 2007; Foltz and McPhaden, 2008; Mahowald et al., 2010; Klose et al., 2010; Cowie et al., 2013).

Dust emission from bare soil is mainly driven by surface wind interacting with dry soil particles. When the surface is vegetated, the vegetation protects underlying soils and plays an important role in modulating the quantity of dust emitted. However, the relationship between wind and vegetation as well as their roles in dust emission is not fully understood. For example, there is a suggestion that decreasing surface wind speed since the 1980s in North Africa can be explained by increased vegetation that enhances surface roughness (Vautard et al., 2010; Bichet et al., 2012; Wang et al., 2012; Cowie et al., 2013). While some studies find that precipitation and vegetation together strongly constrain dust over the Sahel and other semi-arid source regions (e.g., Prospero and Lamb, 2003; Zender and Kwon, 2005; Cowie et al., 2013), others do not find a direct link between the dustiness of the Northern Atlantic and the land use or vegetation change over the source region (e.g., Ridley et al., 2014).

Because the Sahara is mostly bare, experiencing no significant seasonal or interannual variability in surface characteristics, we expect any variability in dust sources from this area will be due to meteorology, specifically surface wind speed, and not due to changes in vegetation. If there is variability in dust source strength in North Africa linked to vegetation cover, that variability will be introduced by Sahel sources with their seasonal and interannual vegetative cover variability. That is why characterizing dust source processes in the Sahel is central towards better understanding the relative roles of meteorology and land surface processes in dust emissions for the Sahel and the North Africa. The goal of this study is to better understand the relationships between surface wind, rainfall, surface vegetation, dust emission, and dust loading over the Sahara and Sahel using wind and vegetation data sets and global dust model simulations in a multi-decadal time span from 1982 to 2008.

In this paper, we first define in Section 2 the sub-Saharan semi-arid region (i.e., the Sahel) using the satellite observations of Normalized Difference Vegetation Index (NDVI), and describe the NASA Goddard Chemistry Aerosol Radiation and Transport (GOCART) model used in this study. In Section 3.1 we compare modeled dust optical depth (DOD) with remotely sensed and in situ observations. In Section 3.2 we examine the long-term climatological mean seasonal relationships between surface conditions and meteorological parameters over the Sahara and Sahel. We then estimate the contribution of the Sahelian dust transport to the dust loading over the North Atlantic in Section 3.3, followed by a time-dependent analysis of model-derived dust emission with two independent observationally-based trends of surface wind and surface vegetation over the time span between 1982 and 2008 in Section 3.4. Discussion and summary are given in Sections 4 and 5, respectively.

2. Methods

2.1. Sahel area determined by the AVHRR NDVI

We have utilized the Normalized Difference Vegetation Index observed from the Advanced Very High Resolution Radiometer satellite (AVHRR-NDVI) to build a Sahel area map (Kim et al., 2013). The 8-km, half-monthly AVHRR NDVI composite data (version NDVIg) is from the NASA Global Inventory Monitoring and Modeling Systems (GIMMS) that spans the years August 1981 to December 2008 (Tucker et al., 2005; Brown et al., 2006; Anyamba et al., 2014). Our method for Sahel area determination relies on a condition that may characterize the behavior of NDVI in North Africa based on an analysis of the NDVI throughout the period of NDVIg availability (January 1982 to December 2008) to be consistent with the method developed in the previous study (i.e., Kim et al., 2013), even though a newer version (NDVI3g) has expanded to cover the present time (Pinzon and Tucker, 2014; Anyamba et al., 2014).

The Sahara and Sahel exhibit different values and variability of NDVI throughout the year. NDVI is always lower than 0.15 in the northern part of the domain and always greater than 0.2 in the southern part of the domain (Fig. 1a and b). In the transition zone, the NDVI is below 0.15 during the dry season and it is greater than 0.20 during the wet season. Thus, we define the annual semi-arid transition zone, or the Sahel, as the area that complies with the following criteria:

$$\mathrm{NDVI_{min}} < 0.15 \text{ and } \mathrm{NDVI_{max}} > 0.20 \quad (1)$$

where $\mathrm{NDVI_{min}}$ and $\mathrm{NDVI_{max}}$ are the minimum and maximum monthly values of NDVI in a particular latitude-longitude grid point in a given year. We have applied these conditions to the area for 10°N-20°N and 17°W-40°E (Fig. 1c). The shape and location of the Sahel defined by equation (1) is quite similar to other studies using precipitation amount (e.g., Herrmann et al., 2005; Kottek et al., 2006; Anyamba et al., 2014). The semi-arid area defined here clearly excludes all permanent deserts from the Sahel similar to the precipitation based map (e.g., the Bodélé depression at 17°N, 18°E). There is some year-to-year change in the southern Sahel border and in the total area of the semi-arid region, but the northern Sahel border is generally the same. A climatological semi-arid region calculated based on the AVHRR NDVI in this study, which can be considered as the general Sahel area, is shown in Fig. 1d at 1° latitude × 1.25° longitude resolution. In the map, a grid point is determined as the Sahel when it satisfies equation (1) for more than 5 years out of the 27-year data base. The blue area is identified as the semi-arid Sahel (3.6×10^6 km^2) and the red indicates the permanent Sahara desert (1.1×10^7 km^2).

2.2. GOCART model description and simulation setup

The Goddard Chemistry Aerosol Radiation and Transport (GOCART) model is used to simulate key tropospheric aerosols including sulfate, dust, black carbon, organic carbon, and sea-salt (Ginoux et al., 2001; Chin et al., 2002, 2009, 2014). The model is driven by the meteorological reanalysis data from the Modern-Era Reanalysis for Research and Applications (MERRA) (Rienecker et al., 2011) with the input of the meteorological fields from MERRA every 3 h, which were linearly interpolated to the GOCART model dynamic time step (15 min, in this case). The model is run as an offline chemistry transport model with no feedback between dust and meteorology. We run the model simulation at a spatial resolution of 2° latitude × 2.5° longitude and 72 vertical layers up to 0.01 hPa. Aerosol advection is computed by a flux-form semi-Lagrangian

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