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The role the Saharan Heat Low plays in dust emission and transport during summertime in North Africa

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ABSTRACT

The Saharan Heat Low (SHL) is an important element in the meteorological system in North Africa in summer. However, it is unclear how the SHL affects North African dust emission and transport. Here we investigate the impact of the SHL on dust emission and transport on synoptic time scales in North Africa during the summer over the period 2003–2015 using satellite retrievals of dust optical depth (DOD) and vertical profiles. During the cool phases of the SHL, dust is preferentially emitted from the Bodélé depression. Then, as the SHL warms, the dust emitted from the Bodélé depression is advected westward due to the intensified African Easterly Jet, resulting in anomalously high DOD values over Mali and Mauritania, where persistent lower troposphere convergence within the SHL sustains the high concentrations of dust. Thus, the persistently high dust DOD from satellite retrievals over Mali and Mauritania in conditions of warm SHL are a combination of dust advection from the east and local emission.

1. Introduction

Aeolian dust is the most pervasive aerosol in the atmosphere (Kaufman et al., 2005) and it has various impacts on the Earth system. Dust can absorb and scatter visible and infrared radiation and thus affect the atmospheric radiation budget (Golitsyn and Gillette, 1993; Kaufman et al., 2002). Dust can act as a cloud condensation nuclei, indirectly changing the atmospheric radiation budget and the hydrological cycle by modifying cloud cover (Wurzler et al., 2000; DeMott et al., 2003) and cloud properties (Miller et al., 2004; Andreae and Rosenfeld, 2008; Rosenfeld et al., 2008; Creamean et al., 2013). In addition, dust plays a non-negligible role in biogeochemical processes by transporting nutrients to oceanic (Savoie and Prospero, 1980; Swap et al., 1996; Okin et al. 2011) and terrestrial ecosystems (Swap et al., 1992; Formenti et al., 2001; Das et al., 2013).

The Sahara is the world's largest source of aeolian dust (D'Almeida, 1986), and it is estimated that each year several hundred teragrams (Tg) of African dust is transported over the Atlantic to the United States, the Caribbean and South America (Prospero, 1996; Chin et al., 2007). There are a number of major dust source regions in North Africa, including Tunisia and Northern Algeria, the foothills of the Atlas, the Ahaggar and the Aïr Mountains, the coastal region in Western Sahara and western Mauritania, the Mali-Algerian border region, Central Libya, the Bodélé depression, and Southern Egypt and Northern Sudan (Brooks and Legrand, 2000; Caquineau et al., 2002; Prospero et al., 2002; Israelevich et al., 2002; Goudie, 2003; Schepanski et al., 2009; Formenti et al., 2011; Scheuvens et al., 2013). Among those dust source regions the Bodélé is found to be the largest contributor to the atmospheric dust load, accounting for 64% (±16%) of the total North Africa dust emission (Evan et al., 2015a,b).

Meteorological processes prompting dust emissions and transport are different at the north and at the south of the Intertropical Discontinuity (ITD), the interface between the cool moist southwesterly monsoon flow and the warm and dry northeasterly flown, which location exhibits a significant variability at diurnal to seasonal scales. North of the ITD, the northeasterly Harmattan flow drives dust emissions and transport in summer (Rodríguez et al., 2015) whereas dust mobilization south of the ITD is influenced by the monsoon front (Bou Karam et al., 2008) and African easterly waves (AEW, Jones et al., 2003).

The Saharan Heat Low (SHL) plays an important role in the dynamics of the West African monsoon system. The SHL is an area of high surface temperature and low surface pressure within the

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summertime Sahara Desert, and is characterized by a low-level cyclonic circulation and mid-level anticyclonic circulation about the SHL center (Lavaysse et al., 2009). The warm phases of the SHL indicate a dilatation of the lower atmosphere in response to an increase in low-level temperature and are associated with a strengthened low-level cyclonic circulation that opposes the northeasterlies along the southeastern branch of the SHL and enhances them along the northwestern branch. Lavaysse et al. (2010b) and Chauvin et al. (2010) showed that AEWs, Rossby waves (and other mid-latitude circulations) and low level advection of moisture from the south (monsoon intrusions) or the north (Mediterranean surges) influence the structure and intensity of the SHL at synoptic scales.

During the summer, the warm phases of the SHL are associated with an intensification of the African easterly jet (AEJ, Lavaysse et al., 2010a), and barotropic and baroclinic energy conversions from the AEJ are the main maintenance mechanisms for AEWs (Norquist et al., 1977). AEWs dominate synoptic-scale variability over West Africa (Kiladis et al., 2006) and modify dustiness over the Atlantic (Jones et al., 2003) and West Africa (Knippertz and Todd, 2010).

In this paper, we describe how the intensity of the SHL affects dust emission and transport on the synoptic scale over North Africa during the summertime (July and August) via analysis of 13 years of reanalysis and satellite data. We aim to provide a comprehensive description of the relationship between the phase and strength of the SHL and the North African dust cycle. The remainder of our paper is organized as follows: In section 2, we describe the datasets used in this study. In section 3, we examine the periodicity of the intensity of the SHL and how the variability in the SHL is related to dust emission and transport over North Africa. A brief conclusion is provided in Section 4.

2. Data

Here we describe the reanalysis and satellite data used in this study to understand how dust emission and transport is associated with the phase and strength of the SHL.

2.1. The SHL index

The SHL index is defined as the difference in the mean of low-level atmospheric thickness (LLAT) between the 700 and 925 hPa pressure levels over West Africa (10 °-0 °W, 15 °-25 °N) (Lavaysse et al., 2009),

$$LLAT = \frac{R}{g}\int_{p2}^{p1} Td(\ln(p))$$

where R is the gas constant for air, g is gravitational acceleration, and T and p are temperature and pressure at 925 and 700 hPa. LLAT, and thus the strength of the SHL, increases as the low-level temperature warms, and vice versa.

We constructed daily time series of the SHL index in July and August from 2003 through 2015 using 0600 UTC pressure and temperature at 700 hPa and 925 hPa from the European Centre for Medium-Range Weather Forecasts Interim Reanalysis (ERA Interim; Dee et al., 2011). Lavaysse et al. (2013) found the SHL based on ERA Interim is a good estimate of the location and the intensity of the SHL from daily to seasonal timescales compared with brightness temperature from the advanced microwave sounding unit (Lavaysse et al., 2013).

2.2. Reanalysis

ERA Interim has modeled variables on 23 pressure levels from 1000 to 1 hPa. We use 600 hPa, 925 hPa and 10 m winds with a horizontal resolution of $1^\circ \times 1^\circ$ at 0600 UTC from ERA Interim reanalysis daily product in July and August from 2003 through 2015 to examine the variability of winds with the strength of the SHL. Winds from ERA Interim have been proven to be well suited for analysis of dust emission and transport in North Africa compared to other reanalysis products (Evan et al., 2016; Largeron et al., 2015).

2.3. Satellite data

Satellite products are useful to study dust transport as they represent the only observational method to characterize the large-scale variability of aerosols. Observations from the Moderate Resolution Imaging Spectroradiometer (MODIS), aboard the Terra and Aqua satellites, have been widely used to study dust over the ocean and the land (e.g. Kaufman et al., 2005; Ginoux et al., 2012). MODIS daily level 3 aerosol products provide global coverage of aerosol properties using the Dark Target and Deep Blue algorithms at a 1° by 1° spatial resolution (Levy et al., 2015). The Dark Target algorithm retrieves aerosol optical depth (AOD) at 550 nm over ocean and dark land surfaces, while the Deep Blue algorithm covers both dark and bright land surfaces (Hsu et al., 2013). Following the methodology of Ginoux et al. (2012) we classify a scene as dust over land based on the follow criteria. The first criterion is that Angstrom exponent is less than 0.6 (Schepanski et al., 2007) as fine aerosols have larger Angstrom exponent. The second criterion is that the single scattering albedo (ω) at 412 nm is less than 0.95 as sea salt ω is near 1 (Ginoux et al., 2012). The third criterion requires ω at 660 nm to be larger than ω at 412 nm as dust absorption increases sharply from red to deep blue spectrum (Ginoux et al., 2012). We eliminate fine AOD from AOD for DOD over the ocean. Since Terra has a relatively short period of Deep Blue aerosol data availability (2000–2007) due to the lack of polarization corrections to the L1B data, we use the Aqua Atmosphere Level 3 daily products to examine how the spatial pattern of DOD over North Africa and the tropical Atlantic varies with the strength of the SHL in summertime from 2003 through 2015.

In order to examine the vertical distribution of dust we use data from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) launched in April 2006 as part of NASA's A-Train constellation that crosses the equator at around 1:30 pm and 1:30 am local solar time. The main instrument carried by CALIPSO is the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), an along-track, nadir-pointing two-wavelength lidar that measures attenuated backscatter extinction coefficients at visible (532 nm) and infrared (1064 nm) wavelengths. We use both the CALIOP Level 2 5-km aerosol layer product and the 5-km aerosol profile product to construct vertical profiles of dust. The aerosol layer product contains a vertical feature mask (VFM) to separate aerosols from clouds based on particulate backscatter color ratio. This product also distinguishes dust from other types of aerosol, namely marine, continental, polluted continental and biomass burning, based on the extinction-to-backscatter ratio (Vaughan et al., 2004). Schuster et al. (2012) found that the lidar ratio for the CALIOP dust retrieval is too low with regard to retrievals from the Aerosol Robotic Network (AERONET). However, Liu et al. (2009) suggested that the success rate of aerosol classification is above 90% based on one-day manual verification. The aerosol layer product gives an aerosol optical depth for up to 8 layers from the surface to 40 km based on the output of the VFM. The aerosol profile product contains extinction coefficients at 60 m resolution.

We construct vertical profiles of DOD at a 60 m vertical resolution using the following method: The column DOD (τ) identified by the VFM in the aerosol layer product is given by

$$\tau = \alpha \times z$$