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The pulsating nature of large-scale Saharan dust transport as a result of interplays between mid-latitude Rossby waves and the North African Dipole Intensity

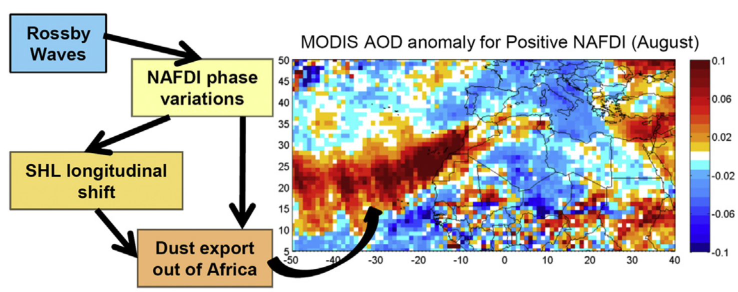
E. Cuevas [a, *], A.J. Gómez-Peláez [a], S. Rodríguez [a], E. Terradellas [b], S. Basart [c], R.D. García [a, d], O.E. García [a], S. Alonso-Pérez [e]

[a] Izaña Atmospheric Research Centre (AEMET), c/ La Marina 20, 38001 Santa Cruz de Tenerife, Spain
[b] SDS-WAS Regional Centre (AEMET), Edificio Nexus II, c/ Jordi Girona 29, 08034 Barcelona, Spain
[c] Earth Sciences Department, Barcelona Supercomputing Centre, Edificio Nexus II, c/ Jordi Girona 29, 08034 Barcelona, Spain
[d] Air Liquide S.A., Delegación de Canarias, Plaza Industrial Valle Güímar Manz, 38500 Güímar, Santa Cruz de Tenerife, Spain
[e] Universidad Europea de Canarias, Campus de la Orotava, c/ Inocencio García 1, 38300 La Orotava, Santa Cruz de Tenerife, Spain

HIGHLIGHTS

- Saharan dust transport out of Africa shows a pulsed behaviour.
- The North African Dipole Intensity (NAFDI) modulates Saharan dust export.
- NAFDI intra-seasonal variations are driven by mid-latitude Rossby waves.
- NAFDI drives the temporal evolution of the Saharan Heat Low longitudinal shift.
- NAFDI may modulate dust emission in central-western Sahara.

GRAPHICAL ABSTRACT



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ABSTRACT

It was previously shown that during August the export of Saharan dust to the Atlantic was strongly affected by the difference of the 700-hPa geopotential height anomaly between the subtropics and the tropics over North Africa, which was termed the North African Dipole Intensity (NAFDI). In this work a more comprehensive analysis of the NAFDI is performed, focusing on the entire summer dust season (June–September), and examining the interactions between the mid-latitude Rossby waves (MLRWs) and NAFDI. Widespread and notable aerosol optical depth (AOD) monthly anomalies are found for each NAFDI-phase over the dust corridors off the Sahara, indicating that NAFDI presents intra-seasonal variability and drives dust transport over both the Mediterranean basin and the North Atlantic. Those summer months with the same NAFDI-phase show similar AOD-anomaly patterns. Variations in NAFDI-phase also control the displacement of the Saharan Heat Low (SHL) westwards or eastwards through horizontal advection of temperature over Morocco-Western Sahara or eastern Algeria-Western Libya, respectively. The connection between the SHL and the NAFDI is quantified statistically by introducing two new daily indexes that account for their respective phases (NAFDI daily index -NAFDIDI-, and SHL longitudinal shift index -SHLLSI-) and explained physically using the energy equation of the atmospheric dynamics. The Pearson's correlation coefficient between the one–day-lag SHLLSI and the NAFDIDI for an extended summer season (1980–2013) is 0.78. A positive NAFDI is associated with the West-phase of the SHL, dust sources intensification on central Algeria, and positive AOD anomalies over this region and the Subtropical North Atlantic. A negative NAFDI is associated with the East-phase of the SHL, and positive

* Corresponding author.
E-mail address: ecuevasa@aemet.es (E. Cuevas).

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AOD anomalies over central-eastern Sahara and the central-western Mediterranean Sea. The results point out that the phase changes of NAFDI at intra-seasonal time scale are conducted by those MLRWs that penetrate deeply into the low troposphere.

1. Introduction

Mineral dust from deserts is the second most important contributor to the global atmospheric aerosol burden after sea-salt aerosols (Huneeus et al., 2013 and references herein). The largest and most active dust source worldwide is the Sahara desert (i.e., Ginoux et al., 2012; Goudie and Middleton, 2001) with an emission range between 400 and 2200 Tg yr^{-1}. Dust impacts on climate (i.e. Foltz and McPhaden, 2008; Prospero and Lamb, 2003; Tegen and Torres, 2005), air quality (e.g., Prospero, 1999; Prospero et al., 2014) and health (e.g., Díaz et al., 2012; Karanasiou et al., 2012; Prospero and Lamb, 2003). The Saharan Air Layer (SAL), usually heavily laden with mineral dust, reaches regions as far away as the Caribbean and the Americas (e.g., Adams et al., 2012; Gläser et al., 2015; Perry et al., 1997; Prospero and Carlson, 1972). Dust also reaches the Mediterranean basin (Basart et al., 2009; Moulin et al., 1998) with implication even in the compliance of European air quality standards (Escudero et al., 2007; Marconi et al., 2014; Rodríguez et al., 2001). In the Sahel region, dust is associated with meningitis epidemics during the dry season (Pérez García-Pando et al., 2014; Thomson et al., 2006). Concerning ecosystems, the Saharan dust deposition fertilises the Amazon rainforest (Yu et al., 2015) and triggers marine phytoplankton growth in both the North Atlantic (Ravelo-Pérez et al., 2016) and the Mediterranean Sea (Gallisai et al., 2014), playing a key subsequent role in controlling the chemical composition of sea-water and hence in the carbon cycle (Conway and John, 2014).

Given this wide variety of impacts, a good knowledge of Saharan dust outflows variability at different spatiotemporal scales is absolutely essential to assess the variability induced by Saharan dust in changes observed in climate, air quality, and ecosystems, as well as to improve operational forecasting capabilities to predict dust storms (Benedetti et al., 2014; Huneeus et al., 2011; Stein et al., 2015).

African dust emission and transport exhibits a high variability from diurnal (Cuesta et al., 2009) to multi-decadal time scales (Wang et al., 2015; Evan et al., 2016). The seasonal variation of Saharan dust outflows has been reasonably well studied in affected regions (Barnaba and Gobbi, 2004; Israelevich et al., 2012; Prospero et al., 2014, and references therein). Tegen (2013) investigated the role of the atmospheric circulation in the inter-annual variability of dust source activation frequency. Inter-annual dust outflows variations are relatively well known in the winter period (Nakamae and Shiotani, 2013), which are mostly associated with the North Atlantic Oscillation (Chiapello et al., 2005; Ginoux et al., 2004). However, only in recent years research on inter-annual variations of Saharan dust outflows during the summer period has been carried out (i.e., Ben-Ami et al., 2009; Engelstaedter et al., 2009; Rodríguez et al., 2015). In this season Saharan dust mobilization shows its peak (Engelstaedter and Washington, 2007).

Rodríguez et al. (2015) introduced the North African Dipole Intensity (NAFDI) index, which is the difference of the 700-hPa geopotential height (Z700) anomalies averaged over the subtropical (30-32°N, Morocco) and the tropical (10-13°N, Bamako) North Africa regions close to the Atlantic coast (at 5-8°W). These authors used satellite Aerosol Index and the 28-year-long in-situ dust concentration record at the high-mountain Izaña Observatory to explain the influence of changes in the NAFDI intensity to the dust outflows from west Sahara to the tropical Atlantic in August. Note that a similar approach was applied later to account for dust transport in southwest Asia with the Caspian Sea-Hindu Kush Index (CasHKI) (Kaskaoutis et al., 2016). Since inter-annual variability in dust outflows towards the North Atlantic is observed (Rodríguez et al., 2015), it seems reasonable to expect a certain relationship between NAFDI and dust emissions over the Sahara. On the other hand, Rodríguez et al. (2015) did not determine whether the NAFDI and associated dust outflows show intra-seasonal variations whereas it is well known that dust transport occurs in the form of strong pulses along the Mediterranean-Europe-Middle-East and North-Atlantic-Caribbean-North-America routes (Guerzoni et al., 1999; Prospero, 1996; Prospero and Mayol-Bracero, 2003). In this paper we answer the following question: what atmospheric processes produce the pulsed behaviour of dust outflows observed at the intra-seasonal time scale?

It is well known that changes in the strength and location of the Saharan heat low (SHL) (Lavaysse et al., 2009) constitute a crucial issue for understanding regional dust mobilization because changes in the SHL are tightly linked to the activation of some key meso-scale processes such as density currents, low-level jets (LLJ), and severe convective phenomena present in the equatorial convergence zone (Allen and Washington, 2013; Knippertz and Todd, 2010; Lavaysse et al., 2010a; Marsham et al., 2013; Roehrig et al., 2011). Since the SHL is associated with dust mobilization processes over the Sahara and NAFDI drives Saharan dust transport out of Africa, the following questions arise: 1) Is there a statistically significant relationship between the SHL-phase changes and the intra-seasonal variations we might find in NAFDI?; 2) If so, which of them acts as a driver of the other, and through which physical mechanism? On the other hand, the SHL is also a central meteorological system associated to the West African monsoon (Sultan and Janicot, 2003), which interacts with mid-latitude circulation (Chauvin et al., 2010; Knippertz, 2008, 2010; Lavaysse et al., 2010b; Roehrig et al., 2011). However, the specific reasons that might explain the SHL shifts and changes in intensity as well as in the associated atmospheric dust loadings are still poorly understood (Engelstaedter et al., 2015). According to Chauvin et al. (2010), the longitudinal position of the SHL is linked to the propagation of mid-latitude Rossby waves (MLRWs) over North Africa. However, these authors did not explore in detail nor identify the subjacent atmospheric processes behind that statistical relation. Therefore, we wonder about the role that MLRWs might play in the intra-seasonal variability of NAFDI, and if it is possible to explain the mechanisms that control the interaction between Rossby waves and the NAFDI and SHL phases.

To properly address these questions we set the following objectives in this study: 1) investigate intra-seasonal changes in dust transport over the Sahara and outflow regions driven by changes in NAFDI during summertime (June–September; hereinafter denoted as JJAS); 2) identify and analyse the atmospheric processes which might connect NAFDI variations with changes in the SHL position; and 3) identify and quantify the atmospheric physical mechanisms by which MLRWs might modulate at intra-seasonal scale the SHL-