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The magnitude, timing and abruptness of changes in North African dust deposition over the last 20,000 yr

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ABSTRACT

Reconstructions of eolian dust accumulation in northwest African margin sediments provide important continuous records of past changes in atmospheric circulation and aridity in the region. Existing records indicate dramatic changes in North African dust emissions over the last 20 ka, but the limited spatial extent of these records and the lack of high-resolution flux data do not allow us to determine whether changes in dust deposition occurred with similar timing, magnitude and abruptness throughout northwest Africa. Here we present new records from a meridional transect of cores stretching from 31°N to 19°N along the northwest African margin. By combining grain size endmember modeling with ^{230}Th-normalized fluxes for the first time, we are able to document spatial and temporal changes in dust deposition under the North African dust plume throughout the last 20 ka. Our results provide quantitative estimates of the magnitude of dust flux changes associated with Heinrich Stadial 1, the Younger Dryas, and the African Humid Period (AHP; ~11.7–5 ka), offering robust targets for model-based estimates of the climatic and biogeochemical impacts of past changes in North African dust emissions. Our data suggest that dust fluxes between 8 and 6 ka were a factor of ~5 lower than average fluxes during the last 2 ka. Using a simple model to estimate the effects of bioturbation on dust input signals, we find that our data are consistent with abrupt, synchronous changes in dust fluxes in all cores at the beginning and end of the AHP. The mean ages of these transitions are 11.8 ± 0.2 ka (1σ) and 4.9 ± 0.2 ka, respectively.

1. Introduction

North Africa is the world's largest source of mineral dust to the atmosphere, emitting hundreds of Tg (10^{12} g) of dust per year (Goudie and Middleton, 2001; Engelstaedter et al., 2006; Ridley et al., 2012). Historical dust emissions from the region appear to sensitively track variations in continental aridity and atmospheric circulation (Prospero and Lamb, 2003; Chiapello et al., 2005; Mukhopadhyay and Kreycik, 2008; Doherty et al., 2012). An estimated 250 Tg of dust per year is transported over the tropical North Atlantic Ocean (TNA) (Ridley et al., 2012), with substantial impacts on precipitation (Miller et al., 2004; Yoshioka et al., 2007), sea surface temperatures (SSTs) (Evan et al., 2009, 2011) and marine biological productivity (Moore et al., 2009). North African dust may also have far-ranging impacts on precipitation and radiation balance by providing condensation nuclei for ice clouds (DeMott et al., 1993).

Records of North African dust emissions over the last 20 ka highlight the sensitivity of North African climate to both local summer insolation and high-latitude conditions (deMenocal et al., 2000; Adkins et al., 2006; Tjallingii et al., 2008; Mulitza et al., 2008). Two periods of cold North Atlantic SSTs – Heinrich Stadial 1 and the Younger Dryas (Bard et al., 2000; Shakun et al., 2012) – are marked by maximum dust concentrations in offshore sediments (Tjallingii et al., 2008; Mulitza et al., 2008). The early Holocene African Humid Period (AHP; ~11.7–5 ka), a time of high local summer insolation and warm North Atlantic SSTs, is marked by low dust deposition, consistent with records indicating lake expansions and a northward expansion of Sahelian vegetation at this time (Hoelzmann et al., 1998; Gasse, 2000). At the end of the AHP, Ocean Drilling Program (ODP) Site 658C records a doubling of dust fluxes over at most several centuries, followed by a gradual rise in dust fluxes over the last 5 ka paralleling the decline in summer insolation (Adkins et al., 2006).

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Several studies have reconstructed the relative abundance of dust in African margin sediments using endmember modeling of geochemical, grain size or magnetic data (Tjallingii et al., 2008; Mulitza et al., 2008; Itambi et al., 2009). Though these studies corroborate many findings from ODP Site 658C, they suggest that terrigenous sediments in the region are derived from both eolian and hemipelagic sources (Holz et al., 2004; Tjallingii et al., 2008; Mulitza et al., 2008); as a result, the record of total terrigenous flux from ODP Site 685C may overestimate eolian fluxes and underestimate the amplitude of changes in eolian fluxes due to hemipelagic inputs. Significantly, endmember modeling studies also suggest a gradual end to the AHP, raising the question of whether ODP Site 658C is representative of other regions of North Africa.

Here we present records of eolian and hemipelagic sediment fluxes over the last 20 ka from five sediment cores forming a meridional transect between 31°N and 19°N along the northwest African margin. This study provides the first records from the region that separate eolian and hemipelagic sediment fluxes using a combination of grain size endmember modeling and ^{230}Th-normalization. These records offer new estimates of changes in dust flux associated with deglacial climate changes, the AHP and Late Holocene drying. Carbonate records from these five cores and four additional cores provide a further test of the spatial coherence of past dust flux changes. We model the impact of bioturbation on our records to determine whether dust flux changes occurred with similar abruptness and timing throughout the North African dust plume and to provide age estimates for dust flux changes at the ends of the Younger Dryas and the AHP. Our quantitative estimates of dust fluxes offer targets for models of past dust emissions and efforts to quantify dust-related climate and biogeochemical impacts associated with the LGM, Heinrich events, and the AHP.

2. Regional setting

North Africa produces mineral dust throughout the year, with high emissions in boreal winter, spring and summer and a minimum in fall (Engelstaedter et al., 2006; Ridley et al., 2012). Satellite estimates of aerosol optical depth (AOD) highlight two main source regions in the Sahara – one in the Bodélé depression of Niger and Chad, the other in western Mauritania and eastern Mali – as well as a number of smaller sources (Fig. 1) (Prospero et al., 2002). Dust is mobilized by a variety of meteorological conditions, including cold air outbreaks from higher latitudes, surface trade winds (Harmattan), and downward mixing from low level jets in winter, and convective outflows in summer (Chiapello et al., 1995; Engelstaedter et al., 2006; Warren et al., 2007; Williams, 2008; Schepanski et al., 2009; Ridley et al., 2012). In the winter and spring, dust tends to be transported at altitudes below 2 km toward the southwest within the trade winds, while in the summer dust travels west at altitudes of 3–5 km in association with easterly waves (Chiapello et al., 1995; Engelstaedter et al., 2006; Huang et al., 2010; Ridley et al., 2012).

Measurements of near-surface airborne dust concentrations (Chiapello et al., 1995) and lithogenic fluxes in sediment traps (Neuer et al., 1997; Ratmeyer et al., 1999; Bory and Newton, 2000) indicate a peak in dust deposition along the northwest African margin in winter and early spring. Airborne dust (Stuut et al., 2005) and dust collected in sediment traps (Ratmeyer et al., 1999) in this region is relatively coarse, with modal grain sizes typically $> 10\ \mu$m, suggesting proximal sources. Extensive dune fields near the coast, in particular in western Mauritania and northern Senegal near our southern sites, likely serve as sources of coarse dust (Lancaster et al., 2002). Though dust fluxes at our core sites may primarily reflect winter deposition from local sources, reconstructed dust fluxes at Cape Verde are strongly correlated both with boundary layer dust concentrations near Barbados (representative of the summer dust plume) and with satellite estimates of mean annual dust optical depth over the TNA (Mukhopadhyay and Kreycik, 2008; Evan and Mukhopadhyay, 2010). These findings suggest that dust fluxes along the northwest African margin are plausibly representative of North African dust emissions over the TNA.

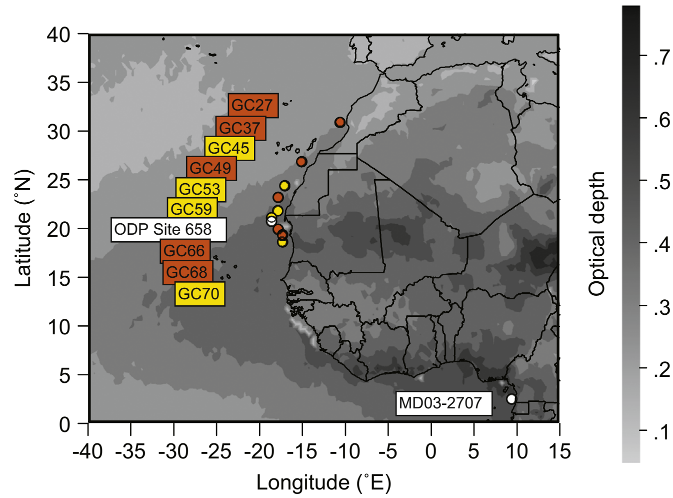

Fig. 1. Map of core sites and satellite-derived aerosol optical depth (AOD) at 555 nm for 2001–2007. Grain size, U–Th and carbonate data were collected for cores shown in orange; only carbonate data has been collected for cores shown in yellow. Shown in white are the locations of ODP Site 658 (deMenocal et al., 2000; Adkins et al., 2006) and MD03-2707 (Weldeab et al., 2007). The location for GeoB7920-2 (Tjallingii et al., 2008) is the same as that for ODP Site 658. AOD data are from the MISR satellite and were retrieved from the Giovanni online data system, developed and maintained by the NASA GES DISC. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Observational records of African dust emissions show strong interannual- to decadal-scale variability, with dust concentrations in Barbados air and dust fluxes reconstructed from a Cape Verde coral each rising by a factor of ~4 from the late 1950s to the early 1980s (Prospero and Lamb, 2003; Mukhopadhyay and Kreycik, 2008). Recent work finds that variations in winter dust emissions are best correlated with the position of the ITCZ over North Africa, with a southerly position associated with increased surface winds over central and western North Africa (Doherty et al., 2012). Precipitation appears to play a relatively minor role in modern interannual variability (Doherty et al., 2012), consistent with the fact that Saharan source areas are perennially dry (Engelstaedter and Washington, 2007a).

Sediments off the northwest African margin show the imprint of the region's dust emissions. The lithogenic fraction of sediments matches the Sr and Nd isotope composition of dust source regions in Mauritania, Mali, southern Algeria and Morocco (Grousset et al., 1998; Meyer et al., 2011), regions identified as dominant sources of modern dust transport to the region (Skonieczny et al., 2011; 2013). The quartz content and silt content of northeast tropical Atlantic sediments mimics the shape of the modern dust plume (Kolla et al., 1979; Sarnthein et al., 1981; Holz et al., 2004). Provenance data suggest that the orientation and sources of the dust plume have remained roughly constant over the last 25 ka (Sarnthein et al., 1981; Grousset et al., 1998; Cole et al., 2009).

3. Core descriptions and chronologies

The gravity cores used in this study were taken by the R/V Oceanus during the 2007 Changing Holocene Environments in the