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Millennial-scale variations in dustiness recorded in Mid-Atlantic sediments from 0 to 70 ka

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ABSTRACT

Sedimentary records of dust deposition in the subtropical Atlantic provide important constraints on millennial- and orbital-scale variability in atmospheric circulation and North African aridity. Constant flux proxies, such as extraterrestrial helium-3, yield dust flux records that are independent of the biases caused by lateral sediment transport and limited resolution that may be associated with age-model-derived mass accumulation rates. However, Atlantic dust records constrained using constant flux proxies are sparsely distributed and generally limited to the past 20 ka. Here we extend the Atlantic record of North African dust deposition to 70 ka using extraterrestrial helium-3 and measurements of titanium, thorium, and terrigenous helium-4 in two sediment cores collected at 26°N and 29°N on the Mid-Atlantic Ridge and compare results to model estimates for dust deposition in the subtropical North Atlantic. Dust proxy fluxes between 26°N and 29°N are well correlated, despite variability in lateral sediment transport, and underscore the utility of extraterrestrial helium-3 for constraining millennial-scale variability in dust deposition. Similarities between Mid-Atlantic dust flux trends and those observed along the Northwest African margin corroborate previous interpretations of dust flux variability over the past 20 ka and suggest that long distance transport and depositional processes do not overly obscure the signal of North African dust emissions. The 70 ka Mid-Atlantic record reveals a slight increase in North African dustiness from Marine Isotope Stage 4 through the Last Glacial Maximum and a dramatic decrease in dustiness associated with the African Humid Period. On the millennial-scale, the new records exhibit brief dust maxima coincident with North Atlantic cold periods such as the Younger Dryas, and multiple Heinrich Stadials. The correlation between Mid-Atlantic dust fluxes and previous constraints on North African aridity is high. However, precipitation exerts less control on dust flux variability prior to the African Humid Period, when wind variability governs dust emissions from consistently dry dust source regions. Thus, the Mid-Atlantic dust record supports the hypothesis that both aridity and wind strength drive dust flux variability across changing climatic conditions.

1. Introduction

Aeolian dust is an influential component of the climate system due to its radiative effects (Miller and Tegen, 1998; Rosenfeld et al., 2001) and the nutritional boon it brings to otherwise limited ecosystems (Bristow et al., 2010; Jickells et al., 2005; Martin, 1990). Constraints on variable dust emissions through changing climatic regimes are essential to understand the past and to forecast future scenarios (Albani et al., 2015, 2016; Evan et al., 2016; Mahowald et al., 2009, 2006; Pausata et al., 2016). The Sahel and Sahara regions of North Africa provide the largest contribution to modern global dust emissions (Goudie and Middleton, 2001; Prospero et al., 2002) and generate dust plumes that influence African and Atlantic surface temperatures, precipitation, and tropical cyclone development (Booth et al., 2012; Dunion and Velden, 2004; Evan et al., 2011).

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Twentieth century records of Atlantic dustiness demonstrate a strong correlation between decreased North African rainfall and increased dust emissions on inter-annual timescales (Chiapello et al., 2005; Mukhopadhyay and Kreycik, 2008; Prospero and Lamb, 2003). Wind strength, however, also influences dustiness and recent studies suggest that wind strength, rather than aridity, is the primary driver of inter-annual variability in North African dust emissions (Ridley et al., 2014; Rodríguez et al., 2015). On millennial and orbital timescales, significant restructuring of atmospheric circulation may alter the relative importance of wind strength versus aridity in driving dust emissions. Separating these two effects, however, has been difficult because there are few records (Adkins et al., 2006; Bradtmiller et al., 2007; McGee et al., 2013; Tjallingii et al., 2008; Williams et al., 2016) that constrain North African dust deposition with sufficient resolution to evaluate the changing distribution and drivers of emissions associated with millennial-scale climatic oscillations.

Marine sedimentary records of dust deposition can constrain climatic variability in continental aridity, wind strength, and the spatial pattern of atmospheric circulation (Grousset et al., 1998; Kohfeld and Harrison, 2001; McGee et al., 2010a; Parker et al., 2016; Rea, 1994; Ruddiman, 1997; Werner et al., 2002; Winckler et al., 2008). Sedimentary dust records, however, have often been calculated using mass accumulation rates estimated from the sediment core age-model and dry bulk density (Adkins et al., 2006; deMenocal et al., 2000; Ruddiman, 1997). Such accumulation estimates are limited to the temporal resolution of the age-model and typically assume constant sedimentation rates between chronostratigraphic tie-points. Age-model-derived fluxes are additionally subject to biases introduced by lateral sediment transport. These biases complicate the interpretation of age-model-derived records because the magnitude of sediment winnowing or focusing at a given location can vary across climatic cycles (Suman and Bacon, 1989; Costa and McManus, 2017; Higgins et al., 2002; Marcantonio et al., 1996).

In contrast, constant flux proxies, such as excess thorium-230 (Bacon, 1984; Francois et al., 2004; Marcantonio et al., 2001a) and extraterrestrial helium-3 ($^3He_{ET}$; McGee and Mukhopadhyay, 2013), can be used to constrain vertical sediment rain rates that are independent of age-model tie-points and lateral sediment transport. The increased resolution of dust records determined using constant flux proxies permits improved quantification and evaluation of dust flux variability. However, existing records of North African dustiness constrained using constant flux proxies are sparse and limited to the past 20 ka (Adkins et al., 2006; Bradtmiller et al., 2007; McGee et al., 2013; Williams et al., 2016). These records indicate a broad mid-Holocene dust flux minimum (∼5 to 11 ka) in the equatorial Atlantic, the western tropical Atlantic, and along the Northwest African margin, that is coincident with the African Humid Period. On millennial timescales, however, there is less agreement. Dust maxima are observed along the continental margin during the Younger Dryas and Heinrich 1 (McGee et al., 2013), yet the far-field records from the equatorial Atlantic and the Bahamas exhibit a singular early Holocene peak (Bradtmiller et al., 2007; Williams et al., 2016). Increased Atlantic coverage is essential to determine if such far-field locations provide clear records of continental dust generation or if they are affected by long distance transport and depositional processes. Furthermore, new and longer records improve constraints on African emissions in global dust cycle models (Albani et al., 2015, 2016; Mahowald et al., 2009) and are required to determine whether the past 20 ka are representative of typical dust flux variability prior to the Last Glacial Maximum.

Here we present new records of dust flux from two subtropical North Atlantic sediment cores collected at 26°N and 29°N on the Mid-Atlantic Ridge. Dust fluxes are determined from analyses of terrigenous helium-4 using extraterrestrial helium-3 as a constant flux proxy. Flux records of common thorium-232 and titanium are additionally examined to evaluate reproducibility between dust proxies in the Mid-Atlantic sediments. The new data extend the subtropical North Atlantic dust record to 70 ka and allow for evaluation of orbital- and millennial-scale variations in dust generation and long-distance transport through the last glacial period.

2. Geochemical background

2.1. Dust proxies

Marine sediments include biogenic, authigenic, and lithogenic inputs. Thorium-232 (common Th), terrigenous helium-4 ($^4He_{terr}$), and titanium have all been used to constrain the lithogenic component of marine sediments due to relatively high concentrations of these tracers in continental crust (Marcantonio et al., 2001a; Mukhopadhyay and Kreycik, 2008; Murray et al., 2000; Patterson et al., 1999; Winckler et al., 2005). Thorium and $^4He_{terr}$ are distinctly advantageous as dust proxies because sedimentary concentrations of Th and $^4He_{terr}$ are less sensitive than Ti to the presence of volcanic inputs (Gale et al., 2013; Graham, 2002; Patterson et al., 1999). Consequently, Th and $^4He_{terr}$ have been increasingly utilized in combination with the excess ^{230}Th and extraterrestrial ^3He constant flux proxies to constrain aeolian dust fluxes (Adkins et al., 2006; Anderson et al., 2006; Kienast et al., 2016; Marcantonio et al., 2001a; Serno et al., 2014; Winckler et al., 2005, 2008).

Ideally, the conversion of sedimentary Th or $^4He_{terr}$ concentrations into absolute dust concentrations would be based on tightly constrained values of Th or $^4He_{terr}$ in the dust endmember. However, $^4He_{terr}$ concentrations of North African dust sources are seldom measured (McGee et al., 2016; Mukhopadhyay and Kreycik, 2008) and dust concentrations of $^4He_{terr}$, Th, and Ti are each known to vary with grain size and among source regions (Castillo et al., 2008; McGee et al., 2016). Thus, absolute concentrations of sedimentary dust are difficult to constrain from analysis of a single lithogenic proxy. We examine $^4He_{terr}$, Th, and Ti fluxes in the Mid-Atlantic sediments to evaluate the sensitivity of proxy-based dust records to each element of interest.

2.2. Extraterrestrial helium-3 as a constant flux proxy

Helium-4 accumulates in marine sediments primarily via the delivery of terrigenous dust, whereas ^3He is primarily delivered to the seafloor via interplanetary dust particles (IDPs; Farley, 1995; Nier and Schlutter, 1992; Takayanagi and Ozima, 1987). Sediment concentrations of extraterrestrial ^3He ($^3He_{ET}$) are determined by correcting total ^3He for its small terrigenous contribution (see Section 3.3). Previous work has shown that $^3He_{ET}$ can be utilized as a constant flux proxy to calculate vertical sediment rain rates throughout much of the Cenozoic (Farley and Eltgroth, 2003; Farley, 1995; Marcantonio et al., 2001b, 1995; Mukhopadhyay et al., 2001; Winckler et al., 2005). The term 'rain rate' refers to the vertical sediment flux as distinct from the traditional mass accumulation rate that may reflect the addition or subtraction of laterally advected material.

When the influx of IDP $^3He_{ET}$ from space (f) is known, the vertical sediment rain rate (Φ_{sed}) can be determined through the relationship:

$$\Phi_{sed} = \frac{fR}{[^3He_{ET}]} \quad (1)$$

where R is the fraction of deposited He retained within the sediments (Farley, 1995). Observations of $^3He_{ET}$ retention in ∼480 Ma limestones suggest negligible variations in R over relatively short