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Helium and thorium isotope constraints on African dust transport to the Bahamas over recent millennia

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ABSTRACT

Despite its potential linkages with North Atlantic climate, the variability in Saharan dust transport to the western North Atlantic over the past two millennia has not been well-characterized. A factor of 4 increase in dust production in sub-Saharan Africa has been attributed to the onset of Sahelian agriculture 200 yr ago. The regional extent of this anthropogenic dust increase, however, remains uncertain. Additionally, while millennial-scale cold periods of the last deglaciation have been associated with strong increases in North African dust emissions, few adequate records exist to observe dustiness during the Little Ice Age, a century-scale cooling of the North Atlantic (AD 1400–1800). In this study, we develop a new technique for the paired use of ^{230}Th-normalized ^{232}Th fluxes and ^{3}He-normalized ^{4}He fluxes in Bahamian tidal flat sediments. After justifying the fact that ^{230}Th and ^{3}He have had relatively constant sources to tidal flat and banktop waters, and accounting for the smoothing effect of bioturbation, a factor of 4 change in far-field dust transport to the western North Atlantic between the pre-industrial and modern era is not supported by our dust proxies over the past 2000 yr. Furthermore, we speculate why the response of western North Atlantic dust deposition associated with the Little Ice Age climate anomalies may have been modest compared to prior climatic events of the early Holocene or the last deglaciation.

1. Introduction

Aerosols constitute one of the largest uncertainties in global climate models, and mineral dust makes up roughly 70% of the global aerosol burden by mass (Tsigaridis et al., 2006). Predictions of future climate scenarios disagree in the magnitude and sign of changes in mineral dust deposition. Thus, we are motivated to provide observational records of dust deposition during past climatic changes to test and refine models of future change. Constraints on dust loads during the last two millennia are particularly lacking, leading to uncertainty as to anthropogenic impacts on dust emissions and aerosol loading used in simulations of preindustrial and last-millennium climate. Because the Sahara is the world's largest source of mineral dust, the North Atlantic Ocean has been a focus of dust time-series investigations. Dust flux has been reconstructed at millennial resolution using deep sea sediments, in particular over the Holocene (Albani et al., 2015, and the references therein). Methods that provide annual-to-sub-annual resolution cover at most the past 5 or 6 decades, such as direct aerosol collection (Prospero and Lamb, 2003), corals (Mukhopadhyay and Kreycik, 2008) or satellite optical depth (Evan et al., 2011). In this study, we seek to fill this temporal gap between the instrumental period and the late Holocene using sedimentary records from a Bahamian tidal flat.

A Mauritanian shelf sediment core (Mulitza et al., 2010) demonstrates a factor of four increase in eolian dust deposition beginning at the intensification of agriculture in the Sahel 200 yr ago. The inference of anthropogenic influence is consistent with concurrent observations of deforestation over the past 50 yr and increased land use concurrent with increases in dust production in the Senegal River basin (Niang et al., 2008). Based in part on this study, some models assume that preindustrial dust loading was only 50% of modern dust loading (e.g., Albani et al., 2014). However, anthropogenic dust emissions from North Africa, coming largely from the Sahel, account for only 15% of total North African dust emissions, which are dominated by natural emissions from

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the Sahara (Ginoux et al., 2012). Additionally, much of the anthropogenic increase seen on the Mauritanian shelf was due to dust of large grain-size (>10 μm) (Mulitza et al., 2010). Only very fine dust (<5 μm) is exported out into the western Atlantic (Muhs et al., 2007; Reid et al., 2003). Furthermore, a model reanalysis suggests that dust optical depth over the North Atlantic was close to its present value in AD 1850 (Evan et al., 2016) and a study in the Everglades of South Florida found no change in the concentration of quartz grains, taken to represent Saharan dust, over the past 2800 yr (Glaser et al., 2013).

There is a seasonal aspect for expecting dust deposition very close to the source to differ from that in the far-field North Atlantic. The Bahamas area receives Saharan dust predominantly in summer (Prospero, 1999) due to the seasonal movement of the Intertropical Convergence Zone (ITCZ). In summer, the northward excursion of the trade winds at the northern boundary of the ITCZ acts to both increase Saharan dust emissions as well as to facilitate trans-Atlantic dust transport to more northerly (20–30°N) destinations (Rodríguez et al., 2015). In contrast, in winter with the ITCZ further south, total African dust emissions are reduced and eastward dust transport occurs mostly at latitudes south of 15°N. For these reasons, we expect the modern increase in Sahel dust production was not representative of changes in the Bahamas and the western North Atlantic region.

On longer timescales, millennial variations in North Atlantic dust deposition have been documented back through the last ice age. Records of Holocene and last glacial variability in Saharan dust has been limited mostly to deep ocean sedimentary records. Periods of pronounced (several degrees Celsius) cooling in the North Atlantic region, such as Heinrich Stadial 1 (15–18 ka) and the Younger Dryas (12–13 ka), have been associated with increases in African dust emissions to roughly 2–3 times modern levels (McGee et al., 2013, and the references therein). Furthermore, the Early Holocene African Humid Period (5–11.7 ka) has been characterized by dust fluxes on the West African margin that were a factor of 2–5 lower than modern (McGee et al., 2013). Since the end of the African Humid Period, there is evidence for a further, gradual aridification of tropical Africa over the past 3000 yr from the Mauritanian shelf dust record (Mulitza et al., 2010), continental precipitation records (Shanahan et al., 2015), and reduced Niger river outflow (Weldeab et al., 2007).

A general mechanism has been proposed for these variations, applicable to modern inter-annual variability as well, involving the meridional sea-surface temperature and/or pressure gradients in the Atlantic and the position of the ITCZ over the African continent (e.g., Evan et al., 2011; Rodríguez et al., 2015). The present Andros Island records offer an opportunity to test the coherence of African dust and North Atlantic climate over the Little Ice Age. This period (roughly 1400 to 1800 AD) has been characterized by a modest cooling (~0.5 °C) found most strikingly in the extratropical Northern Hemisphere continents (Mann et al., 2009).

2. Approach

Our approach to reconstructing dust input here is geochemical. Thorium and helium share a unique property in that both elements have a dominant isotope (^{232}Th and ^{4}He) associated with aerosol mineral dust and a minor isotope (^{230}Th and ^{3}He) that has a relatively constant source to the ocean. In the case of ^{230}Th, the current study is a novel application in that normally the use of sedimentary ^{230}Th as a normalizing factor is restricted to ocean water depths in excess of a few hundred meters, where a large, predictable inventory of ^{230}Th, scavenged from water column decay of ^{234}U, has developed. On the tidal flat, in shallow water (<1 m), or even on a tidal channel level crest above mean tide level, the source of ^{230}Th in the sediments is likely dominated by release from banktop pore waters (Robinson et al., 2004), as described later in this section. In the case of ^{3}He, the dominant source is atmospheric deposition of interplanetary dust particles highly enriched in ^{3}He. This extraterrestrial ^{3}He supply has had indistinguishable and constant rates in equatorial deep-sea sediments and polar ice caps over the Late Quaternary (McGee and Mukhopadhyay, 2013, and the references therein), supporting the expectation of constant supply to this shallow water setting.

In the Triple Goose Creek area of Andros Island (Fig. 1), we have cored within a well-studied system of beach ridges, tidal channels, levee crests and mangrove ponds abutting an inland algal marsh (Hardie, 1977; Maloof and Grotzinger, 2012; Shinn et al., 1969). The carbonate particles accumulating here are primarily derived from aragonite-producing marine algae on the Great Bahama Bank and subsequently are washed inshore by tides. The levees are built up by overbank flooding and the low ponds are normally flooded twice daily by tides with a range of roughly 40 cm (Hardie, 1977). The dust concentrations recorded in these accumulating sediments therefore reflect the interplay of dust deposited from the local atmosphere, dilution by the dominant carbonate sediments, and dust swept in by the tides from the shallow (~3 m water depth) Great Bahama Bank.

Our goal is to reconstruct atmospheric deposition from the bulk sediment record. Therefore, we need a way to correct for temporal variations in carbonate dilution and lateral addition of dust. Fortunately, any ^{232}Th and ^{4}He supplied to a core site laterally from the bank top should also be accompanied by a proportional amount of ^{230}Th and ^{3}He. This is an assumption that deserves critical evaluation, which we present in the following paragraphs of this section. Less controversially, dilution will affect all these isotopes equally. Thus, the two ratios ^{232}Th/^{230}Th and ^{4}He/^{3}He provide proxies of atmospheric dust input that account for possible changes in lateral addition with time. The lateral addition of sediments is termed sediment focusing, and the magnitude of sediment focusing can be expressed as a focusing factor (F): the ratio of the total accumulation rate of the isotope in question to its local production, or deposition, rate.

In the case of ^{230}Th, its production in water over the Great Bahama Bank consists of two sources. The first is the strictly known production from the decay of dissolved ^{234}U in seawater. As mentioned, in the deep ocean this source predominates, but in such a shallow setting as the tidal flat, another source is likely to be much larger. This second source is release of ^{230}Th from sediment porewaters derived from ^{234}U decay within the high U (~3 ppm, Fig. 2) aragonite sediments and supplied to porewaters by recoil associated with alpha decay. Robinson et al. (2004) found evidence for this benthic source in that banktop water had much higher ^{230}Th content than at similar depths in the surrounding deep ocean. Using a box-model approach with reasonable assumptions, these authors determined the ^{230}Th supply from the sediments to the overlying water could easily be 30 times the in-situ production in the water column above the bank. There have been no independent determinations of this flux. Without precisely knowing the benthic supply of ^{230}Th, we cannot make quantitative estimates of sedimentary fluxes as is done using ^{230}Th-normalization in deep ocean studies (Francois et al., 2004). Nonetheless, we do expect the benthic ^{230}Th flux to be constant over the timescales considered in this study. Our justification of this expectation is as follows. The uranium content of the banktop sediments is largely set by its authigenic incorporation into aragonite. This is a factor that is not likely to change on a millennial timescale. Additionally, variability in the processes that lead to pore water release of ^{230}Th, such as sediment resuspension and hydraulic flow within the porous Great Bahama Bank, is likely controlled by stochastic physical forces. Again, at least on centennial- to millennial-timescales, in the absence of evidence for changes in the long-term averages of these