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Dust generation and drought patterns in Africa from helium-4 in a modern Cape Verde coral

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[1] We show that helium-4 (^{4}He) concentrations in a modern *Porites* coral from Cape Verde provides a robust reconstruction of mineral dust loading over the Eastern Tropical Atlantic from mid-1950's to mid-1990's. The ^{4}He record demonstrates pronounced increases in dust emission from North Africa associated with the severe droughts in the Sahel. Our record provides direct evidence that dust emission rates in the 1950's, prior to the onset of the Sahel droughts, were a factor of nine lower than during 1980–84. This large change in dust emission rate indicates global aerosol contents would have increased by ~45% over this period, which may have contributed to a reduction in solar radiation reaching the Earth's surface. We find that dust emission from North Africa is most closely related to drought patterns, rather than to changes in atmospheric circulation patterns resulting from climate oscillations, such as North Atlantic Oscillations and El Nino/Southern Oscillation. **Citation:** Mukhopadhyay, S., and P. Kreycik (2008), Dust generation and drought patterns in Africa from helium-4 in a modern Cape Verde coral, *Geophys. Res. Lett.*, *35*, L20820, doi:10.1029/2008GL035722.

1. Introduction

[2] The progressive drying of the Sahel from 1960s to early 1990s has had devastating social, economic, and environmental consequences. An environmental consequence of the droughts in the Sudano-Sahel region is enhanced mineral dust loads in the atmosphere [*N'Tchayi Mbourou et al.*, 1997; *Prospero and Lamb*, 2003; *Chiapello et al.*, 2005]. The dust mobilized in the Sahara and Sahel regions of Africa can affect precipitation in the Sahel [*Rosenfeld et al.*, 2001], nutrient cycling in the Amazon [*Swap et al.*, 1992], Atlantic cyclogenesis [*Evan et al.*, 2006], and regional air quality in the Caribbean and southeast USA [*Prospero and Lamb*, 2003]. Clearly, variability in dust emission in the Sahara-Sahel region can have important environmental consequences. Current climate models suggest anywhere from a 60% decrease [*Mahowald and Luo*, 2003] to a 10% increase in dust emission rates [*Tegen and Fung*, 1995] from the Sahara-Sahel region over the next century. Hence, both the predicted sign and magnitude of dust flux variations remain model dependent. A long-term dust emission record, close to dust sources in Africa, would be valuable for understanding the controls on North African dust emission rates and for benchmarking climate models that seek to predict future dust emission rates.

[3] Since 1979, satellites have monitored dust emission from North Africa. These records indicate that Sahel drought is a strong control on dust export to the Atlantic, particularly during the summer months [e.g., *Chiapello et al.*, 2005]. Prior to the satellite record, the Barbados dust sampling station, operating since 1966, provides the only high-resolution record of dust emission from Northern Africa [*Prospero and Lamb*, 2003]. The atmospheric dust concentrations during the summer months at Barbados also show a strongly negative correlation with Sahel rainfall [*Prospero and Lamb*, 2003]. However, African dust reaches Barbados primarily during the summer months, while approximately half of the dust export from Northern Africa occurs during the winter months [*Ginoux et al.*, 2004]. Additionally, dust transport and dust depositional processes may have influenced some of the variability seen in the Barbados dust record [*Prospero and Lamb*, 2003; *Mahowald et al.*, 2005]. Here we use a new technique to reconstruct annual dust emission rates from North Africa during the 2nd half of the 20th century from a site close to the sources of dust. Our technique utilizes a *Porites* coral as a high-resolution dust archive and helium-4 (^{4}He) to trace the total amount of mineral dust trapped in the coral skeleton. ^{4}He is produced by radioactive decay of U and Th and is, therefore, highly enriched in dust derived from continental crust. ^{4}He is not adsorbed onto mineral surfaces, scavenged by particles, or incorporated into biogenic phases. As a result, the ^{4}He concentration will be directly proportional to the amount of mineral dust. The utility of ^{4}He as an excellent proxy of mineral dust has been demonstrated from studies in deep-sea sediments [*Patterson et al.*, 1999; *Mukhopadhyay et al.*, 2001; *Winckler et al.*, 2005].

2. Method

[4] We selected a *Porites* coral from the island of Sal, part of the Cape Verde archipelago, which lies beneath both summer and winter dust export trajectories from Northern Africa. Sal is approximately 600 km west of Senegal in the Atlantic Ocean and located close to, and directly west of, the dust sources in the Sudano-Sahel region. The *Porites* coral was collected near Pedra de Lume on Sal (16° 45′ 44″N and 22° 53′ 23″W) at a water depth of ~5m. The *Porites* coral provides an archive with annual resolution over the period 1955–1994. Sample powders were extracted from each annual band using a dremel tool. Following decarbonation of the coral skeleton matter, the residue was wrapped in tin foil cups and He was extracted by heating the sample at ~1400°C in a radiatively heated vacuum furnace. He was measured using a Nu Noblesses mass spectrometer using established protocols [*Gayer et al.*, 2008]. The ^{4}He flux was determined by multiplying the ^{4}He

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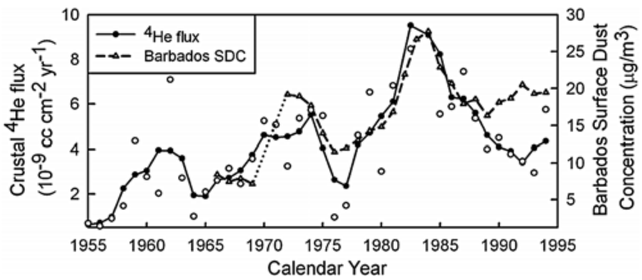

Figure 1. Crustal ^{4}He flux compared to the summer surface dust concentration (SDC) at Barbados. The summer SDC is from *Prospero and Lamb* [2003]. The dotted line indicates a break in the SDC record from 1970–71. ^{4}He in the *Porites* coral is derived from mineral dust (Crustal ^{4}He) and from interplanetary dust particles with high ^{3}He/^{4}He ratio. The crustal ^{4}He is dominantly >99% of the total ^{4}He and was deconvolved using the measured ^{3}He/^{4}He ratio [e.g., *Patterson et al.*, 1999]. The open symbols are ^{4}He flux for individual years. To reduce the effects of occasional sampling of rare large mineral dust particles, the ^{4}He flux was smoothed using a 3-year running mean. To directly compare the SDC record with the ^{4}He flux, the SDC signal was also smoothed with a 3-year running mean. Both the ^{4}He and SDC signals show a remarkable co-variation.

concentration per gram of $CaCO_3$ with the coral calcification rate (see auxiliary material[1] for details).

3. Results and Discussion

[5] Figure 1 shows the annual ^{4}He depositional flux from mineral dust, as reconstructed from the coral. There is a high-frequency scatter in the annual depositional flux, which is most likely a statistical artifact indicating that our measurements do not representatively sample the size distribution of dust grains in the coral. Such statistical artifacts are well documented in studies of extraterrestrial ^{3}He in deep-sea sediments, where a small number of interplanetary dust particles carry the ^{3}He signature [*Mukhopadhyay et al.*, 2001], leading to undersampling of rare large particles (see auxiliary material). In addition, some of the high frequency fluctuations may arise from sediment resuspension events and processes of sediment incorporation into the corals [*Barnard et al.*, 1974]. A 3-year running mean reduces the scatter and shows a remarkable similarity between the ^{4}He depositional flux and the surface dust concentration (SDC) record from Barbados [*Prospero and Lamb*, 2003]. For the period 1966 to 1994, both records show the same overall trends: ~2-fold increase in the baseline values, and two prominent peaks, one in the early 1970s and one in the early 1980s corresponding to severe droughts in the Sahel. The correlation between the summer SDC at Barbados and the ^{4}He-based proxy record is 0.81 (r = 0.73 for the unsmoothed time-series), significant at >99% confidence level (Table 1).

[6] The correlation between the ^{4}He record and Barbados SDC validates the use of corals as dust archives (Figure 1) and strongly suggests that the reconstructed depositional flux reflects variability in the total atmospheric dust loads, and not variability in the dust transport trajectories or depositional processes. This is further supported by the relationship between the ^{4}He flux and aerosol optical depth (AOD) over Cape Verde (Figure 2). AOD is a measure of the total column abundance of atmospheric aerosols. Coincident with the severe drought in the early 1980's in Sahel, both ^{4}He and AOD increase dramatically and then decrease during the late 1980's as drought conditions abate. During the early 1990's AOD values increase, reflecting increased atmospheric aerosol loading generated from oil fires in Iraq and Kuwait and the Mt. Pinatubo eruption [*Torres et al.*, 2002]. ^{4}He, however, is not sensitive to volcanic [*Patterson et al.*, 1999] or carbonaceous aerosols. Hence, the decline in ^{4}He flux reflects the decrease in dust emission rates from Africa. Overall, the relationship between AOD and ^{4}He flux lead us to conclude that mineral dust incorporation into the *Porites* coral is proportional to the column abundance of atmospheric dust.

[7] We estimate the total depositional flux of mineral dust at Cape Verde, averaged over the period 1955–1994, to be ~7.4 g m^{-2} yr^{-1}. The average depositional flux of mineral dust was 1.6 g cm^{-2} yr^{-1} in the mid-1950's (1955–1958), increased to 14.3 g cm^{-2} yr^{-1} between 1980–1984, and decreased to 7 g cm^{-2} yr^{-1} in the 1990's. These estimates are based on the ^{4}He flux determined from the coral and the average ^{4}He concentrations of 5.6 x 10^{-6} cc g^{-1} in terrigenous sediments derived from the sub-Saharan region of Northwest Africa that were deposited off Cape Blanc, Mauritania (ODP Site 658C; see auxiliary material). The ^{4}He-based reconstruction of mineral dust deposition rates are within the range of estimates of 3–50 g m^{-2} yr^{-1} around Cape Verde that are based on sediment trap data from 1992–1994 [*Ratmeyer et al.*, 1999; *Bory and Newton*, 2000] and model reconstructions [*Mahowald et al.*, 2005]. The relatively close agreement between our reconstruction of absolute rates of mineral dust deposition and estimates based on model reconstructions and sediment trap data suggests that the *Porites* coral rejects sedimentary particles inefficiently.

[8] The ^{4}He-based proxy record provides the first observations of atmospheric dust emission rates from North Africa during the 1950's, the wettest decade of the 20th

Table 1. Correlation Between ^{4}He Depositional Flux at Cape Verde and Climate Indices Over the Period 1955–1994[a]

	Smoothed Records	*Confidence Level*	*Unsmoothed Records*	*Confidence Level*
Barbados SDC	0.81	99.8	0.73	99.8
SSPI[b]–1 yr lag	−0.83	99.9	−0.66	99.9
SSPI	−0.82	99.9	−0.62	99.9
NINO3.4–1 yr lag[c]	0.40	98.5	0.32	99[d]
Winter NAO	0.44	86	0.30	87

[a]The NINO 3.4 is defined by *Trenberth* [1997], and the Winter NAO index is from *Hurrell et al.* [2001]. For all time series, confidence level for the correlation coefficients are calculated using the random phase method for serially correlated data (see auxiliary material).

[b]SSPI is the Sudano-Sahel precipitation index and is from *Prospero and Lamb* [2003].

[c]No correlation is observed between NINO3.4 and dust and from same year.

[d]The confidence level is higher than calculated from the t-test. This is because the power spectrums of the two time series are significantly different.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL035722.

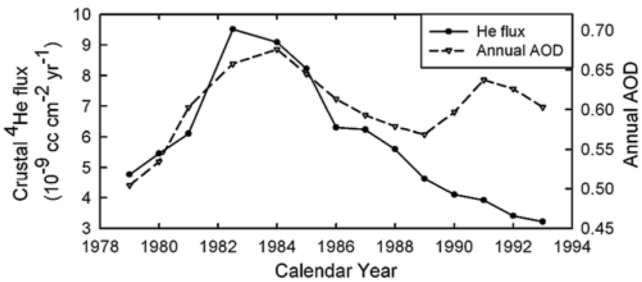

Figure 2. Comparison of ^{4}He flux with annual AOD over Cape Verde. Both the ^{4}He and AOD records were smoothed using a 3-year running mean. The AOD values were calculated from the TOMS data (http://toms.gsfc.nasa.gov/aerosols/aot.html). Only pixels with at least 5 days of observations in a month were included in the AOD calculations.

century in the Sahel. Dust emission rates from North Africa were ∼9 times lower in the mid-1950's (1955–58) than during 1980–84 (Figure 1). Mineral dust is the single largest component of atmospheric aerosols, accounting for ∼40–50% of the total budget, with ∼50% of mineral dust originating from the Sahara-Sahel region of Africa [*Cakmur et al.*, 2006]. Hence, the 9-fold increases in mineral dust emission from North Africa between the mid-1950's to mid-1980's suggests that global atmospheric aerosol loading increased by ∼45% over this period, even if we assume all other aerosol components to have remained relatively constant. By the early 1990's, global atmospheric dust loads would have returned to within 20% of the 1950's level.

[9] The large changes in mineral dust emission inferred from the ^{4}He record indicate that the arid and semi-arid regions of Northern Africa can dramatically alter the global aerosol budget over a relatively short period. While the climatic impacts of dust are not completely understood, the strongly reflecting Saharan mineral dust appears to have a net negative radiative forcing [*Myhre et al.*, 2003]. Hence, it is plausible that the increased atmospheric dust load from mid 1950's- to the 1980's may have contributed to a reduction in solar radiation reaching the Earth's surface [*Stanhill and Cohen*, 2001] and partially masked the magnitude of global temperature rise resulting from increased greenhouse gases in the atmosphere.

[10] The increase in mineral dust export from North Africa, related to the progressive drying of the Sahel, is observed in the summer SDC record at Barbados (Figure 1) [*Prospero and Lamb*, 2003]. However, changes in atmospheric circulation patterns associated with the Sahel rainfall anomalies could have influenced some of the variability in summer SDC at Barbados [*Prospero and Lamb*, 2003]. Indeed, major peaks in the Barbados SDC records are associated with major El Nino events [*Prospero and Lamb*, 2003]. Likewise, annual variability in dust transport to Barbados is affected by the migration of trade winds and the strength and position of the trade winds are in turn affected by NAO [e.g., *Ginoux et al.*, 2004]. Hence, although Barbados dust fluxes may be highly correlated with aridity in the Sahel, the correlation may arise in part from dust transport processes influenced by ENSO, NAO, and convective disturbances within the African easterly waves.

[11] The reconstructed mineral dust deposition rates from Cape Verde, a site close to the African continent, provides insight into whether the major trends seen in the atmospheric dust loads (Figure 1) are largely controlled by source region aridity, or result from changes in dust transport processes driven by ENSO and NAO. We find that the correlation between the ^{4}He-based record of dust from Cape Verde and climate oscillations, such as winter NAO and ENSO, to be weak (Table 1). NAO is supposed to influence winter dust export from Africa [e.g., *Ginoux et al.*, 2004; *Chiapello et al.*, 2005] and Sal does lie beneath the winter dust transport trajectories, as demonstrated by measured dust deposition rates near Cape Verde [e.g., *Ratmeyer et al.*, 1999; *Bory and Newton*, 2000]. Therefore, the weak correlation observed between the Cape Verde dust record and winter NAO is not an artifact of Cape Verde lying outside the realm of winter dust export pathways from North Africa. The reconstructed dust flux from Cape Verde, however, shows a strong negative correlation with rainfall in the Sudano-Sahel region (Figure 3 and Table 1). The ^{4}He-based proxy record of dust from the *Porites* coral shows the strongest negative correlations with rainfall patterns in the Sahel (Figure 3b), suggesting that the Sahel may be the dominant contributor to atmospheric dust loads over Cape Verde. Additionally, vegetation cover in the Sahel takes up to a year to recover following the return to more wet conditions [*Nicholson et al.*, 1998]. Hence, the one-year lag between dust emission rates and precipitation [*Prospero and Lamb*, 2003; *Chiapello et al.*, 2005] is consistent with soil desiccation and vegetation cover most strongly influencing the variability in dust export to the tropical Atlantic. As a result, while NAO and ENSO do probably affect dust mobilization, such as by influencing the strength and position of the trade winds, Sahel droughts appear to be a more direct link to variability in atmospheric dust loads over Cape Verde and Barbados.

4. Concluding Remarks

[12] In summary, our new technique can be used to reconstruct mineral dust emission rates and the *Porites* coral from Sal provides a high-resolution archive of the atmospheric dust loading over the Eastern Tropical Atlantic. The correlation between the dust records and Sahel rainfall (Figure 3), and the similarity between the Cape Verde and Barbados dust records, indicate that the observed variability in atmospheric dust loads are most closely related to the aridity of the dust source regions in North Africa. The strong coupling between atmospheric dust loads and the hydrologic cycle suggests that corals can be utilized to reconstruct past variations in the continental precipitation patterns to understand how future climate variability may affect the hydrologic cycle and dust mobilization. Combining modern coral reefs with fossil coral reefs can provide a near continuous high-resolution dust archive over at least the past 10,000–20,000 years. Such archives can be found in the Caribbean, South China Sea, Indian Ocean [e.g., *Guilderson et al.*, 1993; *Sun et al.*, 2005], regions downwind of the most important dust export

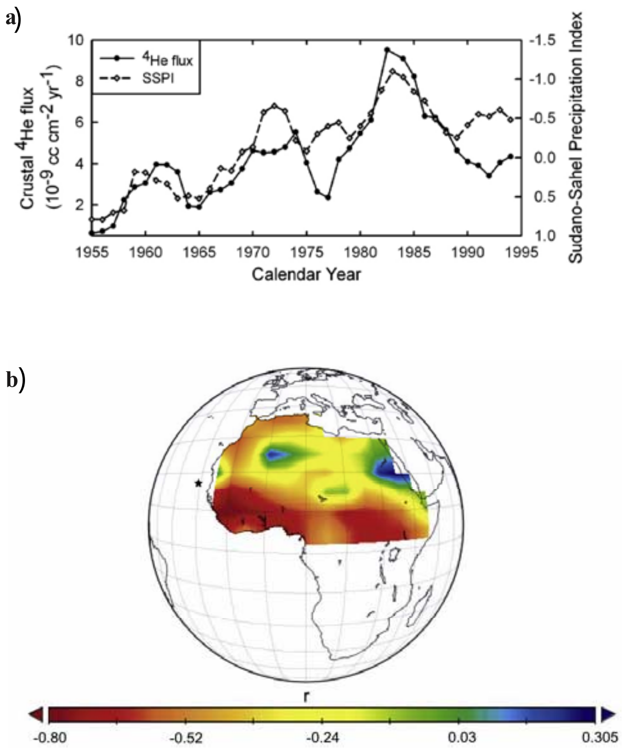

Figure 3. Relationship between the ^{4}He flux and precipitation. (a) Time-series of the crustal ^{4}He flux and the inverse of the Sudano-Sahel Precipitation Index (SSPI). SSPI is defined as the yearly averages of normalized April–October rainfall departures in the region between 11°N–18°N, expressed as standard deviations from the 1941–2001 mean. The SSPI values are from *Prospero and Lamb* [2003]. Negative SSPI values correspond to drier than average years. Both the He record and the SSPI were smoothed using a 3-year running mean. (b) Correlation between the ^{4}He-based proxy record of dust reconstructed from the Cape Verde *Porites* coral and previous year's precipitation in different regions of Northern Africa. The girded precipitation time series were obtained from the Global Historical Climatological Network. The star marks the location of the island of Sal.

trajectories from North Africa, East and Central Asian, and the Arabian Peninsular.

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