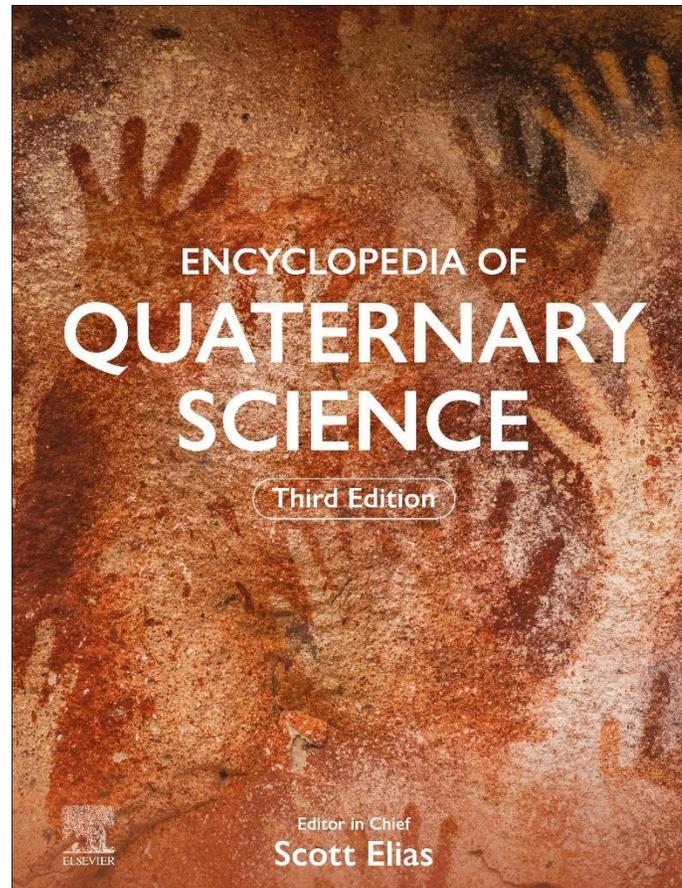


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## Subaquatic dust deposits

**J-BW Stuit<sup>a,b</sup> and APE van Boxtel<sup>a,c</sup>**, <sup>a</sup>NIOZ—Royal Netherlands Institute for Sea Research, Department of Ocean Systems, Texel, The Netherlands; <sup>b</sup>VU—Vrije Universiteit Amsterdam, Faculty of Science, Department of Earth Sciences, Amsterdam, The Netherlands; <sup>c</sup>Utrecht University, Department of Earth Sciences, Utrecht, The Netherlands

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### Abstract

Mineral dust deposited in lakes and the ocean are here termed subaquatic dust deposits. In this chapter, a state-of-the-art overview is given of these subaquatic dust deposits and their importance as archives of environmental change. Examples are given of present-day Saharan dust that is dispersed across and settling into the equatorial North Atlantic Ocean, and how its physical properties relate to the environmental conditions at which it was emitted and deposited. Subaquatic dust deposits that register environmental conditions under which these deposits came to be will be discussed as well as how these archives can be read to reconstruct paleo-environmental conditions in the dust source regions over millions of years. The most commonly applied tools (so-called proxies) as well as recently developed new proxies to reconstruct paleo-environmental changes from subaquatic deposits are presented and discussed. Ideally, subaquatic dust deposits are continuous through time, can be dated relatively easily, reflect total deposition of mineral-dust particles [including both *dry* –the result of gravity—and *wet* –the result of deposition with precipitation—deposition] and do not change with the elevation at which they are deposited and with time. The combination of these properties makes subaquatic dust archives a very valuable asset as a recorder of Quaternary environmental change and in our understanding of the Earth system.

### Keywords

Atmosphere; Climate; Deposition; Dust; Emission; Ocean; Paleoclimate; Proxy; Transport

### Glossary

**Aerosol** Any type of material blowing through the air in gas, liquid, or solid phase including mineral dust, salt, soot, ash, smoke, spray, and water vapor.

**Mineral dust** Clay-, Silt- and Sand-sized minerals that are emitted in dust-source areas, transported through the air, and deposited by gravity and rain or snow.

### Key points

- State-of-the-art aeolian-dust studies from a marine and lacustrine perspective
- Present-day monitoring of Saharan dust across the Atlantic Ocean
- Reconstructions of past aeolian dust deposition, related to paleo-environmental conditions in the dust source area(s)
- Overview of proxies for paleo-dust studies
- Significance of paleo-dust studies for global climate

## Introduction

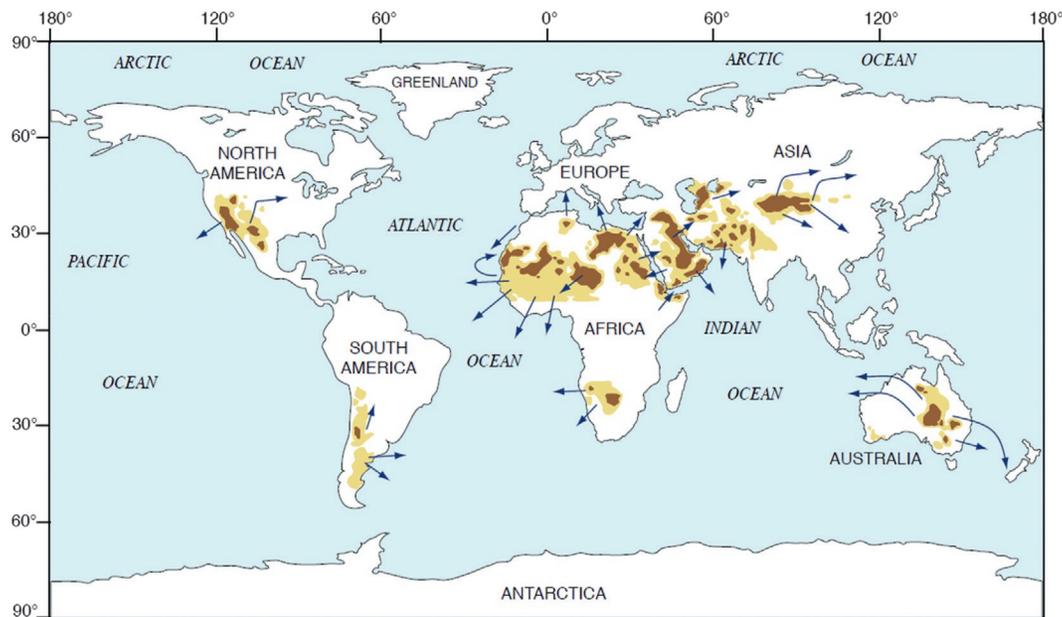
Charles Darwin is commonly considered the first scientist to report mineral dust blowing across the ocean, with his famous “account of the fine dust which often falls on vessels in the Atlantic Ocean” (Darwin, 1846). However, it was not until the mid-1960s that dust-sampling campaigns were set up in remote places such as the Isles of Scilly (UK) and in the Caribbean (e.g. Parkin and Hunter, 1962). By then, it was still thought that the dust particles that were collected were mostly of extra-terrestrial origin. Since the discovery that dust particles originating from northwest Africa can easily be transported across tens of thousands of kilometers through the atmosphere and be deposited far from their source(s) in the Caribbean, scientists have become aware of the importance of mineral dust as an initiator and driver of climate change.

In 1978 NASA launched the Earth Probe Satellite, including the TOMS – Total Ozone Mapping Spectrometer that was meant to measure the ozone layer but could also observe particles in the atmosphere. Using the TOMS, scientists for the first time could observe dust being emitted in desert areas and dispersed across large distances, mostly over the ocean. In addition, longer-term studies of satellite images led to the identification of dust-source areas and their (seasonal) variability.

When studying the global distribution of dust source areas and the dispersal of their emitted dust by the general global wind systems (Fig. 1, after Muhs et al., 2014), it directly comes to mind that most of this material is blown ‘out to sea,’ where it can be deposited through time. Fig. 1 shows that most of the dust-source areas are in the mid-latitude deserts, which are related to the descending air from the Hadley Cell and that dust is blown mainly: (1) offshore to the West, North and East of northern Africa into the Atlantic, Mediterranean, and Indian Oceans, respectively; (2) to the East offshore the major Asian deserts as well as to the West offshore the north American deserts into the North Pacific; (3) to the northwest and southeast of Australia into the Indian and southwest Pacific Oceans, respectively, (4) and to the East offshore the south American pampas into the Atlantic Ocean.

In the last few years, much attention has also been drawn to so-called “high-latitude dust sources” and their subsequent deposits both on land and in the ocean.

On the ocean floor, and to a lesser extent on lake floors, wind-blown deposits have accumulated through geologic time, and hence form a continuous archive of environmental changes.<sup>1</sup> Usually, such depositional sites are relatively far (several hundred kilometers) away from the dust source areas as they need to be undisturbed and far from the influence of rivers, estuaries, canyons, and ice shelves. Examples of such undisturbed conditions through time are predominantly found in crater lakes where both dust deposition and rainfall are solely ombrotrophic (cloud-fed).



**Fig. 1** The major global dust sources and the general dispersion direction of their emitted dust. Colors indicate frequency of occurrence where the TOMS absorbing aerosol index (AAI) is  $>0.7$  (significant amounts of dust or smoke) or 1.0 (abundant dust or smoke) in days, with yellow colors indicating 7–21 days and dark brown: 21–31 days. From Muhs DR, Prospero JM, Baddock MC, and Gill TE (2014) Identifying sources of aeolian mineral dust: Present and past. In: *Mineral Dust: A Key Player in the Earth System*. Springer.

<sup>1</sup>Marine sediments are a mixture of marine organic material (fossil remains and organic tissue produced by different types of plankton) and terrigenous sediments. To isolate the terrigenous fraction, the marine biogenic one is typically removed chemically. Usually, this is done by treating the bulk sediments with  $H_2O_2$  to remove organic tissue, HCl to remove  $CaCO_3$  tests of e.g. foraminifera and coccolithophores, and NaOH to remove  $SiO_2$  tests of e.g. diatoms and radiolaria. The downside of this approach is that with the use of  $H_2O_2$  also pollen and spores are removed and that with the use of HCl also terrigenous carbonates may be removed.

The main advantages of subaquatic dust deposits are:

- They are usually easy to date, thanks to carbonate-building organisms that deposit concurrently with the settling dust particles. These carbonate tests (shells) can be dated using various techniques, such as AMS- $^{14}\text{C}$  dating,  $\delta^{18}\text{O}$  and paleo-magnetic properties of the sediments. This is a big advantage compared to terrestrial dust deposits (loess) that are sometimes difficult to date.
- Crater-lake deposits are usually varved, meaning that age control can be obtained simply by counting the seasonally-defined deposits.
- They reflect both wet- and dry deposition of dust particles that were suspended in the atmosphere, both at low- and high altitudes. This is a big advantage compared to dust in ice cores, which are often heavily influenced by wet/snow deposition at high altitudes and therefore only register long-distance/high-altitude dust.
- The proxy-derived inferences can be verified using modern analogue techniques. This is a big advantage compared to loess deposits, which often do not have a modern analogue.
- Given that mineral dust disperses globally, subaquatic dust deposits can be found on large parts of the Earth's surface.

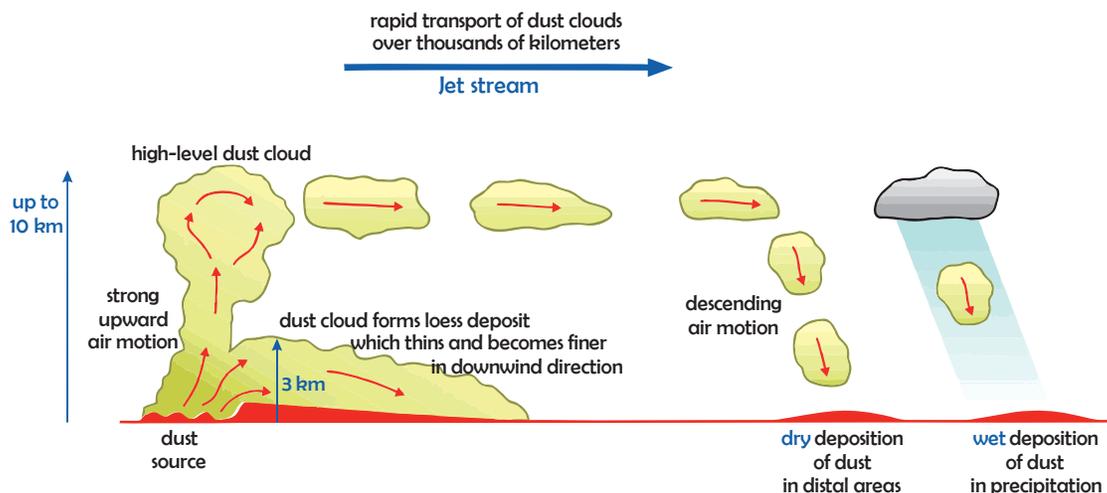
### From desert sources to subaquatic sinks: dust transport processes

The details of the processes of desert dust production, entrainment, and deposition are dealt with in other chapters in this volume. To be able to interpret the various subaqueous deposits, these processes and their consequences for the resulting physical properties (e.g., particle-size distribution (PSD)) of the deposited dust are very important. The whole suite of processes, including dust emission at the source, transport at different altitudes and the eventual deposition both by gravity and by precipitation was conceptualized by Pye and Zhou (1989), see Fig. 2.

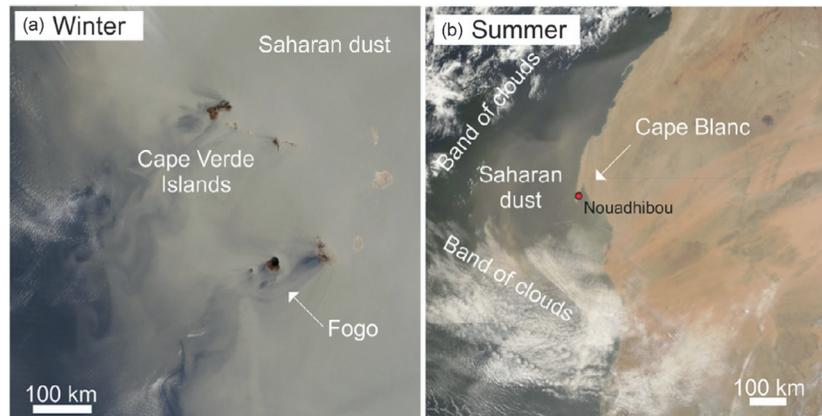
Pye and Zhou (1989) argued that there are basically two end members to atmospheric transport: low-level short-term suspension and high-level long-term suspended dust clouds both travelling downwind. These end members were described in detail by Friese et al. (2016) who studied 4 years of Saharan dust deposition between 2003 and 2007 in a sediment trap located 200 nm offshore Cape Blanc, Mauritania. They typically observed low-level dust transport during winter as opposed to high-altitude dust transport during summer (Fig. 3).

### Lessons learned from present-day dust observations over the Atlantic Ocean

Present-day dust deposition into the marine realm can be studied by dust collection onboard ships, which results in snapshots in space and time. Continuous time series of deposition at one point in space can be obtained by using so-called sediment traps: funnel-shaped devices that are attached to mooring lines, which autonomously intercept all particles settling to the sea floor, and which typically stay suspended in the ocean for a period of 1 year. For example, Van der Does et al. (2020) monitored Saharan dust deposition for 2 years along a trans-Atlantic array of five sediment-trap moorings at  $12^\circ\text{N}$ , and found clear seasonal differences in the PSD of the deposited dust that relate to several processes. Due to increased heating of the earth's surface during summer, stronger convection occurs in the hot season, leading to the emission of larger particles. As a result, summer particles are slightly, but



**Fig. 2** Schematic diagram showing different dust-transport mechanisms in the high- and low-level atmosphere. Redrawn –with Elsevier's permission– after Pye K and Zhou L-P (1989) Late Pleistocene and Holocene aeolian dust deposition in North China and the Northwest Pacific Ocean. *Palaeogeography, Palaeoclimatology, Palaeoecology* 73: 11–23.



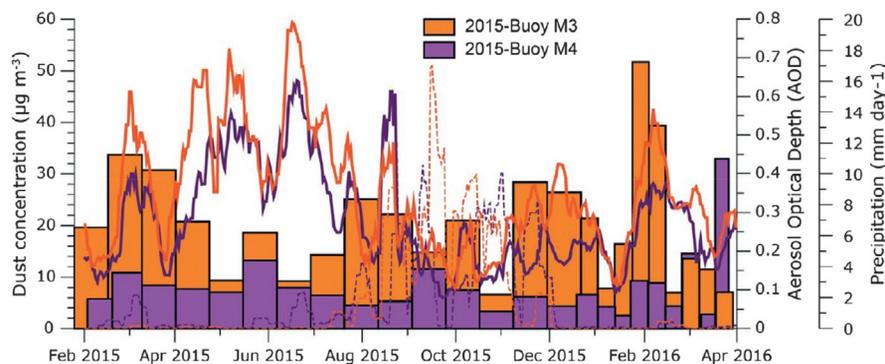
**Fig. 3** Typical winter (a: low-level) and summer (b: high-elevation) transport of Saharan dust. In winter, the Cape Verde Islands of Santa Antao (max altitude: 1979 m), Santiago (max altitude: 1392 m) and Fogo (max altitude: 2829 m) can be partly observed by satellites through the dust plume. In summer, these islands are completely masked by the dust layer, meaning that the dust travels at elevations higher than 2829 m. From Friese C, Does MVD, Merkel U, Iversen MH, Fischer G, and Stuu J-BW (2016) Environmental factors controlling the seasonal variability in particle size distribution of modern Saharan dust deposited off Cape Blanc. *Aeolian Research* 22: 165–179, re-used under Creative Commons CC-BY license.

significantly, coarser than dust particles deposited in winter. In addition, the PSDs of winter samples are slightly, but significantly, better sorted than their summer counterparts, which is interpreted as the effect of winter dust being the result of dry deposition only, as opposed to summer dust being the result of both dry and wet deposition. The latter process washes dust particles out from higher altitudes, where generally only the smaller dust particles are blown (Friese et al., 2016). This effect of vertical sorting in the atmosphere was also observed by Stuu et al. (2005), who collected dust from the atmosphere onboard the research vessel FS Meteor while sailing along the northwest African coast.

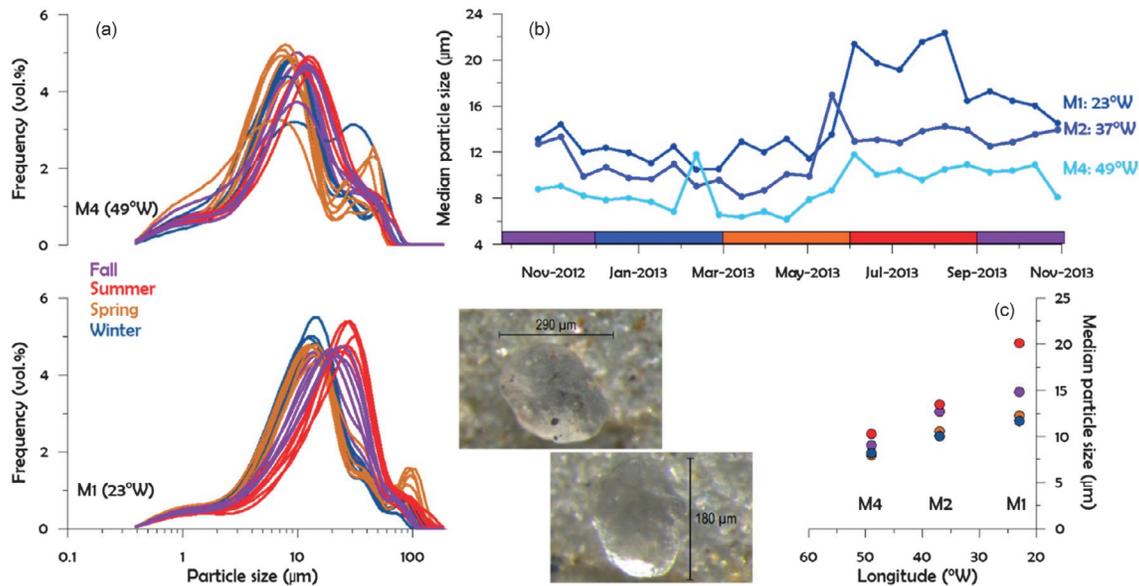
By comparing time series of *dry* dust –collected by the dust-collecting surface buoys, that only sampled material when it was not raining— and total (*dry + wet*) dust –collected by the subsurface sediment traps—Van der Does et al. (2021) argued that the present-day seasonal signal of dust deposition across the Atlantic Ocean is dominated by wet deposition during summer and fall (Fig. 4).

In addition to vertical sorting, gravitational settling also causes downwind sorting with coarser-grained particles deposited closer to the source (proximal) and finer-grained matter deposited further downwind (distal). Using a trans-Atlantic array of dust-sampling sediment traps, moored at 12°N between 23°W and 57°W, Van der Does et al. (2016) monitored Saharan dust deposition for 1 year (between October 2012 and November 2013). They observed a similar seasonal difference between coarser-grained less well-sorted particles in summer and finer-grained and better-sorted particles in winter. This seasonal difference in size decreased downwind but was still apparent at a distal site located ~4400 km away from the African west coast (Fig. 5).

The downwind sorting that was observed in the particle size of the deposited dust, was also visible in their particle composition along the same trans-Atlantic set of sediment traps, with preferential settling of quartz particles at the eastern/proximal side of the transect, compared to the western/distal part of the transect (Korte et al., 2017).



**Fig. 4** Measured atmospheric dust concentrations (bars) on  $N = 24$  buoy filters on surface buoys Michelle (site M3: 12°N/38°W) and Laura (site M4: 12°N/49°W), aerosol optical depth (AOD, from Moderate Resolution Imaging Spectroradiometer (MODIS) Terra; solid lines) and precipitation (from Tropical Rainfall Measuring Mission (TRMM), dashed lines) between February 2015 and April 2016. Orange colors are used for site M3/Michelle, purple colors are used for site M4/Laura. From Van Der Does M, Brummer G-J A, Korte LF, and Stuu J-BW (2021) Seasonality in Saharan dust across the Atlantic Ocean: From atmospheric transport to seafloor deposition. *Journal of Geophysical Research: Atmospheres* 126: e2021JD034614, re-used under Creative Commons CC-BY-NC-ND 4.0 license.



**Fig. 5** Particle-size trends along a transatlantic transect at 12–13°N. (a) Comparison of PSDs of sediments collected at M1; 12°N/23°W (lower panel) and at M4; 12°N/49°W (upper panel) grouped and color-coded for the four seasons. A clear downwind fining can be observed for all seasons. (b) Time series of median particle size showing a sharp contrast with coarser-grained particles in summer as opposed to winter. (c) Median particle size averaged per season and plotted against longitude for sites M1, M2 and M4, demonstrating a clear downwind fining as well as a downwind decrease in seasonal contrast. Middle: two individual quartz particles sampled at site M2 (13°N/37°W) located ~2300 km away from the African west coast. Modified under Creative Commons Attribution 3.0 License from Van Der Does M, Korte LF, Munday CI, Brummer GJA, and Stuit JBW (2016) Particle size traces modern Saharan dust transport and deposition across the equatorial North Atlantic. *Atmospheric Chemistry and Physics* 16: 13697–13710.

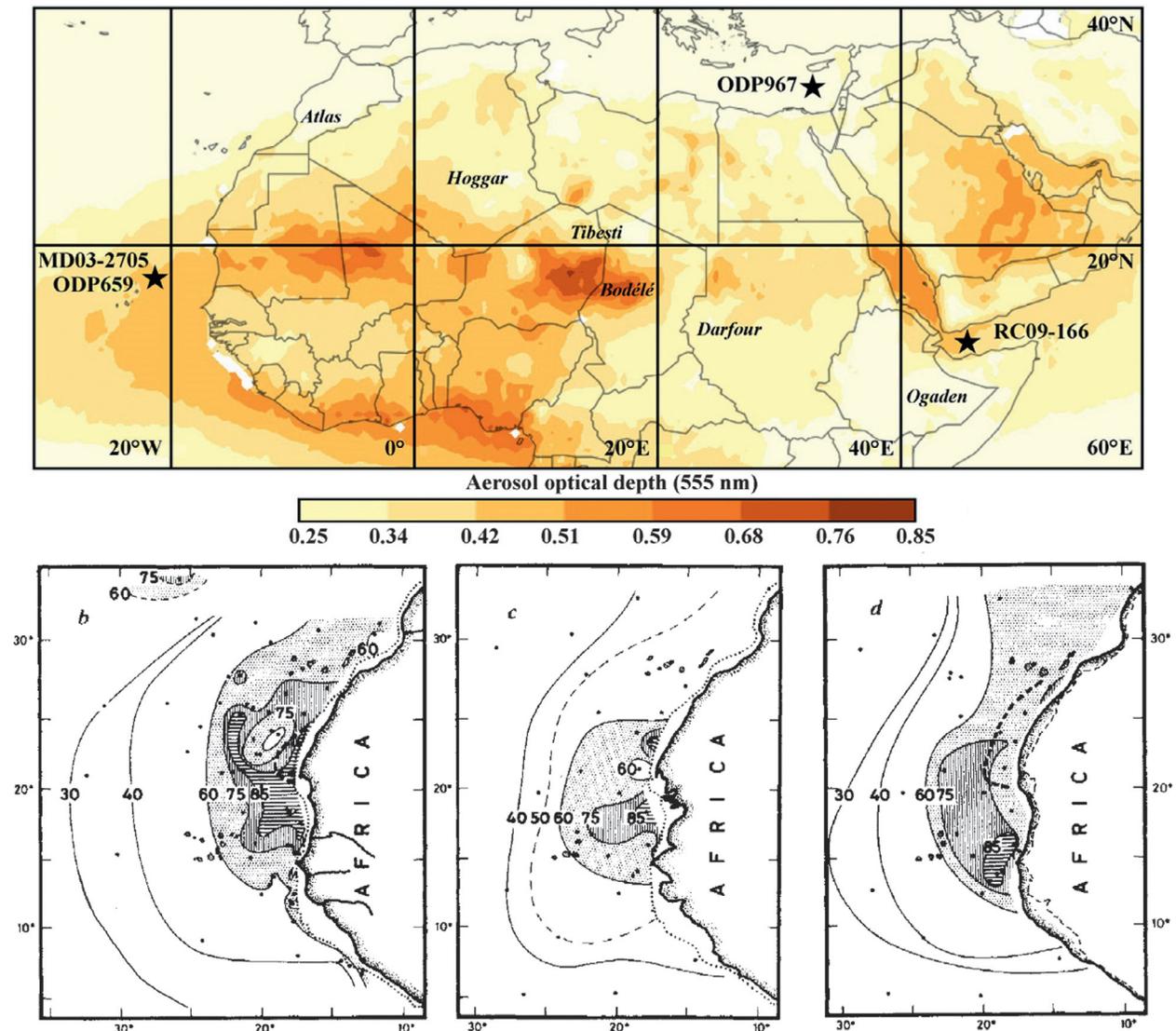
The individual dust particles that were found in the sediment traps were much larger than anticipated. Typically, meteorologists and climate modelers assumed a maximum of very small (<10 μm) particle sizes for long-range transported dust (>100 km) (e.g. Tegen and Schulz, 2014). However, each of the subsurface sediment traps that collected particles settling through the water column contained a few dozen of these so-called ‘giant’ particles (>75 μm) per m<sup>2</sup> sampling area per week. These observations were confirmed by dust sampling that was done on autonomous dust-collecting surface buoys and which also contained particles up to 450 μm at station M3, located at 12°N/38°W: a distance of 2400 km away from the northwest African coast (van der Does et al., 2018). To transport such significant amounts of ‘giant’ particles across such large distances requires additional forces keeping the particles in suspension, which are not included in the Pye and Zhou (1989) scheme (Fig. 2). To accomplish this long-range transport of ‘giants,’ Van der Does et al. (2018) proposed mechanisms such as repetitive (convective) uplift and tribo-electrification. As a result of these in situ findings of wind-blown mineral dust across the ocean, new definitions of wind-blown particle size classes needed to be established (Adebisi et al., 2023). Giant particles can also have substantial effects on the radiative properties of the atmosphere and climate models are presently being adjusted to accommodate these ‘giants.’

## Aeolian dust in subaqueous sedimentary archives: Recorder of environmental changes

### The marine sediment archive

With the knowledge of the present-day dust processes, we can try to interpret the marine archive of dust deposition in the past. Particularly, the PSDs and amount of material (flux) of wind-blown dust have been applied to study dust deposition in marine archives. However, the sedimentation rates of deep-sea sediments are often in the order of a few cm per thousand years. Already in the early 1980s, the combination of dust flux and dust particle size was used to map the deposition of present-day Saharan dust in the equatorial eastern North Atlantic in a set of  $N = 84$  surface samples, which were then also compared with past (6 kyr BP; the Holocene climate optimum, characterized by a ‘green Sahara’ and 18 kyr BP; the Last Glacial Maximum) Saharan dust deposits reconstructed in  $N = 32$  sediment cores (Sarnthein et al., 1981; Fig. 6b-d). The authors acknowledged that, at present, dust is blown from northwest Africa with different wind systems; the Harmattan in winter and the Saharan Air Layer in summer, and concluded that the Harmattan is dominant in delivering wind-blown sediments to the Atlantic Ocean. In addition, Sarnthein et al. (1981) concluded that the fine-grained particles (<6 μm) observed in the terrigenous sediment fraction must have been transported to the ocean by rivers.

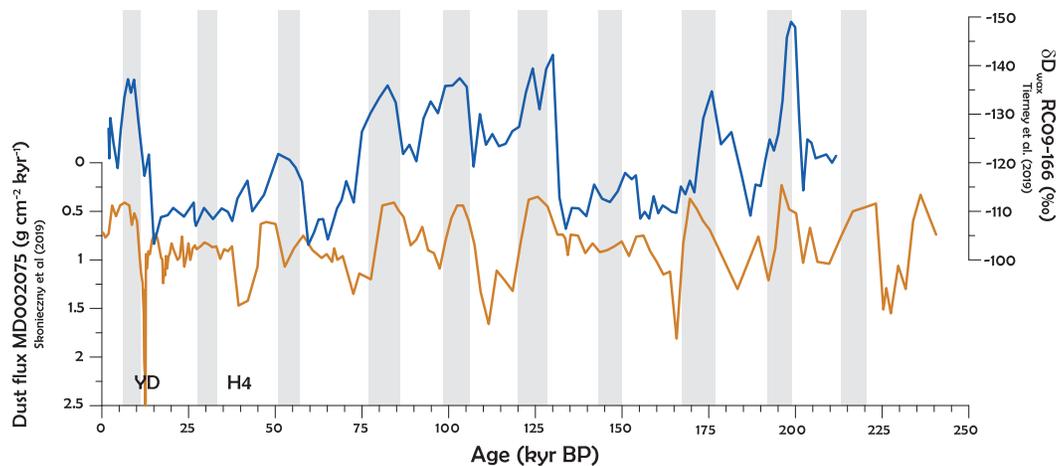
The sedimentary archive that can be found within the sea floor is always a mixture of various components like erosion products from land, plankton remains from the surface ocean, and biogenic components from the sea floor. The erosion products from land are transported to the ocean by rivers, winds, and ice. On nearly all parts of the sea floor in the (sub)tropical oceans the land-derived



**Fig. 6** Modern and past Saharan dust deposition in the eastern subtropical North Atlantic Ocean. (a) Satellite-derived modern distribution of Saharan dust over northwest Africa. AOD – Aerosol Optical Depth measured at 555 nm. (b–d) Distribution (percentage) of the coarse-grained (>24 μm) terrigenous sediment fraction indicating the dispersal pattern of proximal south Saharan/Sahelian dust for three time slices: the present (b), 6 kyr BP (c) and 18 kyr BP (d). (A) From: Skonieczny C, Mcgee D, Winckler G, Bory A, Bradtmiller LI, Kinsley CW, Polissar PJ, De Pol-Holz R, Rossignol L, and Malaizé B (2019) Monsoon-driven Saharan dust variability over the past 240,000 years. *Science Advances* 5: eaav1887, re-used under Creative Commons CC-BY license. (D) From Sarnthein M, Tetzlaff G, Koopmann B, Wolter K, and Pflaumann U (1981) Glacial and interglacial wind regimes over the eastern subtropical Atlantic and North-West Africa. *Nature* 293: 193–196, re-used under Creative Commons CC-BY license.

fraction—in the absence of ice—consists of a mixture of river-flown sediments and wind-blown dust. Even when nowadays no active river systems are present, environmental conditions in the geologic past may have favored river runoff. A classic example of this is the Sahara Desert in northwest Africa, which presently is hyper-arid and basically only producing dust with very limited fluvial activity, but was characterized by the so-called African Humid Period about 10,000 years ago (e.g., deMenocal et al., 2000). At that time, there was so much more rainfall that present-day deserts were turned into grasslands with ample shrubs and trees (e.g., Tjallingii et al., 2008). Such humid periods occurred regularly through geologic time at a pacing of about 23,000 yrs., and the lakes that were filled with water during these wet phases now act as sources of dust. Undoubtedly, such high amounts of rainfall also caused significant river runoff and evidence of this is found in large paleo-river systems. As a result, the terrigenous fraction of deep-sea sediments that was carried to sea in such intervals in geologic history most likely was dominated by river-transported sediments instead of dust.

Dust-flux records are typically derived from the percentage of dust (established on the basis of e.g. particle size or bulk chemistry) in the terrigenous fraction, multiplied by the mass-accumulation rate (MAR; e.g. Brummer and van Eijden, 1992). The temporal



**Fig. 7** Skonieczny et al. (2019)'s reconstruction of the African monsoon for the past 240 kyr. Orange record:  $^{230}\text{Th}$ -normalized northwest African dust fluxes from core MD032705 in the subtropical eastern North Atlantic, Blue record:  $\delta\text{D}$  values of plant waxes recovered from sediment core RC09-166 in the Gulf of Aden (Tierney et al., 2017). Grey bars: occurrence of sapropels in the Mediterranean Sea derived from sediment core ODP967 (Kroon et al., 1998). YD = Younger Dryas, H4 = Heinrich Event 4. Redrawn from Skonieczny C, Mcgee D, Winckler G, Bory A, Bradtmiller LI, Kinsley CW, Polissar PJ, De Pol-Holz R, Rossignol L, and Malaizé B (2019) Monsoon-driven Saharan dust variability over the past 240,000 years. *Science Advances* 5: eaav1887, re-used under Creative Commons CC-BY license.

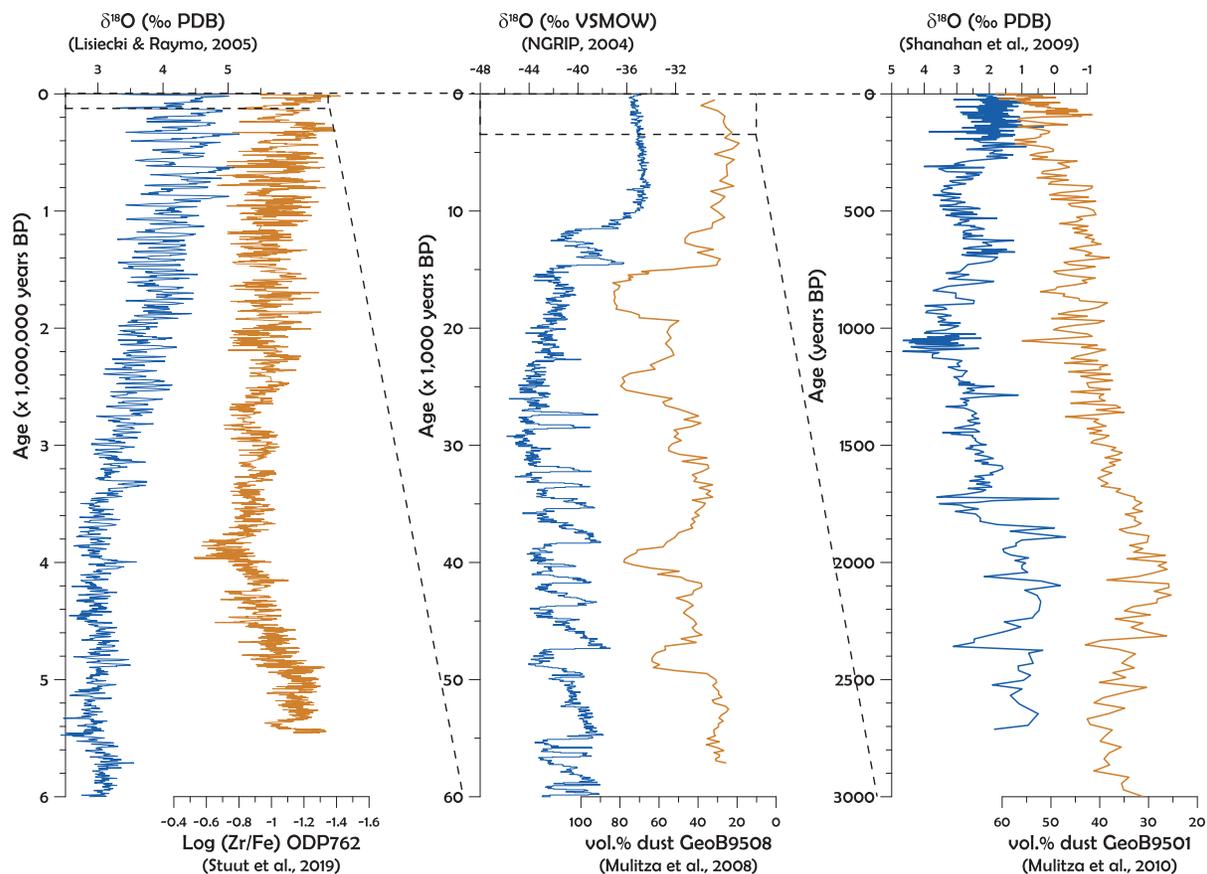
resolution of the MAR strongly depends on the amount of so-called 'tie points' in the age model.<sup>2</sup> These age-model issues can be overcome by normalizing to the flux of  $^{230}\text{Th}$  scavenged from seawater by settling particles (Francois et al., 2004). This approach is based on the fact that  $^{230}\text{Th}$  is produced in the ocean (through decay of  $^{234}\text{U}$ ) at a constant rate and it is consequently scavenged from the ocean by settling particles. If sedimentation rates are constant through time, the excess  $^{230}\text{Th}$  should remain constant throughout sediment accumulation. Changes in the amount of  $^{230}\text{Th}$  in the sediment archive are therefore an effect of changes in sedimentation rates. Assuming that the deposition of biogenic particles (fossil remains of plankton living in the surface ocean and settling to the sea floor) is constant through time, changes in sediment fluxes can be interpreted in terms of changing terrigenous sediment input. Skonieczny et al. (2019) followed this approach in sediment core MD032705, recovered from the subtropical eastern North Atlantic Ocean at  $18^{\circ}05'\text{N}/21^{\circ}09'\text{W}$  (Fig. 6a), more than 500 km off the Mauritanian coast. By assuming that this core site is too remote for fluvial sediments to be transported to the site, the authors interpret the resulting record of terrigenous sediments as exclusively wind-blown and the resulting  $^{230}\text{Th}$  flux as a northwest African dust flux (Fig. 7). By comparing the dust record of the Atlantic Ocean with the timing of occurrence of sapropels (Nile-runoff related events) in the Mediterranean Sea and  $\delta\text{D}$  values (a proxy for precipitation) of plant waxes recovered from a sediment core in the Gulf of Aden, they were able to reconstruct an African-monsoon record for the past 240 kyr (Fig. 7). Depending on the proximity of the core site to the source(s) of terrigenous sediments, sedimentation rates vary greatly, and so does the length of the recovered stratigraphy (Fig. 8).

### The lacustrine sediment archive

Compared to the regional character of dust deposited in marine sedimentary archives, lacustrine archives contain a more local signal of environmental conditions leading to dust generation, entrainment, and finally deposition. Early recognition of the potential of lake deposits as archives of dust deposition dates back to the studies of Grove (1972) and Bowler (1976). These were followed by now well-established paleo-environmental records derived from lacustrine deposits including the southern German Alpine lakes, the German Maar records, the Patagonian crater lakes, the central North American lakes, and the central Saharan Ounianga lakes. Another advantage of lake sediments is that often they are varved, which is the result of seasonal differences in environmental conditions, which also makes them relatively easy to date. There are rare examples of varved marine sediments (e.g. von Rad et al., 1999), but the varve potential in lakes is much higher as, for example, high-latitude lakes may be frozen over during winter, which leads to a seasonal banding of the sedimentary deposits on the lake floor.

Especially the Maar records are examples of lakes where wind-blown material is the only terrigenous input and thus where the dust can relatively simply be isolated from the biogenic sedimentary fraction that is produced in both the lake waters and on the lake floor. Sirocko et al. (2005) argue that the sediments that were retrieved from the various Maar lakes in central Germany are a

<sup>2</sup>In the study of paleo-environmental reconstructions from deep-sea records, the depth to age conversion is of vital importance. Typically, this is achieved by correlating (wiggles matching) a standard parameter to a stacked global record of which the age is well established. One such standard is the ratio of oxygen isotopes in the ocean, which is assumed to be globally the same and reflecting the amount of ice on the planet. Lighter isotopes of oxygen are stored in the ice, enriching the remaining ocean water in the heavier isotopes. The ambient oxygen-isotope composition is registered by short-lived  $\text{CaCO}_3$  building organisms, of which the test settles to the sea floor and fossilizes there; usually, the  $\delta^{18}\text{O}$  of a common single species of planktonic or benthic foraminifera is measured and then compared to the global  $\delta^{18}\text{O}$  stack published by Lisiecki and Raymo (2005).



**Fig. 8** Comparison of marine dust records at three different time scales. All blue plots depict  $\delta^{18}\text{O}$  records, which are used as a global temperature proxy. From left to right these are the global  $\delta^{18}\text{O}$  stack (Lisiecki and Raymo, 2005), the  $\delta^{18}\text{O}$  record from the Greenland NGRIP ice core (NorthGRIP community members, 2004), and the  $\delta^{18}\text{O}$  record from Lake Bosumtwi by Shanahan et al. (2009). Note the scales of the time axes changing from left to right from myr, kyr to yr Before Present. The orange records depict dust (proxy) records. From left to right these are the Log(Zr/Fe) ratio of core ODP762 off northern West Australia (Stuuat et al., 2019), percentage dust (fraction  $>10\ \mu\text{m}$ ) in core GeoB9508 off Mauritania (Mulitza et al., 2008), and percentage dust (fraction  $>10\ \mu\text{m}$ ) in core GeoB9501 on the Senegal mudbelt (Mulitza et al., 2010), respectively. From Lisiecki LE and Raymo ME (2005) A Pliocene-Pleistocene stack of 57 globally distributed benthic  $\delta^{18}\text{O}$  records. *Paleoceanography* 20: PA1003, re-used under Creative Commons CC-BY license. Members NC (2004) High-resolution record of Northern Hemisphere climate extending into the last interglacial period. *Nature* 431: 147–151, re-used under Creative Commons CC-BY license. Shanahan TM, Overpeck JT., Anchukaitis KJ, Beck JW, Cole JE, Dettman DL, Peck JA, Scholz CA, and King JW (2009) Atlantic forcing of persistent drought in West Africa. *Science* 324: 377–380, re-used under Creative Commons CC-BY license. Stuuat J-BW, De Deckker P, Saavedra-Pellitero M, Bassinot F, Drury AJ, Walczak MH, Nagashima K, and Murayama M (2019) A 5.3-million-year history of monsoonal precipitation in Northwestern Australia. *Geophysical Research Letters* 46: 6946–6954, re-used under Creative Commons CC-BY license. Mulitza S, Prange M, Stuuat J-BW, Zabel M, Von Döbenek T, Itambi AC, Nizou J, Schulz M, and Wefer G (2008) Sahel megadroughts triggered by glacial slowdowns of Atlantic meridional overturning. *Paleoceanography* 23: <https://doi.org/10.1029/2008PA001637>, re-used under Creative Commons CC-BY license. Mulitza S, Heslop D, Pittauerova D, Fischer HW, Meyer I, Stuuat J-B, Zabel M, Mollenhauer G, Collins JA, Kuhnert H, Schulz M (2010) Increase in African dust flux at the onset of commercial agriculture in the Sahel region. *Nature* 466: 226–228, re-used under Creative Commons CC-BY license.

two-component mixture of dark biogenic material produced in the lake and light-colored quartz particles blown into the lake. As a result, the authors argue that during warm periods, organic-rich sediments are deposited as opposed to colder periods when deposition of wind-blown particles dominates. Thus, the grayscale of these sediments can be used to reconstruct variability in the input of the two individual components (Fig. 9).

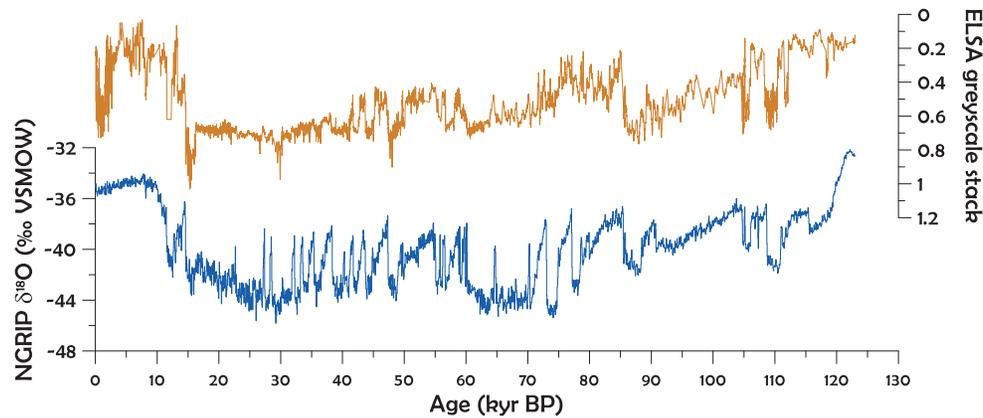
By combining cores from different Maar lakes, synchronized ‘simply’ by layer counting, and by events like bomb spiking and tephras, the famous ELSA stack was established (Sirocko et al., 2016; Fig. 10), now covering the last 60,000 years, annually resolved.

The advantage of recording mere local environmental conditions may turn into a disadvantage in the case of very small lake basins where very local conditions (like a nearby field of sand dunes) potentially dominate the depositional system. It is hard to say what the appropriate lake size should be to avoid such artifacts.

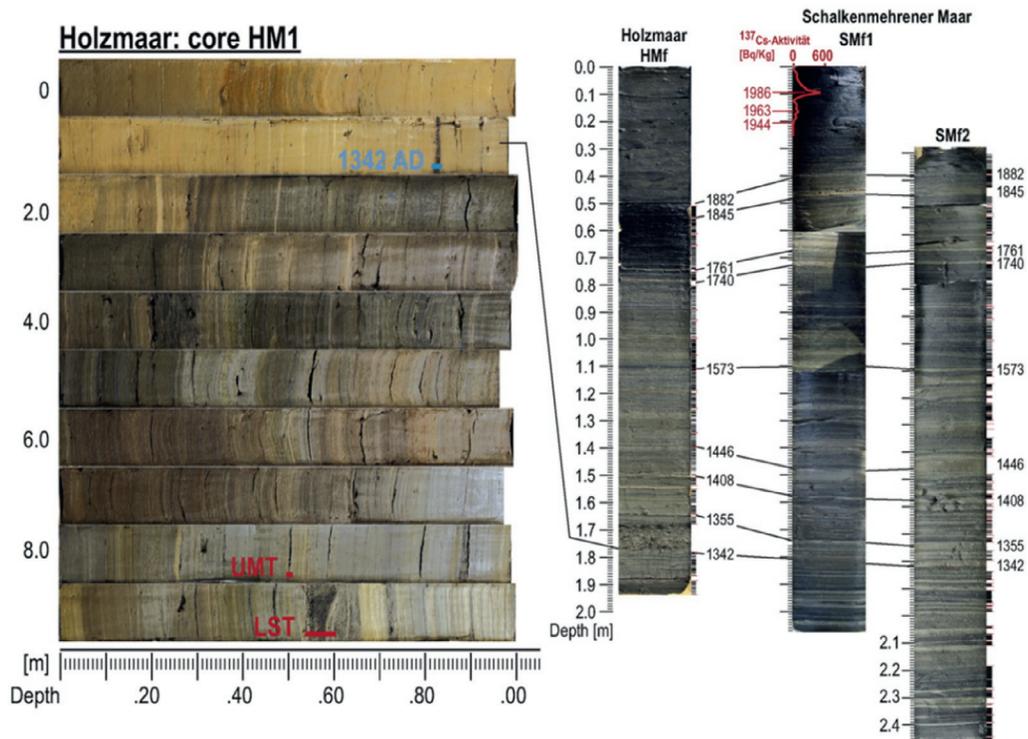
## Proxies used in subaquatic sediments to reconstruct paleo-environmental conditions

### Particle size of mineral dust

The particle size of the wind-blown sediment fraction is intuitively related to wind vigor (e.g., Janecek and Rea, 1985) and several studies therefore used the particle size of the wind-blown sediment fraction to reconstruct atmospheric circulation patterns



**Fig. 9** Comparison of the ELSA - Eifel Laminated Sediment Archive greyscale stack (Sirocko et al., 2005) with the oxygen-isotopes record from the Greenland NGRIP ice core (NorthGRIP community members, 2004). High values of  $\delta^{18}\text{O}$  and low values of the greyscale (note reversed scale on greyscale axis) indicate warm conditions. From Sirocko F, Seelos K, Schaber K, Rein B, Dreher F, Diehl M, Lehne R, Jäger K, Krbetschek M, and Degering D (2005) A late Eemian aridity pulse in central Europe during the last glacial inception. *Nature* 436: 833–836, re-used under Creative Commons CC-BY license. Members NC (2004) High-resolution record of Northern Hemisphere climate extending into the last interglacial period. *Nature* 431: 147–151, re-used under Creative Commons CC-BY license.

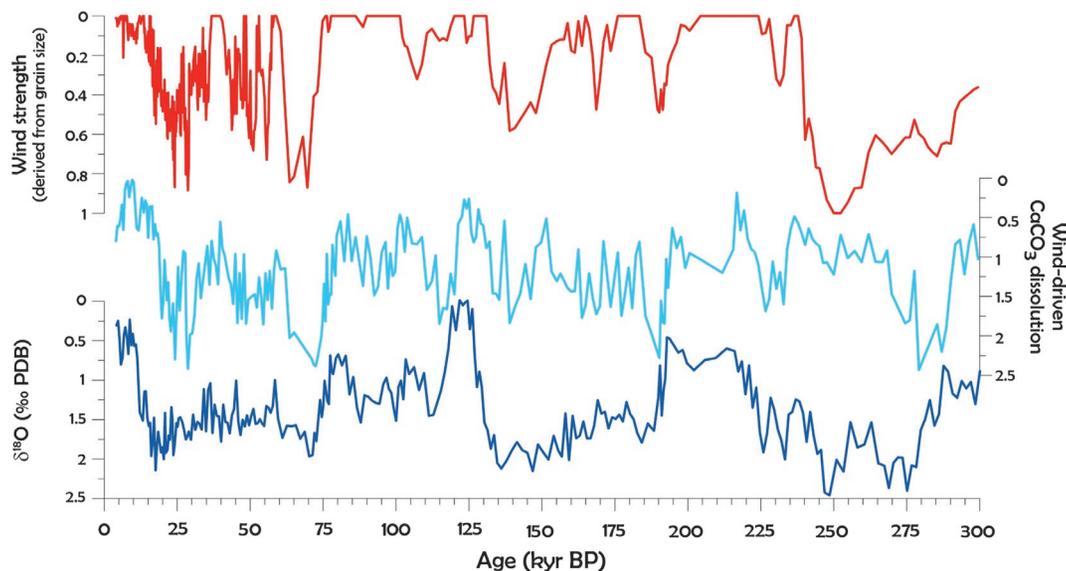


**Fig. 10** Photos of varve-counted cores HM1 (last 13,000 years) and HMFfreeze from Lake Holzmaar (last 1000 years) together with varve-counted freeze cores from Schalkenmehrener Maar. Historically documented flood layers are indicated when visible in both maar lakes. From Sirocko F, Knapp H, Dreher F, Förster MW, Albert J, Brunck H, Veres D, Dietrich S, Zech M, Hambach U, Röhner M, Rudert S, Schwibus K, Adams C, and Sigi P (2016) The ELSA-vegetation-stack: Reconstruction of landscape evolution zones (LEZ) from laminated Eifel maar sediments of the last 60,000 years. *Global and Planetary Change* 142: 108–135, re-used under Creative Commons CC-BY license.

in the past. Generally, throughout the Quaternary, glacial periods were characterized by intensified atmospheric circulation due to increased latitudinal pressure gradients. These increased winds are often reflected in larger wind-blown particles, even when dust fluxes decreased dramatically, or were overprinted by calcium carbonate production and deposition. Although state-of-the-art climate models have large problems incorporating them, giant particles ( $> 75 \mu\text{m}$ ) are observed both in sediment archives, as well as in present-day sampling campaigns.

The southeast Atlantic Ocean, offshore Namibia, is dominated by the upwelling of deep waters, driven by trade winds and causing high primary productivity in the surface ocean. These same trade winds also carry dust from the Namib Desert, which settles on the seafloor. Stuut and co-workers demonstrated how the variability of the trade-wind system varied throughout the late Quaternary based on the PSDs of both the marine sediment fraction (Stuut et al., 2002a) and the land-derived sediment fraction (Stuut et al., 2002b). Generally, during the glacial stages of the late Quaternary, atmospheric circulation intensified, leading to enhanced wind-driven upwelling, which is reflected in the particle size of the carbonate fraction. As the upwelled waters are cold, they are more corrosive to carbonate tests of unicellular plankton and will consequently influence their particle size. Simultaneously, the intensified winds had a larger carrying capacity, which enabled them to carry coarser-grained dust particles (Fig. 11).

As discussed before, similar to using the size of the wind-blown sediment fraction as a proxy for wind strength in the past, the flux of the wind-blown sediment fraction can be considered a proxy for paleo-aridity in the source area (Fig. 7). Many studies have followed this approach, resulting in various paleo-environmental reconstructions based on marine sediment cores established in the Indian Ocean, southeast Atlantic, southeast Pacific, equatorial North Atlantic, and Mediterranean Sea. In addition, several size-derived proxies were suggested to characterize dust in subaqueous sediments such as certain size fractions (Table 1).



**Fig. 11** Proxy records from core MD962094. Bottom:  $\delta^{18}\text{O}$  record showing glacial-interglacial swings throughout the last 300 kyr BP. Middle: wind-driven carbonate dissolution record [unitless fragmentation index]. Top: relative wind-strength record [unitless particle-size derived end-member ratio], as reconstructed from the dust fraction. High values of the wind-strength record (ratio ranging from 0 to 1) and low negative values of the carbonate dissolution index indicate higher wind speeds and increased fragmentation due to increased upwelling. Redrawn from Stuut J-BW, Prins MA, and Jansen JHF (2002a) Fast reconnaissance of carbonate dissolution based on the size distribution of calcareous ooze on Walvis Ridge, SE Atlantic Ocean. *Marine Geology* 190: 563–571; Stuut J-BW, Prins MA, Schneider RR, Weltje GJ, Jansen JHF, and Postma G (2002b) A 300-kyr record of aridity and wind strength in southwestern Africa: Inferences from grain-size distributions of sediments on Walvis Ridge, SE Atlantic. *Marine Geology* 180: 221–233.

**Table 1** Grain-size derived proxies for desert dust in marine sediments used in literature.

Grain-size proxy	Proxy for	Location	Citation
terrigenous sediment <63 $\mu\text{m}$	total dust	distal North Pacific proximal Tasman Sea	Rea and Janecek (1981) Hesse (1994)
terrigenous sediment >6 $\mu\text{m}$	total dust	eq. Atlantic Indian Ocean	Sarnthein et al. (1981) Clemens and Prell (1990)
terrigenous sediment >60 $\mu\text{m}$	total dust	Indian Ocean	De Deckker et al. (1991)
bulk sediment >63 $\mu\text{m}$	wind stress	eq. Atlantic	Matthewson et al. (1995)
moment statistics (mean, median) after Folk and Ward (1957)	total dust	Indian Ocean	Prins and Weltje (1999)
bulk sediment, unmixed with EMMA	aridity	Indian Ocean	Prins and Weltje (1999)
bulk sediment, unmixed with EMMA	wind stress	Indian Ocean	Prins and Weltje (1999)
terrigenous sediment 18–63 $\mu\text{m}$	total dust	eq. Atlantic	Nizou et al. (2011)
terrigenous sediment >10 $\mu\text{m}$	total dust	eq. Atlantic	Meyer et al. (2013)

In an attempt to characterize and quantify the wind-blown portion within the land-derived sediment fraction, Prins and Weltje (1999) presented the end-member modelling approach, which is based on the assumption that every sediment-transport mechanism leaves its characteristic imprint on the PSD of the material it transports; ice-rafted sediments tend to be completely unsorted as opposed to aeolian sediments, which are very well-sorted. Based on this assumption, a numerical model was developed, with which a data set of PSDs can be modelled and deconvolved into subpopulations –without a priori information about these subpopulations—that can subsequently be interpreted in terms of sediment-transport mechanism. The end-member modelling algorithm (EMMA) does not prescribe anything in terms of the shape of the PSDs of the subpopulations and has been successfully applied to recognize ice-rafted sediments and wind-blown dust. Using the end-member approach, the river-transported and wind-blown fractions can be distinguished and quantified downcore provided the source-to-sink distance is small enough for the aeolian fraction to be coarser than the river-derived sediment fraction, which is typically around 4–6  $\mu\text{m}$  in deep-marine sediment archives (e.g., Prins and Weltje, 1999). With time, other EMMA techniques were developed and for the last  $\sim 10$  years the EMMA has been a common approach for the interpretation of grain size data in dust archives.

### Other proxies for wind-blown dust

Besides the PSDs of the terrigenous sediment fraction, several other proxies were suggested to characterize dust in subaquatic sediment archives (Table 2). The first published detailed study of the composition of Saharan dust was done by Ehrenberg (1847), who received material that Charles Darwin had collected on his travels onboard HMS Beagle from 1831 to 1836. Ehrenberg recognized different kinds of biogenic material in the dust, which he classified as freshwater diatoms and plant-derived biogenic silica called phytoliths. These freshwater diatoms and phytoliths were later found in North Atlantic sediments and consequently used to reconstruct the Saharan climate and southwestern African climate.

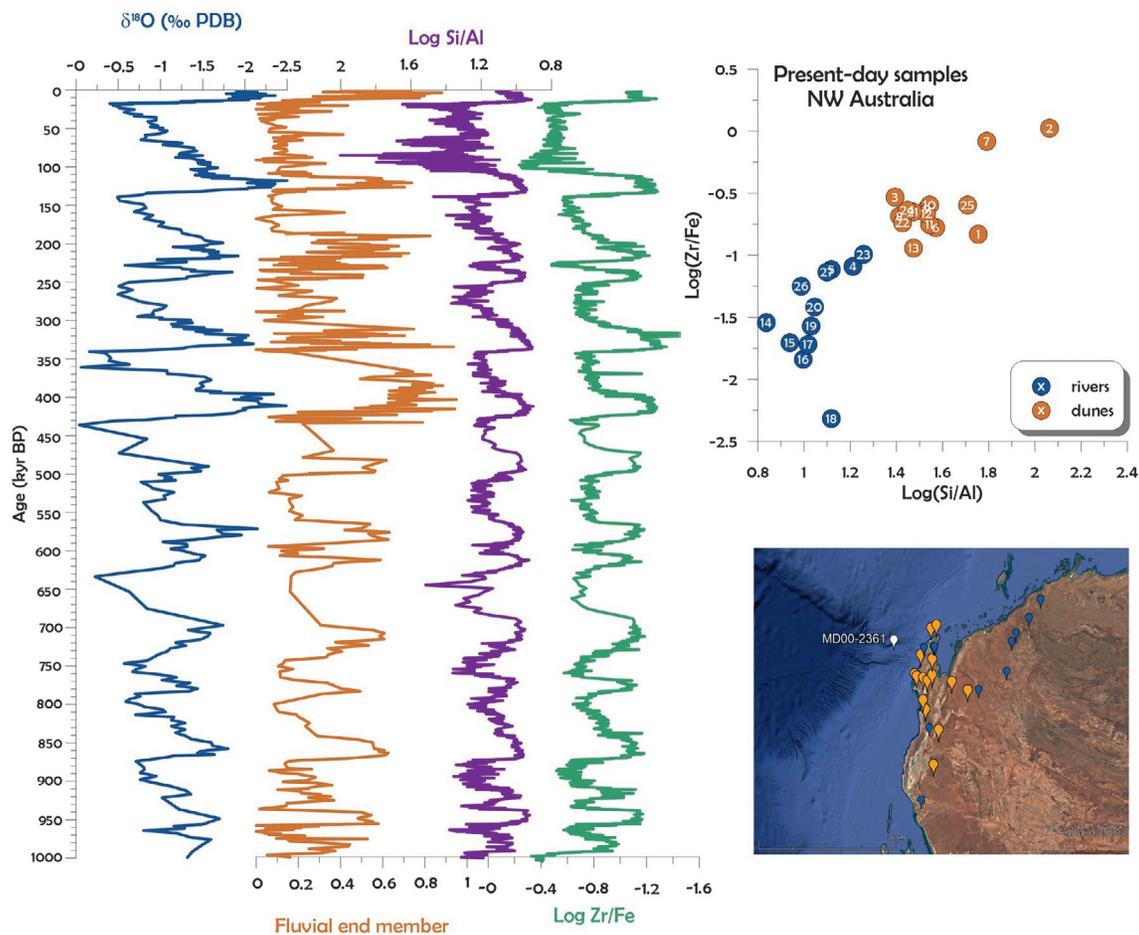
An alternative wind-blown land-derived organic fraction is pollen, which has been widely used to reconstruct paleo-environmental conditions in dry areas around the world, both in marine and lacustrine settings: in South America from sediments in the eastern Pacific and in the numerous lakes of the Andes mountains, in Australia from sediments in the western Pacific and in Lynch's crater lake, in north Africa from equatorial Atlantic sediments and presently dry lakes, and in South Africa from marine sediments in the eastern Atlantic Ocean as well as on-land deposits such as the Pretoria Saltpan and even Hyrax middens.

Although there is much debate about the transport mechanism of pollen (fluvial versus aeolian), assemblages of the different pollen can be used to characterize vegetation types, and downcore variability in the different vegetation types can be interpreted in terms of environmental changes.

Several proxies have been developed in the field of organic geochemistry; homologous series of long-chain *n*-alkanes, *n*-alcohols, and fatty acids are typical lipids found in dust. These lipids are part of terrestrial higher plant epicuticular waxes, and are used by these plants as a protective coating on leaves and stems. The wax particles are easily eroded off the surface of the leaves by wind, especially by a sandblasting effect, and can then become airborne. Alternatively, decaying plant organic matter in soils can be lifted during dust storms and transported by wind. A pitfall of this approach is that plant waxes may have been stored in river- and lake sediments, before they were blown out to sea (e.g. Eglinton et al., 2002). The plant waxes have been found in marine sediments up to 4 million years old and can be used to reconstruct environmental conditions in the source areas of the dust (Martinez-Garcia et al., 2011). Finally, complex sugar molecules, such as levoglucosan, are typical products of burned vegetation (derived from cellulose) and were demonstrated to be transported across the Atlantic Ocean and to be preserved in seafloor sediments (Schreuder et al., 2018).

**Table 2** Other proxies for desert dust in marine sediments used in literature.

<i>Proxy</i>	<i>Proxy for</i>	<i>Location</i>	<i>Citation</i>
Phytoliths	aridity	eq. Atlantic	Pokras and Mix (1985)
Freshwater diatoms	aridity	eq. Atlantic	Pokras and Mix (1985)
Pollen	aridity	SE Atlantic	Coetzee (1976)
Lipids from plant waxes	aridity	eq. Atlantic	Simoneit (1977)
Burnt cellulose (levoglucosan)	fires	eq. Atlantic	Schreuder et al. (2018)
Ti/Al (Ti in dust, Al in river mud)	total dust	Indian Ocean	Weedon and Shimmiel (1991)
Zr/Rb (Zr in dust, Rb in river mud)	total dust	eq. Atlantic	Matthewson et al. (1995)
Si/Al (Si in dust, Al in river mud)	total dust	eq. Atlantic	Mulitza et al. (2010)
Pb isotopes	total dust	eq. Atlantic	Abouchami and Zabel (2003)
He isotopes	total dust	eq. Atlantic	Mukhopadhyay and Kreycik (2008)
Sr/Nd isotopes	provenance	eq. Atlantic	Meyer et al. (2011, 2013)
Palygorskite (trace mineral)	provenance	Sahara	Schütz and Sebert (1987)
Magnetic minerals	aridity	eq. Atlantic	Bloemendal et al. (1988)



**Fig. 12** Proxy records from core MD032607 recovered offshore northern West Australia at 22°2'S/113°16'E. Blue record:  $\delta^{18}\text{O}$  of the planktonic foraminifer *Globigerinoides ruber* showing glacial-interglacial swings throughout the last 1 Myr. Orange: particle-size derived proxy for fluvial run-off; Purple: Log (Si/Al) ratio and Green: Log (Zr/Fe) ratio, both derived from XRF scanning. Top right insert: chemical composition of samples collected onshore in potential source areas with blue dots representing samples from rivers and river terraces, and orange dots representing samples collected in (fossil) dunes. Bottom right insert: map of the study area in northern West Australia. From Stuu J-BW, De Deckker P, Saavedra-Pellitero M, Bassinot F, Drury AJ, Walczak MH, Nagashima K, and Murayama M (2019) A 5.3-million-year history of monsoonal precipitation in Northwestern Australia. *Geophysical Research Letters* 46: 6946–6954.

Next to these organic proxies for wind-blown deposits, increasing numbers of studies appear in which element ratios as derived from XRF core scanning and individual samples are used to characterize aeolian dust. For example, by studying the elemental composition of both ancient river systems and fossil dunes in northern West Australia that are potential source areas for the terrigenous fraction in the sediment cores below the northwestern Australian dust path, Stuu et al. (2019) could distinguish between different sediment sources by combining different elemental ratios. When applying these same elemental ratios to the sediment cores, they could be interpreted in terms of continental aridity and monsoon-driven precipitation (Fig. 12).

Great care has to be taken when interpreting these bulk chemical records as they are controlled by the source region(s) of the wind-blown particles and different geological terrains that in turn have differing geochemical compositions. As a result, element ratios are not generally applicable around the world to characterize mineral dust.

Further geochemical proxies can be found in radiogenic isotopes such as those of Sr, Nd, and Hf. Especially when applied together, these radiogenic isotopes can be used as provenance tools as they vary strongly with the geological age of the source rocks. This way, potential source areas (PSAs) can be defined (e.g. Guoinseau et al., 2022). For example, using the radiogenic isotope chemical composition of the aeolian sediment fraction (>10  $\mu\text{m}$ ), Meyer et al. (2011) reconstructed the provenance changes of Saharan dust throughout several geological stages with well-established contrasting paleo-environmental conditions. Like Samthein et al. (1981) three periods were compared: (1) the Last Glacial Maximum (~18 kyr BP), which was characterized by extreme aridity and intensified atmospheric circulation; (2) the African Humid Period (~10 kyr BP), which was characterized by increased rainfall and decreased atmospheric circulation relative to today; and (3) the present-day situation, which is characterized by relatively dry conditions and “normal” atmospheric circulation. Environmental conditions of all three periods obviously had an effect on the amount and size of the material transported by winds, which is reflected in their differing provenance (Meyer et al., 2011).

Other isotopes like the Pb series ( $^{204}\text{Pb}$ ,  $^{206}\text{Pb}$ ,  $^{207}\text{Pb}$ , and  $^{208}\text{Pb}$ ) were successfully used to characterize dust in sediment cores from the equatorial North Atlantic to reconstruct increased dust input during the Last Glacial Maximum (~18kyr BP; [Abouchami and Zabel, 2003](#)). Great care should be taken using Pb isotopes in modern mineral dust as the combustion of long-chained hydrocarbons also emits considerable amounts of Pb that end up in the marine sediment archive.

Another marine archive with great potential for high-resolution dust records is tropical corals. Although tropical corals are very efficient in removing pollutants from their polyps, they seem to store dust that rains down on them within the He isotopes (there are nine He isotopes, of which only  $^3\text{He}$  and  $^4\text{He}$  are stable) that they precipitate in their carbonates. Without comprehending exactly why and how corals register these isotopes, [Mukhopadhyay and Kreyck \(2008\)](#) observed a close co-occurrence of  $^4\text{He}$  in *Porites* corals from the Cape Verde Islands and the summer surface dust concentration (SDC) record from Barbados. As *Porites* corals can grow several hundreds of years old, they bear great potential for highly resolved long-term paleo-aridity records.

Next to the chemical composition, also the mineralogical composition of marine sediments can be used to reconstruct the amounts of dust being blown around. A classic example is the mineral palygorskite, which is typical for Saharan dust ([Schütz and Sebert, 1987](#)), and of which the abundance in marine sediments can be used to quantify Saharan dust in the marine sediment archive. Related to the mineralogical proxies are various magnetic proxies, which are based on the magnetic properties of various minerals and mineral coatings in wind-blown dust. These coatings form under various environmental conditions with the iron-oxide minerals hematite and goethite as the main indicators of wetter or drier conditions. As with all proxies, there are some pitfalls with magnetic proxies, related to diagenetic (post-depositional) alterations of the magnetic minerals or occurrence of magnetic minerals produced by magnetotactic bacteria.

### The significance of aeolian dust physical properties for global climate

It is of utmost importance to understand the physical/optical properties of aeolian particles and their depositional mechanisms; their PSDs, shape and mineralogical/chemical composition are closely related to the atmosphere's radiative balance as well as the ocean carbon pump. The amount of incoming solar energy that is reflected at the top of the atmosphere depends on the particles' size, shape and color. Similarly, the amount of absorbed outgoing energy/greenhouse effect by dust particles in the lower atmosphere depends on the same physical properties. In addition to these physical properties affecting the global climate, metals and macronutrients that the dust particles carry, are the main nutrient source for many phytoplankton species across the open ocean, in which 93% of the active carbon presently is stored ([DeVries, 2022](#)). During the process of photosynthesis,  $\text{CO}_2$  is sequestered indirectly from the atmosphere and stored in the biomass that the phytoplankton produces.

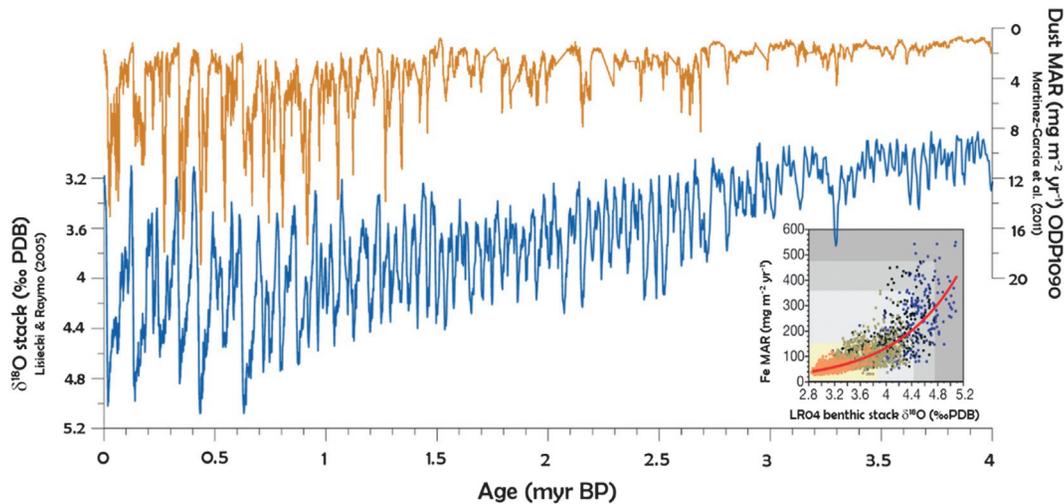
Dust deposition might also have played an important role in glacial-interglacial variations in global atmospheric  $\text{CO}_2$  concentrations. In the late 1990s John Martin hypothesized that mineral dust deposition in the ocean may play a crucial role in the global climate on glacial-interglacial timescales. This so-called Fe-hypothesis relates to the Fe-limited parts of the ocean, so-called High Nutrient, Low Chlorophyll (HNLC) zones, where plenty of macronutrients are available yet primary productivity is very low. As mineral dust carries Fe and macro- as well as other micro-nutrients, increased iron-rich dust transport during glacial periods may have stimulated plankton growth, which in turn may have led to lower atmospheric  $\text{CO}_2$  concentrations ([Martinez-Garcia et al., 2011](#); [Wolff et al., 2006](#)). This hypothesis has been tested extensively by many so-called fertilization experiments (see [de Baar et al., 2005](#) for a synthesis of the results) which demonstrated that indeed primary productivity can be stimulated using dissolved Fe. However, the net effect of these experiments in terms of the export of organic matter and hence actual  $\text{CO}_2$  sequestration is still under debate. Also, so far there is only one known example of observed ocean fertilization by mineral dust ([Bishop et al., 2002](#)) that indeed led to an increase in organic matter export from the surface ocean to the deep sea.

[Martinez-Garcia et al. \(2011\)](#) demonstrated that there is indeed a coupling between dust input into the Southern Ocean and global climate through phytoplankton-growth stimulation by dust and the resulting  $\text{CO}_2$  effects throughout the last 4 million years ([Fig. 13](#)). It was further hypothesized that mineral dust not only stimulates phytoplankton growth through nutrient supply but also by increasing the export of organic matter from the surface ocean to the deep sea through ballasting effects ([Iversen and Ploug, 2010](#)), which comes down to relatively large and heavy mineral particles that sink to the sea floor at relatively high speed and on their way scavenge organic matter from the surface ocean downward. If this ballasting process is fast enough, there is less time for the organic tissue to be remineralized and enhanced export of organic matter can be realized.

Although mineral dust currently does not seem to have large-scale fertilizing effects in HNLC zones, dust deposition might still affect primary productivity in Low Nutrient Low Chlorophyll (LNLC) zones in closer proximity to present-day dust sources such as the Saharan Desert. In contrast to HNLC regions, primary production in LNLC waters is mainly limited by macronutrients (N, P), sometimes co-limited by Fe. The effects of mineral dust deposition on nutrient availability and primary production have long been underestimated by models ([Guieu et al., 2014](#)). However, episodic deposition of micro- and macronutrients can temporarily relieve nutrient limitation in these regions, leading to enhanced productivity on short (daily to weekly) timescales.

Next to the supply of essential metals and macronutrients by dust particles, the particle size of the dust plays a huge role in the ocean carbon cycle as well, since smaller particles have a higher surface area (coatings of metals are therefore yielding much more mass in finer-grained dust and fine-grained dust consists of iron-containing minerals, such as mica's) and through increased ballasting potential of larger dust particles, increasing carbon export to the deep ocean ([Van der Jagt et al., 2018](#)).

Obviously, the speed of the downward transport from the surface to the deep ocean is directly related to the size of the dust particles that act as the anchors. In contrast, the bio-availability of the nutrients that are potentially supplied with the dust is most



**Fig. 13** Evolution of global ice volume, and Southern Ocean dust and iron variability throughout the last 4 Myr. Blue record: benthic  $\delta^{18}\text{O}$  stack (Lisiecki and Raymo, 2005); Orange record: dust MAR. Insert: regression between benthic  $\delta^{18}\text{O}$  and Fe MAR, showing how glacial stages are generally relatively 'dusty.' Colors indicate key time intervals: 0–0.7 myr BP (blue), 0.7–1.25 myr BP (black), 1.25–2.7 myr BP (brown) and 2.7–4 myr BP (orange). Redrawn from Martínez-García A, Rosell-Mele A, Jaccard SL, Geibert W, Sigman DM, and Haug GH (2011) Southern Ocean dust-climate coupling over the past four million years. *Nature* 476: 312–315, re-used under Creative Commons CC-BY license.

likely inversely related to the size of the dust particles; the faster they sink, the smaller the chance that the phytoplankton can actually benefit from the nutrients carried by the dust grains. However, to what extent dust deposition leads to enhanced primary production and carbon sequestration through enhancing the strength of the biological pump is still debated. More research is needed to confirm these ideas and picture in detail what the role of the particle size of the deposited dust on the ocean is, both in terms of nutrient supplier as well as in terms of carbon-pump accelerator.

## Summary

Subaqueous sediments form a significant archive of mineral dust, and present-day observations of dust dispersal across the ocean and deposition into the ocean have given us insights into how the different sediment-transport and sediment-deposition processes are related to climate. There are many dust proxies related to particle size based on the idea that PSD and wind-carrying capacity are tightly coupled. However, care has to be taken with this approach as not only the horizontal- but also the vertical distance of the transport path determines the PSD of the wind-blown deposits. In addition, there are several other well-established proxies to characterize and quantify dust back in time. To reconstruct the paleo-environmental conditions that led to the deposition of these dust particles, these proxies have to be interpreted. There are still many open questions related to the particle size and chemical composition of mineral dust and its role in global climate.

**See also:** Chronology of dust archives; Dust archives within polar ice cores; Dust sources; Dust transport and deposition; Formation of dust grains and dust emission processes; Introduction; Loess records; Paleoclimatic information from loess archives; Paleosols in loess deposits

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