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The role of dust in abrupt climate change: insights from offshore Northwest Africa and Alboran Sea sediment records

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Abstract

Marine sediments are one of the best archives of past climate change since they are essentially continuous in character and their age can be determined relatively easily. During the last few decades, many paleoclimatic studies have focused on abrupt climate changes, which could be used as models of future climate changes. One of the key questions to be answered is the role of the atmosphere in triggering and transferring abrupt climate changes. In this respect, investigating the influence of eolian dust particles on climate change deserves special attention. The study of eolian dust accumulation in marine sediments is crucial not only to understand past climate change but also to explain the mechanisms of climate change in general. In this article, interactions among dust in the atmosphere and rapid climate change are discussed after a review of marine sediment records, at the glacial-interglacial and millennial temporal scales, from off the coast of Northwest Africa and the Alboran Sea.

Resum

Els sediments marins són un dels millors arxius dels canvis climàtics del passat pel seu caràcter essencialment continu i pel fet que datar-los és relativament senzill. En les darreres dècades, molts estudis paleoclimàtics s'han centrat en els anomenats «canvis climàtics abruptes», els quals hom pot prendre com a anàlegs dels canvis que poden produir-se en el futur. Un dels punts clau és el paper de l'atmosfera en el desfermament i la transferència dels canvis climàtics abruptes. En aquest marc, investigar la influència de les partícules de pols eòlica sobre el clima mereix una atenció especial. L'estudi de l'acumulació de pols eòlica en els sediments marins esdevé, doncs, crucial, no només per a entendre els canvis del passat sinó també per a explicar els mecanismes del canvi climàtic. En aquest article, hom presenta les interaccions entre la pols atmosfèrica i el canvi climàtic ràpid a partir de l'estudi del registre sedimentari marí profund aigües enfora de l'Àfrica nord-occidental i del mar d'Alboran a dues escales temporals, la glacial-interglacial i la mil·lenària.

Keywords: Eolian dust, abrupt climate change, paleoclimatology, marine sediment record

1. Overview

1.1. Present eolian dust and climate interactions: the "chicken-egg" problem

Global atmospheric circulation influences climate variability mainly through the poleward transport of the tropical *heat excess* by means of evaporation/condensation of water vapor. The modifications in location and extension of the convective cells in the atmosphere and shifts of the intertropical convergence zone (ITCZ) have had a major influence in modulating the Earth's climate throughout the Quaternary, since these processes regulate the amount of atmospheric heat transport [15]. The climatic impact of heat transport alterations can be observed at seasonal to glacial-interglacial time-scales.

While recognizing the above well-known mechanism of atmospheric control of climate variability, the Intergovernmental Panel on Climate Change (IPCC) [35] proposed prioritizing research on other processes and mechanisms involved in climate-atmosphere interactions. Therefore, one of the main priorities of the IPCC is investigating the role of atmospheric dust in present-day climate change, a topic that has received increasing attention during the last few decades. It must be noted at this point that eolian dust from desert sources accounts for 50% of the total eolian particles nowadays injected into the atmosphere, which represents $1{,}500 \times 10^6$ Tm/yr [7].

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Dust particles exert both direct and indirect influences on climate. As an example of the former, radiative and optical properties of the atmosphere are modified because of the absorption and reflection of visible, infrared and ultra-violet radiation emitted by eolian particles. *Radiative forcing* is a measure of the variation in the energy balance of the Earth-atmosphere system. Present-day radiative forcing is affected by various factors, amongst which is the presence of mineral dust in the atmosphere (Fig. 1). Whether the final effect of mineral dust on radiative forcing is overall positive or negative, however, remains unknown.

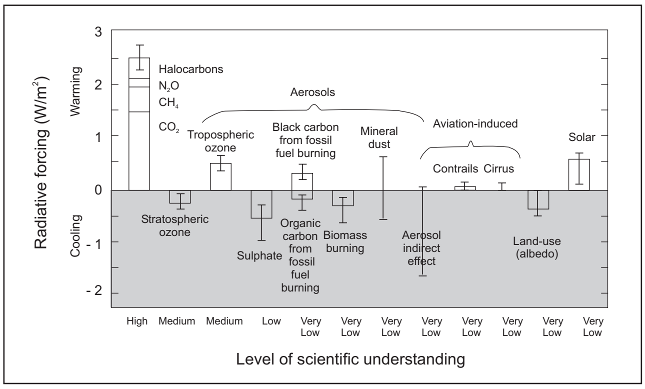

Figure 1. Several external factors that modify the global mean solar radiation. Rectangular bars, estimates of the contributions of the different forcings, some of which yield warming, and some cooling; vertical lines, a range of estimates, as guided by the spread in the published values of the forcings and physical understanding. Figure modified from the IPCC 3rd report [35].

Eolian particles in the atmosphere can cause either warming or cooling, depending on factors such as the particles' optical properties [80], their mineralogy [16], grain-size and distribution in the atmosphere [33], and the albedo of the surface on which they lie [34, 42]. For these reasons, the direct influence of dust particles on climate is far from being understood, and there is a strong need for further research before radiative forcing can be included in climate models [4].

The indirect influence of eolian mineral dust on the weak *climatic equilibrium* in our world occurs through various mechanisms, which are briefly described below. Modification of biogeochemical cycles is probably the most significant one. It has been demonstrated that eolian dust may react with ozone and N and S atmospheric compounds, thus altering the ozone concentration and modifying the biogeochemical cycles of N and S [6, 48, 32]. Moreover, since desert dust is a source of nutrients for both terrestrial and marine ecosystems, through its addition to continental soils [29] and ocean surface waters [24, 41, 51], it can modify productivity and subsequently alter the carbon cycle. An increase in oceanic productivity has been indeed observed at several places after the input of Fe via mineral dust [8, 38].

This mechanism could explain the atmospheric CO_2 reduction during glacial periods because of enhanced dust input to the ocean [9]. Dust would have caused an increment of oceanic productivity and, therefore, enhanced carbon export to the sediments and detraction from the atmosphere [10, 25]. Confirmation of this hypothesis will have dramatic implications for understanding the carbon cycle and the *greenhouse effect*.

The relationship between eolian dust and climate is bidirectional since climate influences dust generation, transport and final deposition. For several years, it was accepted that the increase in aridity and the intensification of atmospheric circulation during glacial periods led to a higher dust supply to the atmosphere. However, higher-resolution studies with large spatial coverage have recently demonstrated that the situation is more complex: the increase in eolian dust is far from being uniform, either spatially or temporarily [43, 70]. Investigating dust generation, transport and deposition requires two complementary approaches: (i) *compilation of present-day data* [5, 17, 29, 65, 74], and (ii) *implementation of models* able to reproduce the mechanisms influencing the mineral dust cycle [3, 28, 39, 50,72]. One mechanism that is currently being investigated is the influence of the sea surface temperature (SST) of the Atlantic Ocean on the variability of rainfall in the Sahel, and thus on dust transport [27, 66].

Since, currently, little is known about the nature of the feedback between dust and climate, a study of their interactions in the past may provide some clues to help climatologists better understand the observed links. As a matter of fact, the current climatic situation, or the modeled near-future scenario, can be related to past climate scenarios of abrupt climate change. The term "abrupt" in climate change research implies not only rapidity but also reaching a breaking point, a threshold. This physical definition equates abrupt climate change with a strongly nonlinear response to forcing [67]. Some examples of abrupt climate changes are found along the last glacial-interglacial cycle or at transitions (called terminations) from glacial to interglacial periods. Such changes occur over just a few decades and correspond to dramatic alterations in the climate system. The study of the forcing mechanisms for abrupt climate change, including the role of eolian dust, remains an unsolved question that occupies the paleoclimatological community worldwide.

1.2. Abrupt climate change: main theories and their pitfalls

A better understanding of the climate system on the time scale of decades or human life-time is particularly important in order to predict climate changes and to discern among natural and anthropogenic variability [35]. Paleoclimatologists have the opportunity to analyze major perturbations of the climate system that happened over a period of decades during the last glacial-interglacial cycle. These perturbations, first detected in the ice record of the Greenland Ice Core Project (GRIP) as rapid atmospheric temperature switches over Greenland, are known as Dansgaard/Oeschger cycles (D/O) [19]. These cycles occur during as little as 10-20 years, and constitute a jump of 7–10°C in mean annual atmospheric temperatures over both Northwest Europe and the Greenland ice sheet. D/O climatic fluctuations have been found in marine and lake records too, mainly in the North Atlantic region but also in tropical regions far from the direct influence of the North Atlantic [85]. Despite the many theories proposed, no consensus exists about the primary trigger of this rapid climate variability. The observed climate fluctuations over a time scale of decades cannot be related to insolation changes that occur at the scale of orbital parameters variability as explained by the Milankovitch theory. Abrupt climate fluctuations are coeval with essentially constant insolation, i.e. isotopic stage 3, or they represent general cooling when insolation reaches a maximum, such as during the Younger Dryas.

Nowadays, the most accepted hypothesis for D/O variability relates to the instabilities of global thermohaline circulation (THC), a phenomenon referred to as the *oceanic conveyor belt circulation* by Wallace Broecker in the 1980s [11] (Fig. 2a). Differences in salinity among the oceans control most of the heat transport at present. The water vapor transported from the Atlantic Ocean to the Pacific Ocean substantially helps to increase salinity in the North Atlantic thus favoring deep-water formation. The saltier, colder and denser North Atlantic deep water (NADW) flows southwards at depth into the Pacific and Indian oceans thereby compensate for their salinity deficit. The NADW is upwelled to the surface both in the Pacific and Indian oceans before being finally redirected to the North Atlantic, where it has a profound impact on European climate because of the huge amount of energy it carries back. THC oscillations have major global climatic implications and are significant modulators of continental environmental conditions. Interpretation of decadal to multi-decadal climate variability requires an understanding of THC dynamics and their importance in ocean-atmosphere feedback studies [88].

The THC hypothesis for abrupt climate change at a D/O scale relies on modeling experiments that have demonstrated that different THC modes are possible both at present and during the last glacial period [26]. The three main modes are: (i) a warm mode with strong convection in the Nordic Seas, (ii) a cold mode with weaker convection occurring south of the Greenland-Scotland sill, and (iii) a 'collapsed' mode with virtually no deep-water formation in the North Atlantic and severe cooling. Transitions between these modes appear to be most clearly associated with D/O cycles (Fig. 2b).

However, since many records showing D/O fluctuations are found outside the direct influence of deep-water convection centers, other transfer mechanisms for this climatic variability have been suggested. It is also necessary to explain the similarities and differences between latitudes. The role played by atmospheric circulation in abrupt climate change during isotopic stage 3 illustrates these hypotheses. Both a stronger latitudinal temperature gradient and a widespread polar cell reinforced wind systems during the last glacial cycle (see Sect. 1.1) [22]. Circulation over Greenland, as represented by the polar circulation index (PCI) record, also intensified during cold periods (stadials) within the D/O time-scale (Fig. 3). The PCI record was calculated from salt and dust concentrations in Greenland ice cores [52, 81]. Wind strength proxies from low-latitude regions indicate a stronger atmospheric circulation during D/O stadials too. Since the same pattern is found in loess records from China [2, 14, 49], in monsoon-influenced regions [47, 77, 86, 87] and in the western Mediterranean Sea [56, 57, 18], it demon-

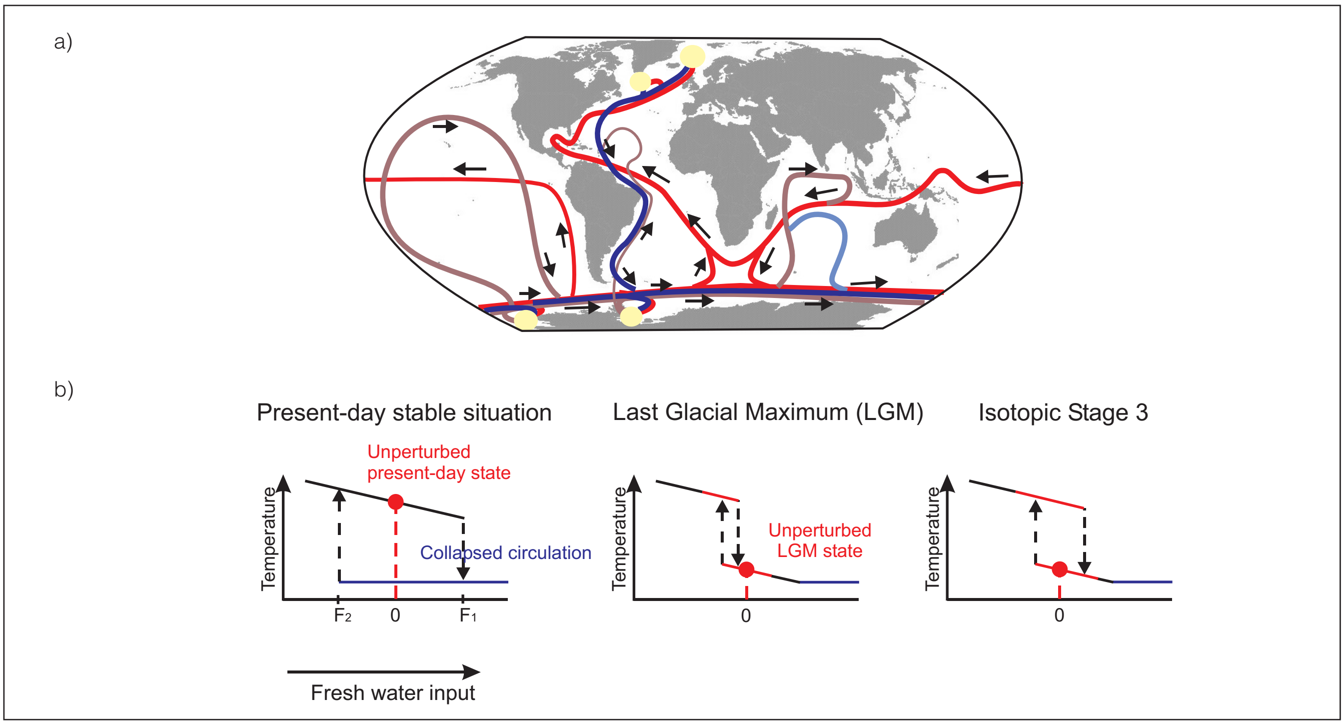

Figure. 2. **a** Cartoon of the global thermohaline circulation, as modified from [68]. Near-surface waters (red lines) flow towards the main deep-water formation regions (yellow ovals) and recirculate at depth (deep currents shown in blue; bottom currents in purple). **b** Climate (temperature) stability as a function of freshwater input at high latitudes, as modified from [61]. In this representation, the influence of freshwater (horizontal axis) on temperature (vertical axis) is shown during three different climatic periods: the stable present-day situation (left), the Last Glacial Maximum (LGM) (center), and the isotopic stage 3 (right). F2 and F1 are two threshold situations defining the hysteresis cycle: the width of this hysteresis indicates the stability of the system, which is much more unstable during the LGM or during isotopic stage 3.

strates that atmospheric circulation varies with D/O oscillations at least on a hemispheric scale.

What remains to be determined is the role of dust in rapid climate variability as related to global circulation and to the intensity of wind systems. However, only a few studies have addressed this question, through eolian dust research on sediments from the last glacial period or the inclusion of dust in model simulations. A study carried out recently in the Indian monsoon region observed that the increase in dust supplied from nearby deserts was simultaneous with the settling of colder temperatures related to D/O stadials [45]. Both the enhanced aridity and the influence of the Saharan winds detected in the Western Mediterranean during cold D/O periods point out that low-latitude feedback processes must be involved in the forcing and transfer of millennial climatic variability [56, 57, 58, 75].

In spite of the efforts made in the study of D/O oscillations, there are, of course, issues for which convincing explanations are still lacking, for example, uncertainties about tropical *versus* high-latitude teleconnections in the triggering and modulation of these abrupt climate changes. In the following section, we outline one research strategy that could be of great help in better constraining the interactions between dust and climate.

1.3. Paleorecords, databases and models

Compilation of actual data and modelling have been proposed as two research lines that can be used to study dust-climate interactions in the present-day situation (see Sect. 1.1.). In addition, the study of these interactions in certain, selected paleoclimate scenarios may be of help. Three different approaches have been taken:

Climate research on paleorecords

During the last several decades, eolian dust has been studied in many marine and terrestrial records. Although it is clear that the terrestrial environment is the most suitable for studying eolian dust accumulations, such as *loess*, more continuous and easily datable marine records provide significant advantages in carrying out eolian dust studies. Marine sediment cores indicate that dust deposition from the atmosphere at some locations was 2–20 times greater during glacial periods, raising the possibility that mineral aerosols might have contributed to climate change on glacial-interglacial time scales [71].

Creation of databases

The compilation of information regarding eolian dust has allowed the creation of specific databases, such as DIRTMAP, which has proven to be of special interest. DIRTMAP, an acronym for *Dust Indicators and Records from Terrestrial and MArine Paleoenvironments*, is an example of a database created to compare the dust-input paleodata from marine and terrestrial environments with the eolian flux model generated for the Holocene and the Last Glacial Maximum climatic periods [43]. The main objective is to evaluate the correctness of model simulations by characterizing climate change and source areas variability by means of the paleodata. In addition, these paleodata will be of great utility as inputs for new, increasingly complex and, hopefully, more accurate and realistic simulations (Fig. 4).

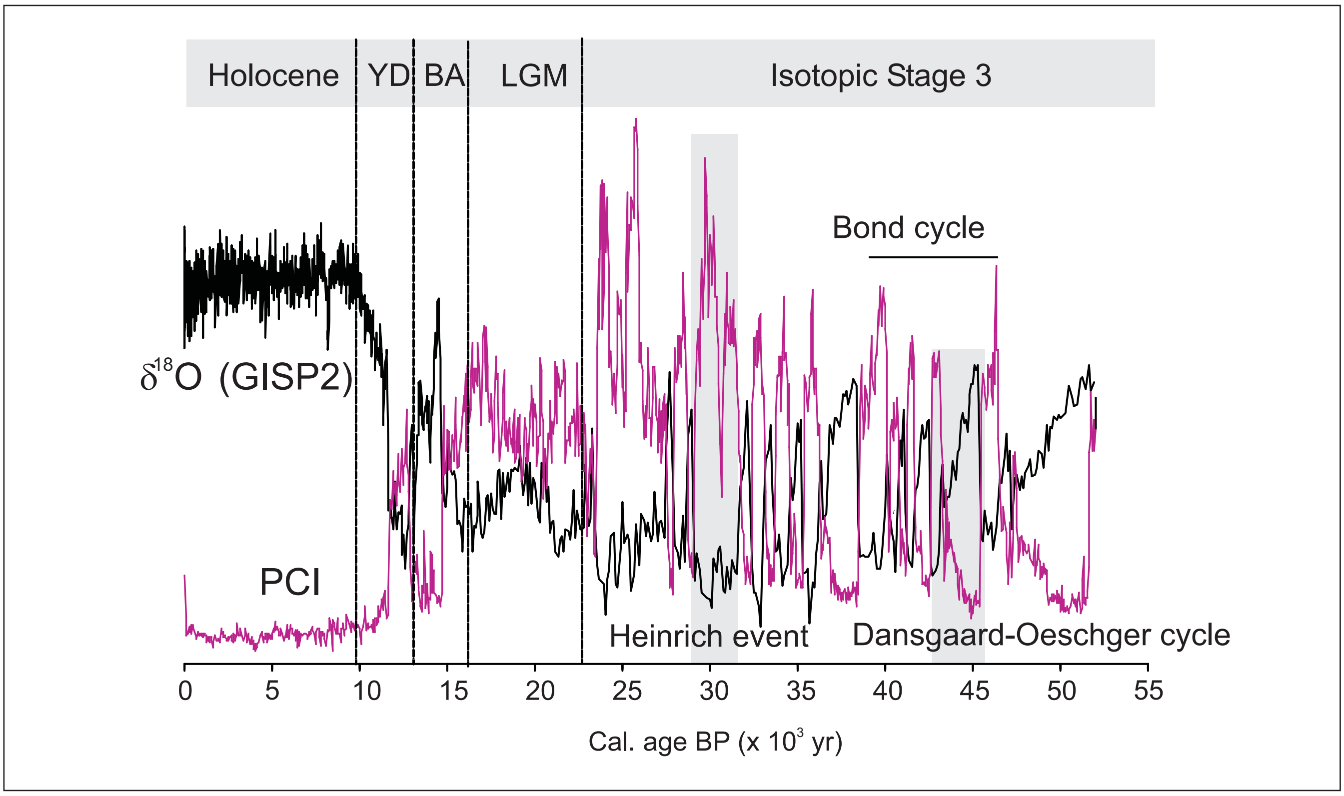

Figure 3. Records of the polar circulation index (PCI) and $\delta^{18}O$ from the GISP2 Greenland ice core plotted over the last 55 kyrs. Data were obtained from [30, 53]. Dansgaard-Oeschger cycles, Heinrich events and Bond cycles are indicated. BA, Bölling-Allerod; YD, Younger Dryas, LGM, Last Glacial Maximum.

Generation of models

Both paleorecords and databases provide an approach to understanding past climatic conditions by means of the inferences that can be made about wind stress and source areas variability. However, variations in dust flux are influenced by a combination of factors difficult to isolate. At this point, the use of models is necessary to predict the response of some environmental variables to any change in the dust supply. Several authors have used linked terrestrial biosphere, dust source, and atmospheric transport models to simulate the dust cycle in the atmosphere for current and last glacial maximum climates [3, 28, 50, 72, 79]. However, in spite of significant improvements in such simulations, some characteristics of dust particles, such as color, mineralogy, shape or grain-size, or particularities of the source area, such as type of vegetation cover, grade of humidity or roughness, have not been totally incorporated into recent models [34]. In the following discussion, we will focus on two singular studies, carried out at different time scales, that highlight the important role of dust in abrupt climate change and that do much to clarify the climatic teleconnections between tropical and high latitudes. These investigations are mainly based on results obtained from the study of marine sediment paleorecords, the first step in the paleoclimatic research strategy that was outlined above.

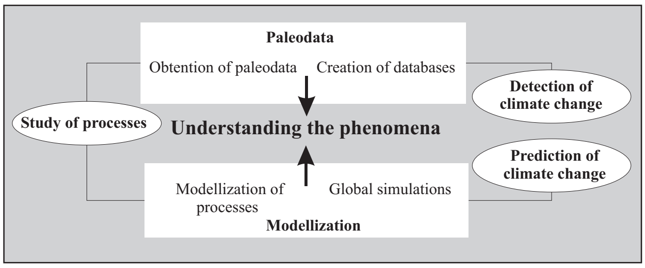

Figure 4. Relation of paleodata and models in paleoclimatic research.

2. Results and discussion

2.1. The Northwest African margin: an example of eolian dust variability at glacial-interglacial time-scales

The Northwest African margin has been a region of great interest in paleoclimatology research for nearly three decades [21, 44, 46]. In this region, a strong interaction between the atmospheric and ocean circulation systems occurs: Trade winds drive seasonal coastal upwelling while dust storm outbreaks from the neighboring Saharan desert are the major source of terrigenous sediments. In the North Canary Basin, located between 34°N and 28°N latitude in the Northwest African margin, the recovery of nearly a hundred sediment cores in the framework of the CANIGO European project (*Canary Islands, Azores and Gibraltar Observations*) during the last 5 years has promoted high-quality paleoclimatic research, as can be seen in the CANIGO special volume in *Deep-Sea Research II* [62]. Two of these gravity cores, GeoB 5559-2 and GeoB 4216-1, were studied in detail in order to investigate the forcing mechanisms for dust input and

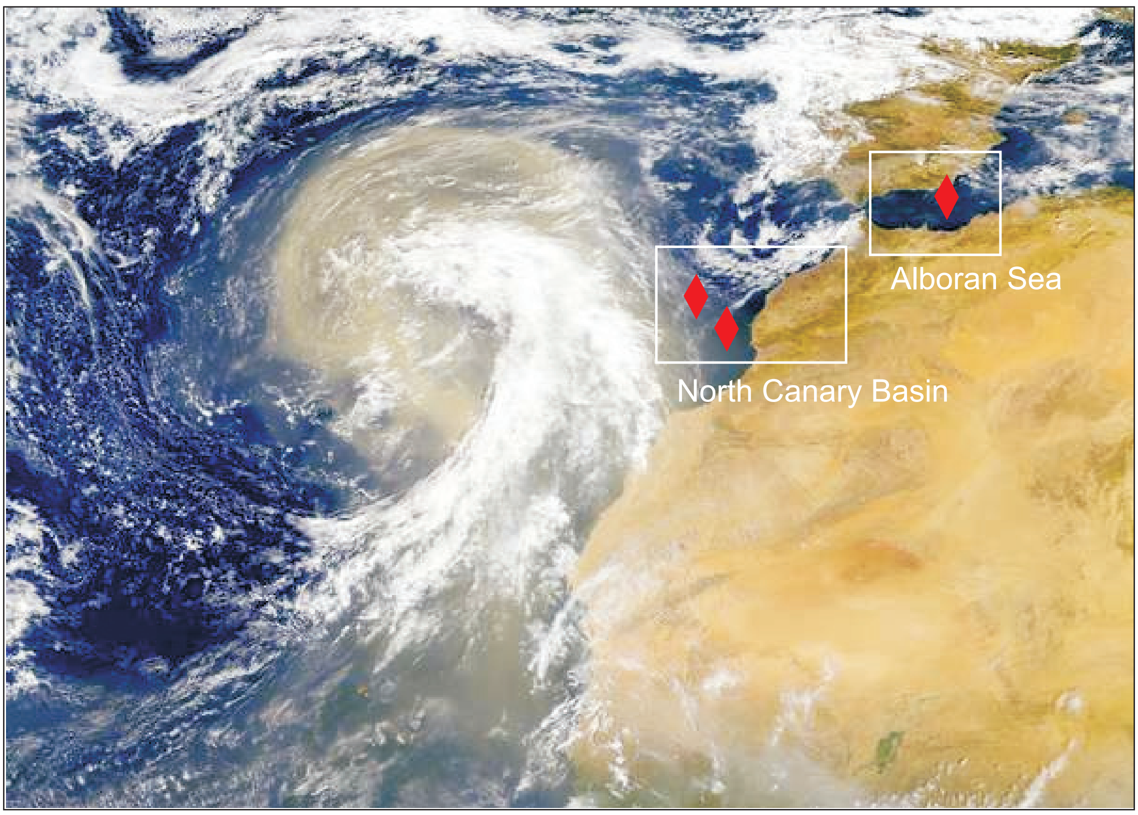

Figure 5. Situation of the studied cores (red diamonds). The satellite image shows a massive Saharan dust plume that affected the Northwest African margin and the Western Mediterranean. The photograph was taken February 26, 2000, by the SeaWiFS Project and the Distributed Active Archive Center, Goddard Space Flight Center, Greenbelt, MD, USA.

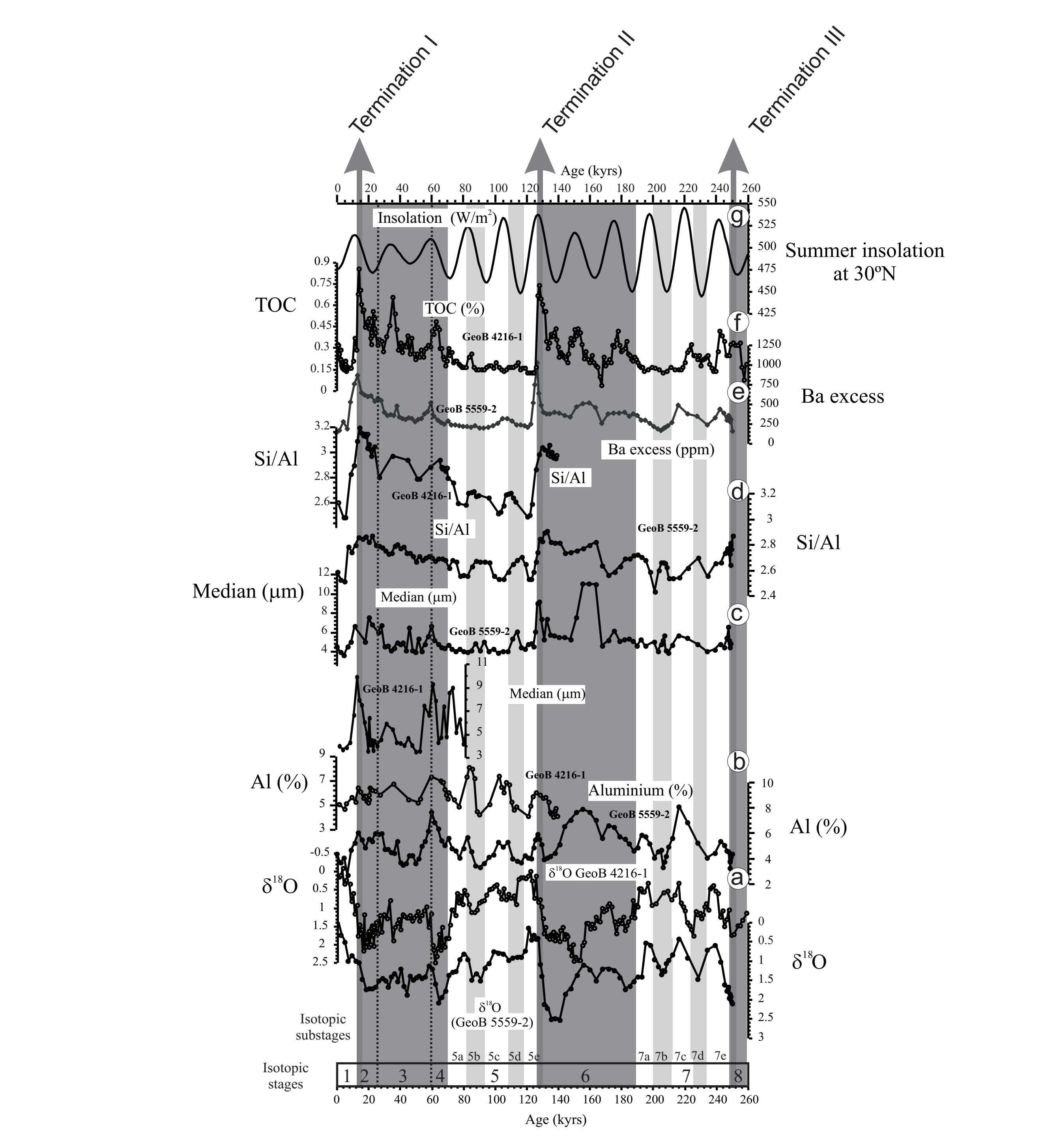

Figure 6. Downcore profiles of selected proxies obtained from GeoB 5559-2 and 4216-1 cores recovered from the North Canary Basin. Shaded bars, glacial isotopic stages and cold substages; gray arrows, glacial terminations. From bottom to top and in both cores: (a) oxygen isotopes that mark glacial-interglacial switches; (b) percentage of aluminium, (c) median grain-size (µm) of the terrigenous fraction and (d) Si/Al ratio, as dust supply indicators; (e) Ba_{excess} and (f) percentage of total organic carbon (TOC), as paleoproductivity markers. Summer insolation at 30˚N is presented in (g).

wind strength in the North Canary Basin, and the climatic teleconnections between high and low latitudes in the glacial-interglacial transitions (Fig. 5).

The Saharan region is the major source of dust particles to the deep-sea sediments of the Atlantic Ocean [78]. The vertical transport of dust particles through the water column can be fast and effective enough to reflect mass concentrations and grain-size spectra of dust entering the surface ocean [69]. Therefore, lithogenic components obtained from the studied deep-sea sediment cores will allow the history of continental aridity and wind strength fluctuations to be monitored, thus helping to understand mechanisms involved in climate change. Along the Northwest African coast, oceanic productivity is linked to the Trade winds and the Canary Current systems through the outgrowth of coastal upwelling and upwelling filaments [59]. Thus, the location of the Azores' high-pressure center and its pressure gradient are the main forcings behind upwelling intensity and the resulting productivity pattern in this upwelling region [54]. From the study of paleoproductivity variations in the sediments of the North Canary Basin, changes in Trade winds and Canary Current intensity along the last three glacial-interglacial cycles (the last 250,000 years) should be detectable. In the two studied cores, wind-strength changes are reconstructed from detailed grain-size analyses of the lithogenic sediment and geochemical markers as the Si/Al ratio. The relation between dust flux and continental aridity is obtained from the analysis of the aluminum concentration, the terrigenous flux and the Fe/Al ratio [55]. In addition, the study of paleoproductivity involved a multi-proxy approach, using calcium carbonate, barium excess (Ba_{excess}), total organic carbon (TOC) and diatoms records [56]. In Fig. 6 selected results from this study are shown. Based on a comparison of the terrigenous records (Fig. 6 b,c d) with summer insolation variation at 30°N (Fig. 6g) and after spectral analyses to detect the presence of cyclicities (not shown), we observed that the temporal variation of the terrigenous input to the North Canary Basin is mainly controlled by two orbital parameters: precession (23,000-year cycle) and eccentricity (100,000-year cycle) [55, 56]. The effect of precession has been interpreted as the influence of seasonality on dust generation and its posterior transport to the North Canary Basin. As can be presently observed, a high seasonality favors dust production and export to the atmosphere. Thus, during hot and wetter summers, monsoonal rains in the Sahel region provide the humidity that is needed for the generation of dust particles of a suitable size to be wind-transported. During cold and arid winters, the meteorological scenario facilitates the transport of dust particles by the Saharan winds [82]. Precession controls the seasonality in the source area and thus the generation and transport of dust particles, as observed by the coherent increase in Al (%) in Fig. 6b with insolation maxima (higher seasonality). However, why are maxima in grain-size of the terrigenous fraction (Fig. 6c) and in the Si/Al ratio (Fig. 6d) observed at glacial-interglacial transitions? The observed variations at terminations can be interpreted as being related to changes in the energy of the transporting wind [31]. [71] and [76] found glacial-interglacial patterns of variation in their records, south of the Canary Islands. They concluded that the increase in particle grain-size under full glacial conditions was related to higher Trade-wind intensities. Although there is also a glacial-interglacial variation in the North Canary Basin grain-size records, the coarsest grain sizes are recorded at terminations and not at glacial maxima. Notably, these grain-size maxima coincide with peaks in Ba_{excess} and TOC records (Fig. 6e, f). As argued before, wind and productivity are linked to Trade-wind strength. Therefore, the Trade winds in this region are strongly intensified at terminations. Terminations are unique intervals of climate change in which the climate switches from a glacial to an interglacial mode. In these intervals, maxima in boreal summer insolation, rapid ice-sheet melting and fast rates of sea-level rise concur. These characteristics deserve attention when trying to explain the wind strength and productivity peaks found in GeoB 5559-2 and GeoB 4216-1. [60] proposed, and tested using general circulation models, that the lowering of the North Atlantic sea surface temperature (SST) by glacial-melt-water releases during deglaciation strengthened the North Atlantic high-pressure system, thus favoring the enhancement of Trade-wind velocities. This ocean-wind system connection can be explained taking into account the higher thermal difference between land and sea that was reached during terminations. The temperature contrast may modulate the Azores' high-pressure intensity leading to an enhancement of the Trade-wind system. This hypothesis of a coupled tropical/high-latitude North Atlantic climate system operating during the last deglaciation is, in addition, supported by various tropical records [20, 36, 80]. Therefore, high-latitude low SST anomalies at terminations can enhance the Trade winds and thereby explain productivity events observed in the areas located under their influence. Finally, this study postulates that the lowering of the North Atlantic SST by melt-water discharges, which in turn strengthened the Azores' high-pressure center and increased Trade-wind velocities, can be the mechanism to explain the enhancement of the coastal upwelling and associated filaments at terminations. This new finding is relevant to the investigation of the interactions among dust input and climate because it aid in determining whether the higher dust supplied at the end of glacial periods was caused by a climate change or whether this higher input of eolian dust was one of the potential triggering mechanisms for the glacial-interglacial switches by means of the interferences of dust in the solar radiation that the Earth receives. The evidence presented here, together with several recent paleoclimate studies carried out at tropical latitudes [23, 63, 83, 84], demonstrates the participation of the tropics in global climate changes. The sentence *"the tropics return to the climate system"* that is ascribed to R. A. Kerr [40] reflects clearly that low latitudes are now an extremely interesting area of paleoclimate research. The key is to find out whether low latitudes act as a *participant* or a *driving force* in these abrupt climate changes. To delve further into this question, higher resolution studies of dust input and wind strength from tropical areas are needed to detect the temporal leads and lags between high and low latitudes.

2.2. The Western Mediterranean: investigation of Saharan dust input at suborbital time-scales in a high sedimentation area

The higher sedimentation rates found in the Alboran Sea (Western Mediterranean) allow investigation of the above outlined question at greater temporal resolution than obtained in the cores from the Northwest African margin. The intermediate position of the Mediterranean region and its semi-enclosed character that often amplifies environmental changes make this area a key location in investigating climatic connections between high and low latitudes during abrupt climate changes, such as those related to D/O cycles (see Sect. 1.2). Recent studies have shown a strong correla-

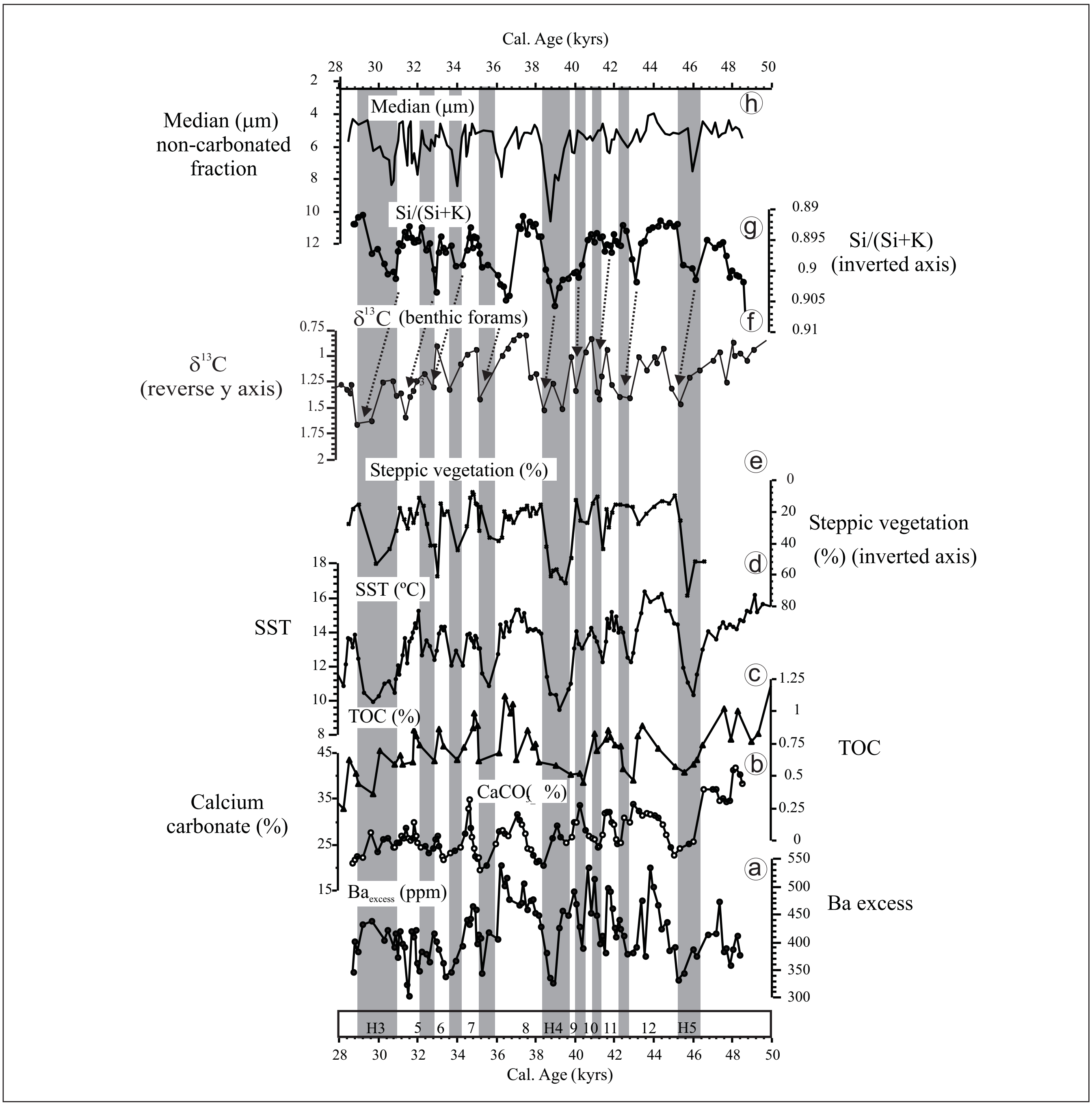

Figure 7. Downcore profiles of selected proxies obtained from the IMAGES MD95-2043 core recovered from the Alboran Sea. Shaded bars, cold Dansgaard/Oeschger (D/O) stadials and Heinrich events; D/O interstadials are numerated. From bottom to top: (a) Ba_{excess}; (b) percentage of calcium carbonate, (c) percentage of total organic carbon (TOC) as paleoproductivity markers; (d) sea surface temperature (SST) obtained from the alkenones concentration, (e) abundance of steppic vegetation, (f) $\delta^{13}C$ measured in benthic forams, (g) Si/(Si+K) ratio and (h) median grain-size (μm) of the terrigenous fraction. Arrows, temporal lead of the Saharan dust indicators (e.g. Si/Si+K ratio) with respect to the northwesterly proxies (e.g. $\delta^{13}C$ as a measure of deep-water ventilation [13]).

tion between marine and lacustrine sediment records in the Mediterranean area and Greenland ice core records at the scale of the D/O cycles [1, 12, 75]. Therefore, we carried out grain-size and geochemical analyses in the IMAGES core MD 95-2043 (Fig. 5) in order to provide new terrestrial records that can be compared with previously published marine and vegetation cover indicators from the same core without dating uncertainties in the proxy correlation. This approach allows a better understanding of the temporal leads and lags between marine and terrestrial environmental shifts and helps to elucidate the underlying mechanisms of millennial-scale climatic variability. Several selected results of this study are presented in Fig. 7 [57]. Millennial variability linked to D/O cycles is evident in the entire dataset. We propose that the observed proxy pattern is best explained by a variability in wind systems and precipitation patterns over the Mediterranean region that was driven by rapid switches between two modes of atmosphere circulation over the North Atlantic region. Therefore, our results can be interpreted according to the following two scenarios: (1) as being related

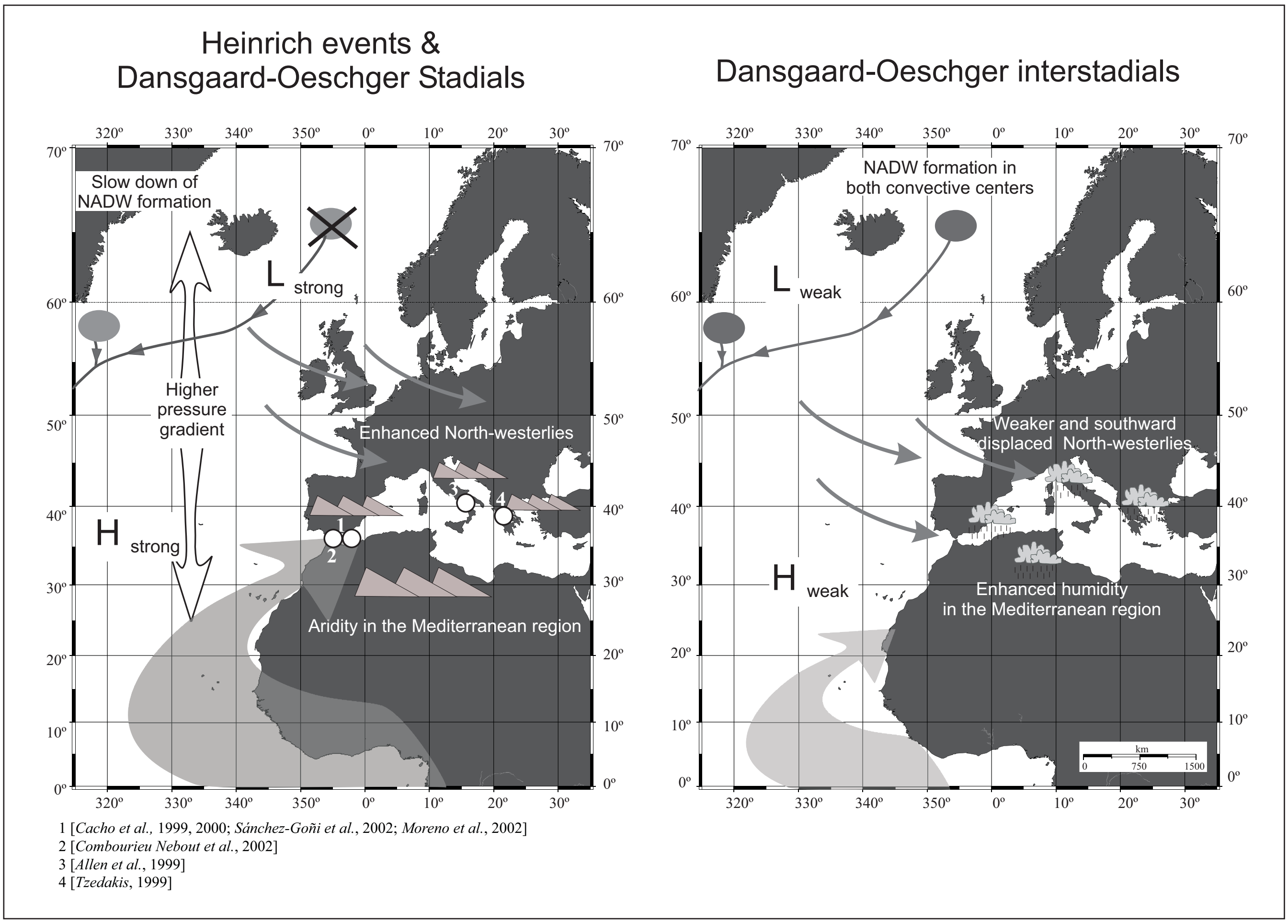

Figure 8. Dansgaard/Oeschger (D/O) scenarios that summarize the main processes and features that controlled the Alboran record during Heinrich events and D/O stadial (left) and D/O interstadial periods (right)

to cold stadial periods (lower SST), and (2) associated with a warm interstadial period (higher SST) of a hypothetic D/O cycle (Fig. 8). The definition of these two scenarios is based on several present-day mechanisms, such as the North Atlantic Oscillation, NAO, and, in (1), modeling results obtained with millennial-resolution [26]. The NAO drives much of the present-day climate variability in the studied region on a time-scale of decades [73]. This climatic system connects the properties of the North Atlantic ocean with the atmospheric variability in the Northern Hemisphere [37]. The NAO index results from measuring the normalized winter sea-level atmospheric pressure difference between the Azores' High and the Icelandic Low. A high NAO index (stronger pressure gradient) pushes westerlies northwards and induces drier conditions over the Mediterranean region. During low NAO index years, weaker north-westerlies are displaced southward, causing higher precipitation over the Mediterranean and large areas of North Africa. We therefore suggest that an atmospheric pressure gradient seesaw similar to today's NAO system may explain the records we obtained for the Alboran Sea. This glacial atmospheric oscillator operated on a millennial time scale, causing prolonged states of climate that are similar to the much shorter periods of today's NAO extremes. Thus, in one mode (Fig. 8a), atmospheric pressure gradients in the North Atlantic region were high so that northwesterly wind intensity over the Mediterranean area was increased, as pointed out by some previous studies in which the intensity of the Mediterranean overturning was analyzed by means of terrestrial biomarkers and $\delta^{13}C$ measured in benthic forams [13]. This mode would arise in response to a decreased North Atlantic SST driven by a slow-down of the thermohaline overturn and decreased northward marine heat transport during D/O stadial periods and Heinrich events. This would have favored both drier conditions and more intense Saharan winds, which ultimately would have resulted in increased meridional transport of Saharan dust. Records of Si/K, grain-size and abundance of steppic vegetation are coherent with this reasoning (Fig. 7e, g, h). By contrast, the interstadial periods (Fig. 8a) would have been characterized by weak atmospheric pressure gradients in the North Atlantic that may have favored the southward displacement of northwesterly winds. This situation implies an enhancement of rainfall in the Mediterranean region [75]. The southward location of the westerly winds and the stronger input of fluvially transported nutrients may have been the triggering mechanisms for the increases in paleoproductivity, as highlighted by the maximum values of barium, TOC and carbonate (Fig. 7a, b, c). In this way, the obtained results in the Alboran core can be integrated into the climate context of the North Atlantic and at the same time demonstrate the close connection with subtropical latitudes. Previous studies have suggested that the tropics responded at the climatic millennial time-scale with an increase in the strength of the wind system (see also [2], [47], [64], [77]). However, in order to assign a role to the tropical latitudes in these observed abrupt changes, the temporal leads and lags between wind systems should be determined. From the Alboran record presented in Fig. 7, it seems that the maxima in the Saharan winds lead to maxima in the northwesterly wind system (see arrows connecting maxima in Si/K ratio and the $\delta^{13}C$ measured in benthic forams, Fig. 7f, g) by an average of 250 years. Although the leading of tropical processes with respect to those from higher latitudes needs to be confirmed by further studies, our results highlight the potential importance of dust supply from low latitudes in the global rapid climatic variability.

3. Towards a better understanding of the role of dust in abrupt climate change

The study of abrupt climate change, particularly paleoclimate research related to D/O cycles and glacial terminations, seems to have arrived at a critical point in its evolution. Until now, most efforts have focused on obtaining a detailed dataset from high-sedimentation areas, especially from the North Atlantic region but also from the Southern Ocean and the tropical regions. In the following, we discuss several ideas that may be taken into account in order to improve this line of paleoclimate research and to understand the role of dust in abrupt climate switches. First of all, a wider spatial coverage of eolian dust paleodata is required. It is necessary to produce eolian dust records from all the latitudes with enough resolution to detect abrupt climate changes. The temporal resolution is crucial in order to be able to identify the leads and lags between different areas or processes and then to assess the climatic teleconnections. Thus, indicators from land and sea paleoenvironments should be compared and interpreted together without dating uncertainties. For that purpose, the integration of eolian paleodata in datasets, such as DIRTMAP, is a very helpful initiative to better understand the atmospheric-oceanic links. We think that a similar paleodata base with the D/O cycles as the selected time slices needs to be created so that eolian indicators provided by these databases can be incorporated into new models and aid in the simulation of the characteristics of both stadial and interstadial scenarios. The conclusions from the last IPCC report [35] alert to the forthcoming climate changes and its potential repercussions in the following years. The study of abrupt climate change during selected intervals of the Earth's history is an opportunity to evaluate the approaching global warming from a historical perspective. In that kind of paleoclimate research, the role of dust should be studied and discussed.

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