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Orbitally-induced changes of the Atlantic and Indian monsoons over the past 20,000 years: New insights based on the comparison of continental and marine records

ANNE-MARIE LÉZINE¹, FRANCK BASSINOT² and JEAN-YVES PETERSCHMITT²

Key-words. – African and Indian monsoon, Last glacial period, Holocene, Continental hydrology, Wind transport, Marine records.

Abstract. – Variations of Atlantic and Indian monsoon systems since the last glacial period are investigated by comparing eolian fluxes from two marine cores (ODP site 658 off western Africa and core 74KL off the Arabian peninsula) with 2147 hydrological records (lacustrine, palustrine, spring and fluvial, arid) gathered over a large continental area extending between 10 and 30°N across Africa, Arabia and western India. We show that the hydrological response to the Holocene humid phase in the northern tropics strongly differs from a region to another. The humid period is significantly shorter in the Arabian peninsula and the horn of Africa compared to northern Africa even though its maximum is contemporaneous (11,000-7,000 cal yr BP). Western India displays a specific hydrological signal characterized by the importance of well-developed fluvial systems from the Himalayas and the paucity of lakes compared to the other regions. In western India, the humid peak is shifted toward the mid Holocene (8,000-6,000 cal yr BP). Both marine records show a peak between ~ 11,000 and 7,000 cal yr BP for the Holocene humid period, in good accordance with African-Arabian records. However, while continental hydrological data suggest that the onset and termination of this humid period might have been relatively progressive, the marine windborne records indicate abrupt transitions, somewhat out-of-phase with continental evidence (e.g. abrupt decrease of aeolian proxies as early as ~ 15,000 cal yr BP). Discrepancies between marine and continental likely result from the fact that aeolian fluxes at a given marine location do not simply record monsoon-related changes of humidity over the adjacent continental sources but could be affected also by changes of the source area (e.g., emersion of the Arabo-Persian gulf associated to the glacial, low sea-level stand), and changes in wind intensity and/or direction.

Changements orbitaux et variations des moussons atlantique et indienne au cours des derniers 20 000 ans : nouveaux développements basés sur la comparaison de données continentales et marines

Mots-clés. – Mousson africaine et indienne, Dernière période glaciaire, Holocène, Hydrologie continentale, Transport éolien, Enregistrements marins.

Résumé. – Les variations des moussons atlantique et indienne depuis la dernière période glaciaire sont étudiées en comparant les flux éoliens enregistrés dans deux carottes marines (Site ODP 658 au large de l'Afrique occidentale et carotte 74KL au large de la Péninsule arabique) avec 2147 témoins hydrologiques datés (lacs, marécages, sources, fleuves et témoins d'aridité) provenant d'une vaste zone continentale s'étendant entre 10 et 30°N à travers l'Afrique, l'Arabie et l'Inde occidentale. Nous montrons que la réponse hydrologique à la phase humide holocène dans les zones nord-tropicales diffère fortement d'une région à l'autre. La période humide est nettement plus courte dans la Péninsule arabique et la Corne de l'Afrique par rapport à l'Afrique du Nord, même si son maximum est contemporain (11,000-7,000 cal BP). L'Ouest de l'Inde affiche un signal hydrologique spécifique caractérisé par l'importance de systèmes fluviaux prenant leur source dans l'Himalaya et la rareté des lacs par rapport aux autres régions. Dans cette région, le pic humide est déplacé vers le milieu de l'holocène (8,000-6,000 cal BP). Les deux enregistrements marins montrent un pic entre ~ 11,000 et 7,000 cal BP pour la période humide holocène, en accord avec les enregistrements africains et arabes continentaux. Cependant, alors que les données hydrologiques continentales suggèrent que le début et la fin de cette période humide ont pu être relativement progressifs, les données de transport éolien indiquent des transitions brusques, un peu hors de phase avec les données continentales (par exemple, diminution brutale de proxies éoliens dès ~ 15,000 ans cal BP). Les écarts entre les données marines et continentales trouvent probablement leur explication dans le fait que les flux éoliens n'ont pas seulement enregistré les changements d'humidité liés à la mousson sur les continents adjacents, mais pourraient également être affectés par des changements de zone source (par exemple, émergence du golfe arabo-persique associé à la baisse du niveau de la mer en période glaciaire), et par les changements dans l'intensité et/ou la direction du vent.

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INTRODUCTION

Northern tropical semi-arid and desert areas from Africa, Arabia and western India have experienced high amplitude climate changes during the last thousand years with dramatic effects on human populations. During the early Holocene Humid period, agriculture and animal husbandry extensively developed [Küper and Kröpelin, 2006]. Then, as climate became drier toward the end of the Holocene [e.g., Gupta *et al.*, 2003; Kröpelin *et al.*, 2008], deep social changes accompanied the exploitation of decreasing resources by human populations [e.g., setting of sedentary populations in the Nile valley at the origin of the Pharaonic civilization after 4,500 cal yr BP [Küper and Kröpelin, 2006]; rise of complex social systems at the beginning of the Early Bronze Age in southern Arabia [Lézine *et al.*, 2010]; collapse of the Harappan civilization 3,900 years ago in the Indus valley [Giosan *et al.*, 2012]. Several studies combining proxy data and climate model simulations have shown that changes in insolation controlled by the slow variation of the Earth orbital parameters (mainly precession), have been the major driver of Holocene changes in atmospheric circulation and in the hydrological budget, which are ultimately linked to the afro-asian monsoon system [e.g. COHMAP, 1988; Prell and Kutzbach, 1987; Joussaume *et al.*, 1999; Liu *et al.*, 2003; Marzin and Braconnot, 2009 a,b; Bassinot *et al.*, 2011; Lézine *et al.*, 2011a]. During the first half of the Holocene, orbital configuration resulted in enhanced seasonality in northern tropical areas compared to the late Holocene. The stronger early Holocene insolation during boreal summer led to the increase in inter-hemispheric and land-ocean temperature contrasts, which triggered summer pressure lows over the Tibetan plateau and in the Sahara. This enhanced the monsoon flow from the moist tropical ocean into land during the early Holocene. However, regional feedback mechanisms such as the impact of water column stratification on monsoon inception and intensity [e.g. Ohgaito and Abe-Ouchi, 2007; Braconnot *et al.*, 2008; Marzin and Braconnot, 2009] or the role of vegetation on open water surfaces evaporation/precipitation mechanisms [e.g., Krinner *et al.*, 2012] have been at the origin of short-scale climate variations superimposed to the above mentioned insolation-driven, large-scale monsoon changes.

In this article, in order to better unravel the orbitally-driven changes in African and Indian monsoons since the last glacial period, we compare an extensive dataset of continental sedimentary records with two well-known marine records from the sub-tropical eastern Atlantic and western Arabian sea. This comparison makes it possible to address properly the significance of proxy changes and discuss the timing and amplitude of the late Pleistocene-Holocene climate changes in the north tropical areas along a West-East transect extending from the eastern Atlantic ocean, to the northern Indian ocean between 10 and 30°N. The time-interval studied extends from the last glacial period to the present day.

MODERN CLIMATIC SETTING AND TRANSPORT OF CONTINENTAL SEDIMENTARY MATERIAL TO THE OCEAN

The climate of the studied area is characterized by seasonal reversal of the atmospheric circulation (fig. 1, two upper

panels) and migration of the intertropical convergence zone (ITCZ) with its associated tropical rain belt. In summer, southwesterly surface winds carry moisture from the Atlantic and Indian oceans to the adjacent continents. Atlantic monsoon fluxes penetrate far northward over northern Africa to the tropic of Cancer and eastward to eastern Sudan whereas the easternmost areas of northern Africa are mainly subjected to the Indian monsoon influence. SW Indian monsoon fluxes follow the southern Arabian coasts then penetrate eastward to southern Iran, Pakistan and western India. In winter, Mediterranean depressions penetrate south through the Red sea and the Arabo-Persian gulf corridors whereas strong, northeasterly winds intensify dry conditions over continents. In these arid and semi-arid areas, availability of sediments for aeolian transport from arid and semi-arid areas, together with the vigorous atmospheric circulation result in the transfer of large quantities of lithogenic material to the adjacent oceans providing a direct link between continental climate and marine sedimentation. Airborne lithogenic material from the Sahara and Sahel are transferred over long distances across the sub-tropical Atlantic. Dust source areas are mostly located in mountains foothills where episodic drainage and the wadis opening to fluvial fans provide a large amount of sediment available for aeolian erosion [Washington *et al.*, 2003; Schepanski *et al.*, 2007]. These main sources are located in the Bodélé depression, as well as the central Saharan massifs (Hoggar and Tibesti) and western Sahara. During summer, large dust outbreaks that can be traced as far as the Caribbean are associated with strong convective disturbances in the monsoonal frontal systems, which uplift dust particles to the mid troposphere. These particles are then transported westward by the African easterly jet [Schültz *et al.*, 1981; Pye, 1987; deMenocal *et al.*, 2000a; Goudie and Middleton, 2000].

Over the Arabian sea, sediment trap data and meteorological observations of mineral aerosol concentration indicate that aeolian transport of lithogenic material is also maximal during the summer season [Middleton, 1986; Ackerman and Cox, 1988; Sirocko *et al.*, 1991], and decreases by at least an order of magnitude during the winter season [e.g. Savoie *et al.*, 1987]. Satellite images and mineralogical analyses of windborne particles show that most of the dust transported to the ocean comes from Arabia, with the northernmost transport track running from Mesopotamia via the Arabo-Persian gulf to the coast of Oman [Ackerman and Cox, 1988; Sirocko *et al.*, 1991, 1993]. Most of the fine particles brought to the Arabian sea are convectively lifted from arid areas to the low and mid troposphere where they are transported by northwesterly winds, which override the low-level southwest monsoon winds. In comparison to this dominant transport by mid-troposphere winds, the proportion of lithogenic dust uplifted in Somalia and transported to the Arabian sea by the low-altitude, southwest monsoon winds seem to be relatively insignificant [Sirocko *et al.*, 1991], although Clemens and Prell [1990] reported grain size variations in upper Pleistocene marine sediments that suggest a link with past changes in SW monsoon intensity. A transport by SW monsoon winds is also evidenced by the occurrence of East African pollens in sediments from the Arabian sea [van Campo *et al.*, 1982; Prell and van Campo, 1986].

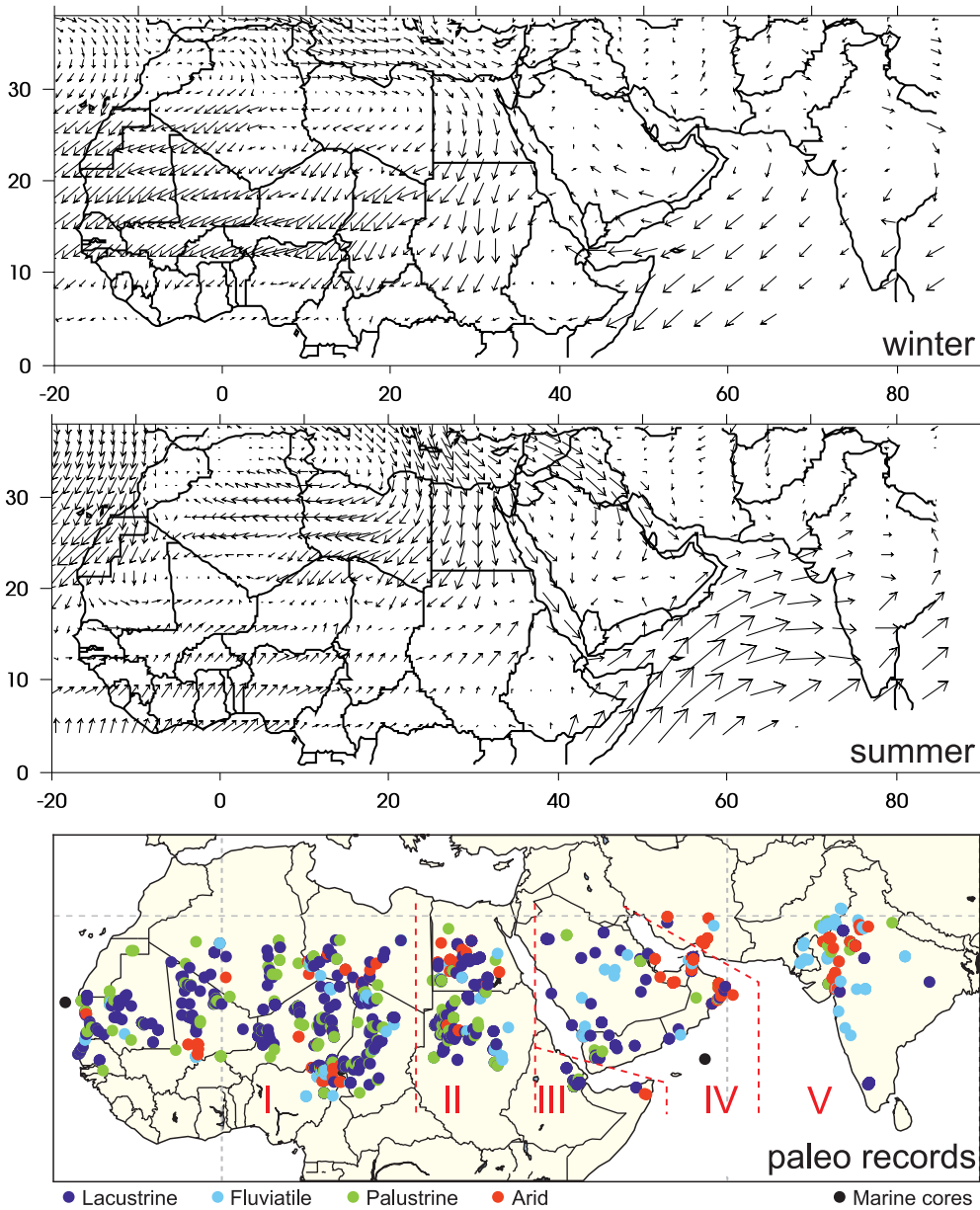


FIG. 1. – Upper panels: surface wind conditions (1000 hPa) for winter (DJF) and summer (JJA) months (ECMWF analyses 1990-1997). Lower panel: location of the dated sedimentary records used in this paper. Numbers refer to the four areas detailed on figure 2.

DATA AND METHODS

Continental data

Past extension of lakes, wetlands and rivers can be reconstructed from a variety of paleolimnological evidence including abandoned shorelines, sedimentary outcrops, aquatic pollen types from sediment cores, remains of aquatic faunas such as hippos, fishes and shells and fluvial paleo-terraces. Paleohydrological variations can also be inferred from paleosalinity reconstructions based on micro-remain assemblages (diatoms, chironomids, ostracods) and stable oxygen isotope ratios of carbonates (bulk carbonates, ostracods or gastropod calcite...). Our data set is composed of 2147 dated samples extracted from 303 publications (fig. 1, lower panel). This data set covers a wide area, from the present day Sahara and Sahel to eastern

Africa, Arabia and India between 10 and 30°N. We have grouped these samples into four hydrological categories: (i) “lacustrine”, corresponding to high levels/permanent lakes and playas; (ii) “fluvial terraces” and “spring deposits”; (iii) “palustrine”, corresponding to intermediate and low lake levels, swamp deposits and paleosoils; and (iv) “arid” including aeolian-formed deposits (sand dunes). Each sample was assigned to its specific category by taking into account the original interpretation of the authors and our own knowledge of tropical paleohydrology [Lézine *et al.*, 2011]. Dating is based (i) on accelerator mass spectrometry (AMS) and conventional radiocarbon dates obtained on lake carbonates, remains of aquatic faunas and organic matter, and (ii) on optically-simulated luminescence and thermoluminescence (OSL/TL) dates obtained on quartz grains. Raw ¹⁴C dates were converted to calendar ages using CALIB6.0 [Stuiver *et al.*, 2005] taking into account, when possible,

^{14}C age distortions linked to old carbon from the aquifer [Fontes and Gasse, 1991]. Paleohydrological records from northern Africa have already been discussed in Lézine *et al.* [2011a]. Additional records located around the Arabian sea (eastern Africa, Arabia, and western India) come from the literature and our own investigations in southern Arabia [Lézine *et al.*, 1998; 2010]. Most of these records are dated levels occurring in discontinuous sedimentary sequences, as is usual under predominantly arid climate conditions.

Our database contains only dated samples. Thus, it may underestimate the full duration of events and may fail to resolve rapid fluctuations of the water level linked to short-term, climatic changes. These radiocarbon or OSL dates show also various levels of accuracy. Nevertheless, the compilation of a large number of dated samples and their spatial and temporal occurrence should compensate for the discontinuity of individual, sedimentary records and database heterogeneity. One thousand years is the shortest time interval that we can resolve given uncertainties associated with conventional radiocarbon dates. The database only imperfectly reveals the hydrological response to rapid climate fluctuations but gives valuable information on the long-term relations between rainfall patterns, aquifers and fluvial systems over the whole region.

Marine data

ODP site 658 [deMenocal *et al.*, 2000a,b] and piston core 74KL [Sirocko *et al.*, 1993] provide reference records of regional climate fluctuations during the late Pleistocene and the Holocene in the eastern tropical Atlantic ocean and in the Arabian sea, respectively.

ODP Site 658 provides a detailed (~100 yr resolution) and well-dated (31 AMS ^{14}C dates to 24,000 cal yr BP) record of aeolian (% terrigenous) sedimentation off Cap Blanc, Mauritania (20°45'N, 18°35'W, 2263 m). We used the revised age model published in deMenocal *et al.* [2000b] in which ^{14}C dates were converted to calendar ages using the CALIB software [Stuiver and Reimer, 1993] and assuming a constant surface reservoir age of 500 ± 50 years. The record covers continuously the last ~14,000 cal yr BP, and from ~17,400 to 24,500 cal yr BP with a brief hiatus detected between 328 and 324 cm (17,400 and 14,300 cal yr BP). ODP 658 is ideally located to provide a record of dust availability and transport from the subtropical African area since it is positioned below the summer African dust plume, which transports fine terrigenous minerals from the sub-Saharan and Sahel regions [Sarnthein, 1978; Tetslaff and Wolter, 1980; Grousset *et al.*, 1998].

Core 74KL is located in the upwelling area of the western Arabian sea (14°19'N, 57°21'E, 3212 m). The lithogenic material found in core 74KL is mainly aeolian, originating from the adjacent Arabian area. We focused on the proportion of dolomite, a windborne material derived from Mesozoic strata that are predominant only in the northern Arabia, or from Sebkha sediments around the Persian gulf [Sirocko *et al.*, 1991, 1993; El-Sayed, 1999]. The %dolomite record of core 74KL [Sirocko *et al.*, 1993] provides a continuous and well-dated (14 AMS ^{14}C dates to ~24,000 cal yr BP) record of dust availability and transport from the North and East of Arabia. We revised the published age model of core 74KL [Sirocko *et al.*, 1993] by converting the ^{14}C dates to calendar ages using the

CALIB6.0 software [Stuiver and Reimer, 1993; Stuiver *et al.*, 2005] with the recent Marine 09 calibration curve [Reimer *et al.*, 2009] and assuming a global surface reservoir age of 400 yr with a regional correction of $\Delta R = 215 \pm 52$ (estimated based on the 9 most proximal reservoir ages from the database of Southon *et al.* [2002]). This revision led to calendar ages that are in average ~700 years younger than the published age model, with a maximum shift of ~1,400 years at around 14,700 cal yr BP.

Because core 74KL is located within an upwelling system driven by active Eckman pumping during the SW monsoon, it is likely that reservoir ages may have varied in the past in response to changes in monsoon wind intensity. Saliège *et al.* [2005] have studied past changes of Holocene reservoir ages in the Arabian sea. Using Saliège *et al.*'s estimates of past reservoir ages, we constructed an alternate age model. It results in similar calendar ages down to ~5,500 cal yr BP. During the Holocene climatic optimum, however, alternate ages depart significantly from ages obtained assuming a constant age-reservoir; the alternate ages being about ~600 yr younger at about 8,500 cal yr BP (around the expected maximum of summer wind intensity associated to the peak in boreal summer insolation). Before this period, the age difference drops down to only ~300 yr at ~11,000 cal yr BP, the lower limit of Saliège *et al.*'s study. The curve of percent dolomite in core 74KL is displayed with these two age models on figure 3.

ODP Site 658 is also located in an upwelling area. Past changes of upwelling intensity have been scrutinized by normalizing carbonate and opal fluxes based on excess ^{230}Th [Adkins *et al.*, 2006]. Results show that the early Holocene humid period corresponds to a decrease in coastal upwelling. This decrease in upwelling intensity off western Africa is out of phase, therefore, with the early Holocene increase in western Arabian sea upwelling [e.g., Bassinot *et al.*, 2011]. Although no data is available to estimate and correct past changes in age reservoir at ODP 658, we expect that ^{14}C -derived chronologies of sites 74KL and ODP 658 may be off by several hundred years over specific intervals due to changes in upwelling intensity. This uncertainty should be kept in mind when considering phase relationship between these marine records, as well as between these records and continental datasets.

RESULTS

Continental data

In order to subdivide our continental dataset into internally consistent, climate areas, three main regions have been distinguished in Africa based on the respective influence of monsoons originating from the Atlantic and/or the Indian oceans. These three African regions are, from west to east: (i) western Africa from the Atlantic coast to the eastern border of Chad which encompass areas under the predominant influence of the African monsoon, (ii) eastern Africa including Sudan and Egypt, which are also potentially influenced by the Indian monsoon, and (iii) the horn of Africa including northern Ethiopia, Djibouti and Somalia, which is exclusively influenced by the Indian monsoon. Other data from landmasses surrounding the western Indian ocean have

been grouped into two distinct sub-provinces: the Arabian peninsula (iv) and the western coast of the Indian sub-continent (including Pakistan, Iran and western India (v).

“Arid” (mostly sand dunes) dated samples are irregularly distributed without any direct link with the occurrence of dry areas in the present-day landscape, particularly in Africa. Humid paleohydrological indicators (lacustrine *s.l.*, palustrine and fluvatile) display a rather wide distribution. There are mostly found in Africa with 1445 “humid” records, 848 of which coming from western sites, and 486 from eastern sites. The amount of dated records reflecting humid conditions drops to only 118 in the horn of Africa. A total of 186 dated records reflecting humid conditions has been reached for both Arabia and western India (*s.l.*) sites. The striking difference in the amount of dated samples indicative of humid conditions that are found in sedimentary records from the five main regions does not simply result from the more or less intensive involvement of the scientific community in specific areas (i.e. the strong German research effort in the eastern Sahara [Lézine *et al.*, 2011a and references therein]). This difference also results from local hydrological and geomorphological conditions, which are not always favorable to the establishment of lakes. In particular, paleolakes are scarce in areas bordering the Arabian sea and the eastern Indian ocean (except in Rajasthan). In the later region, however, fluvial terraces have been extensively studied and provide evidence of variations in past fluvial activity related to monsoon fluctuations [e.g., Sinha *et al.*, 2007]. Our study does not include the Himalayan highlands even though most of the large rivers found in our “western India” area originate from this region. Data explicitly related to tectonic activities and/or sea level fluctuations [Bourget *et al.*, 2010] have been excluded from our inventories.

As can be seen readily in figure 2, hydrological response to changes in African monsoon from 16,000 cal yr BP onward differs considerably from one region to another. In western Africa, the increase in lake expansion is rather progressive, starting from the beginning of the Holocene, at about 15,000 cal yr BP, then accelerating from 12,000 cal yr BP to reach a maximum at ~9,500 cal yr BP, in phase with the summer (june-july-august-september; JJAS) insolation maximum at 30°N [Berger and Loutre, 1991] (fig. 2). From this optimum period onward, the amount of lake records decreases slowly and regularly to the present. As soon as 8,000 cal yr BP, the development of palustrine areas in association with the progressive decrease of lake records clearly confirms the progressive water table lowering. This trend toward dryness is also reflected by a progressive increase of arid records, which reach their maximum contribution during the last 2,000 cal yr BP. In Sudan and Egypt, the rise of the water table at the beginning of the Holocene appears to be somewhat more abrupt compared to western Africa, with a sharp increase in lake records around 11,000 cal yr BP. Then, the maximum of humidity lasted for about 4 thousand years, from 11,000 to 7,000 cal yr BP. The water table lowering, which started at 8,000 cal yr BP over western Africa, accelerated at 7,000 cal yr BP in eastern Africa and the late Holocene (after 3,000 cal yr BP) was almost completely dry.

In the three remaining areas, which lie today under the influence of the Indian monsoon (horn of Africa, Arabia and western India sectors), two distinct patterns can be

distinguished. In the horn of African and Arabia, the evolution of continental hydrology displays a pattern rather similar to that of Sudan and Egypt even though the amount of available dated records is considerably lower. Over western India, continental hydrology is characterized by the large amount of fluvial terraces from 14,000 cal yr BP onwards, which result from abundant rains on the western slope of Himalayan plateaus. In this area, the peak maximum of lacustrine records is delayed by two millennia compared to the other areas, being dated between 8,000 and 6,000 cal yr BP.

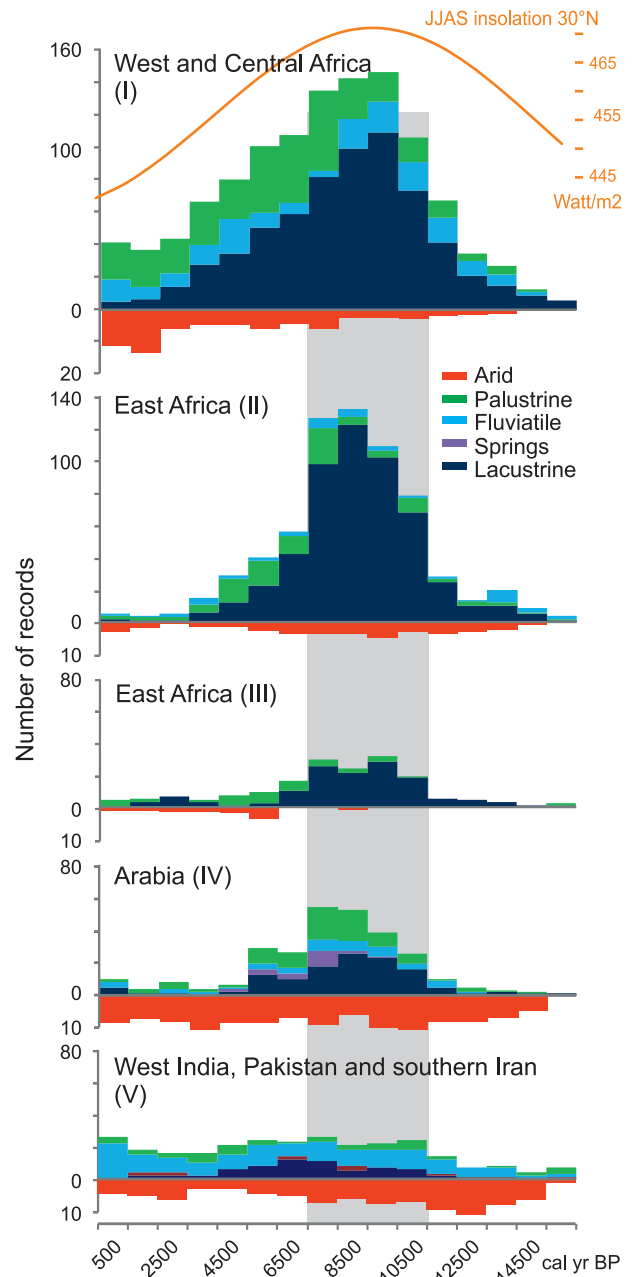


FIG. 2. – Distribution histograms computed over the five studied areas, and showing the respective amount of well-dated lacustrine, palustrine, fluvatile, spring and arid data found in successive 1,000 yr time-slices, from 16,000 cal yr BP to the present. The geographic distribution of the sedimentary sites from which these published data were collected is shown on figure 1. Insolation curve from Berger and Loutre [1991].

Marine data

The eastern Atlantic and Arabian sea aeolian records display striking similarities from the glacial period to the end of the Holocene humid period, around 7,000 cal yr BP (fig. 3). In both records, high values of terrigenous material are measured over the glacial interval. This period of high dust supply ends up rather abruptly in core 74KL, as evidenced by the %dolomite drop from 14% to ~0%, which takes place in two successive steps (each lasting less than ~300 yr) centered at 16,800 cal yr BP and 15,100 cal yr BP, respectively (fig. 3). Over the same time interval, a potentially rapid decrease in %terrigenous seems to take place in ODP 658, although its exact timing, shape and duration cannot be precisely addressed owing to a hiatus, which spans the time interval 17,400 to 14,300 cal yr BP [deMenocal *et al.*, 2000b]. During the deglaciation, records from site ODP 658 and core 74KL show a similar peak in dust supply, which appears to be coeval with the Younger Dryas episode (within the uncertainties of age models). This peak ends up abruptly in both records, and is followed by a well-defined interval of low dust supply spanning the time interval between ~11,000 to ~8,000 cal yr BP, with a peak minimum at about 10,000 cal yr BP (fig. 3). After ~7,000 cal yr BP, the evolution of Atlantic and Arabian sea records is no longer similar. The Atlantic record displays a clear increase in dust supply with a sharp jump at about ~5,500 cal BP, leading to %terrigenous values in the late Holocene that are similar to those measured in the glacial interval. In the Arabian sea record, however, after a peak value around 7,000 cal yr BP, the %dolomite decreases

progressively towards the present, suggesting a less arid climate and/or a decrease in aeolian transport, which is at odds with continental data.

It is striking that tropical Atlantic and Arabian sea dust records show very similar fluctuations from the glacial to the mid-Holocene (fig. 3). It could be tempting to suggest that these fluctuations reflect synchronous aridity/humidity changes (within the limits of the age uncertainties) taking place over a tropical band extending from the eastern Atlantic to the northern Indian ocean. The reality is likely more complex, however, and other factors than monsoon-related changes in humidity might be at play. As far as core 74KL is concerned, for instance, Sirocko *et al.* [1993] suggested that part of the difference in %dolomite between the glacial period and the late Holocene (fig. 3) does not reflect changes in monsoon dynamics but results from the flooding of the Arabo-Persian gulf. The role of lowered sea level on the amount of glacial aeolian material transported to the Arabian sea was suggested also by Preusser *et al.* [2002]. With an average water depth of 50 m and a maximum depth of 90 m, the shallow Arabo-Persian gulf had totally dried out during the last glacial, providing a potentially important source of dolomite dust for aeolian transport that may have decreased during deglaciation, when sea level reached the transgression threshold in this area (~100-65 m below modern sea level [Sarnthein, 1972]). This interpretation is coherent with the evolution of shoreline in the Persian gulf from ¹⁴C-dated samples [Lambeck, 1996]. When converted to calibrated ages using the CALIB6.0 software [Stuiver and Reimer, 1993; Stuiver *et al.*, 2005] with the Marine 09

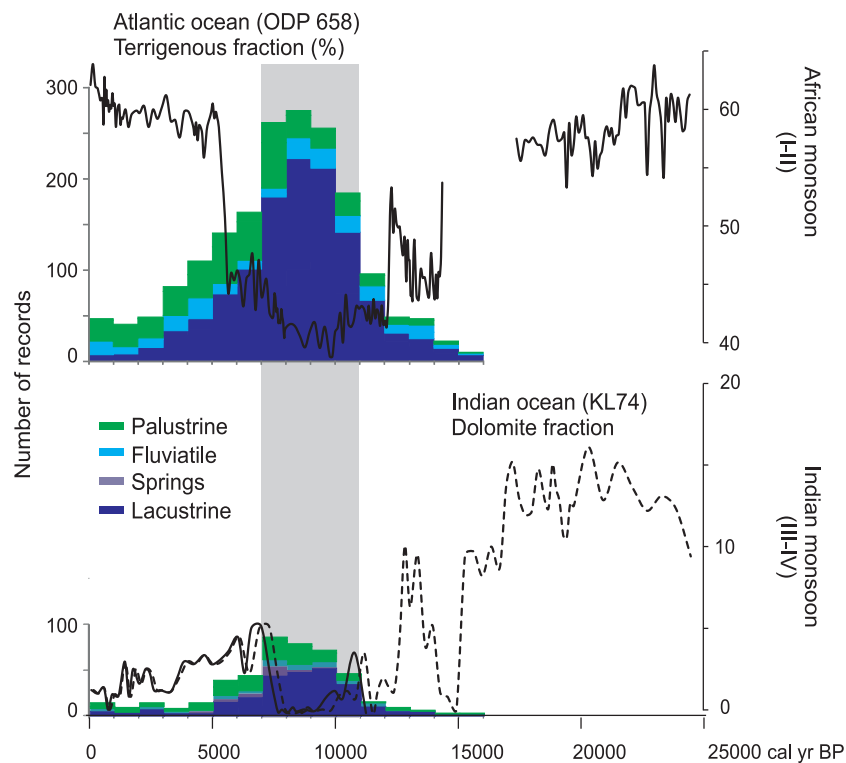


FIG. 3. – The Holocene humid period: marine and continental records of the Holocene humid period in the Atlantic and Indian monsoon sectors. Marine data are from de Menocal *et al.* [2000] (ODP site 658) and Sirocko *et al.* [1993] (74KL). Continental data were grouped according to the dominant influence of the African (I-II) and Indian monsoon (III-IV) systems (western Indian records (V) excluded). Solid line corresponds to Saliege *et al.* [2005]'s age model while dotted line corresponds to the original one. Note the strong dissymetry of the Arabian dust record on both sides of the Holocene humid period compared to the Atlantic one. This probably accounts for the postglacial flooding of the Arabo Persian gulf from which most of the dust originated during the glacial period.

calibration curve [Reimer *et al.*, 2009], Lambeck's data suggest that the strait of Hormuz opened up around ~17,000 cal yr BP and that the flooding of the eastern Gulf of Persia had already started by ~14,900 cal yr BP. In support for such a role of sea-level on the availability of dolomite dust, Sirocko *et al.* [1993] noticed that, within the limits of core 74KL age model, the second drop in %dolomite (centered at about ~15,100 cal yr BP) is associated with a simultaneous, sharp decrease in $\delta^{18}\text{O}$, which was interpreted as meltwater pulse Ia, the first abrupt rise of sea level resulting from the post-glacial ice sheet melting.

Thus, aeolian proxies are complex to interpret, and past changes in aridity over adjacent continental areas may just be one among several factors to take into account in order to explain changes in windborne deposits. In order to help us decipher the real meaning of tropical Atlantic and Arabian sea dust records over the time interval from 15,000 cal yr BP to the present and provide a more accurate picture of mechanisms at play and the role of monsoon-related changes, we propose to take advantage of our extensive continental database by comparing the two marine records with aridity/humidity data from adjacent continental areas.

DISCUSSION

The early onset of the Holocene humid phase (circa 15,500 cal yr BP) has been evidenced in northern tropical Africa by the rise in lake levels [Gasse, 2000; de Menocal *et al.*, 2000; Shanahan *et al.*, 2006]. However, this early wet phase is thought to have been limited [Lézine *et al.*, 2011], which does not seem to account satisfactorily for the abrupt and large drop in terrigenous flux observed at ODP Site 658 (fig. 3). The discrepancy between marine and continental evidence is even more striking for the Arabian peninsula where no lacustrine deposit or speleothem record has been found prior to ~10,500 cal yr BP [e.g. Fleitmann *et al.*, 2007; Van Rangelbergh *et al.*, 2013], making it difficult to interpret the sharp decrease in %dolomite (fig. 3) and non- CaCO_3 material [Sirocko *et al.*, 1993] around 15,100 cal yr BP in core 74KL as resulting mainly from an increase in continental humidity. As we have seen above, Sirocko *et al.* [1993] suggested that the decrease %dolomite at the site of core 74KL since the glacial could be partly related to the flooding of the Arabo-Persian gulf during the deglaciation. Other mechanisms could be also invoked, such as changes in the transport of particles (strength and/or pathway of the wind systems). The drop in dust supply could, for instance, correspond to a geographical shift of the main Arabian aerosol plume away from the location of core 74KL or a decrease in the convective uplifting of this lithogenic material in the troposphere. In their 1991 publication, Sirocko *et al.* produced distribution maps of sedimentary material in the western Arabian sea averaged over two time intervals: 15-27,000 and 0-8,000 cal yr BP. Although the time resolution of these time slices is very coarse, the maps suggest that not only the amount of dolomite but also its geographic distribution may vary through time. Similarly, the apparent abruptness and early occurrence in the %terrigenous drop at ODP Site 658 (over a time period when continental data only suggest limited increase in precipitation) might not reflect an aridity signal but could result from a geographical shift in the main path of the African dust plume and/or an

insufficient upward transfer of dusts to the mid-troposphere. Today, large latitudinal shifts of the African dust plume are experienced on a seasonal and inter-annual basis, with sites located southwards of ODP 658 experiencing winter rather than summer maximum in dust supply [e.g. Chiapello *et al.*, 1995].

During the deglaciation, the Atlantic and Arabian sea aeolian records show a similar, positive peak in dust supply that ends up at about 12,300 cal yr BP and was interpreted in ODP 658 as corresponding to a dry episode that took place during the Younger Dryas (YD) chronozone [deMenocal *et al.*, 2000a]. This episode of high aeolian dust supply corresponds to the lowering of the lake levels in the main hydrological basins of north tropical Africa [Gasse, 2000; Shanahan *et al.*, 2006]. Nevertheless, this dry episode is not clearly documented in our continental database. This suggests that the peak in dust supply associated to the YD at ODP 658 may either result from a change in seasonality or correspond to a highly heterogeneous distribution of precipitations, which is improperly taken into account by our patchy continental database. Similarly to what we have suggested above for the late glacial signal, the marine peak in dust supply may also reflect a change in atmospheric circulation dynamics and the transport of lithogenic material (i.e. increased activity of the convective cells that uplift the lithogenic material to the mid-troposphere, and/or shift in the latitudinal position of the jets that carry the dust plume to the marine sites). As far as the Arabian area is concerned, it is striking to notice that the % CaCO_3 record of core 74KL, which is also interpreted as reflecting aridity over Arabia, does not show a YD peak contrary to the %dolomite record [Sirocko *et al.*, 1993]. The difference between these two indicators is not fully understood at present and could reflect contrasts in spatial distribution and transport. The YD peak aridity suggested by the maximum in %dolomite seems to be confirmed, however, by a coeval increase in dust flux observed in sediments from the northern Arabian sea [Pourmand *et al.*, 2004].

As we have just seen above, discrepancies between the marine dust records and continental records suggest that atmospheric circulation and the geographical distribution of windborne material –rather than changes in aridity/humidity– may largely explain the major features observed in the dust records from ODP 658 and core 74KL, over the time interval lasting from the end of the last glacial to the Younger Dryas chronozone. Changes in humidity are, however, the primary mechanism that should be invoked to explain the low values of dust indexes recorded between 11,000 and 7,000 cal yr BP in ODP 658 and core 74KL. Indeed, it is during this time interval that the largest number of dated lake sediments has been obtained over north tropical Africa and Arabia. The strong anti-correlation between continental humidity indexes and records of marine dust supply (fig. 3) clearly indicates that this early Holocene low in windborne material can be confidently attributed to changes in monsoon-related precipitation onland [Sirocko *et al.*, 1991, 1993; deMenocal *et al.*, 2000a,b]. This conclusion is further supported by changes in Sr isotopic signature and chemical compositions of lithogenic material in sediments from ODP 658. During this time interval, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are markedly less radiogenic, and sediments show higher chemical indices of alterations, suggesting an increased authigenic sediment supply from extensive North African paleolake basins

[Cole *et al.*, 2009]. Pollen data from southern Arabia, however, clearly show that the landscape remained of desert/semi-desert type all along the Holocene wet period [Lézine *et al.*, 1998; 2007] contrary to what happened in northern Africa where tropical ecosystems widely expanded [Watrin *et al.*, 2009]. The paucity of Holocene lacustrine deposits and the continuous edification of sand dunes (fig. 2) in southern Arabia confirm that regional dry conditions persisted in the Arabian peninsula during the Holocene wet phase. In this context, the near absence of dust transport to core 74KL site is highly surprising.

Towards the end of the humid period, the drying out of humid areas in Arabia corresponds to the reactivation of the dune system, such as that of Liwa at 6,800±900 cal yr BP [Bray and Stokes, 2004] and to the increase in %dolomite observed in core 74KL (fig. 3). In northern Africa however, the end of the Holocene wet phase occurred at least 1,000 years later according to ODP 658 [deMenocal *et al.*, 2000b]. This site records an increase of western african windborne material from 5,500 cal yr BP onward, reaching values in the late Holocene as high as those recorded during the last glacial period. That globally mimics the orbital forcing with high terrigenous values in phase with low insolation, and vice versa. High %terrigenous during the late Holocene have been interpreted as reflecting the denudation of the continental surfaces due to increased aridity in the Sahara and Sahel. Our paleohydrological database shows, however, that humid conditions locally persisted, particularly in the western Sahel, after 5,500 cal yr BP. That is confirmed by pollen data which show that the present-day arid conditions were reached at 2,700 cal yr BP only in northern Chad [Lézine *et al.*, 2011b] and that *Rhizophora*, a tropical humid mangrove element, persisted along the littoral of Mauritania up to ~2,400 cal yr BP [Lézine and Hooghiesmtra, 1990; Lézine, unpublished: <http://fpd.sedoo.fr>]. In the Arabian sea, core 74KL provides a complex signal with late Holocene terrigenous values considerably lower (2.5 time) compared to the last glacial ones, probably related to the

modification of the source zone and particularly the flooding of the Arabo-Persian gulf.

CONCLUDING REMARKS

Two main results emerge from our study:

1) the hydrological response to the Holocene humid phase in northern tropics strongly differs from a region to another. If the maximum humidity is roughly contemporaneous in both the Atlantic and Indian monsoon areas (11-7000 cal yr BP), the humid period is significantly shorter in the Arabian peninsula and the horn of Africa, starting from 12-11,000 cal yr BP instead of 15,500 cal yr BP in northern Africa. Similarly, it ended earlier at ca 6,500-7,000 cal BP (at least in the lowlands) instead of 5,500-4,500 cal yr BP. In western India, the hydrological response to increased rainfall at the beginning of the Holocene mainly results in the activation of fluvial systems. Lakes are scarce compared to other regions and display a different distribution with a peak delayed toward the mid Holocene (8000-7000 cal yr BP);

2) the terrigenous signal from marine cores is complex, being not only associated with aridity/humidity changes but likely integrating changes in source zones, (e.g., the drying of the Arabo-Persian gulf during the last glacial period), and/or changes in wind intensity and direction. In order to better decipher between atmospheric transport and changes in humidity/aridity, further studies will be conducted, including reconstruction of sea surface salinities from coupled Mg/Ca- $\delta^{18}\text{O}$ analyses on planktonic foraminifers and the careful examination of GCM reconstructions of wind circulation at different altitudes for the LGM, early Holocene and mid Holocene.

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