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Timing of vegetation changes at the end of the Holocene Humid Period in desert areas at the northern edge of the Atlantic and Indian monsoon systems

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Abstract

This article aims at discussing the ecological response of the terrestrial and fresh water dependant environments to the installation of arid conditions at the end of the Holocene Humid Period in the Atlantic and Indian monsoon domains. It is mainly focused on dry environments from Chad, Oman and Pakistan where new, high-resolution pollen sequences have been provided. Pollen data show that local hydrological conditions have played a major role in the destruction or survival of tropical tree populations at the end of the Holocene Humid Period, as well as partly explaining the asynchronous pattern of recorded environmental changes in most tropical regions. In desert areas, the response of the fresh water dependant systems to the shift from humid to arid climate conditions appears to have followed a threshold-like pattern. In contrast, terrestrial ecosystems have gradually adapted to increased drought, as shown by the progressive decrease of tropical tree species at Yoa or the gradual expansion in dry plant types in Oman and Pakistan from 6000 cal yrs BP to the present. A remarkable synchroneity in environmental change is recorded at the northern edge of the Atlantic and Indian monsoon systems, with the extreme end of the Holocene Humid Period corresponding to the last occurrence of tropical trees in the desert and the last record of prolonged SW monsoon rainfall over north-western Asia around 4700–4500 cal yrs BP. ***To cite this article: A.-M. Lézine, C. R. Geoscience 341 (2009).***

Résumé

Chronologie des changements de la couverture végétale des zones désertiques à la limite nord de la zone d'influence des moussons atlantique et indienne au cours de la fin de la période Humide Holocène. Cet article a pour but de discuter la réponse des écosystèmes (terrestres et aquatiques) au passage des conditions humides à sèches à la fin de la période humide Holocène dans les domaines de la mousson atlantique et indienne. Il est principalement axé sur les environnements arides du Tchad, d'Oman et du Pakistan où de nouvelles données polliniques à haute résolution ont été obtenues. Les données polliniques montrent que les conditions hydrologiques locales ont joué un rôle majeur dans la destruction ou la survie des espèces d'arbres tropicales à la fin de la période Humide Holocène. Elles expliquent en partie l'asynchronisme des changements environnementaux dans la plupart des régions tropicales. Dans les zones désertiques, la réponse des écosystèmes aquatiques au basculement des conditions climatiques humides vers des conditions arides semble avoir été rapide, soumise à des effets de seuil. En revanche, les écosystèmes terrestres se sont peu à peu adaptés à une sécheresse croissante, comme en témoigne la disparition progressive des espèces d'arbres tropicaux à Yoa ou l'extension des écosystèmes arides en Oman et au Pakistan entre 6000 ans cal BP et aujourd'hui. Un remarquable

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synchronisme est enregistré dans l'évolution de l'environnement, à limite nord de la zone d'influence des moussons atlantique et indienne, à la fin de la période humide holocène, avec la dernière occurrence d'arbres tropicaux dans le désert et le dernier enregistrement prolongé des pluies de la mousson du Sud-Ouest en Asie occidentale à 4700–4500 ans cal BP. ***Pour citer cet article : A.-M. Lézine, C. R. Geoscience 341 (2009).***

Keywords: Atlantic monsoon; Indian monsoon; Pollen; Chad; Oman; Pakistan; End of the Holocene Humid Period

Mots clés : Mousson atlantique ; Mousson indienne ; Pollen ; Tchad ; Oman ; Pakistan ; Fin de la période Humide Holocène

1. Introduction

Environmental reconstructions of tropical deserts during the Mid- to Late Holocene have mainly focused on northern Africa. In this region, lake level and pollen data have been used for regional reconstruction of past vegetation or hydrological changes [11,13,20], as well as for paleoclimatic models connecting environmental changes with variations in the Earth's orbit, or investigating vegetation and ocean feedback in the climate system [3,16,17,33]. In contrast, little is known about western Asia, one of the most arid areas of the world with extensive desert areas (Rub al Khali in the Arabian Peninsula, Thar desert in Western India...), although recent studies on speleothems from Oman [10] or paleolakes from Yemen [25] and Oman [31] have yielded high resolution records showing variations of the Indian summer monsoon during the Holocene.

In such arid areas, the scarcity of continuous sedimentary archives due to desiccation and subsequent erosion of the sediment sequences complicate any investigation of the impact of monsoon variability on vegetation and possible feedback of land cover changes on regional climate. I present here a review of pollen data from tropical African and western Asian lowlands, including new results from sectors located at the northern edge of the Atlantic and Indian monsoon systems (Figs. 1 and 2) in order to document the shift from humid to arid environmental conditions in equatorial forest to the desert and the onset of the modern climate regime at the end of the ''Holocene Humid Period''.

2. In the Atlantic monsoon system, a local *versus* regional pollen signal

Considerable changes in vegetation have occurred in the West-African lowlands from the Guineo-Congolian forest zone to the Sahara at the end of the ''Holocene Humid Period''. Changes in the Atlantic Equatorial forest domain have been described in detail by Vincens et al. [44], while a more complete picture integrating pollen sites from the drier vegetation types of Sudanian to Saharan latitudes has been provided by Lézine [21] then analyzed in detail by Watrin et al. [46] (Fig. 2). They showed that forests between 4°S and 7°N were replaced by more open landscapes, wooded grasslands, grasslands or woodlands within a period lasting from 4500 to 1300 cal yrs BP. The local signature of this environmental change strongly varies from site to site according to local hydrological conditions. Some lakes, such as Sinnda, dried out [45], while other sites (e.g., Bosumtwi [42]) remained forested or only partially affected (e.g., Barombi Mbo [26]; Ngamakala [6], Songolo [7]; Nguène [29]), such as rain or swamp forests being replaced by more open formations with increasing importance of light dependent tree species.

In contrast with the Guineo-Congolian domain, Sudanian and Sahelian pollen sites from Benin and Nigeria show a remarkable agreement of environmental changes. In Benin, semi-evergreen rainforest trees which expanded at 8°N around Lake Sélé were replaced by an open savannah between 4500 and 3400 cal yrs BP [38] likely recording the installation of the modern ''Dry Dahomey Gap'', a dry corridor which interrupts the Guineo-Congolian forest domain between roughly 1° and 3°E along the northern coast of the Gulf of Guinea. During the same time interval, Guineo-Congolian gallery forests disappeared from central (Tilla [37]) and northern Nigeria (Bal, Kajemarun, Kaigama and Kuluwu [39]) to the benefit of widespread savannah formations. To the west, along the Atlantic Ocean, specific hydrological conditions linked to the proximity of the sea partly explain the persistence of noticeable forest communities more than 2000 years after the installation of dry climate conditions over the Sahel. Here, the sea which reached its modern level after 7000 cal yrs BP [1], and even raised above it around 6000 cal yrs BP and 3000 cal yrs BP during the so-called ''Nouakchottian'' [12] and ''Tafolian'' transgressions [9], led to the permanence of soil humidity near littoral areas with the fresh water-table lying near the surface at the bottom of interdunal depressions [22]. As a result, Guineo-Congolian gallery forests from the

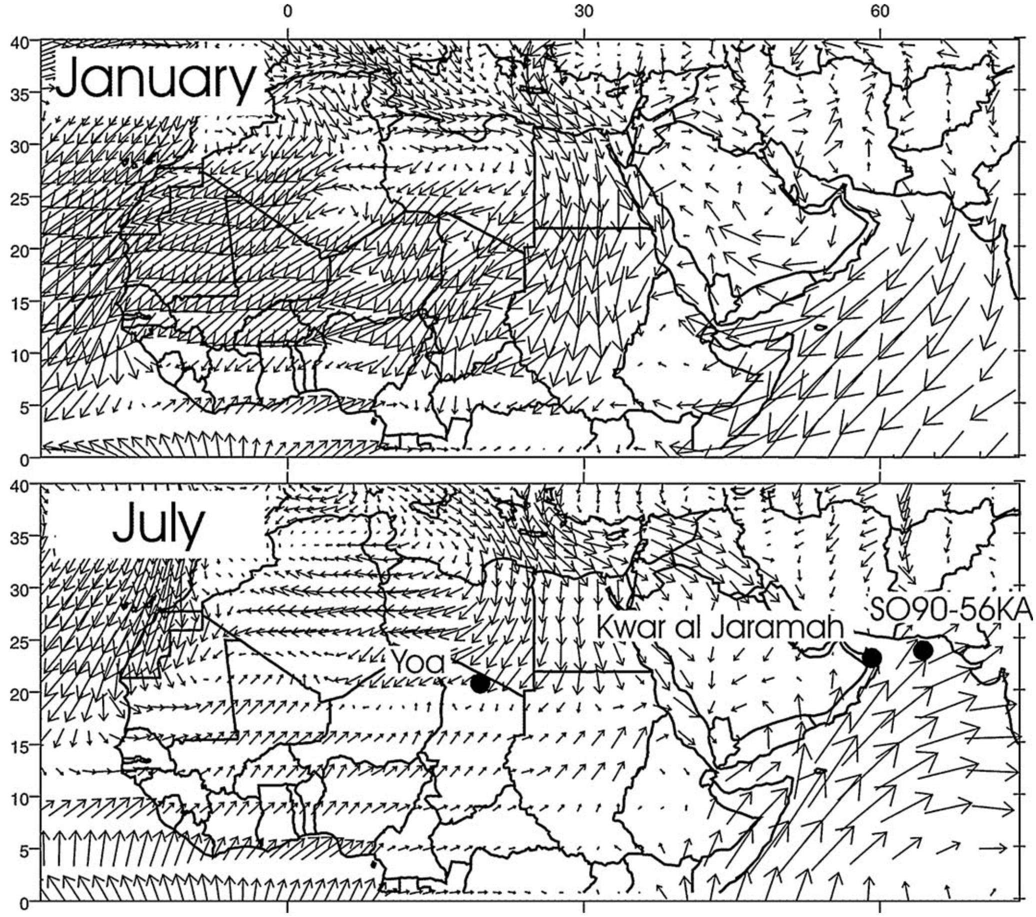

Fig. 1. Map showing the seasonal reversal of surface winds over North Africa and western Asia. Black dots indicate the three new 6000-yrs long pollen sites from the northern edge of the ITCZ.

Fig. 1. Carte montrant le renversement saisonnier des vents de surface au-dessus de l'Afrique septentrionale et de l'Asie occidentale. Les points indiquent la localisation, à la limite nord de l'ITCZ, des nouvelles séquences polliniques datées de 6000 ans.

Niayes area (17–16°N) declined only around 2500 cal yrs BP [19]. Similarly, tropical plant types from the Arguin Bay along the Mauritanian coast (21°N) did not disappear until around 2500 cal BP (Lézine, unpublished data).

Environmental reconstruction in the central Saharan desert is severely limited by the incompleteness of the record, owing primarily to major discontinuities in lacustrine sediments preserved in a predominantly arid climate. The well-known pollen series from Sudan [34,35] and Mauritania [23] only document the Early to Middle Holocene. The only pollen sequence available today that records the end of the Holocene humid period has been recovered at Lake Yoa, northern Chad [15]. Lake Yoa is one of the permanent lakes of the Ounianga region at 19° N (Fig. 1). It yielded a 7.5 m long pollen sequence dated from 6000 cal yrs BP to the present. This exceptionally laminated and continuous sedimentary record allows precise reconstruction of past terrestrial changes in the immediate surroundings of the lake. In contrast with ODP core 658C recovered off Mauritania [5], Lake Yoa shows that the transition from humid to arid environmental conditions was gradual and occurred in several steps from 4700 to 2700 cal yrs BP. The percentage diagram of the most remarkable pollen types is shown in Fig. 3. Pollen types from tropical (*Piliostigma*, Tiliaceae...) and montane (*Erica arborea*-type) plant communities together with fern spores characterize zone 1 between 6000 and 4700 cal yrs BP. This pollen assemblage results in a combination of two factors: the northward expansion of tropical plant species during the Holocene as testified by numerous pollen and botanical data throughout North Africa [20,46] and humid regional conditions responsible for

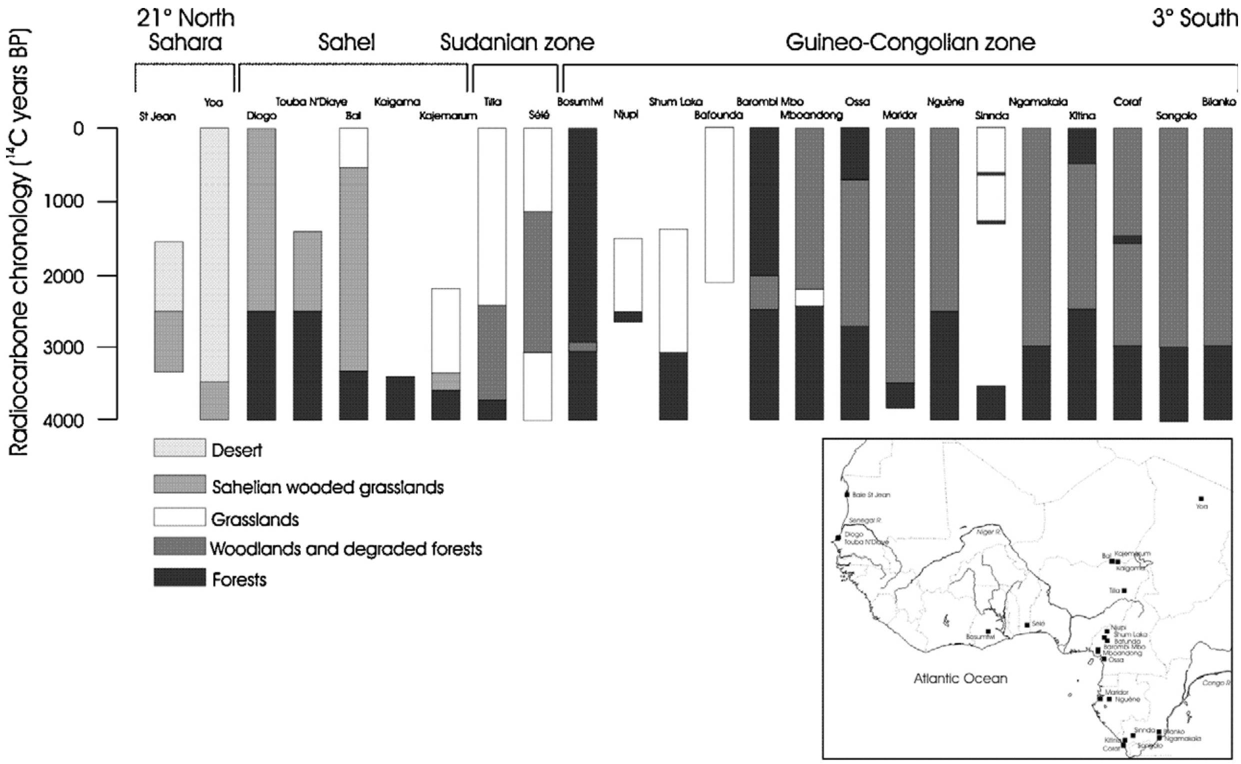

Fig. 2. Schematic evolution of landscape in West Africa from 3°S to 21°N from pollen data. Five main vegetation formations are distinguished with desert scrub, Sahelian wooded grasslands, grasslands (natural or secondary), woodlands and degraded forests, forests. Time is given in radiocarbon years (from [21,44] modified).

Fig. 2. Schéma d'évolution des paysages en Afrique occidentale entre 3°S et 21°N à partir des données polliniques. Cinq formations végétales sont distinguées : la végétation désertique, les espaces herbeux-boisés du Sahel, les prairies (naturelles et secondaires), les forêts claires et dégradées, les forêts. Le temps est donné en années radiocarbone (d'après [21,44], modifié).

noticeable rainfall on the adjacent Tibesti Massif and subsequent increased fresh water supply to the lake. The nearest source zone of *Erica arborea* pollen is restricted to elevations higher than 2900 m in the Emi Koussi Massif [32]. Since peaks of abundance of this pollen taxon are coeval with peaks of ferns and also of fresh water algae [15], they are thought to reflect fresh water runoff originating from the nearby Tibesti highlands. From 4700 to 2700 cal yrs BP (zone 2), is a transition period characterized by the progressive decrease in tropical plant types and their replacement by more xeric populations. Sahelian taxa (mainly *Commiphora* and *Acacia*) develop around Lake Yoa from 4700 to 4100 cal yrs BP (zone 2a and zone 2b). *Erica arborea* progressively disappears whereas *Boerhavia-type, Tribulus*, Amaranthaceae/Chenopodiaceae undiff. increase indicating the progressive aridity of the area. From 2700 cal yrs BP to the present (zone 3), dry steppic conditions definitively took place, with Amaranthaceae/Chenopodiaceae undiff., *Artemisia, Ephedra*, and, among the tree taxa, *Salvadora persica* and *Acacia*. The presence of *Olea* and other Mediterranean pollen types in this zone is interpreted as the result of increased north-south wind strength. During this zone, the successive expansion of *Hyphaene* (zone 3b) and *Phoenix* (zone 3a) likely reflects human impact in the area.

3. The Indian monsoon system

In the East African highlands, a shift to a drier climate, similar to that observed in the Atlantic monsoon domain has been recorded between 5000 and 3000 cal yrs BP [27]. The exact timing of vegetation changes during this period is however unclear though definitely *"asynchronous from site to site"* [27] - and probably complicated by the altitude effect. In addition, the interpretation of data, *"mainly concerning declines in terms of ecological change and/or human interference is not clear"*, even if it is becoming widely accepted that human impact on natural ecosystems of East Africa did not dominate

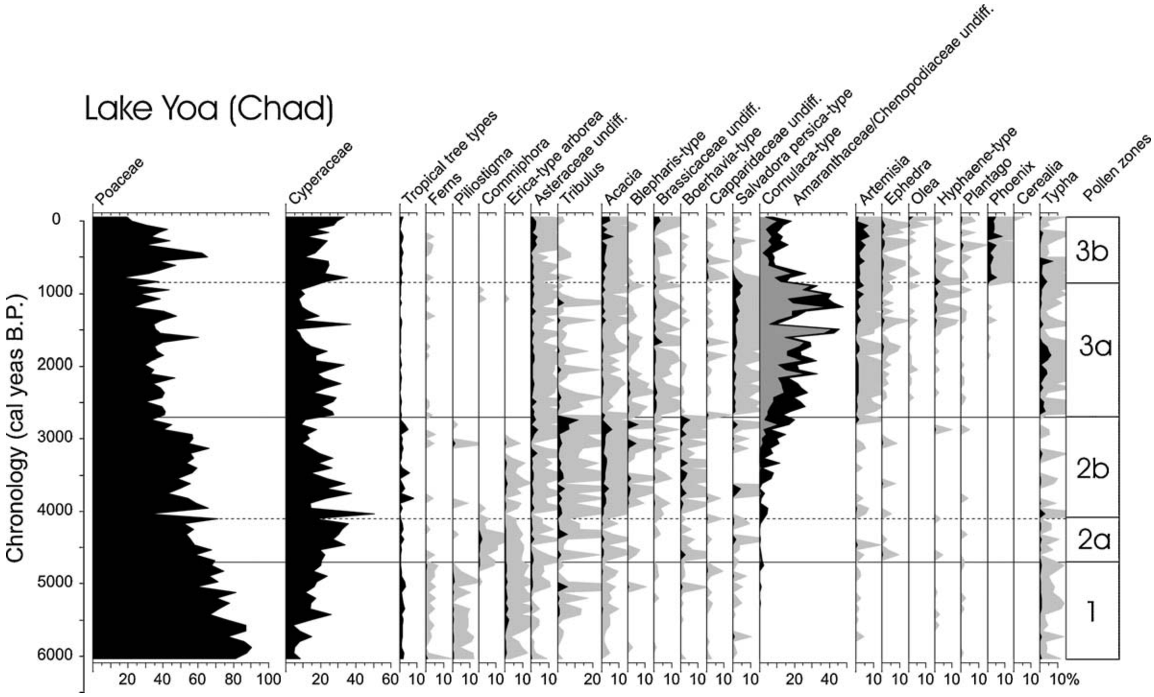

Fig. 3. Simplified pollen diagram for Lake Yoa (Ounianga lakes, northern Chad). This diagram shows percentages of main pollen types. In grey, × 10 magnification.

Fig. 3. Diagramme pollinique simplifié du lac Yoa (Lacs Ounianga, Tchad septentrional). Ce diagramme montre les pourcentages des principaux types polliniques. En gris, multiplication des pourcentages par 10.

before the last two thousand years [21]. To the east, using a large set of paleodata from different natural archives, Morrill et al. [28] report the abrupt weakening in monsoon strength over the whole Asian monsoon domain ca. 5000–4500 cal yrs BP that contradicts, according to the authors, *"previous notions of either a gradual trend towards drier conditions or a series of abrupt events that occurred in an unorganized fashion across space and time"*. New pollen data from high resolution and well dated 6000-year long sedimentary sequences from Oman and the eastern Arabian Sea presented here allows for the characterization of this climate transition in western Asia and the discussion of the related vegetation response in the lowlands.

Kwar al Jaramah is a large, sheltered creek located on the western coast of the Gulf of Oman (Fig. 1). A 440 cm long core has been recovered within the *Avicennia marina* mangrove forest at 22°29.537N and 59°45.896E. The chronology is based on seven AMS ^{14}C ages on carbonates. A time scale was obtained by linear interpolation between two corrected ^{14}C ages, taking into account the local reservoir effect of 210 ± 15 yr [36]. The pollen diagram (Fig. 4) clearly reflects the overall dry environmental conditions which characterized the area during the last 6000 years with the dominance of herbaceous plants from semi-desert communities, such as Amaranthaceae-Chenopodiaceae, *Artemisia*, Asteraceae and Poaceae. However, discrete changes in tree populations allow distinction of three main periods. From 6300 to 4500 cal yrs BP (pollen zone 1), noticeable percentages of *Rhizophora* in association with ferns – even in scattered occurrence with low values – indicate that fresh water was available. *Rhizophora* is currently absent from the Omani mangroves where highly saline conditions linked to the aridity of climate allow only *Avicennia marina* to survive. Its best development is reached under rainy climates in equatorial and tropical humid mangroves; however, its expansion being limited by aridity, cool winter temperatures and seawater salinity [41]. The nearest occurrence of natural *Rhizophora* populations from the core site today is located to the south at Khor Kathib and the Kamaran islands on the Red Sea coast at 15°20N and to the north in the Sirik estuary at 26°30N on the northern coast of the Gulf of Oman. *Rhizophora* at Kwar al Jaramah probably originated from the Early Holocene when maximum of Indian monsoon activity in summer led to the wide

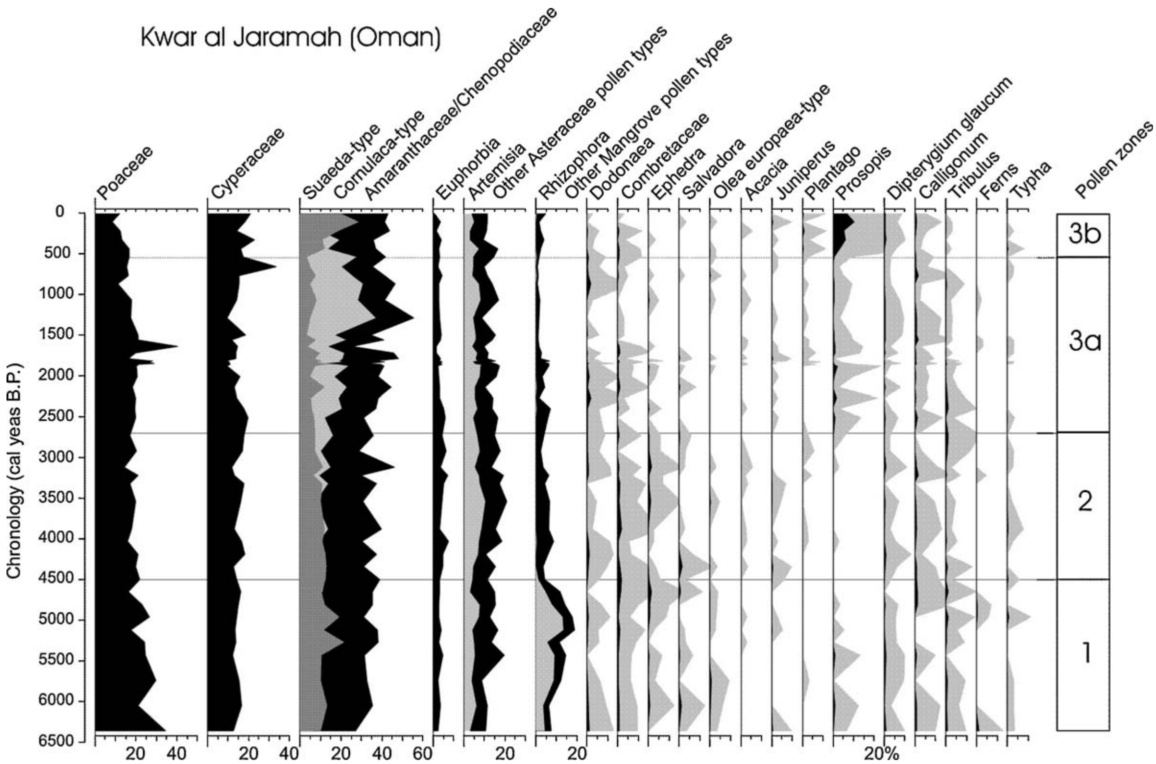

Fig. 4. Simplified pollen diagram for Kwar al Jaramah (Oman) (see Fig. 3 caption for details).

Fig. 4. Diagramme pollinique simplifié de Kwar al Jaramah (Oman) (voir la légende de le Fig. 3 pour les détails).

development of mangroves all along the coasts of the northern Indian Ocean [24,30,43]. At 6000 cal yrs BP, the sea level stabilisation at 1–2 m above the present level allowed sea water to inundate low-lying coastal areas [18], whilst abundant monsoon rains favoured biodiversity increase with *Avicennia* mangroves accommodating more tropical humid elements. Most of the tropical and montane elements (e.g., Combretaceae, *Dodonaea viscosa, Ephedra, Olea europaea*...) progressively decreased from the base of zone 1 at 6000 cal yrs BP to the present, whereas xeric elements remained stable (*Acacia, Commiphora, Artemisia, Calligonum, Diperygium glaucum*) or increased (*Cornulaca*-type, *Prosopis cineraria*). The modern landscape was finally established at 2700 cal yrs BP (zone 3a), when *Prosopis cineraria*, a species that is positively related to winter rainfall and characterizes the lowlands on both sides of the Ormuz Strait, expanded and reached its modern distribution around 600 yrs BP (zone 3b). These observations contradict the assumptions of Morrill et al. [28] and demonstrate the progressive drying of the terrestrial ecosystem in response to the orbitally-induced weakening of Indian monsoon rains. In contrast, the disappearance of *Rhizophora* from the littoral forest at 4500 cal yrs BP shows that a hydrological threshold was reached, beyond which fresh water supply to the mangrove system was not sufficient to allow *Rhizophora* populations to survive. The scattered occurrence of *Typha* pollen all along the sedimentary sequence however indicates that at least seasonal fresh water floods occurred during the last 6000 years.

Core SO90-56KA recovered in the north-eastern Arabian Sea [14] confirms that *Rhizophora* expanded within the mangroves of Pakistan during a humid period lasting from 5400 cal yrs BP (the base of the core) to 4500 cal yrs BP. During this time interval, the prevalence of summer monsoon fluxes over the western slope of the Himalayan plateau where deciduous forests occur was responsible for strong river input and subsequent long distance transport of the pollen grains representing this vegetation. Fresh water influence at the core site was significant as recorded by the occurrence of numerous fresh water algae. As at Kwar al Jaramah in Oman, a gradual decrease in terrestrial indicators of humid conditions is superimposed on the decline of the summer monsoon rainfall signal. Earlier pollen studies from north-western India [40] suggest

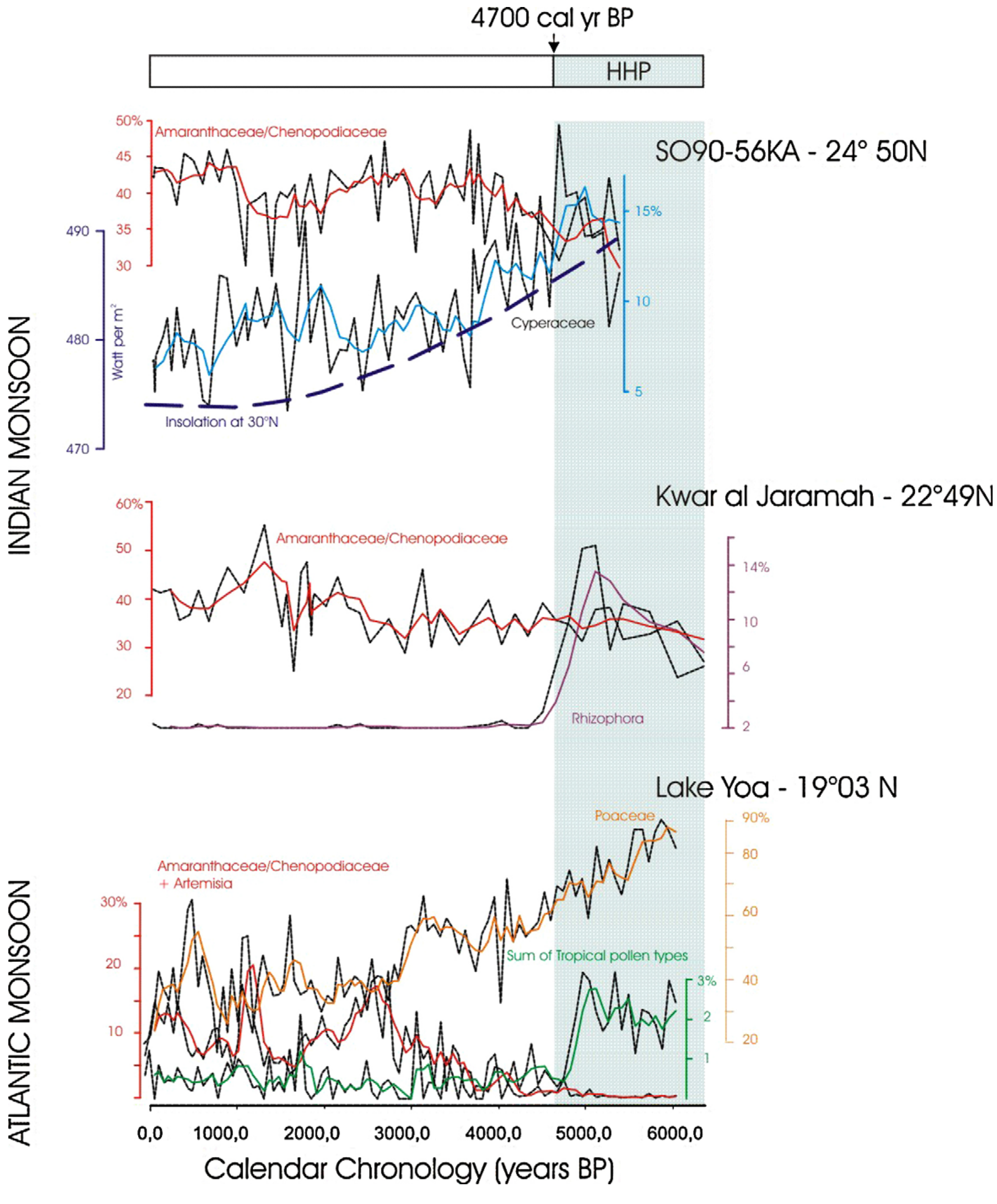

Fig. 5. The end of the Holocene Humid Period (HHP) from three pollen sites from desertic areas of Africa (lake Yoa), the Arabian Peninsula (Kwar al Jaramah) and western Asia (core SO90-56KA off Pakistan). Dotted lines indicate pollen percentages while continuous lines indicate four sample running mean values of pollen percentages.

Fig. 5. La fin de la période humide holocène (HHP) à partir de trois sites polliniques des zones désertiques d'Afrique (lac Yoa), de la péninsule arabique (Kwar al Jaramh) et d'Asie occidentale (carotte SO90-56KA prélevée au large du Pakistan). Les lignes en pointillés indiquent les pourcentages polliniques et les lignes continues, les moyennes mobiles d'ordre 4 correspondantes.

that the deterioration of environmental conditions may have started as soon as 7000–7500 cal yrs BP when the Thar Desert switched from ‘‘savannah’’ grassland to a more steppic landscape dominated by herbaceous plant communities similar to present day or when fresh water bodies from western India [8] and tropical Arabia dried out after 7500 cal years BP [25].

4. Concluding remarks

Our perception of past climate and environmental change is largely dependent upon the quality and the nature of available paleo-archives. Sensitivity of tropical lakes to rainfall variations [11] has long led scientists to associate the end of the Holocene Humid Period to an abrupt ‘‘drought’’ event of probable global extent [2]. However, the timing of corresponding environmental changes in North tropical Africa and surrounding areas is far from comparable from site to site (for instance, the abrupt increase of Saharan dust off Mauritania is dated from 5500 cal yrs BP [5], whereas the peak of aeolian detrital dolomite from the Gulf of Oman is dated from 4025 ± 125 cal yrs BP [4], i.e., about 1500 years later). My purpose here was not to discuss the onset and duration of this climatic event which has been thought not to have exceeded one or two centuries in duration. My interest was focused on the ecological response of the terrestrial and fresh water dependent environments at this key period. This requires that high resolution continuous and well-dated paleovegetation records are available. Unfortunately, perennial lakes are scarce in tropical areas, except in East Africa, and lacustrine deposits are often discontinuous, even in forest domains, complicating any precise reconstruction of ecosystem dynamics from pollen data. The data presented here illustrate the multiple aspects of the past environment including several spatial and temporal scales showing that:

- local hydrological conditions have played a major role in the destruction or in the survival of tropical tree populations at the end of the Holocene Humid Period. They partly explain the asynchronous pattern of recorded environmental changes in most tropical regions (Fig. 2);
- in desert areas, the response of fresh water dependent systems to the shift from humid to arid climate conditions appears to have followed a threshold-like pattern. This is illustrated here by *Rhizophora* which disappeared abruptly from the Omani mangroves as fresh water input from rivers or rainfall fell. Similar observations have been made at Lake Yoa (northern Chad) where the lacustrine system switched abruptly from fresh to saline conditions [15];
- in contrast, terrestrial ecosystems have been gradually adapted to increased drought as shown by the progressive decrease of tropical tree species (Sudanian then Sahelian) at Yoa and gradual expansion in dry plant types in Oman and Pakistan from 6000 cal yrs BP to the present;
- surprisingly, a remarkable synchronicity in environmental changes is recorded at the northern edge of the Atlantic and Indian monsoon systems (Fig. 5) with the extreme end of the Holocene Humid Period corresponding to the last occurrence of tropical trees in the desert and the last record of prolonged SW monsoon rainfall over north-western Asia at 4700–4500 cal yrs BP.

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