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# Palaeoclimate in the Saharan and Arabian Deserts during the Middle Palaeolithic and the potential for hominin dispersals

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A R T I C L E I N F O

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A B S T R A C T

To disperse out of sub-Saharan Africa, it was necessary for hominins to cross the deserts of either the Sahara and/or Arabia. Thus, understanding the palaeoclimate of the Saharo-Arabian region is central to determining the role these deserts played in the peopling of the planet; when did they act as barriers and when were they more humid, opening dispersal routes across them? To address these questions we have conducted a temporal and spatial evaluation of dated sites from 20 to 350 ka using combined probability density function (PDF) and geographical Information System (GIS) analyses of all sites dated using uranium/thorium (U/TH) or optically stimulated luminescence (OSL) methods. Radiocarbon dates were not considered because of contamination problems in this time range. The results show that during MIS 2 there is little evidence for humidity in Arabia as would be expected during the height of the last glacial maximum, however, the Sahara shows a sharp rise in probability at the beginning of MIS 2, peaking near the boundary with MIS 3 at ~29 ka. There appear to be brief periods of humidity in MIS 3 and 6, though at different times in the Sahara (ca. 37, 44, 138, 154 and 180 ka) and Arabia (ca. 40, 54 and 163 ka). During MIS 5, both regions show much evidence for humidity, with PDF peaks corresponding to insolation maxima, though not all maxima are represented in either the Saharan or Arabian record. This situation can be explained by eccentricity-modulated precession: when eccentricity is strong, insolation is enhanced (but also more variable) and the desert climate is generally more humid, particularly at times of high insolation. The opposite happens when eccentricity is low, and deserts tend to be more arid, but local factors exert more of an influence on climate, affecting the timing and strength of the brief humid periods experienced, so that they no longer coincide with insolation maxima. The spatial distribution of humid sites is compatible with a number of different modern human dispersal theories. Southern Arabia experienced humid periods centred on 54 ka and 125 ka, and this could have facilitated dispersal from east Africa to southern Arabia and beyond via the Bab el Mandab. The Sahara shows considerable evidence for humidity during MIS 5 and may have had dispersal across its expanse at this time.

## 1. Introduction

It is becoming increasingly clear that the Saharan and Arabian Deserts were not always arid as they are today (Fleitmann et al., 2003; Drake et al., 2008; Petraglia et al., 2011, 2012), yet we are only just beginning to recognize the timing of these changes and their extent and consequences (e.g. Kuper and Kröpelin, 2006; Drake et al., 2011; Lézine et al., 2011). Understanding past climate change in these regions is important for: 1) determining when these areas were humid and when they were arid; 2) establishing the causes of these arid-humid fluctuations; 3) establishing when it was possible for hominins to occupy these regions; and 4) indicating how extensive this occupation could have been, thus elucidating the role the deserts played in forming barriers, or providing corridors, for the dispersal of hominins across them. The latter three questions are becoming increasingly important as archaeological and genetic evidence both suggest anatomically modern humans evolved in sub-Saharan Africa (e.g. McBrearty and Brooks, 2000; Barham and Mitchell, 2008; Tishkoff et al., 2009) and subsequently dispersed from Africa into adjacent continents. To occupy regions further afield they must have crossed either the Saharan or Arabian Deserts. A number of routes have been proposed, including the Nile corridor (Van Peer, 1998), the 'Green Sahara' route (Drake et al., 2011) and the coastal route, either around the Red Sea (Stringer, 2000), or across the Bab el Mandab

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(Kingdon, 1993) and then along the Arabian coast (Mellars, 2006). None of these routes are as yet well established.

Saharan and Arabian climate change and associated hominin dispersals are likely to have been important during the Middle and Upper Pleistocene as lithic artefacts from this period have been found dispersed throughout large areas of these deserts (e.g. Armitage et al., 2011; Drake et al., 2011; Petraglia et al., 2011, 2012; Rose et al., 2011; Groucutt and Petraglia, 2012). Furthermore, dispersal of modern humans out of Africa may well have occurred at this time, using one or more of the above-mentioned dispersal routes. Yet our understanding of climate changes in the Sahara and Arabia at this time is fragmentary. No integrated analysis has yet been conducted and thus our understanding of the synchronicity between Saharan and Arabian climate change has not been comprehensively evaluated. This could be an important issue for hominin dispersals as some of the proposed routes could have involved dispersal through both deserts (e.g. migrants using the Nile Corridor or the Green Sahara routes may then have crossed the Arabian Desert).

## 2. Saharo-Arabian climate and hypotheses explaining the causes of past climate changes

Our understanding of the causes and timing of Saharo-Arabian climate change are at present limited. There are two competing hypotheses on the causes of climate change in tropical deserts. The first is that the change is driven by high latitude processes, with humid periods during interglacials, arid ones during glacials and a cyclicity of roughly 100 ka (Cooke et al., 1993). The second hypothesis is that climate change is controlled by the enhancement and decline of the monsoon system, driven by the precession of the equinoxes, a process that manifests itself predominantly at low latitudes with a cyclicity of about 26 ka (Trauth et al., 2009).

Recent research indicates that both these hypotheses could play a role in Saharo-Arabian climate change because the desert climate is controlled by two sources of rainfall. Southern regions receive monsoonal rainfall and northern parts obtain precipitation from North Atlantic and Mediterranean Westerlies. Each of these rainfall sources is controlled by a different hypothesis outlined above. The monsoon moves north, and the Saharo-Arabian Deserts contract, at times when precession produces higher solar insolation over the deserts. Monsoon enhancement occurs because increased solar radiation strengthens the thermal contrast between the land and the ocean, causing the monsoon to move northwards, further into the desert belt (Kutzbach and Liu, 1997). The factors that control the location of the mid-latitude Westerlies are less well understood but recent research appears to show that they vary with global temperatures (Toggweiler and Russell, 2008; Blome et al., 2012), strengthening and contracting towards the poles during warm periods (interglacials), or conversely decreasing in strength and expanding towards the equator during colder periods (glacials). Thus the Saharo-Arabian Desert can be expected to contract due to the southward movement of Westerlies when a ‘goldilocks scenario’ prevails whereby the global climate is cool enough to keep the Westerlies in a southern position, but not too cool to make them so weak they do not have enough strength to bring rainfall into the desert.

Given these two opposing climate mechanisms, there could be times when the Westerlies and monsoons converge and the deserts become green, forming dispersal routes across them. We hypothesise that this is likely to occur in the earlier stages of interglacial periods when insolation is high but the Earth is still relatively cool.

## 3. Aims and objectives

This paper reports a temporal evaluation of dated Saharan and Arabian ‘humid deposits’ during the Middle and Upper Pleistocene (from 350 to 20 ka) to evaluate our understanding of climate change in the context of human evolution. Information on sediments deposited during humid periods was compiled from the HOPE ENV Arabian palaeoenvironmental database (Parker and Rose, 2008; Parker, 2009) and from an equivalent database of Saharan data produced by Drake and Breeze (in press) that is broadly analogous to that recently published by Smith (2012), though with a series of statistical filters and selection criteria applied (see below). From these data, probability density function (PDF) curves were calculated for both regions in order to determine humid periods, and to permit cross-region comparisons of the timing of pluvial periods, whilst also accounting for the errors associated with the dates. These PDF curves were compared to each other and to select marine records (oxygen isotopes and aeolian dust) and orbital parameters (eccentricity and insolation). Doing this provides not only a comparison of Saharan and Arabian terrestrial palaeoclimate records but also an assessment of land and ocean records. Finally, in order to determine the region that the curves represent during each of the identified humid periods the location of the samples were mapped using ARC GIS, and the spatial distribution of the dates was evaluated.

## 4. Materials and methods

### 4.1. Data sources

The databases of Parker (2009), and Drake and Breeze (in press) have assembled published data from deposits representative of humid conditions within the respective regions, and record (amongst other parameters) spatial and temporal information associated with dated samples, lab identification codes, and parent publications. Deposits utilised as evidence for humidity were dated lacustrine and fluvial deposits, palaeosols, calcretes, speleothems, and tufas, travertines and sinters. Quaternary hydrothermal travertines from the northern Sahara in Morocco have not been included as pluvial proxies, as Akdim and Julia (2005) assert that travertine formation in this region is likely due to an interplay of hydrothermal activity and precipitation, resulting in a lag between precipitation and travertine formation (Weisrock et al., 2008).

### 4.2. Probability density function analyses

Probability density function (PDF) analyses have increasingly been used as a method to identify clustering of dates with errors during large-scale regional assessments, such as reconstructions of European Holocene fluvial geochronology (Macklin et al., 2006, 2010) and of global loess accumulation phases (Singhvi et al., 2001). PDF analyses have formerly been applied in an Arabian context to Pleistocene alluvial fan geochronology (Blechschmidt et al., 2009) and aeolian deposition studies in the Wahiba sands (Preusser, 2009) and to regional palaeoenvironmental summaries including radiocarbon dates (Glennie and Singhvi, 2002; Parker and Rose, 2008; Parker, 2009). Within North Africa PDFs have also been used to assess Holocene fluvial activity in Tunisian floodplains (Zielhofer et al., 2008) and to evaluate Saharan paleoclimate (Smith, 2012).

PDF analyses were applied to the Saharan and Arabian humidity datasets for the period from 350 to 20 ka. Samples were included in the analysis if data points came from within today’s desert proper (here regarded as regions with average rainfall below 200 mm), as well as those from surrounding semi-arid areas. The latter regions were included as at times during the Middle and Upper Pleistocene, when the Saharan and Arabian Deserts were larger, they would have become deserts. But also, conversely, when these desert fringe areas were humid but the desert proper still arid, the source populations for later hominin dispersals into the desert when it too became green may well have resided there.

### 4.2.1. Data processing

The following series of treatment and selection criteria were applied to the data, prior to construction of the final PDF curves, in order to minimise potential data artefacts.

Although large numbers of radiocarbon ($^{14}$C) dates have been recorded for pluvial deposits in both regions of interest, and although 255 $^{14}$C dates were present in the initial HOPE ENV database, these dates were excluded from analysis in favour of data produced through uranium-series and luminescence dating methods. $^{14}$C ages for lacustrine carbonates dated during several early Arabian studies (McClure, 1976; Whitney et al., 1983; Schulz and Whitney, 1986) have been demonstrated by recent re-evaluations utilising OSL (Rosenberg, 2011; Rosenberg et al., 2011) and uranium-series methods (Immenhauser et al., 2007) to be highly erroneous.

Immenhauser et al. (2007) analysed fracture calcite deposits from Jebel Madar, Oman, using both $^{14}$C and uranium series dating. $^{14}$C yielded ages ranging between 27 and 23 kyr BP, whilst UTh ages ranged between 212 and 158 ka. The authors suggested that the $^{14}$C ages were incorrect and that post-depositional alteration of the calcite had occurred with contamination from younger calcites precipitated into the rock during the Holocene. Similarly Rosenberg et al. (2011) re-analysed lake sediments at Mundafan and Khujaymah, both in the Rub al-Khali desert, Saudi Arabia, originally investigated and dated by McClure in the 1970s. Whilst the youngest sediments in both studies dated to the early Holocene age discrepancies were noted for the older sediments. OSL dating revealed that the late MIS 3 ages proposed by McClure (1976) (20–35 ka) were unreliable, with humid phases with lake formation in fact dating to ~125 ka (MIS 5e), ~100 ka (MIS 5c) and ~80 ka (MIS 5a) (Rosenberg et al., 2011). The explanation for the differences in ages is due to re-precipitated younger calcites within the carbonates being dated.

The age discrepancies noted above have cast doubt upon the validity of comparable data in the Sahara (Fontes and Gasse, 1989) and elsewhere. Furthermore, significant concerns have been raised regarding the use of calibrated $^{14}$C dates within probability density function analyses because calibration is known to influence PDF curves ( Macklin et al., 2006, 2010; Williams, 2011; Chiverrell et al., 2011a). Chiverrell et al. (2011b) have questioned the viability of comparisons of $^{14}$C derived PDFs with proxies that may have a relationship with solar variability.

In a couple of cases, the same deposit had been dated twice, using different methods, with slightly different results. When this happened, as was the case at Bir Tarfawi, Egypt (Wendorf et al., 1993) we used the data that produced the most consistent stratigraphy (e.g. less inverted dates), in this case OSL dating. If there was no obvious stratigraphy, as was the case at Wadi Shati, Libya (Petit-Maire et al., 1980; Armitage et al., 2007; Geyh and Thiedig, 2008) we used the most recent dating method (OSL) on the basis that it was more reliable. From the remaining uranium-series and OSL data (195 Saharan and 319 Arabian dated contexts, respectively), samples highlighted in parent publications as being of questionable accuracy or with exceptionally wide errors (three Saharan and five Arabian dates) were removed. Cases that may represent multiple dates taken from a single deposit were then identified, based upon published descriptions, depth and location data. These cases required statistical analysis since repeated representations of an individual humid depositional event would erroneously amplify the corresponding area of the humid probability plot. Groups of dates identified as potentially relating to the same deposit were therefore subjected to Chi-squared ($\chi^2$) tests (Geyh, 2008) to determine whether dates could indeed be considered to be statistically coeval and to relate to a single depositional event. Where the result of a $\chi^2$ test was $\leq n - 1$ then the test was passed, component dates could be considered as coeval and dates were averaged using the guidelines defined by Geyh (2008) for producing a weighted mean based on the variance of the component dates (or in rare cases of component dates having identical errors, an arithmetic mean). The averaged date and its error then replaced the original data as the sole date for the deposit during subsequent analysis.

Where $\chi^2$ tests for a group of dates failed, combinations of the component dates were tested, in order to identify which dates would group with one another, and which were statistically individual. Data grouping viably were then averaged, whilst individual dates were interpreted to represent previously indistinguishable individual stratigraphic events, and retained as such. In cases where no dates would average, all were retained and used in the final analysis.

Averaging was performed solely upon dates that originated from the same study and location, were produced by the same dating method, and were shown to be statistically identical. However, averaging was also applied to recently published Arabian lacustrine deposits (Rosenberg, 2011; Rosenberg et al., 2011, 2012) which had been dated based on OSL dates from aeolian deposits conformably overlying and preceding the lacustrine event. Averaging of the bracketing aeolian dates was used to produce a weighted mean and associated error lying within the likely range of the date of the lacustrine event for use in the PDF. In all cases $\chi^2$ tests were passed, supporting the hypothesis that the dates for the aeolian deposits tightly bracketed that of the lacustrine event.

Speleothem records, characterised by large numbers of dates resulting from near-continuous deposition phases, required particular consideration. These data, which are particularly prominent in the Arabian database, if included in the analyses uncritically, resulted in significant masking of the signal from other data, due to numerical dominance of dates from these few spatially constrained individual deposits. To reduce this dominance, speleothem data were subjected to the following treatment prior to inclusion in the analysis. Dates from individual speleothems were divided into the growth intervals suggested in original publications (where provided and statistically viable) or alternatively into statistically coeval groups of dates, with viability in both cases assessed through $\chi^2$ tests. The groups of statistically coeval dates were then averaged (Geyh, 2008), reducing the number of dates for speleothem records to individual ages representing statistical clusters of dates and individual dates found to be statistically distinct from all others.

The resultant datasets were then used to produce PDF curves for each region over the period of 350–20 ka (Fig. 1). Details for each date are presented as supplementary information. PDF curves were constructed in Microsoft Excel™ using a custom worksheet to calculate the probability distributions associated with the input dates (based on reported mean and error), sum the probabilities and produce a PDF curve based on these values. To mitigate against probabilities dropping artificially at the extremes of the period of interest, all dates that had PDFs crossing the thresholds of 20 or 350 ka (when considered to the 2 sigma level) were included in the PDF production. The final number of dates contributing to the Arabian and Saharan PDFs were 125 and 144, respectively. These dates are listed in full in the supporting information (SI Tables 1 and 2), with the references for the publications these dates are derived from included in the reference list at the end of this text and in the supplementary information.

Though we have attempted to overcome errors and artefacts that can be associated with the PDF method, criticisms specific to the PDF method itself have been raised. Scatter of reported ages and

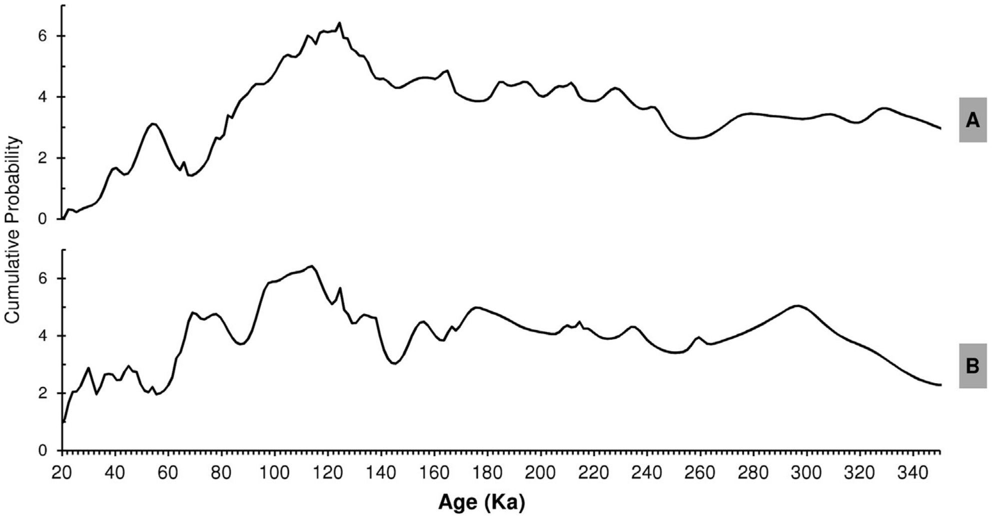

**Fig. 1.** PDF data 20–350 ka BP. A: Final Arabian dataset ($N = 125$). B: Final Saharan dataset ($N = 144$).

errors around the true age due to the probabilistic nature of radiometric dating may be an issue (Chiverrell et al., 2011a). This is a concern inherent in any use of radiometric dates, and may be rectified by applying a systematic Bayesian sequence stratigraphic approach (Chiverrell et al., 2011a, 2011b). However, such a methodology cannot be applied systematically to the spatially distributed data evaluated in this study. Potential directional time lag between dated deposits and the events producing the deposits has also been highlighted (Chiverrell et al., 2011a), however, given the broad temporal resolution of our analysis such lag may be unlikely to affect the PDF plots.

The number of dates contributing to PDF curves have also been raised as being of key importance, with a sufficient number required to minimise the risk of troughs in the PDF curves reflecting sampling rather than environmental change (Hercman, 2000; Michczynska and Pazdur, 2004; Starkel et al., 2006). Prior attempts to recognise and mitigate against this issue have included the use of Bootstrap and Monte Carlo methods to investigate the required number of dates to produce reliable results for a given time period (Hercman, 2000; Michczynska and Pazdur, 2004). Here the stability of the PDF maxima were assessed, following procedures outlined by Hercman (2000) where for each dataset a random 40% of the input data was removed and PDF curves plotted from the remaining dates, repeated 20 times per dataset, to provide a visual estimation of the relative stability of PDF peaks. Fig. 2 displays the stability test data for the final Arabian and

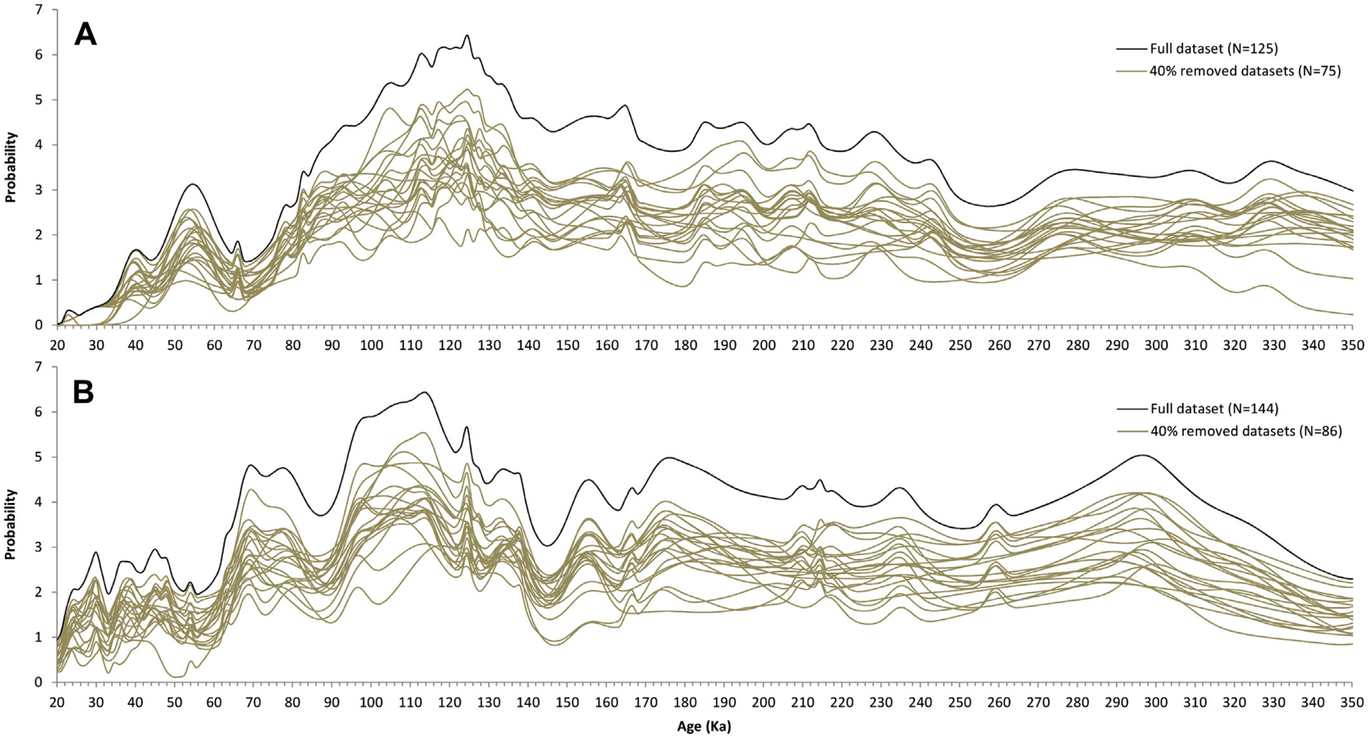

**Fig. 2.** Peak stability assessment for PDF data. A: Arabian dataset, PDF curves for total dataset and for dataset with 40% of data randomly removed (20 repeats). B: Saharan dataset, PDF curves for total dataset and for dataset with 40% of data randomly removed (20 repeats).

Saharan data, and demonstrates the majority of the PDF peaks to be relatively stable and still present in most of the randomly depleted datasets up until around 200 ka, where peak stability reduces, due to the reduced number of dates. Furthermore, in order to highlight potential clustering and the reasons for gaps in the pluvial proxy dates, means and associated errors for the dates used were overlain upon the PDF curves (Fig. 3), thus showing when troughs that do not fall near to zero are due to the presence of a single sample or to overlapping errors from dates with high errors contributed from surrounding peaks in probability.

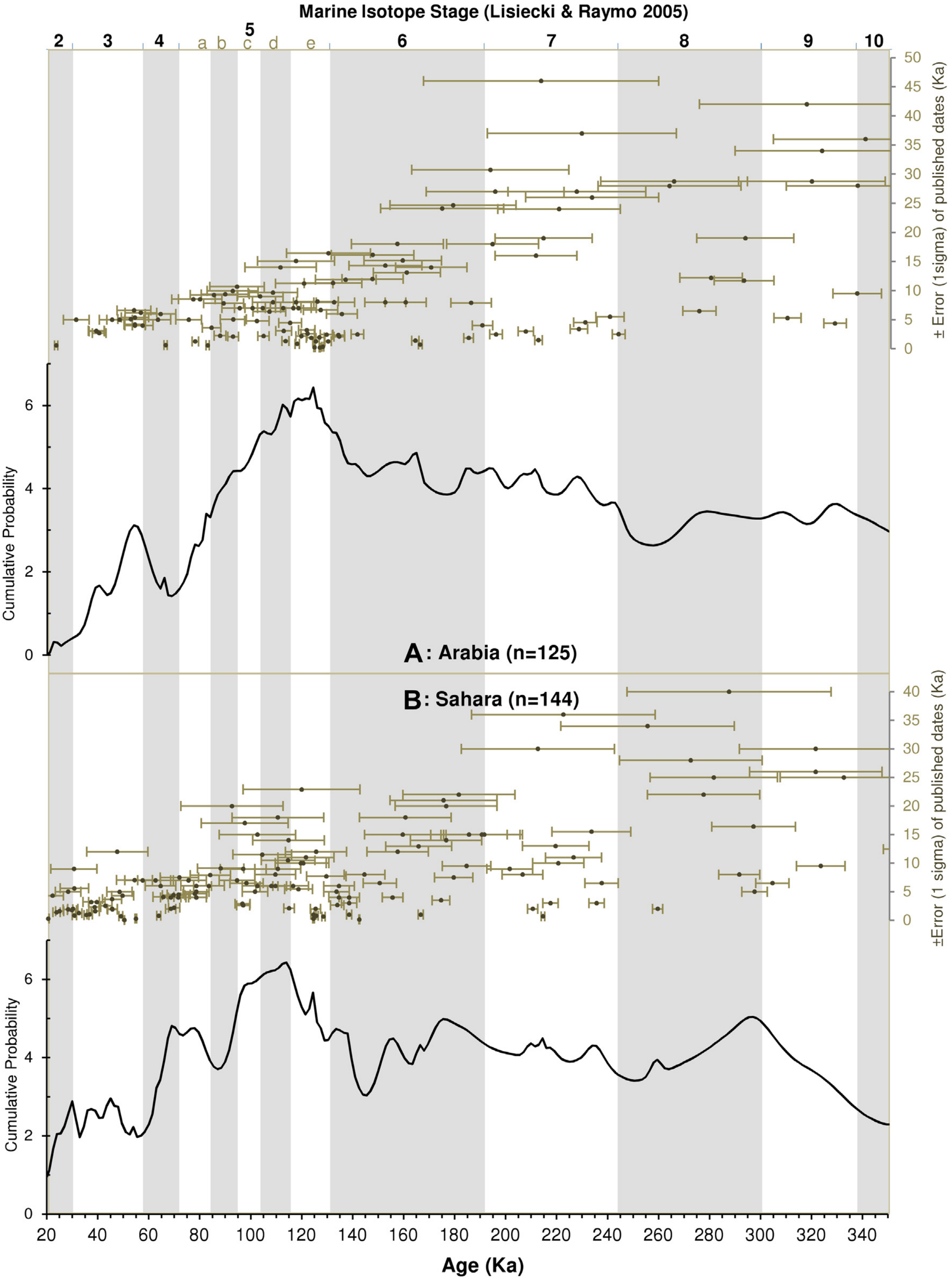

**Fig. 3.** Regional PDF curves for 20–350 ka BP and input dates. A: Arabian data ($N = 125$). Top: Mean ages with errors (1 sigma) used as inputs to PDF analysis. Data have been separated vertically according to size of errors for display. Bottom: PDF curve displaying cumulative probability fluctuations over time. B: Saharan data ($N = 144$). Top: Mean ages with errors (1 sigma) used as inputs to PDF analysis. Data have been separated vertically according to size of errors for display. Bottom: PDF curve displaying cumulative probability fluctuations over time.

### *4.3. Spatial characteristics of analysed data*

To contextualise regional PDF curves, the spatial characteristics of the record must also be considered. This provides an indication of the spatial spread of the dates for individual humid periods thus indicating regional pluvial conditions and potential hominin dispersal routes, but also providing information on any spatial biases in the data. Such biases could arise because although chronologically close pluvial dates will produce a peak in PDF analyses, if these dates originate from a small localised area then independently they can only be interpreted to reflect local, rather than regional pluvial conditions. To examine changes in the indicated spatial extent of humid conditions over time, the published locations of the humid proxy deposits associated with peaks in the PDF curves were plotted using ESRI ARC GIS (Fig. 4). In producing these maps, deposits were assigned to a peak if their reported mean lay within the date range of the peak, as defined by the width of the peak, measured between the bases of the adjacent troughs in the curve. Deposits with one-sigma error bars that intercepted a peak, but with means lying within curve troughs between peaks were not plotted. This conservative approach was taken in order to map only those data most likely to contribute to a PDF peak, and as such, the

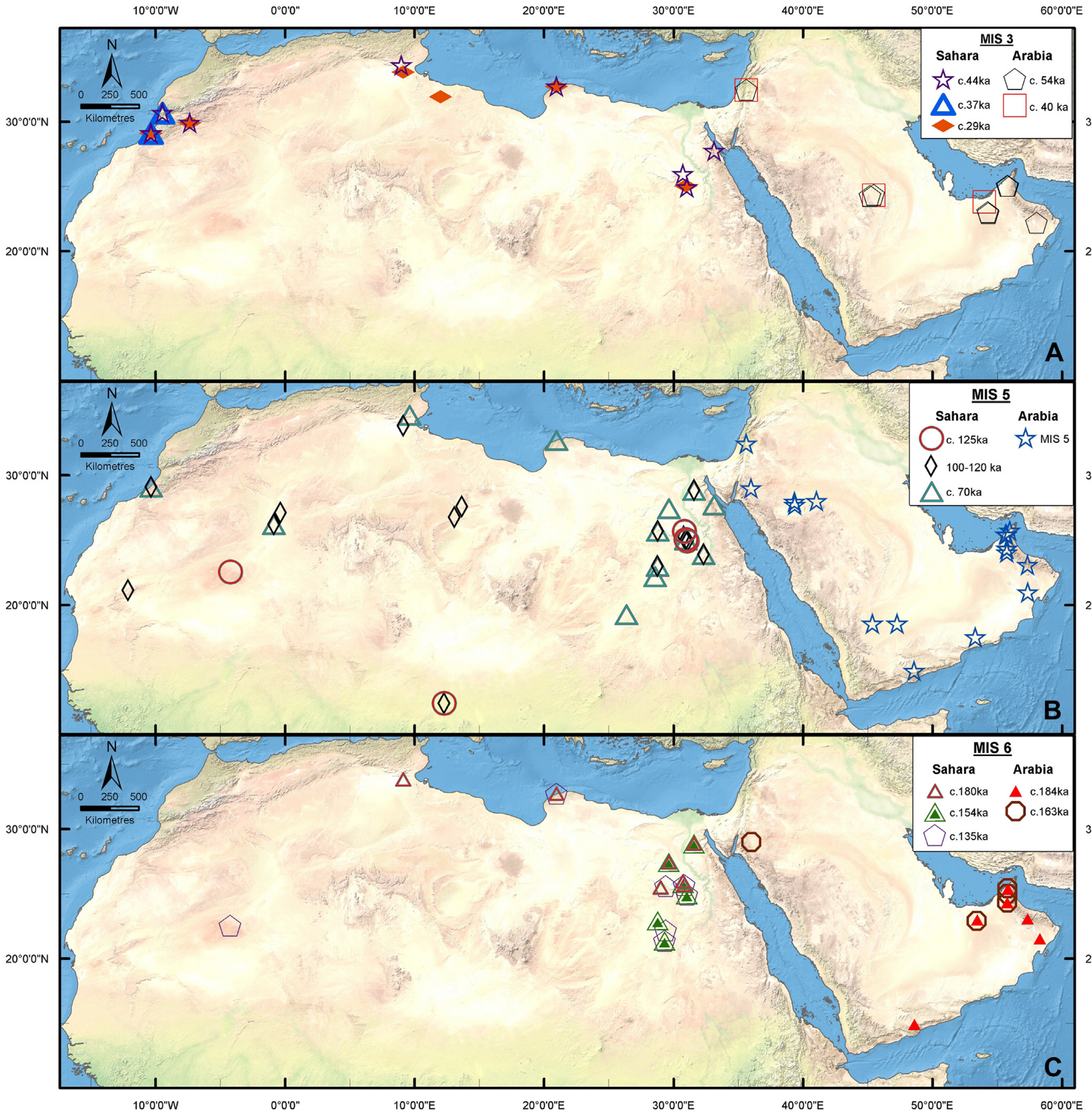

**Fig. 4.** Maps showing the locations of humidity proxy deposits associated with the PDF peaks discussed in the text, divided by marine isotope stage (Lisiecki and Raymo, 2005). Data is overlain on Natural Earth 2 Shaded Relief data, and humidity peak dates and the symbols representing these locations are listed in the key for each map. A: MIS 3 peak locations. B: MIS 5 peak locations. C: MIS 6 peak locations.

spatial plots may underestimate the true number of humidity indicators associated with any given peak. Fig. 4 shows this data plotted by marine isotope stage using the LRO4 chronology (Lisiecki and Raymo, 2005). Where a peak crossed the boundary between two marine isotope stages, it was represented on the map for the isotope stage within which the bulk of the peak lay.

### 4.4. Comparison with proxy records

A range of published palaeoenvironmental proxy data covering the period of 350–20 ka for the mid-latitude desert belt was compiled for comparison with the PDF data. To contrast the pluvial data with continental aridity records, aeolian dust percentage data was sourced for marine core locations receiving dust from the West African (ODP 659: Tiedemann et al., 1994; DeMenocal, 1995) and Arabian (ODP 721/722: DeMenocal, 1995) summer dust plumes. In these cores (locations shown in Fig. 5), dust percentage maxima have been reported to reflect increased continental aridity across the Saharan and Arabian regions (Tiedemann et al., 1994; DeMenocal, 1995). Contextualisation in relation to global chronostratigraphy was provided by orbital eccentricity and summer insolation values (Berger and Loutre, 1991), and by the LR04 stacked global benthic oxygen isotope record (Lisiecki and Raymo, 2005).

Proxy data was sourced from supplementary materials for the above publications and online archives. Further processing of sourced data consisted of production of dates for dust percentage measurements from ODP 659 marine core (Tiedemann et al., 1994) through linear interpolation based on the published age model. Fig. 5 displays these palaeoclimate proxies in relation to each other, to the regional PDF plots, and to oxygen isotope stages (using the LRO4 chronology of Lisiecki and Raymo, 2005).

## 5. Results and discussion

### 5.1. Summary and overview

The PDF curves for the Sahara and Arabian Deserts are shown in Fig. 1. Probability peaks indicate clustering of the pluvial proxy dates, interpreted here to represent humid events. Correspondingly, troughs in the curve represent a reduced number (or an absence) of pluvial proxy dates, and may represent drier periods. It is important to note that the relative height of peaks in the PDF curves reflect the number of dates contributing to the curve at a given point in time. They are therefore a measure of the number of locations that experience humidity at that time, and thus the spatial spread of the humidity, rather than a measure of the intensity of humid events. This is evident in Fig. 3 where the dates and their error bars are plotted above the combined PDF curve and it can be seen how the number of dates and the size of the errors affect the PDF curve. A general smoothing of the curve as age increases is a result of increasing errors for dates as the age increases and the limits of the dating methods is approached (Fig. 3). The general reduction in probabilities for the samples older than about 200 ka is due to the prevalence of dates with very large error bars (Fig. 3) and probably also preservation bias influencing the number of recorded dates (Starkel et al., 2006), with older humid proxy data having a greater chance of being eroded away or buried. As a result, data is discussed for the period from 20 to 200 ka (Fig. 5A and B), which we considered to be the more secure portion of the dataset, in addition to being the key period of interest for discussions of AMH evolution and dispersal. The PDF curves for both deserts are similar in overall terms, both generally following the Marine Isotope Stage (MIS) chronology. However, they differ from each other, and the MIS record, when examined in detail (Figs. 3, 4A–C, and 5A, B and D) as discussed below.

### 5.2. MIS 2

In Arabia MIS 2 shows little evidence for humidity as would be expected during the height of the last glacial, however, the Sahara shows a sharp rise in probability towards the start of MIS 2, peaking near the boundary with MIS 3 at ~29 ka. The evidence for this humid period comes from a range of humid proxies, with lacustrine sediments from the Chott el Djerid in southern Tunisia (Causse et al., 2003), tufa from Kharga Oasis (Blackwell et al., 2012) and Wadi Abu Had-Dib (Hamdan, 2000) in Egypt, calcrete from Ras el Wadi in northern Libya (Giraudi, 2005), travertine from Oued Noun in Morocco (Weisrock et al., 2006, 2008), fluvial sediments from Wadi Zewana in northern Libya (Rowan et al., 2000), as well as Oued Noun (Weisrock et al., 2006) and Tassint in Morocco (Thorp et al., 2002). Thus there is evidence for humidity in the eastern Sahara and along its northern margins at this time, but no evidence in Arabia (Fig. 4A). Evidence for humidity in the Levant at this time (Frumkin et al., 2011) shows that the humid belt around the southern Mediterranean continued further east.

### 5.3. MIS 3

In MIS 3 both regions show a reasonably substantial clustering of dates and associated peaks in the PDF curve. For Arabia this is at 40 and 54 ka, and for the Sahara at 37 and 44 ka. The 37 ka peak consists solely of sites on the northern margins of the Moroccan Sahara, with travertines and fluvial sediments from Oued Noun and a travertine from Imouzzer (Weisrock et al., 2008). Evidence for Saharan humidity at 44 ka is more widespread being provided by spring tufas from the east-central Sahara in Kharga Oasis (Sultan et al., 1997) and Wadi Abu Had-Dib (Hamdan, 2000) in Egypt as well as from fluvial activity in the semi-arid belt on the northern margins of the Sahara in Libya (Rowan et al., 2000), southern Tunisia (White et al., 1996) and Morocco (Thorp et al., 2002; Weisrock et al., 2008) (Fig. 5B). Though the number of dated sites for this humidity peak is small, and again predominantly found along the northern margins of the Sahara, there is further independent evidence for humidity within the Sahara and nearby at ~44 ka. Two marine records off the southern Saharan coast in the eastern Atlantic (Lézine and Casanova, 1991; Castañeda et al., 2009) indicate humidity in the southern Sahara, as well as speleothem (Lisker et al., 2010; Frumkin et al., 2011) and tufa (Waldmann et al., 2010) records in the Dead Sea region, providing more evidence for humidity on the Southern Mediterranean rim. Thus there is evidence for humidity in northern, eastern and southern Saharan region at this time (Fig. 4A), though this evidence is rather sparse and there is little evidence for humidity in the central Sahara.

In contrast to the Sahara, Arabia exhibits pluvials during early and mid MIS 3. There is a small peak at ~40 ka contributed to by fluvial sediments from Saudi Arabia (Mclaren et al., 2009), the UAE (Goodall, 1995) and Oman (Blechschmidt et al., 2009) as well as lacustrine sediments from the highlands of Jordon (Moumani et al., 2003); the latter complementing the nearby evidence for humidity in the Dead Sea area (Frumkin et al., 2011) and the similar aged sediments found in the northern Saharan at ~44 ka, though the Arabia evidence is slightly earlier, sparse, and spread across the continent. Arabia in MIS 3 is, however, dominated by a much stronger and earlier peak at ~54 ka (Fig. 3). Furthermore, there is evidence for humidity from a wide range of proxies at this time, with an extensive geographical distribution (Fig. 4A). Lacustrine conditions are found at Jebel Aqabah (Parton et al., 2010, 2013), Liwa, in the UAE (Wood et al., 2003) and in the highlands of Jordon (Moumani et al., 2003); fluvial activity at Al Quwaiayh in Saudi Arabia (Mclaren et al., 2009), Jebel al-Emaylah in the UAE (Krbetschek, 2008) and Wadi Andam in Oman (Blechschmidt et al., 2009). There

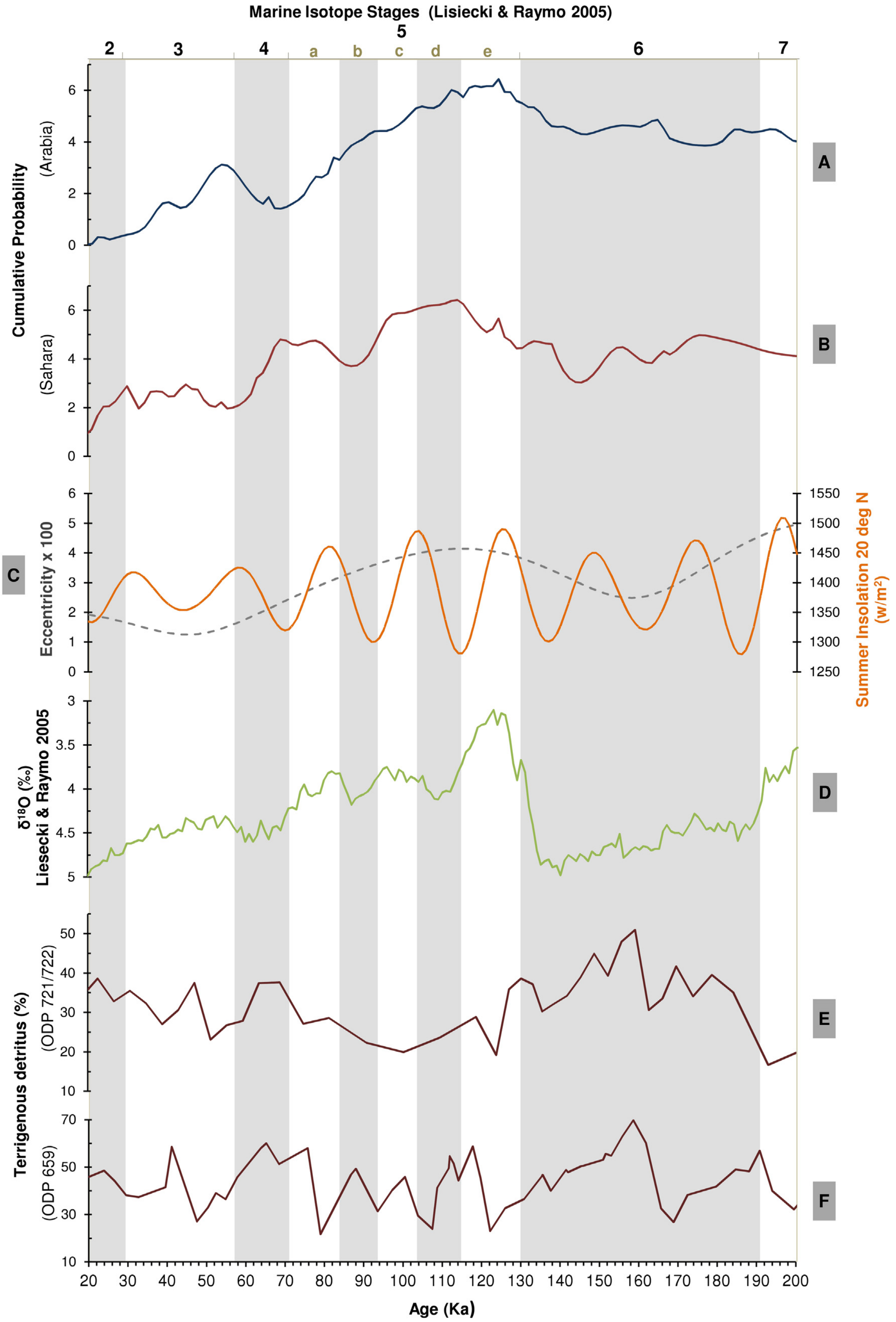

**Fig. 5.** Regional PDF plots for 20–200 ka BP in comparison to global and regional palaeoenvironmental records. Data are overlain for reference by Marine Isotope stages (LR04 chronology, Lisiecki and Raymo, 2005) and MIS 5 substages (Cohen and Gibbard, in press). A: PDF curve for Arabian humidity proxy dataset ($N = 125$). B: PDF curve for Saharan humidity proxy dataset ($N = 144$). C: Summer insolation values for latitude 20° N overlain by eccentricity data (multiplied by 100 for representation) (Berger and Loutre, 1991). D: Stacked benthic oxygen isotope curve LR04 (Lisiecki and Raymo, 2005), inverted to match sea-level curve profiles. E: Terrigenous detritus percentage data from marine core ODP 721/722 in the Arabian Sea (Tiedemann et al., 1994; DeMenocal, 1995). F: Terrigenous detritus percentage data from Marine core ODP 659 in the Northern Atlantic (DeMenocal, 1995).

is also corroborating evidence for humidity in other parts of Arabia and from surrounding regions, with speleothem growth recorded on the island of Socrota (Burns et al., 2003), reduced dust input to the Arabian Sea (Fig. 5E; DeMenocal, 1995; Leuschner and Sirocko, 2003), a corresponding increase in palaeoproductivity (Leuschner and Sirocko, 2003), and hominin occupation associated with fluvial activity in the Western Yemeni Highlands (Delagnes et al., 2013). A similar humid event is found in Lake Naivasha in nearby East Africa (Trauth et al., 2003), a region also affected by the Indian Ocean South-Western Monsoon. Furthermore, the Nile shows enhanced flow at this time (Revel et al., 2010), and given that the majority of this flow comes from the East African Highlands, this can be seen as further evidence for increased humidity in this region.

The different timing of the MIS 3 Saharan and Arabian humid events provides an indication that the Indian and Atlantic Ocean Monsoons have responded to global climate change in a slightly different manner. Furthermore, Mediterranean humidity appears to coincide with that of the Sahara and not Arabia, apart from the Dead Sea region and nearby Jordanian highlands that appears to have provided a pocket of humidity throughout much of MIS 3. Yet the Negev Desert just to the south of this humid region is dry (Frumkin et al., 2011) and the lack of evidence for humidity in northern Saudi Arabia suggests it was dry at 54 ka, thus all the evidence for humidity is found in central and southern Arabia (Fig. 4A). Given these points, current evidence suggests that the Indian Ocean monsoon only penetrated as far north as central Arabia during this ~54 ka humid event, leaving an arid region in the north of the Arabian Peninsula (Fig. 4A). This spatial distribution of Arabian humidity and aridity has implications for hominin occupation and dispersal routes at this time. It appears that occupation of the southern peninsula would have been possible, and indeed evidence for this has recently been found in Yemen (Delagnes et al., 2013) and the UAE (Armitage et al., 2011). Dispersals to the north would seem to have been unlikely as they would have encountered an arid barrier, however, in the southern peninsula at this time movements east–west or west–east would have found a humid environment, both along the coast and further inland.

The dispersal of AMH carrying a sophisticated lithic technology analogous to that of the southern African Howiesons Poort from east Africa across the Bab el Mandab, along the coast of Arabia and thence onwards around Asia to Australasia before 50 ka has been proposed (Mellars, 2006). Our analysis suggests such a dispersal may have been possible at this time by traversing through a humid environment, either along the coast, or further inland. However, there is no archaeological evidence for this dispersal, indeed the two archaeological sites dated to MIS 3 both show Middle Palaeolithic lithic traditions that do not conform to any found in East Africa, or even to earlier traditions in other parts of Arabia, suggesting autochthonous developments (Armitage et al., 2011; Bretzke et al., 2013; Delagnes et al., 2013). A key point is that microlithic and crescentic assemblages of the kind described by Mellars (2006) have not yet been found in Arabia. Therefore such a dispersal can only have happened if the participants traversed the coast and did not move any significant distance inland, with subsequent sea level rise submerging the evidence. Even then the lack of any archaeological evidence is unlikely as much of southern Arabian continental shelf is very narrow and steep so there is not much of a coastal shelf to expose when sea level falls, thus AMH would have been forced to move close to what is now dry land, but no evidence for their presence has yet been found there.

### 5.4. MIS 4

MIS 4 is predominantly arid (Fig. 5), with only the odd site in both the Sahara and Arabia suggesting humidity. However, it is also a time of transition, in the case of the Arabia the PDF is declining from its peak at the start of MIS 3, and for the Sahara is rising from a low point at the start of MIS 3 towards a peak in the PDF at the start of MIS 4 and the end of MIS 5 (c. 70 ka peak, Fig. 4B). There is, though, direct evidence for aridity at this time with dune accumulation recorded in the Liwa region at 63 ka (Stokes and Bray, 2005) and between 60 and 50 ka (Juyal et al., 1998). In the Wahiba, Sands dune deposition occurred during MIS 4 until about 64 ka (Preusser et al., 2002).

### 5.5. MIS 5

MIS 5 is humid in both Arabia and the Sahara, with Arabia providing 48 dates and showing a gradually rising probability back in time through the stage to a maximum during MIS 5e at 127 ka, whereupon the probability begins to decline. Evidence for this humidity is preserved in a wide range of environmental settings including speleothems, palaeosols, fluvial and lacustrine sediments. In Arabia speleothem growth was most pronounced during MIS 5e, more so than all subsequent pluvials, signalled by rapid growth between 135 and 120 ka (Burns et al., 1998, 2001; Fleitmann et al., 2011). MIS 5e is strongly represented in speleothem records from Yemen, southern Oman and northern Oman with the most heavily depleted oxygen isotope values recorded in the last 350 kyr. These records highlight evidence for wetness in Yemen during MIS 5c and during MIS 5a in Yemen and Oman (Fleitmann et al., 2011). Lacustrine evidence from Arabia has been found in the Rub' al-Khali region, including sites at Mundafan with lake sediment accumulation centred ca. 80, ca. 100, and ca. 125 ka (Rosenberg et al., 2011), and at Saiwan between 132 and 104 ka (Rosenberg et al., 2012). At Mudawwara, Jordan, lacustrine sediments are believed to be remnants of a former lake extending over several thousand square kilometres at time intervals between 135 and 116 ka and 95 and 88 ka (Petit-Maire et al., 2010).

The dating results from Arabia suggest a predominantly humid interglacial with a single large peak in the curve through MIS 5 with no significant breaks (Figs. 5A and 4B). However, caution is needed when interpreting the PDF plot as by this time the errors on many of the dates are becoming so large that they could mask short arid periods (Fig. 3), thus other proxy records may provide better evidence of such events. Indeed, in Arabia the dune palaeosol record of Petraglia et al. (2011) the paleolake record of Rosenberg et al. (2011), the Arabian Sea dust and ocean productivity record of Leuschner and Sirocko (2003), and the Wahiba dune record (Preusser et al., 2002), all suggest low humidity during MIS 5 substages b and d; these are periods recognised in many parts of the world as cool and/or dry stadials, as shown by the lower values in the stacked benthic oxygen isotope curve of Lisiecki and Raymo (2005) (Fig. 5D). Yet in contrast, the Arabian marine dust record of DeMenocal (1995) (Fig. 5E) shows generally low levels of dust and little variability throughout most of MIS 5, possibly indicating that the aridity suggested by the above mentioned records was not very severe, as is also suggested by the large number of dated humid deposits that date within these stadial periods (Fig. 3A).

The Sahara has 34 humid dates from MIS 5 from speleothems, tufas, fluvial and lacustrine sediments. The PDF plot differs from Arabia by showing two broad but prominent humidity peaks, one centred on 76–68 ka and the other between 114 and 104 ka, separated by a less humid period around 87 ka. The 76–68 ka humid period is predominantly indicated by 19 dates that show a spatial distribution ranging from the eastern to the central and north-west Sahara (Fig. 4B), but are concentrated in the east, with speleothems from Wadi Sannar Cave and Djara Cave in Egypt (Osmond and Dabous, 2004), tufa from Kharga Oasis (Osmond and Dabous, 2004) and Kurkur Oasis, Egypt (Crombie et al., 1997), travertine from Oued Noun in Morocco (Weisrock et al., 2008), lacustrine sediments from the Western Desert of Egypt and Sudan at Bir Sahara East and Bir Tarfawi (Wendorf et al., 1993), the Selima Sandsheet, Wadi Hussein and Wadi Arid (Szabo et al., 1995) and Algeria at Kadda (Causse et al., 1988) as well as and fluvial sediments from Wadi Zewana in Libya (Rowan et al., 2000).

The evidence for the 114–104 ka humid period is more widespread (Fig. 4B) and dominated by lacustrine sedimentation from Sebkah Chemchane in Mauritania (Lézine and Casanova, 1991), the Toudenni Depression in Mali (Petit-Maire et al., 1994), Azzel Matti and Kadda in Algeria (Causse et al., 1988), Wadi el-Agial and Wadi ash Shati in Libya (Armitage et al., 2007; Armitage, unpublished), Chott el Djerid in southern Tunisia (Causse et al., 2003), Lake Megachad shorelines in Nigeria (Drake et al., 2011) and Daklah Oasis, Bir Tarfawi and Bir Sahara East in Egypt (Wendorf et al., 1993; Brookes, 2010). This considerable evidence for widely distributed Saharan humidity is corroborated by dates on tufas from Kharga and Kurkur Oasis in Egypt (Crombie et al., 1997; Osmond and Dabous, 2004), fluvial sediments from Oued Noun in Morocco (Weisrock et al., 2008) and a speleothem from Wadi Sannar Cave in Egypt (Osmond and Dabous, 2004).

Both of the Saharan humidity peaks roughly correspond with insolation maxima over the Sahara (Fig. 5B and C), and thus could be primarily due to the enhancement of the monsoon. Furthermore, the decline in evidence of humidity during MIS 5b could be attributed to the reduction of insolation at this time. However, from about 110 ka onwards, throughout the rest of MIS 5, the similarity with insolation ceases. Furthermore, no such decline is evident in the subsequent insolation minima at the MIS 5d/e boundary. Indeed this humid period has greater probability than any other in the entire record, and is also the most spatially extensive. Additionally, no substantial peak is found in MIS 5e, though there is a small rise centred on 123 ka during it and a high probability of humidity throughout.

The spatial distribution of Saharan and Arabian humid sites dated to MIS 5 provide interesting contrasts (Fig. 4B). In the Sahara, sites are spread throughout much of the desert, indicating trans-Saharan humidity, as also suggested by Drake et al. (2011). However, dated sites in Arabia are clustered in the north and south, with none in the middle. This difference in spatial distribution suggests that it might have been easier for hominins to disperse northwards across the Sahara than it was across Arabia, however, more work in the centre of the Arabian Desert is needed to investigate this gap and confirm or refute this hypothesis.

### 5.6. *MIS 6*

There is some evidence for humidity in MIS 6 and this is unexpected because this glacial period is traditionally thought to be cold and dry in deserts. However, interpretation of the results for MIS 6 is hard due to the size of the errors on some dates. At the end of MIS 6 there is a small probability peak at ~138 ka for the Sahara preceded by a significant decline in the probability of humidity, and a less pronounced decline for Arabia. The limited Arabian reduction cannot simply be put down to the increase in the size of the errors because Fig. 3A shows a scatter of dated humid deposits throughout MIS 6, quite a few of which have small errors. Interestingly there is a small clustering of humid dates centred around 163 ka producing a small peak in the PDF curve. In contrast, in the Sahara there is more evidence of clustering of humid dates with peaks in probability around 138, 154 and 180 ka. The 138 ka peak is the least distinct of the three, and is the result of lacustrine sediments from the Chott el Djerid in southern Tunisia (Causse et al., 2003), the Taoudenni Depression in Mali (Petit-Maire et al., 1994), the Selima Sandsheet and Debis West from the Western Desert of Eqypt and Sudan (Szabo et al., 1995), Tufas from Kharga and Dakleh Oasis (Smith et al., 2007; Kleindienst et al., 2008) and fluvial sediments from Wadi Zewana in Libya (Rowan et al., 2000). This is followed by clear troughs in probability before the 154 ka and 180 ka peaks that are presumably associated with aridity. The lack of a more substantial decline between peaks is due to dates with high errors contributing to both the peaks and the gaps in between. The dates that straddle the decline in probability between the 154 and 180 ka peaks are from the Wadi Sannar and Djara Cave speleothems (Osmond and Dabous, 2004) and tufas from Kharga Oasis (Sultan et al., 1997), Wadi Abu Had-Dib (Hamdan, 2000) and Dakhla Oasis (Brookes, 1993). The dates that contribute to the 154 ka peak are lacustrine sediments from Chott el Djerid Tunisia (Causse et al., 2003), Bir Sahara and Selima Oasis in Egypt (Szabo et al., 1995) and a tufa from Kharga Oasis (Smith et al., 2004). The fluvial sediments from Wadi Zewana in Libya (Rowan et al., 2000), lacustrine limestones from the Chott el Djerid in Tunisia (Causse et al., 2003) and a tufa from Kharga Oasis (Sultan et al., 1997) and Kurkur Oasis in Egypt (Crombie et al., 1997) contribute to the 180 ka peak.

Unfortunately, we have found little ancillary information to provide further evidence on the status of the Saharan palaeoclimate at this time. The Atlantic dust record of Tiedemann et al. (1994) is an exception, yet it shows little correspondence to our PDF plot of the Sahara region (Fig. 5F). Though the dust record shows variability throughout MIS 6, it provides a similar amount of variability throughout the entire record, and surprisingly the same level of dust variability during glacials as within interglacials. This is in marked contrast to the Arabian dust record that generally conforms to the terrestrial record throughout the period studied here (Fig. 5E). It shows an increase in dust deposition from MIS 5 to MIS 6 suggesting increased aridity, but there is also a lot of variability within MIS 6 that may suggest that this was a time of climate variability in Arabia, with periods of humidity and aridity that were too short to be picked up by the PDF plot because the errors on the dated humid sites were larger than the periods of aridity. The main MIS 6 maxima evident in the PDF plot at 163 ka corresponds with a noticeable minima in dust deposition (Fig. 5E), providing some support for the view that there were brief humid periods, though other declines in dust do not show corresponding increases in probability. However, the notion of stage 6 sub-pluvials is corroborated by the spread of humid dates throughout this period with optical dates on fluvial silts at Sabkha Matti (ca. 147 ka) (Goodall, 1995), two UTh measurements from freshwater mollusca within lacustrine sediments at Mudawwara, on the Jordanian/Saudi Arabian border (ca. 170 and 152 ka) (Petit-Maire et al., 2010), optically dated fluvial silts in the Wadi Dhaid, UAE (ca. 152 ka) (Parker and Rose, 2008), and OSL measurements on evaporitic lacustrine sediments sampled from a relict interdunal sabkha in the Liwa region of the Rub' al Khali, UAE (ca. 160 ka) (Wood et al., 2003). Weak palaeosols in MIS 6 aeolian deposits are also noted in the Wahiba Sands (Preusser et al., 2002).

Within the Sahara, the spatial distribution of MIS 6 humid sites is concentrated in northern and central regions, with no sites found in the south (Fig. 4C), whilst in Arabia sites are found in the northern and southern parts of the peninsula, but not in the middle. Thus with current data there is no evidence for north–south corridors across either desert, yet the paucity of data in some areas means that there is potential for humid corridors if more research is conducted in regions where data is currently absent. For example the sediments of Lake Chad and the shorelines of Lake Megachad have potential to yield further important information on the palaeoclimate of the southern Sahara during MIS 6, a region where there is currently no evidence during this time period.

If it were possible to cross a 'green Sahara' during MIS 6, then this would help explain the archaeological record of modern AMH in the Maghreb. AMH are thought to have evolved in East Africa at ∼150–200 ka (McDougall et al., 2005), yet by ∼160 ka the first archaic AMH remains are found at Jebal Irhoud in Morocco (Smith et al., 2007) and by as early as ∼145 ka the earliest Aterian stone tools are found at Ifri n'Ammar (Richter et al., 2010), the Aterians now being thought to be an early group of AMH. AMH migrating into the Maghreb by this time would have had to cross the Sahara, and a green Sahara during MIS 6 would have provided the opportunity to do so.

To gain a thorough understanding of green corridors across the Saharo-Arabian Deserts, we need to know how glacial/interglacial cycles affect Westerlies, how precessional forcing of insolation affects the monsoon, and how these processes interact. Unfortunately the data presented here only shed light on a few of these issues, and some contradictions arise. For example, during MIS 5 both records show much evidence for humidity, yet the Saharan record shows more similarity to insolation than the oxygen isotope record, whereas in contrast, for Arabia it is the reverse (Fig. 5A–D). Some sense can be made of this when eccentricity is considered. Both records appear to loosely follow eccentricity whereby when it is high both deserts show a tendency to be wet for much of the time and all humid PDF peaks are roughly synchronous with insolation. However, when eccentricity is low, there is a propensity for aridity and any periods of humidity are less intense and out of sync with insolation. This is probably due to the way insolation is modulated by eccentricity. When eccentricity is strong, insolation is more variable but generally enhanced. When eccentricity is low the opposite occurs and presumably local factors exert more of an influence on climate. A similar eccentricity-modulated precession interpretation of African climate has recently been provided by Blome et al. (2012).

## 6. Conclusions

The data synthesis presented here furthers our understanding of Saharo-Arabian climate change by implementing a spatio-temporal analysis and a comparison to other proxies, thus allowing a comparison of land and ocean records. However, the limitations of the data need to be stressed before conclusions are drawn. As with any regional analysis based upon published data, the PDF and GIS analyses presented here are influenced by temporal and spatial biases in regional research strategies and these biases might produce artificial troughs or peaks in the PDF curve, or gaps in the spatial distribution of dated humid sites, reflecting more the nature of published evidence than the true character of the record. Furthermore, differential regional preservation of humid proxy deposits may also affect the published record, as will differential preservation over time. Finally, in the case of the PDF analysis variations in dating procedures can affect how closely the precision of published dates reflect the true age, and the increase in the size of the errors for many of the older dates can mask details in the combined PDF record. Yet given these potential confounding factors the Saharan and Arabian the PDF records are generally similar and exhibit a significant positive correlation ($R\ spearman = 0.694$ $p = <0.005$) that explains 48% of the variance. A similarity between the records would be expected, given that both deserts experience variations in monsoonal and Westerly rainfall as palaeoclimate drivers. Thus, whilst being aware of the potential shortcomings of the PDF approach, we consider the method of sufficient utility to provide a broad summary of the spatio-temporal character of the regional pluvial records from 20 to 200 ka, a period of time when the issues of preservation and the size of the errors do not seem to be onerous. During this time period it is possible to clarify and advance the current state of knowledge, as well as guide further work.

There is some evidence for short periods of Saharo-Arabian humidity at the beginning of MIS 2 and during MIS 3, 4 and 6, though at slightly different times in each region with only two roughly corresponding with insolation maxima (the Sahara at 30 ka and Arabia at 55 ka). During MIS 5, both regions provide evidence for humidity throughout much of the period. Though in fine detail the humidity peaks in the Sahara and Arabia differ, they all correspond to peaks in insolation, although not all insolation maxima are represented in either record.

The different timing of the evidence for humidity in MIS 3, 4 and 6 in the Sahara and Arabia suggest that the Indian Ocean and Atlantic Ocean West African Monsoons responded to forcing at slightly different times. However, during MIS 5 the response was similar. Following Blome et al. (2012), we suggest that this is due to eccentricity-modulated precession, whereby when eccentricity is strong insolation is enhanced but also more variable, and the desert climate is generally more humid, particularly at times of high insolation. When eccentricity is low the opposite occurs; deserts tend to be more arid, and local factors exert more of an influence on climate, affecting the timing and intensity of humid periods.

Radiocarbon dates were omitted from our analysis because of problems of contamination of older samples with younger carbon introduced during following wet phases. Hence we derive different results from the Arabian PDF study of Parker and Rose (2008) that incorporated them. This study indicated an extended Arabian humid period between ca. 20 and 40 ka that is not evident in our analysis and appears to be an artefact of inclusion of contaminated radiocarbon dates (Rosenberg et al., 2011). Our results show a shorter and earlier MIS 3 pluvial event, and this has implications for palaeoclimatic reconstruction, and also for human genetic studies that have utilised this palaeoclimate information in models of Pleistocene human occupation and dispersals (e.g. Fernandes et al., 2011). Interestingly, in the Sahara the debate on the utility of radiocarbon dates older than about 20 ka has been going since 1989 when Rognon (1987) proposed a Saharan pluvial between 20 and 40 ka that was subsequently questioned by Fontes and Gasse (1989), largely on the basis of the contamination issue. Our results do not support the conclusions of either of these studies, as the latter suggest two short pluvials during the humid period proposed by Rognon (1987) and a further one later (∼44 ka).

The compilation of Saharan and Arabian terrestrial records also lends itself to a GIS approach whereby the spatial distribution of the sites for each humid period are analysed in order to see if they are either compatible with dispersal corridors across the deserts, or with the deserts acting as a barrier to dispersals. Though the number of sites is not large enough to provide conclusive evidence our results provide an enlightening first step and are compatible with a number of different dispersal theories. The humid period in southern Arabia centred on 54 ka could have facilitated a dispersal of AMH from east Africa across the Bab el Mandab and through southern Arabia, either along the coast as suggested by Mellars (2006), or in the humid region further inland. It should be noted, however, that there is no archaeological evidence for this proposed dispersal. Archaeological evidence from Arabia at this time suggests the presence is autochthonous, perhaps from existing refugial populations. The extended period of humidity in this region during MIS 5 is also compatible with an earlier dispersal of AMH, as is suggested by Rose et al. (2011) and Armitage et al. (2011). In both cases there is evidence for hominins living in southern Arabia at this time, manufacturing lithics with an East African affinity, suggesting dispersal across the Bab el Mandab during this period. However, the lithic assemblages identified at these two sites are very different from each other, perhaps suggesting multiple dispersals.

Dispersal of AMH across the Sahara during MIS 5 is also entirely feasible given the broad spatial distribution of palaeolake deposits and other proxy records. This would accord with the dispersal of AMH into the Levant at this time (Grün et al., 2005) as it is unlikely that this population came from southern Arabia given the probable arid barrier in the middle of the Arabian peninsula during MIS 5. However, another potential source population for these AMH is the semi-arid and subhumid zone to the north of the Sahara, as the evidence from the Maghreb suggests that AMH crossed the Sahara before MIS 5. Though there are a few dates within both deserts during MIS 6, no humid corridors are found in either the Sahara or Arabia, however, the tantalising evidence for humidity deserves further research, particularly in the Sahara where the implications of early AMH dispersal are profound.

When considering the numerous hominin dispersals that have been postulated, one might argue from a parsimonious perspective that dispersals were most likely to have occurred during peak environmental conditions. If this is the case then the most likely period for dispersal is clearly during MIS 5, either through the Sahara, or across the Ban el Mandab and through southern Arabia, or both. A later dispersal across the Bab el Mandab at about 54 ka is possible; however, a similar late dispersal across the Sahara at ~45 ka appears to be less likely.

In order to develop this research further more dated sites are clearly needed from both deserts, particularly in places where obvious spatial and/or temporal gaps occur, but deposits that have potential to fill these gaps are known to exist (e.g. Lake Chad and Palaeolake Megachad in the southern Sahara). Deposits showing long continuous or semi-continuous records would clearly be ideal, however, they are extremely rare in the Saharo-Arabian region due to problems of long term preservation in deserts prone to hyper arid conditions when erosion of previous humid period deposits occurs. In addition, GIS analysis of dated sites needs to be further developed as this could help to overcome some of the spatial sampling problems evident here whereby potential dispersal corridors can only be loosely defined. This can be achieved by palaeohydrological mapping and then linking the palaeohydrology to the dated humid period sites so that those that are associated with catchments (i.e. fluvial and lacustrine deposits) are not just represented as points on maps, but also the catchment areas feeding into them are highlighted, as these regions would also have experienced humidity. Such an analysis is currently in progress for the entire Saharo-Arabian region. Finally, in order to determine if the recorded humidity was the result of the monsoon or Westerly rainfall, isotope analysis of samples along transects across the deserts might help to determine the sources of the water.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quaint.2012.12.018.

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