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### **published in**

Past Climate Variability through Europe and Africa  
2004

### **document version**

Publisher's PDF, also known as Version of record

[Link to publication in VU Research Portal](#)

### **citation for published version (APA)**

Partridge, T., Lowe, J., Barker, P., Hoelzmann, P., Magri, D., Saarnisto, M., Vandenberghe, J., & Street-Perrott, F. (2004). Climate Variability in Europe and Africa: a PAGES-PEP III Time Stream II Synthesis. In *Past Climate Variability through Europe and Africa* (pp. 583-603)

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**28. CLIMATE VARIABILITY IN EUROPE AND AFRICA:  
A PAGES-PEP III TIME STREAM II SYNTHESIS**

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**Keywords:** Precessional forcing, Abrupt climatic changes, Last interglacial-glacial cycle, Europe, Africa, Tropical monsoon influences, Antarctic circulation influences, N. Atlantic circulation influences, Climate 'teleconnections'.

## Introduction

The PEP III Europe-Africa transect extends from the arctic fringes of NW Eurasia to South Africa. It encompasses the presently temperate sector of mid-latitude Europe, the Mediterranean region, the arid and semi-arid lands of the Sahara, Sahel and the Arabian Peninsula, and the inter-tropical belt of Africa. The palaeoenvironmental evidence available from these regions, which has been summarised in earlier chapters of this volume and which collectively spans the last 250,000 years, clearly bears the stamp of long-term global climate forcing induced by variations in solar insolation. External forcing is ultimately the reason why the Eurasian continental ice sheets waxed and waned repeatedly during the late Quaternary, and why the southerly limit of permafrost migrated southwards across mid-latitude Europe, periodically becoming degraded during warmer episodes. At the same time, pronounced fluctuations in atmospheric and soil moisture have affected the Mediterranean, desert and Sahel regions, while there is abundant evidence from every sector of the PEP III transect for marked migrations of the principal vegetation belts, as well as for other major environmental changes, that are also considered to reflect long-term climate forcing. It is only in the last decade or so, however, that the full complexity of the history of climate changes during the last interglacial-glacial cycle, and their environmental impacts in continental Europe and Africa, have begun to be recognised. The discovery of evidence for the abrupt Dansgaard-Oeschger (D-O) and Heinrich (H) climatic oscillations in Greenland ice-core (Johnsen et al. 1992) and North Atlantic (Bond et al. 1993) records, have prompted a re-examination of the continental record. This, together with a number

of technical improvements in field and laboratory equipment, greater access to sites in remote and difficult terrain, diversification in the range of available palaeoecological and geochronological tools, and closer inter-disciplinary collaboration, have led to a more penetrating examination of the field evidence, which has progressed the science considerably. We can now see that the stratigraphical record is much more complex than appreciated hitherto, and more detailed and refined models of past climatic and environmental models are beginning to emerge. There is, for example, a growing body of evidence which suggests that D-O and H events had significant impacts on the environment of Europe and Africa, as well as on the Mediterranean Sea.

We are, however, still a long way from being able to synthesise these data at a continental scale because the information is patchy at present, while much of the available palaeoenvironmental data is unquantified. Continental records are also fragmentary, especially in the glaciated, periglacial and arid zones, and the records are difficult to date and correlate with adequate precision, particularly those that are older than the limit of radiocarbon calibration. There are, inevitably, major gaps in many of the key stratigraphical records. Exceptions to this rule, however, are continuous lake sediment sequences, especially in lake basins in Southern Europe, though not all of these extend back over the full 250,000 years. Even where long, continuous sedimentary records exist, however, the evidence is not always easy to interpret, and the precise chronology of the sequences is frequently equivocal (see Magri et al. (this volume)).

A second problem is that each sector within the PEP III transect is characterised today by marked climatic variability, which reflects a variety of local influences; presumably the same must have been the case in the past. A regional or global climatic forcing effect could well have been significantly dampened or enhanced by these local influences, but distinguishing between local, regional and global influences on climatic records is difficult. This problem may be compounded by the possibility that regional climatic changes, or, at least, environmental responses to abrupt climatic changes, were measurably time-transgressive. There is evidence to suggest that this may have been the case, for example, in Europe during the last glacial-interglacial transition, an interval for which the evidence can generally be dated more precisely than is the case for earlier intervals (see Vandenberghe et al. (this volume)).

A third issue concerns the manner by which climate mechanisms operate at a global and continental scale. There are presently diverging views as to whether climate changes during the last glacial cycle were synchronous or asynchronous between the two hemispheres (Charles et al. 1996; Blunier et al. 1998; Broecker 1998; Kanfoush et al. 2000). The arguments are made fuzzy, somewhat, by geochronological uncertainties, though a recent study which was based on very precise dating appears to confirm that climatic changes in Japan at the close of the last glacial stage were not synchronous with those in the North Atlantic region (Nakagawa et al. 2003). At issue here is how the major elements of the global climate machine, such as, for example, the Indian Monsoon, North Atlantic circulation, and the 'heat engine' of Tropical Africa, interact, and whether external forcing of the system (caused, for example, by precession) brings about instantaneous changes around the globe. Some assume this to be the case, when, for example, the marine oxygen isotope stratigraphy is used as a basis for inter-regional correlation. Yet evidence presented by Partridge et al. (this volume) indicates that climatic changes in southern Africa, because they were heavily influenced by atmospheric circulation over Antarctica and the Southern Ocean, preceded those in the North Atlantic by some 3 to 4 kyr. Different sectors of the PEP

III transect will have been variously affected by changes in North Atlantic circulation, the Indian Monsoon, Mediterranean circulation, circulation changes in the Southern Ocean, and other components of the global climate system. One should not assume that these different components responded synchronously to external forcing factors; indeed, the evidence seems increasingly to suggest otherwise.

These difficulties notwithstanding, significant progress has been made in understanding the strengths and limitations of the stratigraphical and proxy data at our disposal, while new perspectives are emerging that will surely lead to more effective palaeoclimatic research in the future. Here we summarise the key conclusions to emerge from the reviews of the palaeoenvironmental reconstructions for the PEP III transect during time stream 2, presented in earlier chapters in this volume. We focus especially on those conclusions that may be of most relevance to palaeoclimate modelling.

### **The NW Eurasian ice-sheets**

Ice-sheets play a crucial role in the global climate system, influencing, *inter alia*, albedo, global sea-level, supply of freshwater into the oceans and land drainage. It is extremely important, therefore, to be able to generate reasonable approximations of the dimensions of the ice-sheets that existed at different times in the past, as well as the rate at which these altered. Recent field investigations in NW Eurasia have forced a major re-think on the size and shape of the ice-sheets during the last glacial cycle, and also on how ice-sheets respond to climate (Saarnisto and Lunkka, this volume). One of the crucial conclusions to emerge from recent research is that ice-sheet cover in NW Eurasia may have been greatly over-estimated in earlier models (e.g., Grosswald (1980)), while there is also clear evidence that the dominant centres of ice accumulation shifted across the region during the last interglacial-glacial cycle, presumably in response to local variations in moisture supply.

The ice built up as early as marine isotope stage (MIS) 5d in NW Siberia, while at the same time there was a restricted ice cover in Scandinavia. The centre of ice accumulation then shifted to the Kara-Barents Sea regions during the early part of MIS-4, though this ice mass thinned considerably by the Last Glacial Maximum (MIS-2). In contrast, the Scandinavian ice sheet achieved its maximum extent during MIS-2, at a time when the mainland of Northern Russia was ice-free. It seems, therefore, that the location of the main centres of ice accumulation shifted from the east to the west during the last glacial cycle, possibly as a result of progressive cooling of Siberian and, subsequently, Atlantic coastal waters. As the waters froze, and sea-ice built up, the continental interior became increasingly starved of moisture.

Behind that brief overview lies a much more complex story (Thiede et al. 2001). Until recently our understanding of the behaviour of the Scandinavian ice sheet relied heavily on the analysis of the glacial sedimentary record. This evidence is, of course, very fragmentary; in Scandinavia, for example, because the maximum advance of ice occurred during MIS-2, much of the evidence for earlier episodes has been destroyed, though nearly continuous sequences of glacial diamicts and fossiliferous sediments do appear to have survived in isolated localities, such as Finnish Lapland (Helmens et al. 2000). More continuous records have survived close to, or beyond, the limits of the MIS-2 ice sheet, which help to fill in the gaps. These indicate that the Scandinavian ice mass oscillated markedly throughout the last glacial cycle. For example, sedimentary variations in the Norwegian Sea (Baumann

et al. 1995) reflect whether the Scandinavian ice mass was distal or proximal to the coast, and this evidence indicates that the Scandinavian Ice Sheet was oscillating in size almost continuously during the last glacial cycle, though the actual dimensions of the ice mass at each stage in the process are difficult to determine. Mangerud et al. (2003) report evidence obtained from laminated clay sequences preserved in caves in Western Norway, which have been dated using palaeomagnetic excursions and cosmogenic nuclide peaks, that suggests that some of the oscillations correlate with Greenland D-O events, though they also conclude that not all of the ice-sheet fluctuations were in phase with Greenland climate oscillations. What is clear, however is that the ice sheets in NW Eurasia were able to respond quickly to changes in climate. For example, the ice advanced from the west coast of Finland to east of lake Onega, a distance of some 900 km, during MIS-2 within ca. 7 kyr, a rate of advance that equals the rate of retreat which took place across that region between 17 and 10 kyr BP.

The NW Eurasian ice masses may well have been responding initially to ocean temperature changes, especially in the North Atlantic. The optimal conditions of the Eemian interglacial (MIS-5e) appear to have been 2–3 °C greater than that of the Holocene, and conditions became more oceanic towards the end of the Eemian. Temperatures, although subject to a number of fluctuations, grew gradually colder during MIS-4 and MIS-3, and the most severe conditions were experienced in MIS-2, when winter temperatures were at least 20 °C, and summer temperatures between 5 and 11 °C, lower than present. An important objective for future research is to determine how much of this temperature decrease was caused by feed-back influences resulting from the growth and configuration of the ice-sheets themselves. Given the history of events summarised above, it seems that with an open ocean and relatively mild conditions (MIS-5e/5d), glacier ice would initially have been restricted to the coldest parts of the arctic, where low winter temperatures were the critical factor. A reduction in regional temperature led to expansion of the arctic ice masses, but as that ice expanded and the adjacent seas became colder, the arctic became progressively starved of moisture. This should have led to a steepening of west-east moisture and temperature gradients, with enhanced continental conditions being experienced in the east.

The waxing and waning of the ice sheets also contributed to significant regional palaeo-hydrological changes that must have had wide climatic effects. For example, the blocking of the northern outflows of the Ob and Yenisei rivers by the growth of the Kara Ice Sheet caused an enormous ice-dammed lake to build up, which eventually occupied the whole of the western Siberian plain (Arkhipov et al. 1995). This lake drained southwards via the Aral Sea to the Caspian, overflowing from there into the Black Sea and the Mediterranean. This influx of freshwater may have altered the balance of exchange between Mediterranean and Atlantic waters, which could be thought of as closing a complex feed-back loop, since it is likely that water mass changes in the North Atlantic initiated the growth of ice in NW Eurasia in the first place. Another potentially pronounced climatic consequence of the creation of such huge ice-dammed lakes would be the sudden influx of cold freshwater into Arctic seas and, via the Baltic, into the North Atlantic, a process that might have had dramatic effects on sea surface temperatures and water mass circulation in the NE Atlantic and Arctic seas. River discharge to the Arctic Ocean is linked to fluctuations in the North Atlantic Oscillation (Peterson et al. 2002), while freshwater forcing of N. Atlantic thermohaline circulation during episodes of catastrophic flooding from ice-dammed lakes in N. America is widely believed to have triggered abrupt climatic changes during the latter stages of the last glacial cycle (Clark et al. 2001; Teller et al. 2002; Broecker 2003).

In view of the potentially important palaeoclimatic significance of such environmental changes, future research should be directed towards generating more reliable, quantified estimates of: (i) variations in ice sheet volume and configuration; (ii) the volumes of stored ice-dammed water; (iii) fluxes of reversed/diverted stream flows; (iv) fluxes of freshwater into the Arctic seas and NE Atlantic during the catastrophic drainage of ice-dammed lakes; and (v) the temperature and moisture gradients that existed over NW Eurasia during the last interglacial-glacial cycle.

### **The periglaciated zone of Mid-Latitude Europe**

Quantified temperature estimates based on palaeobotanical data suggest that the Eemian in temperate Europe was characterised by summer and winter temperatures not much different to those that prevail in the region today (Kühl et al. 2001; Litt et al. 2001). There is, however, some debate over whether the Eemian was a period of uninterrupted warmth, or whether significant cooling episodes occurred (see Vandenberghe et al. (this volume)). This is an important issue, which has significance for understanding the nature of climate deterioration from predominantly 'interglacial' to wholly 'glacial' conditions. There is limited information from this region for conditions during this important transition, and indeed scant information for the early Weichselian in general. Exceptions are the lake sediment sequences at sites like Les Echets and La Grande Pile, but these are extremely rare in mid-latitude Europe, and the palaeoclimatic interpretations available for these records are only crudely quantified at present. A priority for future research in this region, therefore, is to improve the database of information for the Eemian and the Eemian-early Weichselian transition, in order to derive more robust reconstructions of the climate conditions that prevailed during these periods.

By MIS-3, when the Kara-Barents Ice Sheet was dominating in NW Eurasia, much of mid-latitude Europe was frozen. The palaeohydrological consequences of this were severe and widespread, for river régimes are drastically altered by the long seasonal freezing of the ground surface. However, it is difficult to quantify the climatic conditions at this time, as frozen ground phenomena provide indications that temperatures were below certain thresholds, but not by how much the temperatures were below those thresholds. Periglacial sediments also tend to be devoid of biological remains, which limits the range of proxy methods that can be used. Intensely cold conditions did not persist throughout MIS-3, however. There is evidence for short episodes of warming, possibly of the order of only 2 to 3 °C, but these were of sufficient warmth and duration to enable some thermophilous plants and temperate insects to migrate northwards. The evidence for these short warm episodes is extremely fragmentary, however, and their precise chronology remains obscure. It is possible that some of them correlate with Greenland D-O events, but the extent to which this is the case remains to be established.

More detailed information is available for conditions during MIS-2. During this period, when the Scandinavian Ice Sheet was building up to its maximum for the last cold stage, mid-latitude Europe was extremely cold. Widespread periglacial evidence suggests a mean annual air temperature for the coldest parts of the region of about -8 °C, with mean temperatures for the coldest month in some areas as low as -25 °C. There is evidence, however, of a north-to-south temperature gradient, with the mean temperature of the warmest month being ca. 4 °C in the north but as high as 8 °C in the south. The climatic conditions were

extremely continental at this time, with an annual temperature amplitude of around 28 to 33 °C (Vandenberghe and Pissart 1993; Huijzer and Vandenberghe 1998). Conditions were also very dry in many districts, especially towards the end of MIS-2, as extensive belts of loess and sand dominated the landscape. Analysis of the regional occurrence of these deposits suggests that they were deposited by winds with a strong northerly component. Most of the rivers incised into their flood-plains at the beginning of MIS-2, while later on they deposited coarse sediments in braided channels as they flooded during the short thaw seasons.

The picture that emerges, therefore, is of a progressive shift towards colder and more arid conditions in mid-latitude Europe as the Scandinavian ice sheet built up during MIS-2. There is clearly a complex set of feed-back mechanisms operating between: (i) the surface temperature conditions and extent of sea-ice cover in the oceans; (ii) the size and location of the NW Eurasian ice sheets; (iii) the local climatic effects (katabatic winds) created by large ice masses; and (iv) the prevailing insolation régime. It should be possible to obtain more precise palaeoenvironmental data to clarify how closely these environmental elements were interconnected during this period.

Warming in mid-latitude Europe at the end of the last cold stage appears to have commenced soon after the LGM, when the European permafrost became degraded, presumably in response to some initial thermal warming. Some further warming may have occurred at ca. 15.0 <sup>14</sup>C kyr BP, as suggested by records in southern Europe and NE Atlantic cores (Walker 1995), though this is not clearly reflected in continental records from mid-latitude Europe. The most marked increase in temperature occurred at ca. 13.0 <sup>14</sup>C kyr BP, and is most clearly reflected in records from the British Isles and The Netherlands (Coope et al. 1998; Witte et al. 1998). Warming was delayed in Scandinavia, however, probably because of the cooling effects of the residual ice mass (Coope et al. 1998; Witte et al. 1998). Thermal gradients steeper than those of today are therefore suggested by the palaeo-data for some intervals between ca. 15 and 11 <sup>14</sup>C kyr BP. Within this interval a series of short-lived episodes of climate cooling occurred, of which the most intense and widely recorded is the event referred to as the 'Younger Dryas'. There is still some dispute about the number of cooling events during this interval, their precise timing, and the geographical areas over which they have left their imprint. It is likely that they reflect the climate oscillations recorded in the Greenland ice-core and North Atlantic records, but the extent to which these were all in phase is not yet clear (Lowe et al. 1995).

### **The Mediterranean region**

Since the Mediterranean region was not glaciated (except in high mountain locations) nor extensively periglaciated during the last glacial cycle, continuous sediment sequences extending from the present time back through the full glacial cycle to the Eemian, and in some cases to much earlier periods, can be found in a number of deep lake basins. Investigations of these sequences have provided a fuller picture of the history of climate events than is generally the case for other sectors of the PEP III transect. There is much to be done to improve the dating of these records, while some of the sequences may be subject to hiatuses and other stratigraphical complications. Furthermore, palaeoenvironmental interpretations based on these records are frequently contradictory (see Magri et al. (this volume)). Nevertheless, they provide probably the best available archives within the PEP



III transect for assessing, at a high resolution, the nuances of climatic change and variability during time stream 2.

Studies of long lake sediment sequences are being complemented by other records that extend through the last interglacial-glacial cycle, from deep marine sediments in the Mediterranean and the eastern fringe of the North Atlantic (e.g., Sánchez-Goñi et al. (1999), Pailler and Bard (2002)) and from cave calcite deposits (e.g., Frumkin et al. (1999)). Collectively, these palaeoenvironmental archives indicate: (i) the imprint of long-term insolation forcing on Mediterranean climate (Tzedakis et al. 1997); (ii) the signature of D-O and H events in marine and continental sequences (e.g., Allen et al. (1999), Cayre et al. (1999), Cacho et al. (2000)); (iii) possible close coupling between marine and continental climate variations (Roucoux et al. 2001; Sánchez-Goñi et al. 2002); and (iv) the importance of Saharan dust transport throughout the Mediterranean and eastern Atlantic during times of enhanced atmospheric circulation in high northern latitudes (e.g., Moreno et al. (2001, 2002), Magri and Parra (2002)).

One of the major palaeoclimatic issues that remains to be resolved, however, is the extent to which climatic changes in the Mediterranean region were in-phase with those in the North Atlantic region, with respect to oscillations of both long (glacial-interglacial cycles) and short (D-O events) amplitude. Tzedakis (2003) argues that long-held assumptions of synchronicity of major climate shifts between, on the one hand, the oceans and the continents, and, on the other, northern and southern Europe, may be erroneous. He concludes that available evidence indicates that the onset of warming which culminated in the Eemian interglacial on land commenced some time after the ocean had warmed at the start of MIS-5e, while cooling at the end of the Eemian appears to have been in-phase with the end of MIS-5e in northern Europe, but considerably delayed in the south. The interpretations are based primarily on palaeobotanical evidence; there is a need to establish the degree to which the inferred vegetational changes represent instantaneous or delayed responses to climatic change.

Establishing the degree to which millennial-scale variations in the Mediterranean were synchronous with the D-O and H events of the North Atlantic is a challenging problem. Magri et al. (this volume) have drawn attention to several difficulties that need to be overcome, before this can be achieved satisfactorily. First is the complex issue of dating the records with the temporal precision required. D-O and H events were short-lived, and were terminated by very abrupt warmings — some transitions (according to the ice-core evidence) taking only a few decades. Ideally, therefore, correlations need to be effected with a decadal precision. The potential exists to achieve this, for some of the lake sequences are annually laminated, and several additional geochronological tools can be applied as independent tests of age-depth models (e.g., Allen et al. (1999)). Nevertheless, considerable uncertainties beset the published age estimates for events within the last interglacial-glacial cycle, and confident correlation at a high (decadal) precision has still to be achieved. Even the boundaries of the youngest abrupt climatic events of the last glacial cycle, such as the 'Younger Dryas' cold event, which lie within the range of radiocarbon dating, cannot yet be defined with a decadal precision because of the problems of calibrating radiocarbon dates that are older than ca. 11,500 cal yr BP (Asioli et al. 1999; Lowe and Walker 2000).

A second issue is that of distinguishing those palaeoenvironmental signals that reflect changes in temperature from those that reflect changes in atmospheric humidity; of course, these two parameters are sure to have varied in concert. The available evidence seems to

point to variations in climatic seasonality as having been the key orchestrator of environmental changes in the Mediterranean zone throughout the last interglacial-glacial cycle. These may have been linked in turn (as appears to be increasingly assumed) to changes in North Atlantic circulation, the controlling mechanism being water mass exchange between the Mediterranean and Atlantic through the Strait of Gibraltar and its resultant effect on salinity. However, as Magri et al. point out, there are influences on climate in the Mediterranean area, other than marine ones, such as incursions of Saharan air masses from the south, which may be driven by changes in atmospheric pressure over North Africa, and perturbations of the climatic regime of the Middle East and eastern Mediterranean basin, which reflect variations in the strength of the Indian monsoon pressure cell. Extreme changes in any one of these climate forcing agents or, more likely, enhanced or modulated signals brought about by the interplay between them, probably account for periodic expansions and contractions of forest cover and in the composition of woodland throughout the Mediterranean, for extremely arid conditions during which the forest cover declined abruptly and dust transport from the Sahara became more prevalent, and for marked changes in water density and circulation within the Mediterranean, the most extreme effects of which may have led to the deposition of sapropel layers on the sea floor.

#### **Sahara-Sahel-Arabian Peninsula**

Records from this sector of the PEP-III transect for time stream 2 are few in number and fragmentary in nature. Most of the evidence consists of lake sediments laid down intermittently, generally during wetter climatic periods, and from which migrations in vegetation types can be inferred from the pollen records that they contain (e.g., Gasse et al. (1990)). These data can be compared with pollen records obtained from the adjacent oceans, which provide more continuous and longer records (e.g., Prell and van Campo (1986), deMenocal et al. (2000)), and with speleothem records from, for example, Northern Oman (Burns et al. 1998). Evidence of groundwater recharge and increased lake levels, which presumably reflect times of increased atmospheric moisture, can also be inferred from studies of sediment chemistry or gas content (Edmunds et al. 1999). Overall, however, the number of records from which such data have been obtained is very low compared with the size and complexity (topographic and climatic) of the region they are taken to represent, and also compared with the higher density of site records that is available to support reconstructions for the other sectors of the PEP III transect. Furthermore, interpretations of site records from the arid zone are constrained by the limited number and statistical uncertainty of radiometric dates currently available. Radiocarbon dates obtained from deposits laid down in the later phases of the glacial cycle are particularly prone to error where the groundwater is calcareous.

In view of these limitations, considerable care is required when generalising about the history and nature of climatic changes in this sector during time stream 2; more confidence can be attached to Holocene reconstructions, a period for which many more site records are available, a greater diversity of proxy records has been investigated, and more reliable site chronologies have been developed (Hoelzmann et al., this volume; Verschuren et al., this volume).

Some tentative conclusions can be drawn, however. Considerably wetter conditions are inferred for the Arabian Peninsula during MIS-5e, both on the basis of pollen records

obtained from marine cores from adjacent seas, and from the speleothem record in northern Oman. A strong south-west monsoon influence is considered to be responsible for this. Climate during the last glacial stage appears to have oscillated between episodes drier and wetter than the present, with some strong indications that the region experienced millennial-scale climatic oscillations which may equate with the sequence of D-O and H events in the North Atlantic region (Schulz et al. 1998; Leuschner and Sirocko 2000). Conditions appear to have been predominantly dry for much of MIS-5d and MIS-4, but significantly wetter than today between about 30 and 19  $^{14}\text{C}$  kyr BP, in both the Arabian Peninsula and the northern Sahara, where lake levels were significantly higher than those of today.

Conditions during the last glacial-interglacial transition (ca. 15–11  $^{14}\text{C}$  kyr BP) appear to have oscillated abruptly in North Africa, though problems of chronology make precise correlations between site records difficult. The majority of records, however, suggest that conditions in North Africa were generally wetter between ca. 14 and 5.5 cal yr BP, the 'African Humid Period' (deMenocal et al. 2000), though not all records accord with this interpretation: either some areas remained dry during this period, or the humid phase was interrupted by brief periods of drier conditions (Hoelzmann et al., this volume).

It is important to improve the overall palaeoenvironmental archive for the Sahara-Sahel-Arabia sector, in several ways: (i) by filling in the gaps in the record for the last glacial stage; (ii) by developing better quantified reconstructions of past climatic conditions, using a more diverse array of proxy indicators; and (iii) by increasing the density of sites that provide data for each important interval, thereby enabling more detailed spatial patterns to be constructed. The strength of the African monsoon is an important climatic parameter, not only controlling the degree of humidity in the arid parts of North Africa and the Arabian Peninsula, but impacting on the climate of the Mediterranean, and playing a key role in the global climate system. DeMenocal et al. (2000) give a pointer as to why this is potentially very significant: they conclude from their study of the marine core off the coast of Mauritania that: (i) variations in the strength of the African monsoon were governed by gradual orbital increases in summer season; (ii) the onset and termination of the 'African Humid Period' were very abrupt; and (iii) that the transitions occurred when summer season insolation crossed a critical threshold, i.e., when it was 4.2% greater than the present value.

### **Inter-tropical Africa**

By contrast with the more arid zones to the north, Tropical Africa provides reasonably abundant opportunities for reconstructing past environmental conditions. The greater humidity and lush vegetation that is characteristic of this sector lead to the generation and preservation of organic sediments in lake basins, while some of the organic detritus is carried by the major rivers to estuaries and the open sea: hence migrations in the forest-savanna boundary and changes in forest composition, as well as changes in river discharge, can be inferred from variations in sediment type and in fossil content of core records obtained from, for example, the Congo Fan (Marret et al. 2001). Past climatic conditions can also be inferred from studies of fluctuations in lake levels; where a number of lake records provide accordant evidence for either a general increase or decrease in lake volume, then this probably reflects a change in regional climatic wetness (Street-Perrott and Perrott 1993). Barker et al. (this volume) draw attention to the growing number of lake and marine records from the inter-tropical sector of the PEP III transect that contain records that extend back to MIS-5e. An

impressive range of proxy indicators are now being studied for many of the key records, and these are enabling the sequence and nature of past climate variations to be reconstructed not only in more detail, but also with a greater degree of confidence, since assessments can often be based on several independent proxy indicators.

What has emerged from these recent studies is the over-riding importance of the 19–23 kyr precession cycle as a driver of climate change in tropical Africa. This cycle is reflected in marine records obtained from localities that lie close to the African coast (e.g., Schneider et al. (1996)), in reconstructions of lake-level variations (e.g., Trauth et al. (2001, 2003)) and in pollen-stratigraphic changes and other stratigraphical records obtained from lake sediments (e.g., Gasse and van Campo (2001)). Tropical Africa forms an important component of the ‘heat engine’ that drives meridional circulation of the atmosphere, which governs the strength of the SW monsoon circulation. This in turn determines atmospheric moisture patterns over Africa. But the influence of low-latitude monsoon circulation may extend much further. Trauth et al. (2003) report new evidence obtained from Lake Naivasha in Kenya, that leads them to the conclusion that changes in the strength of the African monsoon do not correspond to peaks in summer insolation, but may in fact lead them, and the changes that took place in extra-tropical regions. They also conclude that the data provide evidence for low-latitude forcing of deglaciation in the northern hemisphere at around 135 kyr BP.

Understanding the role played by low-latitude atmospheric components of the global system has emerged as a key objective for future palaeoclimatic research. In addition to clarifying the manner in which the global climate system responds to the precession cycle, Barker et al. (this volume) draw attention to other features of the palaeo-environmental archive from inter-tropical Africa that deserve further attention. First, environmental responses in this region were most often abrupt and irregular, and not gradual, as would be expected if insolation factors alone were driving the regional climatic changes. Clearly, as with other sectors in the PEP III transect, feed-back factors have operated to modulate the influence of insolation changes. Second: although for most of the record for the time stream 2 interval, palaeoenvironmental variations appear to accord with expected precession effects, this is not the case for the Last Glacial Maximum (MIS-2). The implication drawn from this is that direct insolation effects may be over-ridden by the impacts of processes operating in the higher latitudes during times of maximal glaciation (deMenocal et al. 1993). Third, the data for the LGM from inter-tropical Africa provide interesting comparisons with the results of GCM simulations. Barker et al. (this volume) and Barker and Gasse (2003) point out that the general synopsis derived from the palaeo-data records, which indicates that most of inter-tropical Africa experienced drought conditions during the LGM, is best simulated by GCMs that use computed SSTs rather than empirical SST values, as employed in the CLIMAP project (Kutzbach and Guetter 1986). Barker et al. conclude that the data indicate that climate in inter-tropical Africa was closely linked to the temperature of the adjacent oceans during the LGM, which in turn reflected the growth of the polar ice sheets.

### **Southern Africa**

Data assembled on southern African palaeoenvironments during the last two glacial cycles, based on lake-level records, cave sediment sequences and some marine records from adjacent oceans, reinforces much of what has been learned from regions to the north (Partridge

et al., this volume). Additional complexity is, however, introduced by the presence of a persistent zone of atmospheric subsidence over the west of the subcontinent, which is itself sufficiently narrow to be influenced strongly by the contrasting current régimes along both coasts. The winter rainfall area of the extreme south-western tip of the continent differed from that receiving precipitation during the summer in displaying inverse responses to major forcings: e.g., the occurrence of a cool, wet Last Glacial Maximum in the zone of influence of the Atlantic westerlies. Most information for the earlier part of the record comes from the Tswaing impact crater (previously Pretoria Saltpan) within the summer rainfall region. Here precessionally-driven changes in moisture receipts dominated the sedimentary record during MIS-6 in conformity with the strength of precessional variance at that time. The sensitivity coefficient between changes in insolation and those inferred for rainfall (estimated by applying a sedimentological transfer function) is 4.5; this compares with a range of 3.5–5.0 estimated for the northern subtropics by Prell and Kutzbach (1987) in model experiments. Evidence for elevated temperatures during the last interglacial, and a  $\sim 3^\circ$  southward shift of the Miombo/Savannah boundary, comes from Border Cave in the eastern hinterland, which is affected strongly by the warm Agulhas Current. Elsewhere increases in both temperature and precipitation were evidently more modest during the Eemian; however, rainfall at Tswaing appears to have increased substantially thereafter during MIS 5d.

A decline in dominance of orbital precession, as the amplitude of the eccentricity signal lessened, after about 60 kyr was matched by an increase in the evidence for other forcings in the Tswaing rainfall record. A number of arid spikes on either side of the Last Glacial Maximum, which were paralleled by discrete episodes of dune activity in the Kalahari, coincided broadly with Heinrich Events in the North Atlantic; however, the onset of each local event led that of the corresponding Heinrich Event on the basis of high-precision, calibrated  $^{14}\text{C}$  dates. The average lead time of 3.1 kyr corresponds closely to the  $\sim 3$  kyr by which South Atlantic temperature responses led their North Atlantic counterparts (Little et al. 1997) and by which phases of warming in the Antarctic led those in the western Indian Ocean (Sonzogni et al. 1998). Since, in almost every case, the onset of southern African aridity coincided with the end of a period of declining temperatures in the Antarctic ice-core records, an atmospheric link between these events (rather than responses via the thermohaline circulation) must be postulated (Partridge 2002; Partridge et al., this volume). The driving mechanism evidently involved changes in the extent and intensity of the circum-Antarctic atmospheric vortex, which were not only sufficient to be felt over widely separated areas of the southern hemisphere, but appear to have driven moist air across the equator, thereby contributing to the rapid growth and collapse of northern hemisphere ice-sheets.

Several findings reported in this volume add credence to this proposition. Barker et al. remark in their chapter that their record of Holocene fluctuations (especially those closely related to the 8.2 kyr event) suggests that the tropics seem to lead Greenland. Export of heat from the tropics is given as a possible cause. The other seemingly significant observation is that records from the Makapansgat speleothem (South Africa), Sacred Lake (Kenya) and Huascarán (equatorial South America) all suggest a pronounced cooling episode centred on 13.5 kyr; this event coincides closely in time with the Antarctic Cold Reversal that is well represented in the southern ice-core records.

A further point seems worthy of comment: diachronism between atmospheric influences from Antarctica and those conveyed over longer timescales via the thermohaline conveyor,

and involving heat transfer via the Agulhas and Benguela current systems, seems to have been manifested in differing ways in the southern African palaeoclimatic record. In some cases the duration of events (e.g., spells of dune building) was extended; in others multiple responses are evident while, in yet others, closely spaced fluctuations were accentuated or suppressed. Considerable modification of signals attributable to primary orbital forcings occurred in the process. It is for this reason that the path of deglaciation in Southern Africa was not intimately connected to that of the northern hemisphere (see also Gasse (2000)).

### Conclusions

While the history of climate changes that affected the PEP III transect during the last two glacial-interglacial cycles remains sketchy, especially for the period prior to 40 kyr BP, some key temporal and spatial patterns are nevertheless emerging from recent palaeoenvironmental research. Attention has been drawn in this summary to the growing potential that the palaeo-data provide for establishing, at a millennial to centennial timescale, the leads and lags between the Eurasian ice sheets, North Atlantic circulation, the tropical-monsoon system and the circum-Antarctic atmospheric vortex. The potential, therefore, also exists to resolve the relative importance of the three orbital insolation parameters (precession, obliquity, eccentricity) in the long-term climatic record, and thereby to assess the manner by which the orbital signals become modulated by internal feed-back processes. This last aim is clearly fundamental to global climate theory and modelling. There is presently some uncertainty over whether orbital insolation forces northern ice sheets directly, through variations in summer ablation, or whether a more complex set of events is set in train, with initial summer insolation changes in the northern hemisphere being transmitted to the southern hemisphere through deep flow in the Atlantic, which leads to further changes in the northern hemisphere ice sheets that are driven by atmospheric CO<sub>2</sub> changes and other feed-backs (Shackleton 2000; Ruddiman 2003). Overarching questions such as these are capable of being addressed by examination and synthesis of palaeoenvironmental records from the different sectors of the PEP III transect, but only if we are able to improve the chronology and correlation of the different archives, and to develop more reliable, quantified palaeoclimatic indices.

Until recently, reliance had been placed on the marine isotope scheme or on ice-core stratigraphy as a basis for correlating continental and marine sequences. This review has shown that several problems confound this approach. Firstly, some terrestrial responses have been shown to be asynchronous with those in the oceans: a case in point are the findings of Sánchez Goñi et al. (1999, 2000), which show that terrestrial manifestations of the Eemian, as reflected in pollen records of the south-western Iberian margin, are not coeval with MIS-5e in the same marine sequence. Secondly, responses of terrestrial plant communities to global changes in ice-volume and orbitally modulated variations in receipts of solar variation are not uniform, even within relatively small regions. Thus Tzedakis et al. (1997) and Magri et al. (this volume) have drawn attention to the occurrence of large changes in Mediterranean vegetation at times when fluxes in global ice volume were relatively small. Nor do plant communities necessarily respond similarly during marine stages with comparable isotopic signatures, probably because of differences in the orbital configuration that characterised each separate stage. In terrestrial environments, ecological responses to such differences remain poorly understood. Under these circumstances the identification of

leads and lags that may throw light on global feedback mechanisms is, at best, ambivalent prior to about 40 kyr.

The record of changing lake levels, which has the potential to resolve questions about hemispheric and inter-hemispheric teleconnections, has been expanded greatly over the past decade. However, the resolution of regional trends during the deglacial period has proved particularly difficult. Thus, while widespread aridity is evident in the tropics and mid-latitudes of Africa at the time of the Last Glacial Maximum, during the lead-up to the Holocene responses to changing insolation receipts were far from consistent. In tropical Africa an increase in insolation from 22 to 12 kyr should have been associated with an increase in rainfall of 35–45% based on orbital parameters (Barker et al., this volume), but, instead, the record of increasing humidity is stepped and interrupted by several dry spikes. Particularly impressive is evidence of substantial lake regressions over a period of about 1000 yr coinciding closely with the Younger Dryas interval. In southern Africa stable isotopes in speleothems indicate that deglaciation was associated with increasing wetness only after 17.5 kyr; drier intervals are evident around 13.5 kyr and again after 12.7 kyr (Holmgren et al. 2003). The fact that, in tropical Africa, the principal increase in precipitation came somewhat later (after 15 kyr), while the first recharge of aquifers in the western Sahara and Nile valley was more recent still (15–12 kyr), suggests that the onset of wetter conditions tracked the slow northward shift of the Intertropical Convergence Zone with the passagage of the precessional cycle.

Although deglacial hydrological records across Africa are broadly comparable in their responses to orbital forcing, important differences are evident which can be attributed, in part, to regional patterns of atmospheric circulation. In western North Africa the hydrology of sites north of 23° varied in response to changes in receipts of precipitation from Atlantic air masses, whereas areas to the south were directly subject to fluctuations in the strength of the West African monsoon. Further to the east the highlands of Ethiopia and the Arabian peninsula were dominated by variations in the Indian Ocean monsoon (Hoelzmann et al., this volume). Monsoonal circulations associated with both Atlantic and Indian Ocean air masses influenced the tropics; their varying seasonal strength is imparted by the twice-annual passage of the Intertropical Convergence Zone, while long-term changes occurred in response to alterations in the zone of influence of the ITCZ induced by orbital precession. In southern Africa similar interactions between Atlantic and Indian Ocean air masses are evident in the palaeo-records, but in contrast to tropical Africa, where the Atlantic circulation is dominant geographically, much of the summer rainfall region of the southern mid-latitudes receives its moisture from the Indian Ocean, and apparently did so during much of the past. What is clear, however, is that the past climatic changes in southern Africa have responded rapidly to changes in the strength and intensity of the circum-Antarctic atmospheric vortex and much more slowly to fluxes in the strength of the N. Atlantic thermohaline circulation, which were transmitted via current systems along both coasts. Expansion of the vortex during cold stadials in Antarctica (which were not always synchronous with those in northern polar regions) caused extension northward of the mid-latitude westerlies and associated equatorward displacement of the subtropical highs with their attendant weather-suppressing subsidence (Partridge 2002). Shifts in the position of the semi-permanent high pressure cell over the western regions of southern Africa are reflected both in lake-levels and in the distribution and alignment of linear dunes.

The Mediterranean Sea appears to have responded to large-scale climatic changes in much the same way as the open oceans, with some amplification of glacial-interglacial  $\delta^{18}\text{O}$  change as revealed by planktonic foraminifera. Important additional hydrological evidence is forthcoming from the sapropel horizons preserved in Quaternary marine sequences of the eastern Mediterranean. These are indicators of enhanced runoff, which led to stratification within the water column and a reduction in deep water oxygenation (Kallel et al., this volume). Six main periods of increased river discharge are indicated; these centre on 195, 170, 122, 96, 80 and 8 kyr. That at 122 kyr corresponds with the lowest  $\delta^{18}\text{O}$  and high  $\delta^{13}\text{C}$  values in Israeli speleothems, confirming that the last interglacial was associated with a marked increase in wetness (Bar-Matthews and Ayalon, this volume). There is evidence to suggest that Heinrich Events were paralleled by cooling and decreased salinity within the Mediterranean, although poor chronological control renders any firm conclusions on the timing of local responses to millennial-scale events premature. There is also a suggestion that climatic seasonality was reduced during cold stadials. Extra-regional climatic influences have, however, resulted in a complex mosaic of local responses, the correlation of which is difficult to resolve.

The interplay between long-range atmospheric circulations is equally apparent across North Africa. Cyclonic disturbances associated with the Atlantic westerlies have been important in bringing moisture to the area north of  $23^\circ\text{N}$  at times in the past. Their influence is apparent in the progressive depletion in  $^{18}\text{O}$  in groundwaters eastwards across the Sahara. Here an important period of aquifer recharge occurred from about 40 kyr up to the Last Glacial Maximum; after a prolonged dry interval recharge did not resume until after 15 kyr. The influence of precessional hemi-cycles is evident in the timing of these events. The Ethiopian Highlands were, in contrast, most directly affected by variations in the strength of south-west Indian Ocean monsoon whose intensity in this locality was modulated over much longer timescales. Wet conditions are indicated by speleothem growth in Oman between 125 and 117 kyr, but the Arabian Peninsula remained dry thereafter until about 30 kyr, after which palaeolakes rose until about 19 kyr. After another arid interval during the deglacial period the south-west monsoon strengthened rapidly in several steps from about 12 kyr, reaching its modern intensity at 9.4 kyr. In this predominantly dry area the influence of precession on this circulation system was thus largely subordinate to those associated with the much longer glacial-interglacial cycles. The third major circulation system affecting North Africa is that of the West African monsoon, which modulates the seasonal advection of moisture from the Atlantic Ocean in the area between the tropics and  $22^\circ\text{N}$ . During MIS 5d the Saharan-Sahelian boundary shifted from around  $23^\circ\text{N}$  to  $15^\circ\text{N}$ , with lesser latitudinal fluctuations evident thereafter. High lake levels around 40 kyr gave way to widespread aridity during the Last Glacial Maximum, which was alleviated by rapid stepwise changes towards wetter conditions at 15 kyr and 10.5 kyr (the latter following a well defined arid spike coinciding with the Younger Dryas). According to Hoelzmann et al. (this volume) these changes (and that in the reverse direction which occurred in the mid-Holocene) imply a very strong amplification of weak orbital signals by atmosphere-surface boundary feedbacks.

Tropical Africa has also yielded persuasive evidence of the important influence of biological changes (in the form of atmospheric  $\text{CO}_2$  and  $\text{CH}_4$  reservoirs) in reinforcing orbital effects. Particularly important among these has been the influence of precessional changes on the intensity of precipitation during the dominant (March) rainy season. However, over



longer time-scales the overriding effect of the insolation forcing associated with full glacials is apparent, particularly at times when the precessional signal weakened (e.g., after about 50 kyr). An important sequence at Sacred Lake on Mt. Kenya displays changes in bulk  $\delta^{13}\text{C}$  and concentrations of grass cuticles that indicate a shift towards a dominance of grasses and sedges possessing  $\text{CO}_2$  concentrating mechanisms during the Last Glacial Maximum. These changes are consistent with lower  $\text{CO}_2$  concentrations, higher aridity and an increased frequency of fires. But, overall, the Sacred Lake sequence is dominated by the precessional cycle and its harmonics.

#### **Future work: recommendations of relevance to the PAGES scientific agenda**

This review has drawn attention to the sheer complexity of environmental responses to both long-term climate changes induced by orbital forcing, and to more abrupt events, such as D-O and Heinrich fluctuations. A number of feed-back loops have been suggested to come into play when controlling thresholds are crossed, some of which may act extremely abruptly, such as the catastrophic melting of the Eurasian ice sheets and associated sea-ice cover, or the sudden release of ice-dammed lakes. Others are more gradual in nature, reflecting, for example, migrations of the ITCZ, or changes in continental biomass. There is clearly a need for increased quantification of the reconstructions based on palaeo-data sets, and for clarification as to which of the purported feed-back mechanisms were the most important, and why. Clearly, this is an area which would profit immensely from increased dialogue between, and joint-research agendas involving, the palaeo-data and climate modelling communities. Some of the links which appear to have been important in the PEP III transect during time stream 2, and which need to be examined in greater detail, include:

- The rate of growth and decay, and configuration of, the Eurasian ice sheets
- The size and development of ice-dammed lakes in Northern Eurasia
- The magnitude and timing of catastrophic drainage of the ice-dammed lakes
- Temperature and moisture gradients over different sectors of the PEP III transect during critical transitional periods
- Impact of the African monsoon on the Mediterranean area
- Impact of sudden influx of freshwater into the Mediterranean derived from the northern Eurasian ice-dammed lakes
- The balance of salinity exchange between the Mediterranean and the Atlantic
- The influx of Saharan dust into the Mediterranean and its likely climatic effects
- Regional differences in lake-level variations in Africa, and continental responses to precessional forcing
- The strength of the Antarctic signal on the climate of Southern Africa and on circulation in adjacent oceans

- The continental biomass in Europe and Africa and its implications for global atmospheric CO<sub>2</sub> levels
- The possible lead of the northern hemisphere by the low latitudes during deglaciation

Of course, the most valuable perspective to be gained would be an over-arching synthesis of how *all* of these elements interact. Here there are major questions to be faced, over such matters as: (i) prioritising the research effort into what are believed to be the *key* links and processes; (ii) the feasibility of setting up appropriate databases that can integrate multi-proxy data at the PEP III or even global scale; (iii) ensuring that future investigations lead to palaeo-reconstructions with the spatial coverage and temporal resolution required to meet the needs of the climate modelling community; and (iv) resolving disparities between palaeo-data reconstructions and climate-model simulations for key climatic episodes. These are pressing questions for PAGES, if the momentum and coherency of global palaeoclimate research are to be maintained.

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