The Sahara
Past, Present and Future

Edited by
Jeremy Keenan
This collection examines the Sahara holistically from the earliest (prehistoric) times through the ‘historical’ period to the present and with political direction into the future. The contributions cover paleoclimatology, history, archaeology (cultural heritage), social anthropology, sociology, politics and international affairs. Structured chronologically, the volume can almost be read as a narrative of the Sahara from the earliest times to the present, i.e. from the past climates of the Sahara in prehistoric times to the current ‘war on terror’ and its implications for the peoples of the Sahara. Importantly, the collection shows how the region must be approached ‘holistically’, highlighting the importance of each of these subjects areas (paleoclimates, history, politics, etc.) in relation to each other. Indeed, the first contribution is a remarkable (and unique) paper, bringing together the work of some 8–9 internationally recognised scientists to tell the story and show the relevance to the present day of the Sahara’s past climates etc. Nearly all the contributions stand in their own right at the cutting edge of research in their respective fields (e.g. archaeology, history, politics, etc.).

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The Climate-Environment-Society Nexus in the Sahara from Prehistoric Times to the Present Day

NICK BROOKS, ISABELLE CHIAPELLO, SAVINO DI LERNIA, NICK DRAKE, MICHEL LEGRAND, CYRIL MOULIN AND JOSEPH PROSPERO

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Introduction

The purpose of this paper is to review the state of the environmental sciences in the Sahara and to consider their wider relevance in a variety of contexts. In particular we focus on the links between the physical and social sciences, and interdisciplinary links between different research areas. A major aim of the paper is to demonstrate the relevance of Saharan research in a number of fields for wider global issues such as climate change and human adaptation. The paper is partly structured as a “narrative history” of the Sahara, on the one hand in order to address a range of issues relating to prehistoric, historic, contemporary and future climatic and environmental change, and on the other to illustrate the relevance of palaeoenvironmental, archaeological and historical information for studies of twenty first century human-environment interaction.

We define the Sahara approximately as the region of northern African where average annual rainfall is currently below 100 mm (Figure 1). This definition should be interpreted loosely given the large fluctuations of rainfall at the fringes of the desert on multiple timescales; the Sahara may be viewed as expanding and contracting as a response to global and regional changes in climate that modulate rainfall at its periphery. In the recent geological past the Sahara thus defined has extended much further south than at present, and has shrunk to such an extent that it effectively disappeared. Any consideration of the past or future evolution of the Sahara must therefore also consider its periphery, particularly at its southernmost edge where

**FIGURE 1**

Isohyets representing mean annual rainfall in mm over northern Africa for the twentieth century

*Source:* From the dataset of New et al. (2000) and obtained from the Climatic Research Unit. The Sahara is defined here loosely as the region where mean annual rainfall is below 100 mm.
the largest variations occur in response to fluctuations in the strength and position of
the monsoon.¹

The paper begins with a brief review of our knowledge of how the Saharan
environment has changed in the past, with a particular focus on the early Holocene
pluvial (approximately six to ten thousand years before present) and the subsequent
desiccation of the region. These changes are viewed within the context of global
climate change, a topic currently of serious concern to scientists and policy makers
tasked with developing strategies to mitigate the severity of, and promote adaptation
to, human-induced climate change in the twenty-first century. This discussion of past
changes in the Saharan environment frames the remainder of the paper, which deals
with the legacy of the past, and what we can learn from it.

The discussion of the physical aspects of past environmental change is followed
by a review of how these changes affected human societies. In particular, processes
of adaptation and their consequences are considered.

Moving on from discussions of the past, the present-day environment of the
Sahara is considered in terms of groundwater resources, and the mobilisation and
transport of mineral dust from Saharan sources. Water resources are considered
within the context of settlement and development. Mineral dust is discussed at
some length due to the importance of the Sahara as a global dust source, and the
impact of dust on human health, ecological productivity and global climate. Ground-
water and dust sources are considered within the context of past changes in the
Saharan environment, particularly fluvial activity, which have determined their
nature and distribution.

Current and future climate variability are also considered within the context of
existing rainfall variability and potential future changes in rainfall associated with
changes in the African monsoon.

Finally, issues of environmental change and variability, adaptation and develop-
ment are synthesised. The lack of international research in the Sahara when compared
with other parts of the world is addressed, and the case for cross-disciplinary research
in the Sahara is presented.

Past Environments of the Sahara

The history of the northern African land mass is one of dramatic changes in the
physical environment, of oscillations between arid phases during which much of
the sub-continent is effectively uninhabitable, and humid episodes that transform
the desert regions of the Sahara into a fertile landscape of lakes and savannah. On
timescales of tens of thousands of years these changes are driven by glacial cycles,
with glacial conditions in the northern hemisphere being associated with cold, arid
conditions over northern Africa.²³⁴⁵⁶ During the last glacial maximum (LGM)
some 21 thousand calendar years before present (21 ka), the Sahara desert covered
a much larger area than today, as apparent from the dating of fossil dunes some 5°
south of the present extent of mobile dunes.⁷ A combination of factors leads to
increased aridity during periods of glaciation, including reduced atmospheric
moisture availability, decreased solar heating of the land surface, and large-scale changes in atmospheric and oceanic circulation.8,9

The Pleistocene
Over the past 1.65 million years, approximately corresponding to the Quaternary period, there have been some 17 glacial cycles, each lasting approximately 100 ka10 and it is the generally held view that glacial periods are arid and interglacials humid. However, determining the effects of Pleistocene climate change on the Sahara is problematic due to the paucity of organic deposits. Organic remains, such as palaeolake sediments, provide important information regarding arid-humid transitions. However, these deposits are rapidly deflated by the wind during arid periods and few ancient deposits have managed to endure the multiple episodes of Pleistocene aridity. Because of these factors the number of lacustrine deposits12 in the Sahara that have been dated to the last interglacial or older is no more than five. However, it is possible to glean some useful information from these studies. Sediments of Lake Megafezzan13 provide one of the longest records, with evidence for lacustrine episodes at 380, 240, 128, 118(+27 - 20), 74(+23 - 16), 47(+17 - 13), 30 ka and from 14 ± 1.7 to about 3 ka.14 This record of humidity conforms with the view that interglacials are associated with humid periods but also indicates that episodic humidity occurs during glacial cycles. A similar picture emerges if we compare these lacustrine episodes to the few others identified in the Sahara. A large lake existed in the Basin of the Tunisian Chotts at 150, 92, 75(+7 - 6) and 42.4 ± 2ka,15 there is evidence for lacustrine conditions at 75 ± 7 ka in southern Algeria,16 and there are indications of humidity between 71 and 87 ka in southern Egypt and northern Sudan.17 Some of these humid episodes are synchronous in two or more regions of the Sahara (e.g. ~128, ~74 and 42 - 47 ka), while others are not (e.g. ~155 ka), although this is not unexpected due to the paucity of the lacustrine record and uncertainties in dating. Encouragingly, studies of alluviation on the northern fringes of the Sahara agree with the data from the central Sahara. Northern Libya was subjected to fluvial activity indicative of a wetter climate at 125 ± 15, 76 ± 4, 42 ± 5.1, 23.2 ± 2.8 and 12.5 ± 1.5 ka,18 while in southern Tunisia incision and subsequent alluviation occurred at 47 ± 12 and from about 8 ± 2 ka.19 Thus in the north and central Sahara there is clear evidence for brief humid episodes occurring during glacials, as well as in interglacials.

The Early Holocene Humid Episode
Summer insolation over northern Africa reached a maximum at the beginning of the Holocene period, around 10 ka,20 by which time humid conditions had been established in the Sahara. This so-called Holocene Climatic Optimum saw a greening of the Sahara as the monsoon rain belt shifted hundreds of kilometres to the north, leading to the formation of numerous lakes in areas that are now hyper-arid, and the development of a mosaic of savannah and woodland throughout much of the Sahara.21,22,23,24 It is during this period that the Sahara was reoccupied by human populations, who initially survived through hunting and gathering, exploiting the
abundant humid climate fauna and flora of the then-moist Sahara, as discussed in more detail below.

The Holocene Climatic Optimum was, however, interrupted by a number of arid episodes, some of which appear to have been associated with transient changes in climate at the global or hemispheric scale. The most important such events were episodes of cooling in the North Atlantic, recurring on millennial timescales. Bond et al. identify a number of such Atlantic cooling events dated at 11.1, 10.3, 9.4, 8.1, 5.9, 4.2, 2.8 and 1.4 ka. The 8.1 ka event coincides, within the envelope of uncertainty associated with the dating of such episodes, with a period of aridity lasting the order of centuries in the Sahara. The 5.9 ka event occurs around the time of a dry episode evident in many, although not all, Saharan lake records, marking the beginning of a shift towards more permanent aridity.

The Desiccation of the Sahara

A number of data indicate that aridity increased in the Sahara after an arid episode occurring around 6 ka. The subsequent desiccation was not a smooth, continuous process characterised by a linear response of the monsoon to steadily declining solar heating or insolation. Instead, it appears that desiccation occurred in a stepwise fashion, with one or more episodes of abrupt drying. It is most likely that the drying of the Sahara was the result of a complex interaction between declining solar insolation, transient climatic perturbations such as the cold arid episode at around 6 ka, and dynamic vegetation-atmosphere feedbacks involving the retention and recycling of moisture.

The earlier ~8 ka cold arid episode occurred at a time when solar insolation was sufficiently strong to drive a recovery in the monsoon and in vegetation cover, once this transient climatic perturbation had passed. However, insolation was considerably weaker by ~6 ka, and may have been insufficient to drive a full recovery of the coupled vegetation-monsoon system after it had been disrupted by the Atlantic cold episode identified around this time. This transient climatic perturbation may well have been the trigger for the final desiccation of the Sahara, occurring at a time when the monsoon system was at least partially sustained through moisture retention and recycling by vegetation systems that originally developed as a result of strong insolation driving a vigorous monsoon. Evidence for abrupt desiccation towards 5 ka in a number of Saharan regions suggests the final collapse of remaining vegetation systems around this time, perhaps as solar insolation crossed a threshold below which vegetation-atmosphere interactions could no longer sustain rainfall, or possibly as a result of further transient perturbations from which vegetation could not recover in a low-insolation regime.

By around 5 ka desiccation associated with the southward retreat of the monsoon system was well established; this process culminated in the formation of the present-day Sahara Desert. The timing and speed of this process of desertification varied from place to place, and was mediated by geography, topography, hydrogeology and the nature of regional climatic systems. For example, in the Wadi Tanezzuft, in the Libyan Fezzan, the depletion of soil water reserves was not completed until about 3.5 ka, and fluvial activity persisted until around 2.7 ka apparently, this was due
to the combined effects of the large rainfall catchment area (the Tassili Mountains.) and of the dune systems bordering the fluvial valley, which acted as water reservoirs.

The climatic and associated environmental changes described above were not restricted to the Sahara. Abundant evidence indicates that the broad pattern of wet conditions in the early to middle Holocene, interrupted by arid episodes and followed by a process of desiccation starting around 6 ka and accelerating around 5 ka, prevailed throughout many subtropical and extra-tropical northern hemisphere regions.\textsuperscript{41} Our understanding of past environmental change in the Sahara thus represents but one component in our wider understanding of global climatic and environmental change which, when coupled with results from other regions, enables us to develop a deeper understanding of the Earth System and of human responses to environmental change. Such an understanding is necessary if we are to confront issues such as long-term climate variability and anthropogenically-driven climate change, processes which can have a profound impact on socio-economic development.

**Linking Past Environmental and Cultural Change**

The Sahara occupies a privileged position in studies of human-environment interaction, as a consequence of the clear climatic signals in Saharan palaeoenvironmental records, and the associated evidence of cultural change during key transition periods between arid and humid conditions. In many other geographical regions archaeology has been bedevilled by arguments over environmental determinism, leading to a reluctance to consider the role of environmental change in mediating cultural trajectories. In contrast, archaeologists working in the Sahara have by and large appreciated the central role of environmental change, without falling into the trap of neglecting other important factors in the development of human societies. In one sense, we may view the Sahara as a laboratory of human response to environmental change, given the overwhelming nature of the climatic changes that have affected the region throughout the relatively archaeologically accessible Holocene. As such, the Sahara can tell us much about processes of adaptation, the understanding of which is crucial for the formulation of policies designed to address the impacts of future climate change, particularly in the developing world.

**Human Occupation of the Sahara in the Pleistocene**

Human occupation of the Sahara has been limited by the availability of water, with little or no occupation away from the Mediterranean coast and the Nile Valley during arid phases associated with glacial epochs. A notable hiatus in human occupation, at least in the central Saharan regions, appears to be related to the Late Quaternary glacial: evidence for Upper Palaeolithic sites is very rare, and the latest clear evidence of human occupation during the Pleistocene (the section of the Quaternary predating the beginning of the Holocene some 10,000 years ago) dates back to the Aterian, from 90 to 60 ka.\textsuperscript{42} A human presence around 30 ka in the Wadi al-Shati region in Libya has also been hinted at, although the evidence is equivocal.\textsuperscript{43} Nevertheless, the spread of modern humans during the Pleistocene
was facilitated by the existence of migration corridors, in particular the Nile Valley, in which water was available even during the least hospitable phases of this epoch.

Evidence of Pleistocene occupation in the central Sahara is almost invariably composed of scatters of lithic tools, most of them deprived of any faunal association or stratigraphic context. Even in the exceptional contexts of the Acacus mountains, well preserved Pleistocene sites have not been identified, although Uan Tabu and Uan Afuda have yielded assemblages of worked stone, dated via optically stimulated luminescence (OSL) and thermoluminescence (TL) methods. The archaeological situation is much more fortunate in the Eastern Sahara, thanks to research by Wendorf and associates, for example in Wadi Kubbanya, Bir Tarfawi and Bir Sahara. Leaving aside technological developments and site organisation, one of the most important issues to be placed on the archaeological agenda is the spreading of modern humans in Africa north of the equator. The Sahara, together with the Nubian corridor, is believed to be a major area for the dispersal of anatomically modern humans, but coordinated international research in this field is lacking. Furthermore, it is essential to build a detailed scheme of Late Quaternary climatic trends, as a prerequisite to analyse and track possible Homo sapiens migration paths. Recent archaeological research emphasises the role of the Aterian complex as a possible technological indicator of the presence of modern humans in the Sahara. ‘Continuistic’ views, based on (single and isolated) radiocarbon determinations pointed in the past to a very late presence of Aterian sites in Morocco and other North African contexts, suggesting a direct relation between Aterian peoples and Upper Palaeolithic North African contexts. Recent research, specifically in Egypt and Libya, pushes back this technological phase to 140–60 ka ago, and underlines, at least in the central Sahara, a break in human occupation related to the expansion of the ‘Ogolian’ desert.

Human-Environment Interaction in the Sahara in the Early-Mid Holocene

The archaeological evidence indicates that the latest phase of human occupation in the central Sahara commenced at the beginning of the Holocene, around or soon after 10 ka. These early Holocene communities consisted of groups of hunter-gatherers, which in many cases practiced a fairly sedentary lifestyle, exploiting abundant locally available food resources in the form of wild fauna and flora. It is worth noting that the scant palaeo-anthropological evidence (from Uan Afuda and Uan Muhuggiag in the central Sahara of Libya) points to sub-Saharan affinities. This fits with more recent human remains from the Egyptian oasis, which indicate a similar affinity on the basis of dental analysis. These findings support the hypothesis of a northwards movement of human populations as they followed the monsoon rains, which strengthened and penetrated further north into the Sahara at the beginning of the Holocene. The gap between the beginning of the humid period in the Sahara after the last glacial maximum (ca. 15–13 ka) and the appearance of the first Holocene occupation sites might be interpreted as a consequence of the time taken for vegetation and fauna to recolonise hyperarid environments.

More cautiously, the first genetic data on Saharan palaeo-populations also indicate a sub-Saharan affinity. Evidence for a southern provenance of the first Holocene
Saharans might also be seen in from rock art, although the subjective nature of such interpretations must be recognised: in the Tassili\textsuperscript{60} and Acacus massifs\textsuperscript{61} depictions of figures with what appear to be black African features have been interpreted as indicating the possible presence of populations originating in sub-Saharan regions. Dating of this material is controversial, but an Early Holocene attribution for the so-called “Round Head” style of painting, as usually claimed in the literature,\textsuperscript{62,63} may reinforce the archaeological and palaeo-anthropological evidence.

It is during the early Holocene that we find the earliest (although still somewhat controversial) evidence for cattle domestication in the eastern Sahara, the driest part of North Africa at this time.\textsuperscript{64,65} Reviewing the literature on the development of cattle domestication in Africa, Marshall and Hildebrand argue that this was a local development based on the exploitation of indigenous species, and driven by the desire of hunter-gatherers to increase the predictability of their food supply, perhaps initially in order to ensure the availability of cattle for slaughter during ritual festivals.\textsuperscript{66} They suggest that this development happened in the eastern Sahara as a result of the greater environmental variability in this region, and hence the greater need for intervention to ensure predictability of food supply, when compared with other Saharan regions. Citing other work,\textsuperscript{67} Marshall and Hildebrand conclude that during the frequent periods of drought affecting the eastern Sahara, cattle would have represented “a more reliable resource than plants because their populations are maintained through movements that exploit local differences in topography, vegetation, and rainfall”.

According to Hassan\textsuperscript{68} and Marshall and Hildebrand, citing numerous sources, cattle pastoralism spread westwards through the central Sahara in an uneven fashion from around 7 ka, where it coexisted with hunting and gathering. Di Lernia suggests that the diffusion of cattle-based culture in the Sahara occurred in response to short, abrupt dry events during the 8th to 6th millennia before present (BP).\textsuperscript{69} The \~8 ka arid episode described above may have played a key role in the spread of pastoralism. Di Lernia and Palombini suggest that the dry interval at approximately 8 ka “probably favoured the integration of cattle herding within foraging communities” in the Libyan Sahara.\textsuperscript{70} If this episode also marked a shift from year-round to seasonal rainfall as has been suggested by some authors,\textsuperscript{71} cattle herding would have represented an appropriate adaptation in order to enhance food security in a more seasonally variable environment.

In the Acacus mountains of Libya, semi-permanent settlements in lowland areas gave way to seasonal migration during the late 7th millennium BP, when climatic conditions deteriorated during a “severe, abrupt dry interval lasting several centuries.”\textsuperscript{72} This new pattern of subsistence involved increased use of mountainous areas in the dry season. Di Lernia and Palombini,\textsuperscript{73} suggest that sheep and goats (most probably introduced from the western Asia in the early 7th millennium BP) were tended in highland regions from late winter to early spring in order to reduce pressure on lowland pasture land, which was set aside for cattle in the dry season; in the study areas in the Libyan Fezzan on which they focus, cattle remains are found predominantly around the interdune palaeo-lakes in the lowland ergs.
The nature of the spread of cattle herding through the Sahara is still a controversial issue. According to Schild and Wendorf, this occurred during wet periods, allowing people to move with their livestock westward. Conversely, Hassan and di Lernia argue that migration by cattle-herding groups was stimulated by aridity. They argue that this explanation is more compatible with the archaeological record, which consists of scattered and isolated contexts throughout the Sahara. Dates associated with these contexts also suggest discrete episodes of migration spanning short periods, implying rapid, intermittent movements of small groups of herders, colonising new and unfamiliar environments as they were forced to move in search of water and pasture during arid crises.

Social and Cultural Responses to Mid-Late Holocene Desiccation

The process of desertification at around 5 ka appears to have been rapid in at least some parts of the Sahara, and was associated with profound changes in human societies. Increasingly harsh conditions would have had a profound effect on culture and belief systems; it has been suggested that an increased diversity in the subject matter of rock engravings and paintings, with a greater emphasis on images relating to sexuality and fertility, and on ‘enigmatic’ or fantastical beings, dates to the period of climatic deterioration, ‘when concerns over human and animal fertility may have become acute’. In reference to the Fezzan region of Libya, Mattingly and associates write that ‘Human activity was not cut off at a stroke, however, but may have become more focussed on specific locations, with the rock art representing a more sophisticated dialogue between people and a powerful spirit world, bordering on formalised religion’. It has been suggested that this kind of relationship dates back to the emergence of the Pastoral cattle cult at 6.4–6.0 ka, when non-utilitarian slaughtering of precious livestock and the flourishing of an artistic tradition focused on cattle appear to represent the first evidence of ritual relationships between human populations, the physical environment, rainfall and ‘divinities’.

Human responses to the desiccation of the Sahara were spatially heterogeneous and mediated by geography, resource availability and local hydrogeological responses. In the Libyan Fezzan two types of response may be identified, according to di Lernia and Palombini. In higher elevation regions cattle herding almost completely disappeared after 5 ka. This was replaced by highly mobile pastoralism based on sheep and goats and involving large-scale round movement in order to exploit remnant water and pasture, the origins of a nomadic lifestyle that persists to this day. In contrast, lower elevation regions were characterised by increasing settlement in relict oases, associated with sedentism and more intensive exploitation of local resources. Di Lernia and Palombini characterise the former as a ‘light’ approach to landscape exploitation, associated with a relative egalitarianism and sustainable use of resources, and the latter as a ‘hard’ and ultimately unsustainable approach to the landscape leading to possible degradation of the landscape, conflict (possibly over land rights) and increased social stratification.

Behavioural adaptations focusing on resource extraction were associated with profound changes in social organisation, as indicated by archaeological studies of funerary monuments and burial practices. Di Lernia and Manzi describe the
period centred around 5 ka as the ‘hinge’ between different pastoral cultures in the Wadi Tanezzuft in the Libyan Fezzan, which they term Middle and Late Pastoral. It is around this time that stone funerary monuments are associated with human burials in the Wadi Tanezzuft; previously these had been reserved for ritual animal burials. This process is reflected in other central Saharan regions. A review of the archaeological work by Sivilli indicates that in southwestern Libya and northeastern Niger, the period 6.4–5.9 ka is represented exclusively by faunal burials; 5.8–4.9 ka by faunal, human and ‘empty’ burials (i.e., cenotaphs); and 4.8 ka onwards exclusively by human burials. Di Lernia and Manzi interpret this innovation in funerary practices as being associated with ‘emerging figures within the pastoral group... [representing] the first evidence in the area of a process of increasing social stratification’.

Di Lernia et al. (2002) interpret the evolution of funerary monuments and practices and settlement patterns as evidence of major changes in population in the Wadi Tanezzuft, and by implication in the greater central Sahara region. Funerary monuments would have served a dual purpose in a landscape occupied by increasing numbers of pastoralists, on the one hand acting as foci for gatherings of related social groups, and on the other serving as markers of boundaries, territories or zones of influence, asserting relationships between clan groups and the landscape.

In the Fezzan, it appears that climatic desiccation was associated with inward migration, increased population density, changes in religious beliefs and practices, social stratification and a more territorial approach to the landscape, as well as diverging adaptations to facilitate resource extraction in a more hostile landscape. In certain localities these changes appear to have provided the preconditions for the emergence of complex urban societies and the formation of entities resembling states, catalysed by the final desiccation of most of the landscape soon after 3 ka. The onset of conditions equivalent to present aridity might be viewed as a threshold that stimulated a step change in social organisation as population groups adopted new techniques to access water and utilise scarce productive land. In the Wadi Tanezzuft, the depletion of soil water reserves was not completed until about 3.5 ka, and fluvial activity persisted until around 2.7 ka. Further to the east in the Wadi al-Hayat, there is evidence that springs dried up around or before 3 ka.

These late dates for fluvial and spring activity correspond approximately to the early stages of the Garamantian civilisation, which dominated the Fezzan between about 1,000 BC and AD 700, a period ‘notable... for the local evolution of urbanism, irrigated agriculture and writing’. The Garamantes are described by the Greek historian Herodotus, writing in the fifth century BC, and later represented a regional challenge to Roman aspirations in the central Sahara and North Africa. The Garamantian ‘capital’ of Garama (or Old Germa, situated within 2 km of the modern town of Germa/Jarma) was located in the Wadi al-Hayat (also known as the Wadi al-Ajal), with Garamantian settlements also located in the nearby Wadis, al-Shati, Barjuj and Tanezzuft.

By 3.1 ± 0.125 ka the springs had dried up and surface water was either very scarce or absent at the base of the escarpment forming the southern boundary of the Wadi al-Hayat. However, the water table was probably very near the surface at the base of the wadi, as is evidenced by the fact that recent archaeological
excavations uncovered a well in the early Garamantian phase of Old Germa sunk to a depth of 70 cm, indicating water at very shallow depths. Archaeobotanical evidence indicates that irrigated agriculture was introduced soon after the desiccation of the springs, in the early part of the first millennium BC, presumably in response to a lack of water caused by the fall in the water table. There is no direct evidence for irrigation systems at this time, but the water table was near the surface in Germa and it is possible that wells were used to tap this resource. The earliest irrigation systems are foggara which were used to tap the elevated water table at the base of the escarpment. Archaeological evidence suggests that they were probably introduced by the final few centuries BC, and definitely before the fourth century AD. Interestingly this roughly corresponds with archaeobotanical evidence for the intensification and diversification of agriculture involving the introduction of a farming system that utilised both winter and summer crops. Foggara would also have allowed the extensification of agriculture at a similar time. In combination these developments could have lead to an increase in agricultural production, and there are likely to be strong connections between this and the rise of the Garamantes as a major political power in the central Sahara.

The Garamantian culture appears to have been the result of local innovation, the outcome of a process of increasing social complexity among the pastoral groups of the Fezzan. Referring to the Wadi Tanezzuft, di Lernia et al. write that ‘In a certain sense, Late Pastoral people became the Garamantes’. This conclusion is supported by the work of Mattingly et al., who find some of the latest Pastoral lithics and pottery in early Garamantian forts along the southern edge of the Wadi al-Hayat. In the Fezzan we thus see the ultimate expression of the human response to desertification in the development of a significant urban civilisation.

The emergence of the Garamantian polity, largely driven by changes in water availability and geographic serendipity, is not the only example of increased social complexity leading to the emergence of what we might call a ‘state-level society’ in a time of increasing aridity. The earlier development of Dynastic Egypt has also been interpreted at least in part as a result of social responses to environmental desiccation. Palaeoenvironmental evidence indicates increasing aridity to the east and west of the Nile Valley during the 6th millennium BP, with a final desiccation of most of this region in the late sixth millennium BP, when the early Dynastic state emerged. Excavations at Hierakonpolis are indicative of attempts to integrate animal herds with a sedentary lifestyle at the beginning of the Dynastic period, suggesting that mobile groups were forced or encouraged to settle permanently in the Nile Valley. Midant-Reynes explicitly links local increases in population density with desertification at the end of the Predynastic period. Archaeological evidence provides abundant support for models of cultural evolution involving increased social stratification and the concentration of political power as a response to increased population densities resulting from a decrease in available productive land, and associated migration/increased sedentism as a consequence of environmental desiccation.

To summarise, linked environmental and cultural change in the Sahara is not simply a matter of poverty and famine resulting from aridity. During the Pastoral
Neolithic, in the 7th and 6th millennia BP, the Sahara gave birth to one of the great cultures of antiquity, the Saharan cattle-based culture. Material cultural, occupation sites, food security, rock art, ideology and funerary practices are all part of an extraordinary culture, the nature of which was driven by a profound relationship with the physical environment. This culture had to cope with numerous fluctuations in resource availability associated with climatic variability on a range of timescale, some of which were extremely severe. This cultural tradition only came to an end with the final desiccation of the Sahara around 5 ka. However, the pastoral societies of the Holocene Sahara did not vanish into the sand: the migration of pastoral groups to refugia such as the Nile Valley, the Sahel, and the Saharan highlands and relict oases made a vital contribution to many subsequent African cultures, including Pharaonic Egypt, the Garamantes, the present-day cultures of the Sahel, and probably the modern day Berber and Tuareg populations.\textsuperscript{118,119,120,121} In a more general sense, we may claim that the essence of this cattle-based culture spread from the Sahara to much of sub-Saharan Africa, shaping the history of the entire African continent.

Water Resources and Human Settlement

As has been the case throughout the Quaternary period, water resources are today the limiting factor in human settlement and development. Increasing populations and associated urbanisation and economic development are placing greater demands on water resources throughout the Sahara. These resources may also be affected by climate change in the near future, for example with elevated surface temperatures further enhancing evaporation, and changes in meteorological patterns resulting in changes in the distribution of rainfall.

Modern permanent settlements in the Sahara are situated where water is available either from rainfall generated as a result of topography or the intrusion of extra-Saharan weather systems (such as in highland and coastal regions), or at oases where groundwater occurs at or near the surface in local topographic minima. Water resources may therefore be affected by rainfall variability and changes in groundwater levels.

Groundwater and Human Settlement

Most inland Saharan settlements rely almost exclusively on groundwater. Modern pumping and irrigation technology has enabled the expansion of agriculture in many locations, such as the Wadi al-Hayat in the Libyan Fezzan, which provides an object lesson in the interaction of water resources, human populations and technological innovation. Here a downward trend in population density started in the first millennium AD with the decline of the Garamantian culture. The cause of the demise of the Garamantes is not known with any certainty, although declining water levels either as a lagged response to the climatic desiccation of the region, or as a result of over exploitation by local populations, has been suggested.\textsuperscript{122} However, other explanations, such as a decline in trade in the later years of the Roman empire, should also be considered.\textsuperscript{123} Whatever the cause of the demise of the Garamantes, it appears that groundwater levels declined between Garamantian
times and the end of the second millennium AD. In recent decades the socio-economic decline of the Wadi al-Hayat has been reversed through the use of irrigation, dependent on the pumping of groundwater from increasingly greater depths. However, increases in population, the expansion of agriculture, and the process of urbanisation have resulted in a lowering of groundwater levels since the 1970s, exceeding 20 m in some locations according to local informants. White et al. used satellite imagery and aerial photography to examine changes in vegetation distributions between the 1950s and the end of the twentieth century in the Wadi al-Hayat, and found a shift in the vegetated zone resulting from the expansion of agriculture at the southern edge of the wadi, and the die-back of vegetation in unirrigated northern areas. The most obvious adverse impacts are on stands of date palms, many of which no longer survive without human intervention, and have given way to more drought or salt-tolerant species.

Such studies raise questions of sustainability: can settlements in central Saharan regions continue to expand given their reliance on fossil water reserves that are no longer replenished by rainfall? Furthermore, how sustainable are schemes such as the Great Manmade River project in Libya? Water use in Libya has been estimated at some eight times higher than its renewable water resources, an extreme example of a situation faced by all the countries of the southern Mediterranean coast which means they are likely to become much more dependent on food imports (essentially a means of importing water) in the future. Pressure on water use is likely to be exacerbated by climate change; in the southern Mediterranean reductions in rainfall of some 20–25 per cent and an increase in average annual temperature of 2–2.75°C by the 2050s have been forecast by global climate models. Increases in temperature will lead to greater evaporation, compounding water scarcity resulting from reductions in rainfall. Such developments are likely to increase pressure on fossil water reserves from the Saharan aquifers. Any expansions in the tourism sector will also increase water demand. Given the likely increased use of fossil groundwater, a better understanding of groundwater reserves and dynamics, and the nature, capacity and behaviour of the Sahara’s large subterranean aquifers is highly desirable. Such aquifers will not reach equilibrium to keep pace with extraction, which will result in the formation of ‘cones of depression’ near populated areas or areas of intense agricultural activity. Ebraheem et al. conclude that the Nubian Sandstone Aquifer under southwest Egypt does not exist in a steady state and is still responding to past humid conditions, and estimate that the planned extraction of 1,200 million m³/year in the East Oweinat area could result in a drawdown of up to 200 m relative to 1960s levels within 100 years, with the cone of depression extending to Dakhla and Kharga oases.

Rainfall Variability

Given the extreme variability of precipitation even in the wetter parts of the Sahara, the concept of ‘mean annual rainfall’ has little practical meaning. However, it is worth pointing out that precipitation in some parts of the Sahara is sufficiently high for local populations to rely at least partially on rainfall, and to be adversely affected during periods when rainfall is anomalously low. Keenan describes how the Kel
Ahaggar Tuareg have developed strategies to cope with drought, and how drought coupled with the social upheavals of Algerian independence led to hardship in the 1960s.

Drought is a concept that is also familiar to the inhabitants of the far west of the Sahara. In the inland regions of the disputed territory of Western Sahara vegetation is relatively abundant, sustained by occasional summer rains representing the extreme northerly penetration of the African Monsoon beyond 20°N, and similarly scarce rainfall associated with the Atlantic Westerlies. Despite the relative abundance of rainfall and vegetation in this region, the lack of surface water (e.g. in the form of oases), as well as the ongoing political conflict with Morocco and the possibility of a resumption of hostilities, mitigates against permanent settlement. Nonetheless, the region is used by nomads whose principal source of water takes the form of milk from their animals.

The Sahelian region, situated at the southern margin of the Sahara, has experienced one of the most persistent and severe changes in climate during the period of meteorological records. This consisted of a multi-decadal scale drying trend commencing in the 1960s and persisting into the 1990s, with severe droughts in the early 1970s and 1980s, and some amelioration in recent years (Figure 2). It is now well established that rainfall in the Sahel is driven largely by patterns of global surface temperature, with the temperature of the Indian Ocean playing a key role. While rainfall data for the Sahara are sparse, there is no evidence for any comparable trend north of the Sahel-Sahara transition zone in those regions of the Sahara where topography results in non-negligible rainfall. For example, both annual and summer rainfall totals for Tamanrasset in the highlands of the Algerian Sahara (home of the Kel Ahaggar Tuareg mentioned above) reveal a wet period in the 1950s, as in the Sahel, but no long-term drying trend in subsequent decades.

**FIGURE 2**


Source: From the dataset of New et al. (2000).
(Figure 3). Instead, the Tamanrasset rainfall record consists of quasi-periodic variations of some 10–15 years, with extreme variations in annual rainfall from 0 to 160 mm. On average, approximately half of the rainfall at Tamanrasset occurs in the summer, although variations between individual years are great. For example, the period from July to September saw no recorded rainfall in 1926 and 1973, whereas all of the recorded rainfall during 1999 occurred in these months.

The near to medium term future of the Sahara is uncertain in climatic terms. While there are no indications that the region will experience a shift to humid conditions comparable to those existing in the early Holocene, a number of climate modelling studies suggest that anthropogenic climate change may be associated with a strengthening of the African summer monsoon and an intensification and northerly displacement of monsoon rains, leading to wetter conditions in the northern Sahel and southern Sahara. Other modelling work suggests that the Sahara may shift northwards, implying that even if rainfall increases in the south of the Sahara, it may decline in regions near the Mediterranean coast. The suggestion that the northern Sahel and the southern margins off the Sahara may become wetter is consistent with recent observations indicating a greening of the Sahel explained partly by increased rainfall and partly by increased vegetation cover due to human activity. However, rainfall still remains below the high levels of the mid-twentieth century, and interannual rainfall variability and drought still pose considerable problems for Sahelian societies, as evident from the famine that is unfolding in

FIGURE 3A
TWENTIETH CENTURY ANNUAL RAINFALL TOTALS FOR TAMANRASSET, OVER WHICH IS SUPERIMPOSED A 5-YEAR MOVING AVERAGE (SOLID LINE)

![Annual Rainfall totals, Tamanrasset](source)

*Source:* The Climatic Research Unit.
Niger at the time of writing (July 2005). The impact of climate change on Sahelian climate is likely to remain unclear for some time, until additional observational and modelled data are available.

A shift in the monsoon rain belt would have profound implications for Saharan societies. Areas that are not currently viable for human populations would become available for pastoralism, and existing marginal areas might become viable for rainfed agriculture. However, an intensified monsoon would also be associated with more frequent flash floods and the likely spread of water borne diseases. Recently high rainfall in the Sahel has enabled locusts to thrive, resulting in the devastation of crops and food insecurity in a number of countries in 2004 and 2005. Grolle describes how heavy rainfall in the Sahel in 1953 triggered famine. While an intensification of the monsoon would undoubtedly bring benefits in terms of pastoralism and agriculture, the consequences would not necessarily be wholly benign.

Extreme rainfall variability on different timescales is a fact of life in on the margins of the Sahara; a failure to fully appreciate this fact was a factor in the expansion of agriculture into historically marginal areas along the Sahel-Sahara boundary in the 1950s and 1960s, which were anomalously wet when compared with the twentieth century rainfall record as a whole. As sedentary agriculturalists expanded northwards, mobile pastoralists were pushed into more marginal desert areas. The vulnerability of both populations to drought was significantly increased.
and the combination of elevated vulnerability and severe rainfall deficits in the early 1970s resulted in widespread famine and the collapse of livelihoods and social systems, representing a significant discontinuity in Sahelian developmental trajectories from which the region is still recovering. Keita describes the droughts of the 1970s and 1980s as a contributory factor in the development of internal conflict in Mali, where it undermined the pastoral livelihoods of the semi-nomadic Tuareg, causing large numbers of them to find refuge in camps or urban areas where they experienced social and economic marginalisation. Many Tuareg migrated to neighbouring countries, and some young men became involved in conflicts throughout North Africa and the Middle East, in which they acquired considerable military experience, eventually returning to Mali having to face unemployment and marginalisation, creating the conditions for the ‘Second Tuareg Rebellion’ in 1990. These conditions were exacerbated by a history of mistrust between the Tuareg and post-independence governments, the lack of available livelihoods and social support networks for returning migrants (as a result of previous drought and conflict), continuing drought and associated competition for resources between nomadic and settled peoples, and the flooding of the region with small arms as a result of conflicts in neighbouring countries, particularly Western Sahara. Keita describes the conflict between the nomadic Tuareg and the settled communities as ‘not so much an ethnic or racial issue as an economic one’ highlighting ‘the economic dimensions of the problem in the north: communities were fighting for scarce resources and jealously insisting that others were not preferred.’ This pattern of marginalisation, drought and conflict has been repeated throughout the Sahel, and demonstrates that climate variability and change can combine with other factors to cause conflict, particularly in marginal environments where populations are facing a number of different environmental, social, economic and political stresses.

Any future increase in rainfall in the northern Sahel and southern Sahara will be associated with the risk of unsustainable agricultural expansion if longer-term climatic variability is not considered in development policies. A modelling study by Maynard et al. suggests that the Sahel may be less prone to drought in a world characterised by low to moderate levels of anthropogenic greenhouse warming, associated with atmospheric greenhouse gas concentrations near current values. However, other studies suggest that the greater levels of greenhouse warming likely to result from the continued intensive use of fossil fuels into the latter half of the twenty-first century may result in global temperature patterns associated with drought conditions in northern Africa. Any expansion of agriculture and settlement into areas made newly productive by a strengthened monsoon may ultimately result in an exacerbation of vulnerability as in the 1950s and 1960s, followed by drought and famine as conditions deteriorate, as they did after the 1960s. The interaction of naturally occurring drought hazard and socially constructed vulnerability during the twentieth century holds important lessons for economic development and agricultural activity in a region where climatic variability on a variety of timescales is the norm.
Non-hydrological Hazards and Urbanisation

While the availability of water must remain the principal consideration in economic development and settlement expansion, human health and comfort are also affected by other environmental factors. In the Sahara, strategies for coping with extreme heat, and also with dust storms, are also of great importance. As mentioned above, climate change is likely to result in higher average surface temperatures, which in turn will lead to more frequent heat extremes.\(^{151,152}\)

A further instance of what may be termed “maladaptation” associated with population expansion and the associated processes of economic development and urbanisation is the move away from traditional architecture. Traditional building materials and architectural styles are well adapted to the extreme desert environment, particularly in terms of temperature regulation. Historically, settlements have been built of mud brick, an inexpensive and readily available material that is an excellent insulator, and have incorporated convection chimneys to encourage the circulation of cool air, and covered walkways to shelter their inhabitants from the sun. The enclosed nature of these settlements also affords some protection from dust. However, many of these settlements are now being abandoned in favour of generic modern towns whose construction pays little or no attention to the particular hazards associated with a desert environment. Streets are now open to sun and dust (partly to accommodate vehicular traffic), and poorly insulated modern buildings fitted with air conditioners have replaced the subtle architecture of the traditional towns. In the town of Ghadames in western Libya, the inhabitants of a traditional town (also a UNESCO World Heritage Site) moved to an adjacent, purpose built modern town in the 1980s. In the summer many return to the old town, where they maintain their old houses and gardens, as it is more comfortable than the modern settlement.

The challenge of urbanisation in the Sahara is to blend the most desirable elements of traditional architecture with modern technology, providing comfort in an extreme environment while ensuring access to modern amenities. Greater use of mud brick instead of concrete and cement (the production of which is energy intensive) would reduce both construction costs and greenhouse gas emissions, assisting both adaptation to and mitigation of anthropogenic climate change. Fathy,\(^{153}\) working in the context of development in rural Egypt, has advocated a greater emphasis on such traditional building materials and styles in order to enhance development and reduce poverty through the use of more affordable materials and the inclusion of local people in the design and construction process.

The Sahara in the Earth System: Airborne Mineral Dust

Water, or rather the lack of it, is not the only ubiquitous feature of the Saharan environment with which its inhabitants have had to contend since the onset of desiccation many millennia ago. The geomorphological processes associated with past environmental changes in northern Africa have also resulted in the Sahara becoming the world’s largest source of airborne mineral dust. The mobilisation, transportation and deposition of dust has major impacts not only within the Sahara, but in many
regions outside of northern Africa. Dust mobilised in the Sahara is transported large
distances and deposited not only within Africa itself but also over the Atlantic, the
Mediterranean, the Middle East, Europe and the Americas.\textsuperscript{154,155,156,157} In many of
these regions dust transport and deposition has significant implications for climate,
ecology and human health. Given the potential for human impacts on the land
surface and anthropogenically driven climate change to affect dust production, the
generation of dust represents another key interface between people and the physical
environment in North Africa, with global implications. Here we consider the role of
dust in the coupled earth-ocean-atmosphere system, before moving on to address the
nature of Saharan dust sources and their evolution over time. Finally the impacts on
human systems (principally on human health) of Saharan dust, and of changes in its
mobilisation, transport and deposition, are discussed.

\textit{Dust Impacts on Climate}

Dust directly affects climate at local and regional scales by modifying the temperature
structure of the atmosphere. On the one hand dust reduces the amount of shortwave
solar radiation reaching the Earth’s surface, causing cooling in the lower atmosphere,
On the other hand dust absorbs outgoing longwave radiation, trapping heat in the
atmosphere and causing warming in much the same way as greenhouse
gases.\textsuperscript{158,159} These two effects act in opposition to one another, and the overall
effect of dust on temperature depends on a variety of factors including the vertical
distribution of the dust, the size distribution of the dust particles, their composition,
the nature of the underlying surface, and the time of day. Where dust exists in an
elevated layer overlying less dusty air, the overall result will be a cooling of the
Earth’s surface and the lower levels of the atmosphere during the daytime. At
night, only the longwave effect acts, resulting in warmer surface temperatures.
Dust thus acts to reduce the daily temperature range at the Earth’s surface.

Dust exists in a elevated layer – the Saharan Air Layer (SAL) – overlying a
humid oceanic air mass over the Atlantic Ocean and over the Sahel during the
monsoon season. Warming within the dust layer, reinforced by near-surface
cooling during the daytime, acts to reinforce the temperature inversion at the base
of the SAL and stabilise the atmosphere, inhibiting convective activity. This phenom-
enon has been detected over the Sahel,\textsuperscript{160} where it has been proposed as a mechanism
of drought reinforcement\textsuperscript{161}. Atmospheric stabilisation by dust has also been
observed to inhibit the development of hurricanes over the Atlantic.\textsuperscript{162} The reduction
of sea surface temperatures by dust over the northern Atlantic may also play a role in
reinforcing or sustaining the dipolar temperature anomaly (cooling over the northern
hemisphere relative to the southern hemisphere and northern Indian Ocean) associ-
ated with drought conditions in the Sahel.\textsuperscript{163,164,165,166} Low altitude cooling will
also reduce evaporation over the ocean or over moist land surfaces, further reducing
the likelihood of rainfall.\textsuperscript{167} Simulations using a general circulation model\textsuperscript{168} indicate
that evaporation and precipitation are reduced globally by dust, although they suggest
that the local presence of dust increases rainfall over deserts. However, this latter
conclusion is not supported by any observational evidence.
Dust can also affect global climate through its influence on marine and terrestrial ecosystems. The most widely known such impact is the fertilisation of the ocean by iron carried in aeolian dust originating in the world’s deserts. Jickells et al.\textsuperscript{169} estimate average global dust production at around 1.7 billion tonnes per year, with almost two-thirds of this material originating from North Africa and 26 per cent of the dust reaching the oceans. Once deposited in the ocean, iron from terrestrial dust is believed to enhance biological productivity, which leads to the sequestering of atmospheric carbon dioxide that is taken up by phytoplankton and exported to deep water and ultimately to the ocean floor to be incorporated in marine sediments.\textsuperscript{170} Thus oceanic dust deposition contributes to a reduction in the greenhouse gas content of the atmosphere, acting to modulate the rate of increase of anthropogenically driven greenhouse warming. The importance of this effect is a matter of debate, however, and further research is necessary in order to quantify the impact of dust on atmospheric greenhouse gas concentrations. Dust also acts to stimulate the production of dimethyl sulphide (DMS) by marine organisms; when emitted to the atmosphere, DMS is oxidized to sulfate aerosol, which scatters solar radiation back to space, thereby acting to cool the Earth’s surface, further offsetting global or regional surface warming.\textsuperscript{171}

Nutrients from Saharan dust, such as phosphorous, are also important for certain terrestrial ecosystems, and are believed to play a vital role in sustaining the Amazon rainforest.\textsuperscript{172} Modelling studies suggest that the forests of Amazonia are vulnerable to large-scale die-back caused by higher temperatures and reduced rainfall resulting from anthropogenic climate change;\textsuperscript{173,174,175} any reduction in the supply of nutrients to the forest canopy may conceivably accelerate this process. Die-back of the Amazon forests would release large quantities of carbon dioxide into the atmosphere, accelerating global greenhouse warming.

Finally, dust may affect climate by modifying the reflectance or albedo of the land surface. Where dust is deposited over snow fields or ice sheets it reduces the reflectance of the surface, increasing the amount of solar radiation absorbed by the surface which results in heating and melting of the snow and ice. While such a process is unlikely to be significant at the global scale today, this mechanism is believed to have been important in regulating past glacial cycles, in periods when global dust transport was much greater than at present.\textsuperscript{176} Dust deposition over mountainous areas may accelerate the melting of glaciers and snow and ice fields, which are already shrinking in many areas as a result of climate change. In certain mountain regions this could impact on water resources, flood hazards and tourism, with significant economic consequences.

Dust is clearly an important component of the atmosphere, and represents a medium via which the Sahara influences global climate through the modulation of global biogeochemical cycles. The Sahara, in turn, is sensitive to global climate change, as demonstrated by its dramatic history of transitions between arid and humid conditions. Any change in the Saharan dust cycle is likely to have significant repercussions for other regions, and perhaps for global climate as a whole. Greater efforts at understanding the dust cycle and the sensitivity of the Sahara to changes in climate are thus required if we are to improve our capability to model and
predict future global climate change. Any such efforts must start with an assessment of the nature of the dust sources themselves.

The Nature of Saharan Dust Sources

Dust is not emitted from the Sahara in a uniform or random fashion; the vast majority of aeolian material is generated from a variety of specific source regions that exhibit particular seasonal patterns of activity. These regions are prescribed by a combination of geomorphological and meteorological factors, principally a supply of free particles available for erosion, little or no vegetation cover, and wind speeds that regularly exceed the threshold value for emissions for the surface in question. Wind erosion may be suppressed by the presence of surface crusts (which are common in arid regions) and the presence of obstacles such as bushes, rocks and pebbles. The process of emission, once the threshold wind speed has been exceeded, begins with the mobilisation of large particles (in the size range 40–500 μm) which are free at the soil surface. These are typically sand particles derived from quartz, often with small clay particles adhering to their surface, and aggregates of clay. The impact of these particles on the ground surface results in their own disaggregation and the breaking up of aggregate particles within the surface. This sandblasting results in the release of particles of dimension less than about 20 μm which are available for uplift into the atmosphere and subsequent long-range transport.

In recent years the major dust sources in northern Africa have been identified by satellite remote sensing, principally using the Total Ozone Mapping Spectrometer (TOMS) Aerosol Index (AI) and the Infra-red Difference Dust Index (IDDI) derived from data acquired by METEOSAT. Global monitoring of aerosols using the TOMS AI indicates that the Sahara is by far the world’s largest dust source, and that the most active source region is the Bodele Depression, variously described as the world’s largest single dust source, or the ‘dustiest place in the world’. The Bodele Depression contains the exposed lake sediments of the now desiccated Lake Megachad, and it is these sediments that provide the material mobilised as airborne dust. However, the importance of the Bodele Depression is also a result of its geographical situation to the southwest of the gap between the Tibesti and Ennedi Mountains, which funnels and amplifies the prevailing northeasterly winds, resulting in a high frequency of events during which surface winds exceed the threshold velocity for sediment mobilisation. In addition, field and satellite observations reveal that the lake sediments are partially covered by mobile sand dunes, which provide an abundant supply of coarse material with which the palaeolake surface is sandblasted.

The western Saharan region straddling the borders of Mali, Mauritania and Algeria also appears to be particularly active; in the IDDI imagery this region is as prominent as the Bodele Depression, and is flanked by additional prominent sources in south-central Algeria and the northern regions of Western Sahara (Figure 4). Satellite imagery and field observations indicate that these source regions are heterogeneous in nature, consisting of a number of different sources including but not restricted to dry lake beds. Field observations by two of the authors (Drake and Brooks) in the north of Western Sahara, coupled with
observations from the Moderate Resolution Imaging Spectrometer (MODIS) have identified clay lake beds as sources of airborne dust. An extensive gravel plain straddling the border of Western Sahara and Mauritania also appears to be a significant source of dust; this plain is cut by dry channels and it is likely that the sediments mobilised by the wind in this location derive from both past wind and water action.

The coarse resolution of the TOMS and IDDI imagery (in the region of 40 km) means that many of the dust sources indicated by long term averages of both types of data remain an enigma. The situation is complicated by disagreement between the TOMS and IDDI datasets, which is due at least in part to the lack of sensitivity of the TOMS AI to low-level dust. The main western source region is more prominent, and located further north, in the IDDI than in the TOMS dataset. In the IDDI, the Bodele region is linked to the western source area by a zone of intermediate IDDI values extending through central Niger and northern Mali (including the location of the western maximum in the TOMS data); similar magnitude values are apparent over much of south-central Mauritania near the northern limit of the monsoon rains. A number of other regions appear as sources in the IDDI but not in the TOMS data. These include a region extending from south to north through the centre of northern Sudan and southern Egypt, approximately following the course
of the Nile and extending several hundred kilometres either side of it, and a region to the northwest of the Tibesti mountains where the borders of Libya, Niger and Chad meet, extending northwards into the central regions of southern Libya.

Despite their disagreement, the TOMS and IDDI data clearly indicate that past fluvial activity plays an important role in determining the distribution and nature of the main Saharan dust sources. Sediments from palaeolake Chad provide the material for wind erosion that makes the Bodele Depression such an active dust source, and smaller dry lake beds are evident as dust sources in Western Sahara. However, while topographic lows containing fluvial sediments from past humid episodes are clearly important in the global dust cycle, a straightforward mapping of dust sources onto such features appears overly simplistic. For example, the second largest enclosed basin, the recently identified Lake MegaFezzan in southwestern Libya, appears to generate little or no dust. This palaeolake exhibits very different geomorphology to palaeolake Chad, as its sediments are capped by hard calcrete and gypsum crusts and large dunes. Clearly, not all palaeolake surfaces act as dust sources. Neither are all dust sources associated with palaeolakes, as illustrated by the emission of dust from the gravel plains of Western Sahara. Instead, dust sources appear to be heterogeneous in nature, with different sources being activated at different surface wind speeds.

**Climatic Versus Human Influences on Dust Source Activity**

During the 1990s it was suggested by a number of authors that apparent increases in the mobilisation and transport of northern African dust over the latter half of the twentieth century were the result of land degradation in the Sahel, combined with climatic desiccation. However, there is little or no evidence for widespread systematic land degradation resulting from human activity in this region, and a number of studies have convincingly argued that what has often been interpreted as systematic, regional-scale desertification (the ‘southwards march of the Sahara’) is nothing more than the physical expression of an oscillation of the ‘desert boundary’ as the activity and maximum northerly position of the Inter-Tropical Convergence Zone and associated monsoon air mass varies on interannual and interdecadal timescales.

Historically, the controversy over the role of land degradation in dust production comes from the paucity of measurements that would permit the identification of any long-term trends in dust mobilisation in the Sahel. Indeed, for many years the only location at which dust was measured on a regular basis was Barbados, some 5,000 km from the western coast of Africa. Available since 1965, i.e., around the beginning of both dramatic population growth in the Sahel and the decline in rainfall in this region, this dataset would have been suitable for the search for trends in production (rather than transport) if its ability to represent processes occurring in the African continent were not so questionable. In contrast to this highly localised record, satellites offer a unique opportunity to monitor atmospheric dust at the global scale. However, suitable satellite imagery for dust monitoring has only been available since the very end of the 1970s, and thus covers too short a period for it to be useful in discriminating between an anthropogenic trend and the ‘natural’ impact of drought in the 1980s and 1990s. Combining satellite imagery and data
from the Barbados record may provide a means of addressing this problem in the near future.

However, as discussed above, assessments of the major dust source regions indicate that they are overwhelmingly located in Saharan regions that are unlikely to have experienced significant human impacts.\textsuperscript{199,200,201} It appears that climatic variations have been the principal driver of observed changes in dust production. On the one hand variations in rainfall have affected vegetation cover and thus influenced the susceptibility of certain surfaces to wind erosion, while on the other changes in atmospheric processes are likely to have resulted in changes in the balance between dust mobilisation and deposition within the Sahel and southern Sahara.\textsuperscript{202,203} Climate change may play a key role in modulating future dust export from the Sahara. Furthermore, Chiapello and Moulin\textsuperscript{204} have shown that the North Atlantic Oscillation (NAO), a large-scale meteorological system that essentially controls the strength of the Trade-Winds during the winter, explains a large part of the year-to-year variability in dust transport from the Sahara to the tropical North Atlantic. Its influence spreads further since a correlation of the NAO index with dust activity in the Bodele depression suggests that the NAO influences dust emissions as well as transport.\textsuperscript{205} It is thus likely that future changes in atmospheric circulation will strongly affect the dust cycle, a problem that numerical models will have to answer in the forthcoming years.

Future Dust Emissions

On long timescales, dust emissions from northern Africa are modulated by large-scale changes in climate, as demonstrated by the abrupt increase in wind-blown dust deposited off West Africa at the end of the last Saharan humid phase around 5.5 ka.\textsuperscript{206} While dust sources do not map directly onto palaeolake surfaces, they are strongly associated with fluvial activity, begging the question of how long they may remain active before their reserves of erodible material are depleted once fluvial activity has effectively ceased.

Wind action is limited to the soil surface, so emission can be sustained in the long term only if the superficial soil layer is constantly supplied with fine material. Such a supply can be explained in terms of the settling of dust from the atmosphere, the disaggregation of larger particles by wind action, and the disturbance of the surface due to the motion of sand dunes (anthropogenic disturbance, e.g. by vehicles, may play a role, but the contribution of such processes has not been quantified and there is no evidence for large ‘new’ dust sources, as discussed above). The occasional action of rainfall and associated fluvial activity also represents an efficient means of disturbing the land surface and of carrying fine material to basins via networks of wadis. While such events are rare in the Sahara, the lack of vegetation means that single events can disturb and mobilise large amounts of material. Furthermore, rainfall does occur fairly regularly over some of the Saharan highlands, providing a means of replenishing erodible material in the adjacent lowlands. Rajot et al.\textsuperscript{207} conclude that the vertical flux of emitted dust is not supply limited, even with a fraction of silt and clay as low as 1.5 per cent near the surface. This finding is
supported by evidence that areas not likely to be replenished by recent fluvial activity, such as flat gravel plains as described above, are also sources of dust.

There thus appears to be little reason to expect the supply of material available for wind erosion in the Sahara to be exhausted in the foreseeable future. However, climate change has the potential to alter the amount of dust mobilised in and exported from the Sahara via its impacts on the land surface. In particular, the possible ‘greening’ of the southern Sahara as a consequence of anthropogenic greenhouse warming as discussed above, may serve to reduce the supply of dust from certain sources through the stabilisation of the land surface. A strengthening of the African Monsoon and resulting expansion of vegetation cover as modelled by Brovkin and Claussen et al. could conceivably cut off the dust supply from sources close to the current monsoon belt, including the Bodele Depression. Given the role of dust in the climatic, meteorological and biogeochemical processes discussed earlier in this section, such a partial greening of the Sahara could have significant global and regional implications.

**Impacts of Dust on Human Systems**

As a component of the Earth system which contributes to the regulation of biogeochemical cycles, ecological productivity and climate, variations in dust mobilisation, transport and deposition have implications for human activities. Impacts on ocean productivity may affect fish stocks, with associated economic implications, while individual dust events affect transport and day-to-day human activities. Large-scale influences of dust on climate and the possible role of dust in modulating rainfall may potentially be implicated in food insecurity. The role of dust in the removal of carbon dioxide from the atmosphere via its influence on marine and terrestrial biological productivity is likely to play a role in the sensitivity of the global climate to anthropogenic greenhouse gas emissions. In order to model and predict future climate changes that will require adaptive responses in human societies, dust must be better represented in global climate simulations. The representation of dust in regional climate models and the incorporation of its effects in regional scenarios of future climate is necessary if certain key processes are to be represented accurately; for example, changes in atmospheric dust content over the northern tropical Atlantic might have profound implications for future trends in hurricane activity. Anticipation of such trends will be crucial in the development of policies, strategies and measures to cope with future changes in climate and their impacts.

Regardless of its impact on future changes in climate, the present-day impact of dust on human health is sufficient grounds for further research into its characteristics, mobilisation, transport and deposition. Mineral aerosols transported large distances are generally less than 20 µm in dimension, and typically contain large numbers of particles of sub-micron dimension. They therefore span the size range for particles associated with adverse impacts the human respiratory system. Saharan dust events regularly contribute to air pollution limits being exceeded in the Mediterranean region, and African dust frequently reaches the Americas and north-western Europe, where it can contribute to high atmospheric pollutant levels when combined with aerosol particles from other sources. Variations in concentrations of particles
whose size is the order of 10 μm (PM10s) in Trinidad are associated predominantly with the transport of dust from northern Africa.\textsuperscript{213}

Very little internationally published research has been carried out into the health impacts of airborne dust within northern Africa (although see Laval, 1967\textsuperscript{214} and Fossati, 1969.\textsuperscript{215}) Nonetheless, research in other parts of the world suggests that these impacts are likely to be great. Lung conditions in populations living in arid or semi-arid regions have been linked with exposure to silica in the Himalayas,\textsuperscript{216} the Thar Desert of India\textsuperscript{217} and the Southwest USA,\textsuperscript{218} and the deposition of silica in the lungs is associated with a widely recognised condition known as ‘desert lung syndrome’.\textsuperscript{219,220} Dust events originating in the interior desert of Australia have been associated with increased incidences of asthma in Brisbane.\textsuperscript{221} The evidence for links between dust and asthma in the Caribbean is more equivocal. It has been suggested that dust clouds originating in the Sahara are associated with increased paediatric asthma accident and emergency emissions in Trinidad, where there is a widespread belief that the passage of Saharan dust exacerbates rhinitis and asthma.\textsuperscript{222} However, emerging findings from an ongoing study by one of the authors (Prospero) and colleagues appear to challenge this conclusion. There is evidence that dust from northern Africa is associated with the long-range transport of micro-organisms; daily aerosol samples collected throughout 1996–1997 from the trade winds reaching Barbados yielded significant concentrations of viable (i.e. culture-forming) bacteria and fungi only when African dust was present.\textsuperscript{223} In parts of the Sahel, dust storms are believed to be responsible for certain potentially fatal sicknesses.\textsuperscript{224}

There is thus a strong public health case for research into the health effects of dust in the Sahara, and into ways to ameliorate any such effects. A greater understanding of the activity and nature of Saharan dust sources, and of their potential future evolution, is therefore relevant for health policy both inside and outside northern Africa, as well as for activities such as climate forecasting. Such an understanding requires comprehensive campaigns of field work to investigate the geomorphological, geochemical and mineralogical nature of the key dust sources and the surface conditions associated with emission, as well as remote sensing studies of dust sources and transport. Such fieldwork is currently underway in the Bodele Depression\textsuperscript{225} source region and is at an early stage in Western Sahara, but there is little such activity in other parts of northern Africa beyond the monitoring of dust event frequencies and visibility.

**Discussion and Conclusions**

Research focusing on regions rather than processes is currently somewhat unfashionable. However, a focus on specific regions such as the Sahara provides an excellent opportunity to investigate linkages between different physical and social systems and to conduct truly interdisciplinary research. The Sahara in particular has been neglected by the research community for a number of reasons, including (i) perceived difficulty of access and security issues, which discourages researchers from conducting field work, (ii) the economic and political marginalisation of the region and the associated lack of participation of Saharan countries in international research
programmes, (iii) the difficulty faced by nationals of Saharan countries in travelling outside of the region, (iv) the isolation of individual researchers working on Saharan issues within countries outside of the region, and (v) the fact that what little research is conducted in the Sahara is often seen as either rather esoteric in nature (e.g. research into archaeology and rock art) or only of relevance to a tiny minority of specialists (e.g. ethnographic and anthropological research).

The lack of interest in the Sahara among the wider research community is remarkable given the proximity of the region to Europe and the strong historical ties between Europe and North Africa, not to mention the importance of a number of Saharan nations as oil producers. Indeed, these factors have drawn the attention of the security community, particularly in the United States, although this attention is not always matched by detailed knowledge of the political reality on the ground. The combination of drought with other economic, social and political issues to precipitate political instability and conflict at the margins of the Sahara has been described above. Developmental and security issues should be sufficient to foster a greater interest in the Sahara in Europe and North America; however, so should the broader issues related to the Sahara’s role in the Earth system and human well-being as discussed in this paper.

The Sahara as a Component of the Earth System

The neglect of the physical sciences in the Sahara is particularly notable. While a number of teams are conducting archaeological and palaeoenvironmental research in a variety of Saharan countries, there has been very little work on contemporary environmental issues in the Sahara. This fact is thrown into sharp relief by the recent investment of millions of US Dollars in research into the transport of mineral dust from Chinese sources. Material from these sources transported over densely populated parts of East Asia, notably the Korean peninsula, has relevance for regional climate, human health and ecological systems, and also reaches North America. However, there is very little funding for, and no concerted programme of, research into the transport of dust from the Sahara, which produces more dust than the Chinese sources, providing up to two thirds of the global atmospheric dust burden and contributing to air pollution in Africa, Europe, the Caribbean and North America. Just as in China, trends in dust storm activity and in the export of dust over adjacent regions have been detected for the Sahara. Furthermore, dust has been implicated in the suppression of rainfall and the possible exacerbation of drought in the Sahel, and has been demonstrated to suppress tropical cyclone and hurricane formation over the Atlantic. Better understanding and monitoring of Saharan dust events thus has the potential to improve seasonal climate forecasts for a key marginal region of sub-Saharan Africa, and enhance hurricane forecasting capabilities. Long-range forecasts of dust mobilisation and transport based on climate change scenarios coupled with dynamic representations of geomorphological processes and vegetation cover may help us forecast climate variability and extremes (specifically droughts and hurricanes), and assist in the development of policies to deal with the potential impacts of climate change.
On longer timescales, a better understanding of how the Saharan land surface responds to climate change in terms of dust production and vegetation feedbacks should enable us to reduce uncertainties in the representation of the carbon cycle and atmospheric aerosols in global climate models. The incorporation of mineral aerosols into such models will improve the representation of the Earth System and should lead to more realistic climate change scenarios, with improved estimates of the sensitivity of global climate and of ecosystems to increases in atmospheric greenhouse gas concentrations and global mean surface temperatures. This in turn will help policy makers to assess climate change risks and design climate change mitigation and adaptation policies. Current computer models suggest that anticipated changes in global climate may lead to a greening of the southern Sahara and northern Sahel in the near to medium term, a process that may reduce the supply of erodible material for aeolian transport. Such a reduction in dust supply could exacerbate global warming via adverse impacts on carbon-storing marine and terrestrial ecosystems, representing a positive feedback in the climate system (although these effects might be offset to a certain extent by increased carbon sequestration in a more densely vegetated Sahara). Reduced dust emissions from northern Africa may also increase the frequency and/or intensity of Atlantic hurricanes, exacerbating hurricane risk in the Caribbean, the southeastern United States, Central America and even northern South America. On the other hand reduced atmospheric dust content may have beneficial impacts in terms of human health and rainfall in certain regions. While the mechanisms associated with all these processes have been clearly identified, the processes themselves are not understood in a quantitative manner; the importance of the associated impacts could be significant, but will remain a matter of speculation pending further research.

Climate Change and Human Adaptation: Lessons from the Past

The past provides us with no exact analogues for the anthropogenic greenhouse warming that is anticipated over the coming centuries. Nonetheless, studies of the Saharan past can teach us many lessons about physical and social systems and their interaction. The Holocene climatic optimum occurring between about 10 and 5 ka, which was associated with humid conditions in the Sahara, might provide us with a very approximate model for future climate change, provided such comparisons are treated with caution – the mechanisms behind the early Holocene warming and monsoon intensification are different from those driving present day anthropogenic climate change. Furthermore, it must be appreciated that global mean temperatures are likely to exceed those of the Holocene climatic optimum before the end of the twenty-first century.

Palaeoenvironmental data can help us develop a better understanding of past changes in climate and the connections between changes at high and low latitudes. Such connections are exemplified by the association between cooling in the North Atlantic, apparently originating at high latitudes, and arid crises in the Sahara and the wider northern hemisphere subtropical and extra-tropical region during otherwise warm humid periods (see Brooks for a review of these changes and their impacts on human societies). It is plausible that such cooling episodes will result from inputs
of freshwater from melting ice and increased river runoff in the Atlantic associated with anthropogenic climate warming. The likelihood of such events being precipitated by human-induced climate change is currently a matter of great debate, and studies of past climates can yield information about the conditions under which such events occur. Alley argues that past events have occurred with little or no external forcing and that the difficulty current climate models have in reproducing such events indicates that they may be more likely to occur in the future than is generally accepted. The occurrence of such events in the warm early Holocene suggests that anthropogenic greenhouse warming may not necessarily mean that such transient cold, arid episodes will be absent from the foreseeable future. Studies from regions such as the Sahara can tell us how severe such events must be in order for their effects to be felt in low latitudes with potentially adverse consequences for human populations. Again, such information can help policy makers develop strategies for avoiding ‘dangerous’ climate change associated with the crossing of critical thresholds in the climate system beyond which we are likely to experience abrupt changes in climate.

As well as yielding information on the workings of the climate system and links between climate change and environmental impacts, studies of the past can tell us much about how human societies respond to environmental change. While patterns of vulnerability and the nature of human responses to climatic and environmental change are context-specific, it is possible to make some very general (although not universal) observations regarding human responses to such changes. The Sahara reinforces the lesson, evident from more recent experiences in the Sahel, that mobility is the key to the long-term sustainability of livelihoods in highly variable environments. The long records of environmental change in northern Africa caution us to beware of complacency during periods of abundance associated with increased rainfall, as these are invariably followed by episodes of scarcity. Social systems in such environments must be flexible and responsive; livestock-based pastoralism is a more appropriate strategy than large-scale rain-fed agriculture where rainfall is scarce and unpredictable. While this observation might be a moot point in the hyper-arid regions of the Sahara, it is of great relevance for marginal regions such as the Sahel, where developmental pressures and aspirations of economic growth led to agricultural expansion in the anomalously wet 1950s and early 1960s, a time of optimism driven by independence from colonial rule and the prevailing ideology of technological progress. This expansion only served to exacerbate the impacts of the subsequent period of drought and desiccation. Although model studies (to a certain extent supported by observations) suggest that the northern Sahel and southern Sahara may become wetter in the near future, the real possibility of occurrence of cold arid episodes as described above, or of a reversal of the greening trend at high atmospheric greenhouse gas concentrations, means that extreme caution should be exercised in the exploitation of climatic amelioration along the Sahel-Sahara boundary. Modelling studies and palaeoclimatic data caution us that social systems in northern Africa must be prepared to confront extreme environmental variability if they are to survive.

Studies of past responses to climatic and environmental change in the Sahara paint a picture of largely reactive, ad hoc ‘adaptation’ occurring during times of
environmental crisis. The rapid spread of cattle herding suggests migration as a last resort to environmental deterioration, rather than a smooth and painless process in which human populations respond to changes as they occur without suffering significant hardship. While this may not appear to be a very controversial conclusion, it stands in sharp contrast to current paradigms of adaptation, which promote the development of resilience and ‘adaptive capacity’ as a means of coping with climate change – the implication being that adaptation is a means of ‘neutralising’ the impacts of climate change and thus of avoiding adverse consequences. In fact the current view of adaptation as something wholly benign is challenged by the archaeological record, which demonstrates that adaptation to environmental change has generally involved compromises, and is often what we may term sub-optimal’ in that, while it enables human populations to survive in the face of change, it often has negative aspects. The archaeological record illustrates that Saharan societies became more territorial and stratified as they responded to climatic desiccation, in response to a reduction in the productivity of the physical environment. Where these processes culminated in the emergence of urbanisation based on technological solutions to adaptation, as in the Nile Valley and the Libyan Fezzan, they proved to be vulnerable to collapse in the face of later climatic crises or simply unsustainable in the longer term. While the factors behind the demise of the Garamantian culture in this region are not known, it is possible that declining groundwater levels played a role, and that the Garamantes were confronted with limits to their technological ability to adapt to environmental change.

**Future Economic Development in the Sahara**

Modern technology enables settlement in previously uninhabitable regions, and permits the rehabilitation of areas where settlement and agriculture have been in decline, such as the Garamantian heartland in the Fezzan. This transformation (in terms of both reality and aspiration) is evident in the local toponymy, with the Wadi al-Ajal (usually translated as ‘Valley of Death’) having been renamed the Wadi al-Hayat (‘Valley of Life’). Another example of technology enabling greater access to water is the Great Manmade River, which transports fossil water from the aquifers of the central Sahara in southern Libya to the Mediterranean coast, providing an expanding population and a developing economy with a vital resource. However, water resources in the central Sahara are finite, and estimates of the amount of water available, and the time until it runs out, vary considerably. A better understanding of the origins of this fossil water, of the dynamics of the aquifers, and of the conditions necessary for their recharge, may contribute to a more sustainable approach with water management. An appreciation of the origins and finite nature of Saharan water resources, coupled with policies designed to encourage water conservation, might go some way towards extending the lifetime of fossil reserves; policies designed to foster more ‘responsible’ use of resources are more likely to succeed when underpinned by campaigns of awareness raising, which must ultimately be based on a sound scientific understanding of the region’s natural resource base.

Water is not the only precious commodity in the Sahara. Oil and tourism underpin much of the economic development in the region. Tourism in the Sahara ultimately
depends on the preservation of natural and cultural heritage, being predominantly based on tourists’ interest in landscapes, history and archaeology. This heritage can be compromised by a number of factors, including insensitive development and oil exploration, which threaten a number of sites of scientific and archaeological interest, and have already damaged or destroyed some.\textsuperscript{243} Of course tourism itself can cause significant damage when it is not carefully managed, through souvenir hunting and practices such as the wetting of rock paintings in order to temporarily enhance their appearance for photographic purposes.\textsuperscript{244,245,246} Nonetheless, tourism represents a potentially lucrative, and sustainable, source of income for many Saharan communities and nations. Whereas oil reserves will eventually run out, or may become significantly less profitable if concerns about climate change lead to a shift to alternative energy sources, natural and cultural heritage represent an unlimited resource if carefully managed. While it may be expedient in the short term to sacrifice heritage for the sake of oil exploration and production, it is neither necessary nor sensible in the long-term. Oil-based development can be complemented by low-impact tourism that exploits the great interest in natural history and the human past among the educated populations of affluent nations, who are constantly seeking novel destinations. Such tourism can be underpinned by research in the physical and social sciences, which furthers our understanding of the natural and cultural heritage. In some parts of the Sahara, local people are educating themselves in subjects such as archaeology in order to participate more fully in heritage tourism and assist in the management of valuable archaeological sites.\textsuperscript{247}

Conclusions

In conclusion, we stress that the Sahara is not merely the ‘empty space’ of the popular imagination. Like other regions, the Sahara is faced with the challenge of ‘sustainable development’ in the face of a growing population and an uncertain climatic future. In the Sahara, this challenge is compounded by a reliance on non-renewable water resources, extreme environmental variability, and a high sensitivity to global climate change. The challenge of coping with variability and change is particularly acute at the southern margins of the desert, along the oscillating Sahara-Sahel boundary. Here, future development policies must be built around this variability, and founded on a profound appreciation of it. There is much that can be learnt from traditional resource management practices, based on flexibility and mobility, and tried and tested livelihood models and coping strategies should not simply be discarded in the name of progress and modernisation. Technological innovation has a role to play in development, for example through the development of methods to access and deploy scarce water resources, provided the consequences of such activities are carefully considered. Economic diversification also has its part to play, for example in the form of locally-run and sensitively managed archaeology-based tourism.

The physical and social sciences have a key role to play in the future development of the greater Saharan region. However, in order that this role be fulfilled, there must be more international support for Saharan research, and much more collaboration...
between members of the international scientific community and their counterparts in the Saharan nations. Finally, the role of the Sahara in influencing global climate requires much more investigation; the potential of Saharan dust to affect the global carbon cycle and perhaps accelerate the process of anthropogenic climate change means that to ignore the Sahara is to neglect a key component of the Earth system.

NOTES
10. Ibid.
11. The Pleistocene corresponds to the majority of the Quaternary period, excluding the last 10,000 years, which constitutes the Holocene.
12. Deposits laid down in the beds of ancient, now dry lakes, or palaeolakes.
13. A recently identified large palaeolake in southwestern Libya.
22. Jolly et al. (note 4).
23. M. Cremaschi, M. Pelfini, L. Arzuffi, V. Di Mauro, M. Santilli and A. Zerboni, ‘A palaeoclimatic record for the late Holocene in the central Sahara: tree rings of *Cypressus dupretiana* from the Wadi Tanezzuft area (SW Fezzan, Libya)’, in M. Kaennel Dobbertin and U. Braker (eds.) *Abstracts*


26. Gasse and van Campo (note 3) & Alley et al. (note 5).

27. Gasse and van Campo (note 3).


29. N. Brooks, ‘Cultural responses to aridity in the Middle Holocene and increased social complexity’, Quaternary International (in press).

30. Ibid.


34. Bond et al. (note 25).


38. di Lernia (note 32).

39. Hassan (note 31).


41. Brooks (note 29).


49. Cremaschi et al. (note 42).


51. di Lernia (note 32).


62. Ibid.


65. Wendorf et al. (note 24).


68. Hassan (note 31).


72. di Lernia and Palombini (note 70).

73. Ibid.


75. Hassan (note 31).

76. di Lernia (note 69).

77. di Lernia (note 45).

78. di Lernia (note 69).

79. Cremaschi et al. (note 23).


81. Ibid.

82. Wendorf and Schild (note 65).
84. di Lernia (note 69).
85. di Lernia and Palombini (note 70).
86. di Lernia and Manzi (note 55).
92. Brooks et al. (note 89).
93. Mattingly et al. (note 80).
98. Mattingly et al. (note 80).
99. Brooks et al. (note 89).
100. Drake et al. (note 90).
101. Mattingly et al. (note 80).
104. Drake et al. (note 90).
105. Ibid.
106. di Lernia et al. (note 94).
107. Mattingly et al. (note 80).
110. Brooks (note 29).
111. Midant-Reynes (note 108).
117. Brooks (note 29).
120. Mattingly *et al.* (note 80).
121. Di Lernia *et al.* (note 94).
122. Brooks *et al.* (note 89).
123. Liverani (notes 95 and 97).
124. Mattingly *et al.* (note 80).
132. Ibid.
133. Brooks (note 1).
141. Anyamba and Tucker (note 139).
142. See www.fao.org
146. Ibid.
147. Ibid, p. 20.
150. Brooks (note 1).


166. Prospero and Lamb (note 155).


168. Ibid.


170. Ibid.

171. Ibid.


177. Brooks and Legrand (note 161).


Brooks and Legrand (note 161).

TOMS measures the amount of ultraviolet radiation reflected by the Earth system (i.e. the surface and overlying atmosphere combined) at different wavelengths; dust is detected using a method that accounts for the different reflective properties of different substances at these wavelengths (Washington *et al.*., 2003 – see endnote 179). The IDDI detects dust using a different technique based on the reduction of infra-red radiation escaping the Earth’s atmosphere due to the cooling effect of atmospheric aerosols resulting from their blocking of incoming solar radiation, coupled with their absorption of infra-red radiation emitted by the Earth’s surface (Brooks and Legrand, 2000 – see endnote 157). The TOMS AI and the IDDI data are therefore derived from very different principles to detect dust, so it should not be surprising that there are differences in the resulting data.

Propero and Lamb (note 155).

Washington *et al.* (note 180).

Ibid.


Brooks and Legrand (note 161).


Drake *et al.* (Note 14).

Marticorena and Bergametti (note 178).


Propero and Lamb (note 155).

Brooks and Legrand (note 161).

Goudie and Middleton (note 188).

Washington *et al.* (note 180).

Brooks and Legrand (note 161).

Propero and Lamb (note 155).


Brovkin (note 135).

Claussen *et al.* (note 136).

211. Rodriguez et al. (note 154).


242. di Lernia and Palombini (note 70).
246. Brooks *et al.* (note 177).
247. J. Keenan, personal communication.