Chapter 8

THE HISTORY AND EVOLUTION OF DESERT HYDROLOGY AND LANDFORMS: THE ROLE OF CLIMATE CHANGE

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1. Introduction: Aridity

The purpose of this chapter is to describe the nature of the evidence that can be used to establish the nature of environmental conditions in deserts, and to demonstrate the changes that have occurred in their hydrology and geomorphology, particularly during the course of the last few millions of years.

Arid lands, which cover about a third of our land surface, occur in every continent (Goudie 2002). They have, predominantly because precipitation is low, a severe shortage of moisture. In some years they may even receive no rain at all. In some deserts aridity also results from high temperatures, which means that evaporation rates are also high (Mainguet 1999).

Aridity can be defined by the water balance concept. This is the relationship that exists between the inputs of water in precipitation (P), the losses arising from evaporation and transpiration (evapotranspiration) (E_t), and any changes that occur in storage (soil moisture, groundwater, etc.) In arid regions there is an overall deficit in the annual water balance, and the size of that deficit determines the degree of aridity. The actual amount of evapotranspiration (AE_t) that occurs varies according to whether there is available water to evaporate, so the concept of potential evapotranspiration (PE_t) has been devised. This is a measure of the evapotranspiration that could occur from a standardized surface never short of water. The volume of PE_t varies in response to four climatic factors: radiation, humidity, temperature, and wind. Thornthwaite (1948) developed a general aridity index based on PE_t:

when $P = PE_t$ throughout the year, the index is 0
when $P = 0$ throughout the year, the index is –100
when P greatly exceeds PE_t throughout the year, the index is +100

Areas with values below –40 are classified as arid, those between –20 and –40 as semi-arid, and those between 0 and –20 as sub-humid (Meigs 1953). The arid category can be subdivided into arid and extreme arid, with the latter being defined as the condition in any locality where at least 12 consecutive months without any rainfall have been recorded, and in which there is not a regular seasonal rainfall rhythm.

Extremely arid areas, such as the Atacama, Namib, inner Arabia and central and eastern Sahara, cover about 4 per cent of the earth's surface, arid about 15 per cent, and semi-arid about 14.6 per cent. In addition, deserts can be classified on the basis of their proximity to the oceans or their continentality. Coastal deserts, such as the Namib or the Atacama, have very different temperatures and humidities from those of continental interiors. They have modest daily and seasonal temperature ranges and are subject to fogs. They are also very dry. In addition to the coastal and inland deserts of middle and low latitudes there are also the cold polar deserts. The precipitation of the Arctic regions can be as low as 100 mm per year and at Vostok in Antarctica can be less than 50 mm.

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2. Causes of aridity

Most deserts are dry because they occur where there is subsiding air, relative atmospheric stability and divergent air flows at low altitudes, associated with the presence of great high-pressure cells around latitude 30°. Such areas are infrequently subjected to precipitation-bearing disturbances and depressions either from the Intertropical Convergence Zone or from the belt of mid-latitude depressions associated with the circumpolar westerlies. The trade winds that blow across these zones cause evaporation, and because of the trade-wind inversion they are areas of subsidence and stability. These global tendencies are often reinforced by more local factors. Of these, *continentality* can be dominant and plays a part in the location and character of the deserts of areas like central Asia. The *rain-shadow* produced by mountains ranges can create arid areas in their lee, as in Patagonia, where the Andes have an influence. Other deserts are associated with cold currents offshore (e.g. Namib and the Atacama). Winds that do blow onshore tend to do so across cold currents (e.g. the Benguela and the Peruvian) and so are stable because they are cooled from beneath, and also have a relatively small moisture-bearing capacity. They reinforce the stability produced by the dominance of subsiding air.

3. Aridity indicators

There are three main categories of phenomena that indicate aridity: geomorphological, sedimentological and biological. These have demonstrated that aridity has both been greater and less than today and that aridity has shown frequent and substantial temporal changes.

Indicators of former higher precipitation levels (pluvials or lacustrals) include: high lake levels marked by ancient shorelines; expanses of fossil soils of humid type (e.g. laterites); spreads of spring-deposited *tufa*; river systems which are currently inactive and blocked by dune fields; and animal, plant and cultural remains in areas now too dry for their survival. The evidence for formerly drier conditions includes the presence of degraded, stable dunes in areas now too wet and vegetated for sand movement to occur.

4. Aeolian phenomena

Large tracts of dunes provide strong evidence of dryness. Chapter 9 discusses in detail the hydroclimatic controls on wind erosion and dust emission in arid landscapes. The existence of heavily vegetated, weathered, and degraded dunes indicates that there has been a shift towards greater humidity (Tchakerian 1999). There is, however, some dispute about the precise precipitation thresholds that control major dune development. Undoubtedly wind strength, which may have been greater during glacials, and the nature of the vegetation cover have to be considered, but systems of demonstrably inactive and stable dunes are today widespread in areas of relatively high precipitation (over 500 mm per annum) (e.g. the northern Kalahari, western India and northern Australia).

Studies where dunes are currently active suggest that vegetation only becomes effective in restricting dune movement in non-coastal areas where annual precipitation totals exceed about 100 to 300 mm. Dunes may also provide evidence for multiple periods of sand movement, because of the presence of palaeosols in them (Allchin *et al*. 1978). Moreover, comparison of modern winds and potential sandflows with those indicated by fixed dunes may suggest that there have been changes in wind directions and atmospheric circulation patterns. The interrelationships of dunes and rivers may indicate alternations of aeolian (dry) and fluvial (wet) conditions, as is made evident by consideration of the courses of some tropical rivers (e.g. Senegal, Niger, Fitzroy), which have in the past been ponded up or blocked by dunes.

Dunes (lunettes) developed from lake basins by deposition of material deflated from their beds on lee sides may indicate changing hydrological conditions, with dunes comprised of clay pellets and salts tending to form from desiccated saline surfaces, and those with a predominance of quartzose and sand-size material tending to form from lake beaches developed at times of higher lake levels (Bowler 1973).

Other aeolian features which have palaeoclimatic significance are loess sheets in areas like China and Central Asia. These result from deflation of silt from relatively unvegetated surfaces and its deposition downwind. Within loess profiles there may be multiple palaeosols which resulted from stabilization of land surfaces under vegetated conditions. A detailed treatment of the significance of such materials is provided by Pye and Sherwin (1999). Dating of loess in China has been used to establish the initiation of desert conditions in that area, possibly as a result of circulation changes produced by the uplift of the Tibetan Plateau.

5. Pluvial lakes

Pluvial lakes are bodies of water that accumulated in basins because of former greater moisture availability resulting from changes in temperature and/or precipitation. Their study developed in the second half of the nineteenth century. Jamieson (1863) drew attention to the former greater extent of the great saline lakes of Asia: The Caspian, Aral, Balkhash and Lop-Nor and Lartet (1865) pointed to the expansion of the Dead Sea. The term pluvial itself was first applied to an expanded lake by Hull (1885). A discussion of these early studies and their bibliographic details is given in Flint (1971). A major advance in the study of pluvial lakes came in the western USA with the work of Russell (1885) on Lake Lahontan and of Gilbert (1890) on Lake Bonneville. The Great Basin held some 80 pluvial lakes during the Pleistocene, and they occupied an area at least 11 times greater than the area they cover today. Lake Bonneville was roughly as big as present-day Lake Michigan, about 370m deep and covered 51, 640 km^2. Lake Lahontan was more complicated in form, covered 23, 000 km^2, and reached a depth of about 280m. It was nearly as extensive as present-day Lake Erie. River courses became integrated and lakes overflowed from one sub-basin to another. For example, the Mojave River drainage, the largest arid fluvial system in the Mojave Desert, fed at least four basins and their lakes: Lake Mojave (including present day Soda and Silver lakes), the Cronese basin and the Manix basin (which includes the Afton, Troy, Coyote and Harper sub-basins) (Tchakerian and Lancaster, 2001).

Much work has been done to date and correlate the fluctuations in lake levels. Smith and Street-Perrott (1983) demonstrated that many basins had particularly high stands during the period that spanned the Late Glacial Maximum, between about 25, 000 and 10, 000 years ago. More recently there have been studies of the longer term evolution of some of the basins, facilitated by the study of sediment cores, as for example from Owens Lake, the Bonneville Basin, Mono Lake, Searles Lake and Death Valley.

The high lake levels during the Last Glacial Maximum may have resulted from a combination of factors, including lower temperatures and evaporation rates, and reduced precipitation levels. Pacific storms associated with the southerly branch of the polar jet stream were deflected southwards compared to today.

Other pluvial lakes occurred in the Atacama and Altiplano of western South America (Lavenu *et al*., 1984). The morphological evidence for high lake stands is impressive and this is particularly true with regard to the presence of algal accumulations at high levels above the present saline crusts of depressions like Uyuni (Rouchy *et al*., 1996). There exists a great deal of confusion about climatic trends in this region, not least with respect to the situation at the Late Glacial Maximum and in the mid-Holocene (Placzek *et al*., 2001). Nonetheless, various estimates have been made of the degree of precipitation change that the high lake stands imply. Pluvial Laguna Lejíca, which was 15-25m higher than today at 13.5 to 11.3 Kyr BP and covered an area of 9-11km^2 compared to its present extent of 2km^2, had an annual rainfall of 400-500 mm, whereas today it has only around 200 mm. Pluvial Lake Tauca (which incorporates present Lake

Poopo, the Salar de Coipasa and the Salar de Uyuni and which had a high stillstand between 15 and 13.5 Kyr BP), had an annual rainfall of 600 mm compared with 200-400 mm today.

In the Sahara there are huge numbers of pluvial lakes both in the Chotts of Tunisia and Algeria, in Mali (Petit-Maire *et al*., 1999) and in the south (e.g. Mega-Chad). In the Western Desert of Egypt and the Sudan there are many closed depressions or playas, relict river systems, and abundant evidence of prehistoric human activity (Hoelzmann *et al*., 2001). Playa sediments indicate that they once contained substantial bodies of water, which attracted Neolithic settlers. Many of these sediments have now been radio-carbon dated and indicate the ubiquity of an early to mid-Holocene wet phase, which has often been termed the 'Neolithic pluvial'. A large lake, 'The West Nubian Palaeolake', formed in the far north west of Sudan, (Hoelzmann *et al*., 2001). It was especially extensive between 9500 and 4000 years BP, and may have covered as much as 7000km^2. If it was indeed that big, then a large amount of precipitation would have been needed to maintain it – possibly as much as 900 mm compared to the less than 15 mm it receives today. The Sahara may have largely disappeared during what has been called 'The Greening of Africa'.

In the Kalahari of southern Africa, Lake Palaeo-Makgadikgadi encompassed a substantial part of the Okavango Delta, parts of the Chobe-Zambezi confluence, the Caprivi Strip, and the Ngami, Mababe amd Makgadikgadi basins. It was over 50m deep and covered 120, 000km^2, vastly greater than the present area of Lake Victoria (68,800km^2). This makes Palaeo-Makgadikgadi second in size in Africa to Lake Chad at its Quaternary maximum. Its dating is, however, problematic (Thomas and Shaw, 1991) as is its source of water. Some of the water may have been derived when the now dry valleys of the Kalahari were active and much could have been derived from the Angolan Highlands via the Okavango. However, tectonic changes may have led to inputs from the Zambezi.

In the Middle East, expanded lakes occurred in the currently arid Rub-Al-Khali and in Anatolia (Roberts, 1983). In Central Asia the Aral-Caspian system also expanded. At several times during the late Pleistocene (Late Valdai) the level of the lake rose to around 0m (present global sea level) compared to –27m today and it inundated a huge area, particularly to its north. In the Early Valdai it was even more extensive, rising to about +50m above sea level, linking up to the Aral Sea, extending some 1300km up the Volga River from its present mouth and covering an area greater than 1.1 million km^2 (compared to 400, 000km^2 today). At its highest it may have overflowed into the Black Sea. In general, such transgressions have been associated with warming and large-scale influxes of melt-water (Mamedov, 1997), but they are also a feature of glacial phases when there was a decrease in evaporation and a blocking of groundwater by permafrost. Regressions occurred during interglacials and so, for example, in the Early Holocene the Caspian's level dropped to –50 to –60m.

Large pluvial lakes also occurred in the drylands and highlands of China and Tibet, where levels were high from 40, 000 to 25, 000 BP (Li and Zhu, 2001). Similarly the interior basins of Australia, including Lake Eyre, have shown major expansions and contractions, with high stands tending to occur in interglacials (Harrison and Dodson, 1993).

As can be seen from these regional examples, pluvial lakes were widespread (even in hyper-arid areas), reached enormous dimensions, and had different histories in different areas. Pluvials were not in phase in all regions and in both hemispheres (Spaulding, 1991). In general, however, dry conditions during and just after the Late Glacial Maximum and humid conditions during part of the Early to Mid Holocene appear to have been characteristic of tropical deserts, though not of the south-west USA (Street and Grove, 1983).

Changes in effective precipitation may also be reflected in the frequency and range of floods in desert rivers and in their load:discharge ratios (see Chapter 10 for interactions between rainfall regime and fluvial landforms). In particular, in sensitive piedmont zones, marked alternations may occur between deposition and erosion. Although phases of alluvial aggradation and entrenchment may be a response to precipitation changes, they can also result from tectonism, from changes in sediment supply resulting from the operation of such temperature-controlled processes as frost-shattering, or from the inherent instability of the fan surfaces themselves.

Less contentious are the remains of river systems in areas where under present conditions flow is either very localised or non-existent. For example, great wadi systems, traced by the presence of both palaeochannels and associated coarse gravels, occur in hyper-arid areas such as the southeastern Sahara (Pachur & Kröpelin 1987, Brookes 2001).

6. Karst, carbonate precipitates and groundwater

Solution of carbonate rocks to produce karstic phenomena (e.g. cave systems) requires water, and so may give some indication of past humidity. More importantly speleothems from caves often provide a record of environmental change that can be studied by sedimentological and isotopic means. Caves are also receptacles in which aeolian, slope and river sediments can accumulate.

Caves can also preserve the remains of small rodents and insectivores, many of which are the result of deposition of regurgitated pellet material by birds. These indicate environmental conditions both through their species composition and through the size of bones, which may be related to palaeotemperature (Avery, 1982).

Also significant for environmental reconstruction are limestone precipitates that occur on the margins of limestone areas in the form of tufas. These freshwater carbonates may contain floral and faunal remains, palaeosols, etc., which provide environmental information, and the tufas themselves may be indicative of formerly active groundwater and fluvial systems (Nicoll *et al* 2001). Notable examples occur in the Naukluft of Namibia and the Kharga oasis of Egypt.

The isotopic dating of groundwater has demonstrated when it was or was not being recharged. For example, Sonntag and collaborators (1980) have indicated that only limited recharge occurred in the Sahara during the last glacial maximum (20,000 – 14,000 BP), confirming that this was a period of relative aridity. Likewise many of the aquifers of Arabia are relicts from Late Pleistocene times.

7. Other geomorphological indicators

In some arid areas there are weathering crusts and palaeosols that exist outside what are considered to be their normal formative climatic ranges, and which are out of equilibrium with the present climate. Examples are the iron-rich or silica-rich duricrusts of the southern margins of the Sahara and in arid Central Australia. The presence of extensive relict frost screes has also been seen as having climatic significance, having been produced under colder, but probably moist, conditions. These are widespread in North Africa and the Middle East.

Elsewhere, slope deposits and mass movements provide evidence of changes in precipitation (Busche, 1998). For example, slumping along the escarpments of the plateaux of Colorado has been attributed to cooler and wetter conditions which caused shales to become saturated and unstable. In the Atacama ancient debris flow deposits have been used to reconstruct the history of El Niño flood events. Likewise, in southern and central Africa, there are sheets of colluvium (slope wash deposits), which have infilled old drainage lines, and which may have formed when steep slopes behind the pediments on which the colluvium was deposited were destabilized by vegetation sparsity under arid conditions, providing more sediment supply than could be removed by pediment and throughflowing stream systems (Price-Williams *et al.* 1982).

8. Fauna and flora

Pollen analysis (palynology) provides evidence of past vegetation and (by inference), climate conditions. Care has to be taken in assessing the significance of any pollen type which is produced in large quantities and which can also be preferentially transported and deposited over large distances by wind or other mechanisms. Nonetheless, there have been some notable studies of long climatic sequences developed from pollen studies (e.g. Ritchie and Haynes, 1987). Other evidence of past vegetation conditions is provided by scanning electron microscopic study of charcoal which can enable the identification of woody plants, sometimes to the species level. Moreover, stumps of trees such as acacia and fig in the Western Desert of Egypt and Sudan indicate the presence of Savanna in what is now a hyper-arid region.

In the southwestern USA there are middens that were accumulated by pack rats – rodents of the genus *Neotama*. These contain extensive plant debris, and those sheltered in caves or overhangs may remain intact for tens of thousands of years (Madsen *et al*. 2001).

Inferences of palaeoclimate may also be drawn from faunal remains and knowledge about their modern habitat preferences. For example, the relative proportions of grazers and browsers may indicate the importance of grassland or predominantly bushy vegetation respectively (Klein 1980).

9. Archaeological and historical evidence

The changing distributions and histories of human groups have been used to infer changes in the suitability of deserts for habitation. The absence of their artefacts has been used to infer increased aridity, while their existence in hyper-arid areas has been used to infer the existence of humid conditions. Considerable care needs to be exercised in attributing the rise and fall of particular cultures to climatic stimuli of this type, given the range of other factors (e.g. warfare, social collapse) that could be important, but there are some instances where the evidence is relatively unambiguous. For example, in the hyper-arid Libyan Desert of Egypt, where the rainfall is less than 1 mm per annum, artefactual materials occur in areas which are far too dry for human habitation today (Wendorf *et al.* 1976), and are often found in association with old spring deposits, drainage lines and small lake basins.

In historical times, attempts have been made to reconstruct African climates on the basis of famine and drought chronologies, and geographical and climatic descriptions in travellers' reports and diaries (Nicholson 1996). Likewise, there are records of El Niño fluctuations dating back to the sixteenth century AD in Peru (Ortlieb, 2000).

10. The ocean core evidence

One of the most important developments in environmental reconstruction since the 1950s has been the use of ocean cores. Information derived from them can cover millions of years, and has been less fragmented than most terrestrial evidence.

Ocean floors off the world's deserts have accumulated sediments derived by aeolian and fluvial inputs from neighbouring land (Sirocko & Lange 1991). These may be susceptible to relatively accurate dating, and record the relative importance of fluvial and aeolian inputs, the degree of weathering of river-borne feldspars, the pollen and phytolith rain, the salinity of the ocean or sea, the intensity of monsoonal winds and of upwelling activity (Prell *et al.* 1980) and the temperature of offshore waters recorded by oxygen isotope ratios in foraminiferal tests.

11. The antiquity of deserts

Although formerly many deserts were regarded as a result of Holocene (post-glacial) progressive desiccation, it is now clear that many of our present deserts are old (Goudie 2002). This applies particularly in the case of the Namib and the Atacama coastal deserts. Their climatic development was closely related to plate tectonics and sea-floor spreading in that the degree of aridity must have been largely controlled by the opening up of the seaways of the Southern Ocean, the location of Antarctica with respect to the South Pole, and the development of the offshore, cold Benguela and Peruvian currents. Arid conditions appear to have existed in the Namib for some tens of millions of years, as is made evident by the Tertiary Tsondab Sandstone – a lithified sand sea (Ward 1988) that underlies the current Namib erg. Likewise the Atacama of South America appears to have been predominantly arid since at least the late Eocene, with hyper-aridity since the middle to late Miocene. The uplift of the Andes during the Oligocene and early Miocene produced a rain-shadow effect while the development of cold Antarctic bottom waters and the Peruvian current at 15-13 million years ago created another crucial ingredient for aridification (Alonso *et al*. 1999).

In India and Australia, latitudinal shifts caused by sea-floor spreading and continental drift led to moist conditions during much of the Tertiary, but they entered latitudes where conditions were more arid in the late Tertiary. Isotopic studies in the Siwalik foothills of Pakistan illustrate increasing aridity in the late Miocene, where C3/C4 analyses show a change from a C3 (mainly forested) setting to a C4 (mainly grassland) setting at about 7 million years ago (Quade *et al*. 1989). In China, Miocene uplift and a resulting transformation of the monsoonal circulation caused aridification. The aeolian red clays and loess of China may have started to form around 7.2-8.5 million years ago (Qiang *et al.* 2001). Indeed it is possible that the uplift of mountains and plateaux in Tibet and North America may have caused a more general change in precipitation in the Late Miocene, as is made evident by the great expansion of C4 grasses in many parts of the world (Pagani *et al.* 1999).

With regard to the Sahara, sediment cores from the Atlantic contain dust-derived silt that indicates that a well-developed arid area, producing dust storms, existed in North Africa in the early Miocene, around 20 million years ago (Diester-Haass & Schrader 1979). It is possible that uplift of the Tibetan Plateau played a role in this by creating a strong counter-clockwise spiral of winds that drove hot, dry air out of the interior of Asia across Arabia and northern Africa (Ruddiman 2001, p. 388).

12. Pleistocene intensification of aridity

In many regions aridity intensified in the late Pliocene and Pleistocene. It became a prominent feature of the Sahara in the late Cenozoic, partly because of ocean cooling and partly because ice cap build up created a steeper temperature gradient between the Equator and the Poles. This led to an increase in trade-wind velocities and in their ability to mobilise dust and sand. deMenocal (1995) recognised an acceleration in dust loadings in ocean cores off the Sahara and Arabia after 2.8 Ma, and attributed this to decreased sea surface temperatures associated with the initiation of extensive Northern Hemisphere glaciation. Likewise, loess deposition accelerated in China after around 2.5 Ma ago (Ding *et al.* 1992). The study of sediments from the central North Pacific suggests that dust deposition became more important in the late Tertiary, accelerating greatly between 7 and 3 Ma (Leinen & Heath 1981), but it was around 2.5 Ma ago that there occurred the most dramatic increase in dust sedimentation.

13. Fluctuations within the Pleistocene

All deserts show the impact of Pleistocene climatic changes. They expanded from time to time, covering areas that are now heavily vegetated. As a consequence stabilised sand seas occur in areas where rainfall levels are currently in excess of 500-800 mm. Stabilised sand seas occur on the south side of the Sahara between Senegal and the Sudan, while in southern Africa the Mega-Kalahari extended as far north as the Congo basin. Relict dunes also occur in parts of South America, including the Llanos in the north and the Pampas in the south. The High Plains of America also have extensive areas of stabilised dunes, the most notable examples of which are the Nebraska sandhills. In North West India the dunes of the Mega-Thar can be traced from Rajasthan southwards into Gujarat and eastwards towards Delhi (Allchin *et al*, 1978), while in

Australia large linear dunes can be found in Kimberleys of the tropical north (Goudie *et al.,* 1993). Changes in the extent of sand seas may be the result of changes in precipitation, but it is also possible that high glacial trade wind velocities played a role (Ruddiman 1997) by increasing rates of sand transport. These higher wind velocities may also have had a marked influence on deflation and dust storm activity. There is clear evidence for dust fluxes into the oceans at the time of the Last Glacial Maximum being 2 to 4 times higher than at present (Grousset *et al.* 1998). Studies have also been made of wind-transported materials (including diatoms deflated from desiccated lakes) to plot wind strength changes over extended periods (e.g. Shi *et al.* 2001).

Conversely, at other times, as we have seen, large, freshwater lakes occupied the Altiplano basins of South America, the many depressions of the Basin and Range Province in the USA (notably Lahontan and Bonneville), the Aral-Caspian of Central Asia, the Chad-Bodélé depression in the Sahara, the Dead Sea in the Middle East and the Lake Eyre basin in Australia. Even in the hyper-arid heart of the Sahara and the Libyan deserts there are lake deposits, tufas, old drainage lines and other evidence of enhanced hydrological activity.

14. The Frequency of climatic change

In addition to being severe, Quaternary climatic changes in deserts were frequent. Dunes were repeatedly reactivated and stabilised, both in the Pleistocene and the Holocene, lakes rose and fell over short spans of time, and pulses of dust were deposited in the world's oceans. The frequency of change is indicated by high-resolution studies of ocean and lake cores and because of the increasing availability of high-resolution optical and thermal luminescence dates for dune sands and loess. The multiple glaciations and deglaciations of high latitudes, and the multiple fluctuations within them, all indicate the instability of Quaternary climates. They were all associated with major changes in the oceans, pressure systems and wind belts which in turn had an impact on deserts. Lake level fluctuations in arid basins may indicate short-lived fluctuations that correlate with Heinrich events (Benson *et al*. 1998) and Dansgaard-Oescheger cycles (Lin *et al.* 1998), while the Younger Dryas also seems to have its counterparts in arid regions (e.g. Zhou *et al*. 2001).

15. The context of change

Pluvials were neither in phase in all areas nor in both hemispheres (Spaulding 1991). In a mid-latitude location like the south-west of the USA (Smith and Street-Perrott, 1983), there was greatly increased effective moisture at the time of the Last Glacial Maximum, eighteen to twenty thousand years ago. This was partly caused by decreased evaporation, but also by an intensified zonal circulation and the equatorward displacement of mid-latitude westerlies and associated rain-bearing depressions, particularly in winter.

The tropics were much less influenced by the displaced full glacial westerlies. They experienced relatively dry conditions at that time, but subsequently experienced a major pluvial in the early to mid-Holocene (Grove and Goudie 1971). Under warmer Holocene conditions, monsoonal circulation was intensified, and in the Northern Hemisphere the Intertropical Convergence Zone would have shifted north, bringing rainfall into areas like West Africa, the Sudan, Ethiopia, Arabia and the Thar. The basis for this may have been increased summer solar insolation associated with the 23,000 year rhythm of orbital precession, for at around 9000 years BP Milankovitch-forcing led to Northern Hemisphere summers with almost 8 per cent more insolation than today (Kutzbach and Street-Perrott 1985). Higher insolation caused greater heating of the land, stronger convection, more inflow of moist air and a higher summer monsoonal rainfall. In contrast, weaker insolation maxima around 35,000 and 60,000 years ago would have created weaker monsoons (Ruddiman 2001).

Changes in insolation receipts at 9000 BP can help to explain the Northern Hemisphere low latitude pluvial, but they have less direct relevance to the Southern Hemisphere (Tyson and Preston-Whyte 2000). Also important in determining the spatial and temporal patterning of precipitation change are sea surface temperature conditions associated with the build-up and disintegration of the great ice-sheets (Shi *et al*. 2000; Rognon and Coudé-Gaussen 1996). In addition, changes in snow and ice cover over Asia, including Tibet and the Himalayas, could have had a major effect on the monsoon (Zonneveld *et al*. 1997).

The Holocene experienced abrupt and relatively brief climatic episodes, which caused dune mobilization in the American High Plains (Arbogast 1996) and alternations of pluvials and intense arid phases in tropical Africa. The Holocene in low latitudes was far from stable and it is possible that a climatic deterioration around 4,000 years ago could be involved in the near simultaneous collapse or eclipse of civilizations in Egypt, Mesopotamia, and Northwest India (Dalfes *et al*. 1997).

These brief events cannot be readily accounted for by orbital changes, so other mechanisms need to be considered, including changes in the thermohaline circulation in the oceans, or in land surface conditions (Gasse and van Campo 1994). Certainly the mechanisms causing changes in atmospheric circulation would have been both numerous and complex, and there will have been lagged responses (e.g. slow decay of ice-masses, gradual falls of groundwater, etc.). It is also apparent that there will have been differing hemispheric and regional responses to change (deMenocal and Rind 1993). For example, Arabia and Northeast Africa may have been especially sensitive to changes in North Atlantic sea surface temperatures, while monsoonal Asia have been especially affected by snow and ice conditions in the Himalayas and Tibetan Plateau.

16. Recent change

At the present day, deserts continue to change, sometimes as a result of climatic fluctuations like the run of droughts that has afflicted the West African Sahel over recent decades (see Chapter 6). The changing vegetation conditions in the Sahel, which have shown marked fluctuations since the mid- 1960s, have been mapped by Tucker *et al.* (1991). Interannual variability in the position of the southern boundary of the Sahara, as represented by the 200 mm isohyet, can be explained in large measure by changes in the North Atlantic Oscillation and the El Niño Southern Oscillation (ENSO) (Oba *et al* 2001). The drought also led to reductions in the flow of rivers like the Senegal and Niger, and to an increase in dust storm activity (Middleton, 1985). The extent of Lake Chad's water surface has also fluctuated dramatically (Nicholson 1996). It was particularly badly affected by the drought, which caused the lake surface area to fall from *c.* 25,000 km^2 in 1960 to just a tenth of that figure in the mid-1980s (Birkett, 2000).

We also know from recent centuries that ENSO fluctuations have had important consequences for such phenomena as droughts and dune reactivation (Forman *et al*. 2001), and through their effect on vegetation cover have had major impacts on slope stability and soil erosion (Viles and Goudie, 2003). Lake levels have responded to El Niño influences (Arpe *et* al. 1997), large floods have occurred, valleys have been trenched (Bull 1997), erosivity patterns have altered (D'Odorico *et* al. 2001), and landslides and debris flows have been generated (Grosjean *et al.* 1997). To that we need to add the increasing numbers of changes being wrought by human agency, changes that are often categorized as 'desertification' (Chapter 18): surface degradation, gully formation, ground subsidence, salinisation, bush encroachment and the like (Middleton and Thomas, 1997). In the future, global warming may increase the aridity of many drylands, leading to further geomorphological changes and placing further pressures on hydrological resources.

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