ABSTRACT During the last 20,000 years, the mountains of Africa between the Mediterranean and the equator have experienced significant climatic changes with important consequences for the vegetation and resource potential. At about 18,000 B. P. present altitudinal belts were depressed and the zonation of climate and vegetation was changed considerably. In the Holocene, higher temperatures led not only to more humid conditions but also to an uplifting of altitudinal belts and transformation of climatic and ecological zones and to increased natural resource potential. These changes in climate, vegetation, and altitudinal zonation are illustrated in a series of schematic diagrams.

The cumulative effects of natural and anthropogenic processes and impacts within the last 2,000 years are also depicted. In particular, human impact on ecosystems formed under more favorable climatic conditions could result in irreversible degradation. The mountains of the sub tropics and tropics very often have more advantageous ecological conditions than the surrounding lowlands. They are an important resource potential for the future, although they may be very sensitive to climatic and anthropogenic changes.

RESUME Climat, modifications de l'environnement et ressources dans les montagnes africaines, de la Mediterranee a l'equateur. Au cours des 20,000 dernieres annees, les montagnes africaines situees entre la Mediterranee et l'equateur ont ete soumises a des changements climatiques considerables qui ont eu des consequences importantes pour la vegetations et les ressources potentielles.

Il y a environ 18,000 ans, les ceintures altitudinales actuelles etaient affaissees et la zonation du climat et de la vegetations a change considerablement. Pendant l'Holocene, les temperatures plus elevees ont non seulement entraine une plus haute humidite, mais aussi une elevation des ceintures altitudinales et une transformation des zones climatiques et ecologiques, ainsi qu'une augmentation des ressources naturelles potentielles. Ces changements de climat, de vegetation et de zonation altitudinale sont illustres au moyen d'une serie de diagrammes schemas.

Les effets cumulatifs des processus naturels et anthropogeniques, ainsi que ceux des impacts au cours des 2,000 dernieres annees, sont egalement decrits. En particulier, l'impact humain sur les ecosystemes formes dans des conditions climatiques plus favorables peut entrainer une degradation irreversibler. Les montagnes des subtropiques et des tropiques jouissent tres souvent de conditions ecologiques plus advantageuses que les basses terres avoisinantes. Elles constituent des ressources potentielles importantes pour le futur, bien qu'elles soient probablement tres sensibles aux changements climatiques et anthropogeniques.

ZUSAMMENFASSUNG Klima, Umweltveranderungen und Ressourcen in den afrikanischen Bergen zwischen Mittelmeer und Aquator. Die Gebirge Afrikas zwischen Mittelmeer und Aquator waren in den letzten 20,000 Jahren bedeutenden Klimaveranderungen unterworfen, die sich auf die Vegetation und die gesamten natuerlichen Ressourcen entscheidend ausgewirkt haben.

Die heutigen Hohenstufen waren um 18,000 B. P. bedeutend tiefer und auch die zonale Ordnung von Klima und Vegetation war vollig verandert. Im Holozan erfolgte mit zunehmender Erwarming ein Wechsel zu feuchteren Bedingungen, die ein Ansteigen der Hohenstufen und eine grossraumige Veranderung der Klima- und Vegetationszonen und dementsprechend den gesamten natuerlichen Ressourcen bewirkte.

In den letzten 2,000 Jahren begannen sich natuerliche und anthropogene Prozesse zu uberlagern und sehr oft auch zu verstarken. Wurden dazu noch Ecosysteme genutzt, die unter gunstigeren Klimaveranderungen standen waren, so konnte das zu irreversiblen Degradationsprozessen fuhren.

Die Gebirge in subtropischen und tropischen Zonen weisen sehr oft gunstigere okologische Bedingungen auf als die umgebenden Tieflander, doch wird dieses fur die Zukunft wichtige Nutzungspotential auf Klimaveranderungen sehr empfindlich reagieren.
INTRODUCTION

Since we began our fieldwork in the African mountains and highlands about 30 years ago, our research objectives and approaches have changed considerably, reflecting our changing attitudes towards the increasing problems of “man and environment.” Earlier climatic and geomorphologic studies have been extended to embrace resource assessment and have been incorporated into integrated research programs that include resource management (e.g., Winiger 1986; Hurni 1988).

Figure 1 shows the main mountain systems included in our research programs, spanning a latitudinal range from the Mediterranean coast with a winter rain climate, over the “islands” of the extreme arid zone, to the tropical mountains with summer rain or even an equatorial humid climate. Our aim was to understand the dynamic changes of the different altitudinal belts, and to integrate the time factor into a three-dimensional view of spatial variations of climatological and ecological conditions.

Over the last 20,000 years, the earth has experienced extremes of cold and warmth as well as periods of marked aridity and humidity. These extreme values during recent geological time may be keys to understanding past and present circulation patterns and may eventually facilitate evaluation of the consequences of future climatic oscillations or climate change. It is not only the middle and higher latitudes with extensive glaciations in the past that have experienced environmental changes; tropical and subtropical regions, particularly in Africa, have also been affected. The result has been extensive and repeated fluctuations in environmental conditions and consequently in resource availability. Only during recent decades have we become aware of the sensitivity of tropical and subtropical ecosystems and of climatic oscillations that occur within very short time periods over wide areas. Such changes have had disastrous consequences for both people and environment. As we approach a new century that may be characterized by continuing population growth and more intensive use of resources, the question of climate change becomes increasingly important, certainly for Africa. Consequently, the growing pressure on resources will increase the vulnerability of the natural and human systems. In this respect mountains play a very special role (Grosjean and Messerli, 1988).

Mountain areas on the southern Mediterranean coast, in arid and humid tropical zones, are climatological and ecological islands with favorable conditions and resources, that differ remarkably from the surrounding lowlands. But very often they are too peripheral, too inaccessible, and too far away from economic and political centers. Their resources are not recognized; the land-use practices suffer from population pressure, and the resources (e.g., water, timber, and agricultural products) are often exploited for distant urban areas with little benefit for the mountain populations. Moreover, it is too often forgotten that mountain ecosystems are very sensitive, not only to overuse of land and resources but also to climatic and environmental changes. In this sense, anthropogenic and natural influences and processes can have cumulative effects, as has occurred in the past and may occur in the future.

Figure 1. Africa showing location of fieldwork and excursions directed by the Geographical Institute of Berne University.
Excursions: Atakor, Air, Mt. Cameroon, Kilimanjaro, Sinai.

Source: GRID/UNEP
Figure 2. The African mountains from the Mediterranean coast to the equator showing horizontal and vertical zonation at present and in the late Pleistocene at the time of the last glaciation.
Vertical and Horizontal Zones of Climatic and Ecological Conditions

Most attempts to divide Africa into climatic zones lead to the conclusion that the different zones are arranged in an almost ideal meridional sequence. However, even conditions in the mountains that border the Mediterranean differ significantly from the Atlas in the west to the Sinai in the east, and contrasts between the Saharan uplands and the highlands of East Africa are fundamental. The mountains of the Sahara are located within a vast area of more or less uniform climate, whereas the Atlas system and the East African mountains act as discrete climatic systems. The consequences are obvious. The climatic variations within the Saharan mountains depend primarily upon elevation, whereas the climate of the Atlas and the East African uplands is determined by aspect as well as elevation (Messerli and Winiger, 1980).

The upper part of Figure 2 is a schematic and simplified diagram of the present altitudinal belts illustrating climatic and ecological factors with emphasis on glacial, periglacial, and fluvial processes. Not included are some well investigated and important mountain systems, such as Jebel Marra (3,042 m) in the Sudan (Menschling, 1978; Babiker, 1988) and Mt. Cameroon (4,095 m) in West Africa (Messerli and Baumgartner, 1978). From our own observations, a comparison is presented, based mainly on a profile from the northwest (Atlas) to the southeast (Mt. Kenya) that excludes the Sinai. Mt. Cameroon is not included since it is a very young volcano that has been active as recently as 1975. There, soil temperature, periglacial processes, and treelines are disturbed by volcanic activity and heat flows in the subsurface. As a consequence, these factors may not reflect the real climatic conditions. In addition, a reconstruction of past climate (upper Pleistocene and Holocene) is impossible due to the recent age of the volcano, although its location in the extremely humid west coast of Africa would otherwise give it significance for studies of climatic history.

The 0° C isotherms of the warmest and coldest month in the free atmosphere (Figure 2) show the climatic differentiation from a thermally seasonal climate in the north to a diurnal climate in the south. In the equatorial tropics (0°–10° N and S) the two isotherms are no more than 300 m apart at any time of the year, and this produces very sharp boundaries between the different geocological belts. A few degrees further north, the seasonal temperature difference becomes more evident, for instance, in the Simen mountains; of particular interest is the thermal differentiation of Tibesti and Hoggar. Although separated by only 2–4° of latitude, they display a great meridional temperature gradient with a strong seasonal reversal of trend. In winter the 0° isotherm in the Tibesti is 600–800 m higher, and in summer 200–400 m lower than in the Hoggar. Furthermore, the mountains north of the Sahara, independent of the precipitation regime, have a typical Mediterranean differentiation between winter and summer seasons. Of course, temperature values of the free atmosphere are only to a limited extent comparable with those of ground-based meteorological stations. In particular, daily fluctuations of surface temperatures are pronounced and valleys experience nocturnal inversions that exert a major control over frost occurrence and plant limits.

Equally critical is whether or not frost occurs during the dry or wet season. In the Mediterranean mountains, cold and wet periods occur simultaneously. The Hoggar and the Tibesti form a transition zone, where the frequent precipitation coincides only occasionally with frost conditions. In the high mountains of Ethiopia, which experience marked diurnal temperature changes, frost is common and effective above 4,000–4,200 m in the Simen and Bale mountains. Needle ice, which is virtually unknown in the Saharan uplands due to lack of soil moisture, is found at elevations down to 3,300–3,800 m every season, and also on Mt. Kenya (for more details, see Messerli and Winiger, 1980). The mean minimum 0° C isotherm of the coldest month in Figure 2 designates the altitude of these frost effects, especially for the tropical and Mediterranean mountains (see also Figure 6). Figure 2 also shows the precipitation occurrence which is quite infrequent and unreliable for the higher elevations. In the Atlas, precipitation increases probably to 1,000 mm or more in the summit area. But aspect is important, as shown by rainfall values of 100–300 mm in the Saharan piedmont and 300–600 mm in the Mediterranean foothills and lowlands. The lowlands surrounding the Hoggar and Tibesti receive an annual precipitation of less than 100 mm but it is two-to-three times more in the summit area. Long-range observation of the Hoggar (Dubief, 1963) shows a zone of maximum rainfall between 2,300 and 2,700 m. Rainfall distribution in the Ethiopian highlands is more complex: two maxima at 1,800 and 3,600 m can be observed in the Simen mountains. Mt. Kenya receives its maximum precipitation at an elevation of about 3,000 m, varying greatly according to aspect, with maxima on the western and southeastern flanks (Winiger, 1981).

Vegetation associations and their boundaries are closely related to annual and seasonal fluctuations in temperature, precipitation, and evapotranspiration. Mountain areas are ecological islands and differ markedly from the surrounding lowlands. Figure 3 is a schematic attempt to illustrate vertical and horizontal vegetation zones from the Mediterranean to the equator, although comparisons between different floristic regions are problematic. Likewise, comparisons between timberline and treeline involve comparisons between quite different species, such as Quercus and Juniperus in the High Atlas (Figure 4), Olea laterrini in the Hoggar, and Erica arborea in Ethiopia and Kenya. Despite these difficulties, there have been a number of fruitful attempts to relate vegetation to climate, both in the mountains of the wet tropics (Troll, 1959; Lauer, 1975) and in the central Saharan uplands (Quezel, 1965).

Lauer and Frankenber (1979) tried to determine the absolute number of plant species of the western Sahara, from the Atlas to the Sahel. They counted the number
Figure 3. The African mountains from the Mediterranean to the equator showing vegetation belts (Messerli and Winiger, 1980).

**High Atlas**
1. Thorny vegetation
2. *Juniperus* scrubs and woodlands
3. *Quercus ilex* forests
4. Dry woods
5. Steppe vegetation

**Sinai**
1. Upper montane desert steppe (*Artemisia*)
2. Lower montane steppe (*Phlomis*, olive trees, *Cupressus*)
3. Montane desert savanna (*Tamarix*)
4. Desert steppe (*Acacia*)

**Hoggar**
1. Upper montane desert steppe (*Artemisia*)
2. Lower montane desert steppe (*Artemisia, Lavandula, Olea lap.*)
3. Montane desert savanna (*Tamarix*)
4. Scrub/tree steppe/savanna (*Panicum, Cassia, Acacia, Tamarix*)

**Tibesti**
1. Upper montane desert steppe (*Artemisia, Erica arb.*)
2. Lower montane desert steppe (*Aristida, Linaria*)
3. Desert steppe vegetation (single *Acacia, Tamarix*)
4. Montane savanna (*Acacia, Cassia, Panicum*)
5. Tree savanna (*Acacia, Cassia, Panicum*)

**Simen**
1. Afro-alpine grassland, pasture (*Lobelia, Helichrysum*)
2. Montane forests (*Erica arb., Hypericum*)
3. Tall savanna forest
4. Dry savanna zone, *Combretum* woodlands (*Adansonia* below 1,000 m)

**Bale**
1. Alpine belt (*Lobelia, Senecio, Alchemilla*)
2. *Erica* scrub (*Erica arb., Helichrysum*)
3. *Hagenia-Hypericum* woods
4. Bamboo zone
5. Montane rainforest
6. *Juniperus* woods (with *Podocarpus* in lower areas)

**Mt. Kenya**
1. Alpine belt (tussock grassland, *Lobelia, Senecio, Helichrysum*)
2. *Erica* belt (*Erica arb., Helichrysum*)
3. *Hagenia-Hypericum* forest
4. Bamboo zone
5. Montane rainforest (*Juniperus, Olea, Podocarpus*)
6. Savanna
of species in grids 80 km x 80 km on a side with a surface of 6,400 km², based on floristic lists. As a rough estimate, 1 species corresponds to a biomass production of 1 gm/m²/year (Lieth, 1974; Frankenberg, 1979) and a ground cover of 1 percent (leaf/area index). On this basis, a map of species variety indicates not only biomass production but also the total surface area covered by plants.

Figure 5 shows the present spatial distribution of species. The vast sand deserts have less than 21 species per unit; the average is 10, the minimum 3-5. The mountains are of special interest. The Atlas system is comparatively rich, with more than 200 species per unit. Surprisingly, the Hoggar, the Tassili, and the Air have the same number. Compared with the mountain areas, the Sahel is much poorer. This well illustrates the higher natural potential of the mountains and, especially in arid zones, their important functions as biological reserves between the Mediterranean and the tropical floristic region, even in cases of climatic change (see Figures 11 and 16 below).

Figure 6 presents a schematic synthesis of the climatic control over ecological and geomorphic processes. The results of this model may be summarized as follows: given sufficient precipitation, soil moisture, and relatively few frost cycles, a dense plant canopy will cover the ground. Erosion by freeze-thaw processes and by running water is minimized except perhaps along the streams, valleys, and very steep slopes. If vegetation is destroyed and replaced by an unadapted land-use system, then geomorphic instability and hazards supervene. Erosion might then become effective, with running water as the dominant agent in arid areas and freeze-thaw processes in humid high areas. In the upper elevations of the arid mountains thermal readiness for frost processes exists but does not become effective due to the lack of moisture (Messerli, 1973). High mountains usually comprise several ecological and morphodynamic zones. These are arranged vertically in regions of certain homogeneous climatic conditions (e.g., in the Hoggar), but in climatically transitional areas differences related to aspect may modify the altitudinal belts, as in the High Atlas and in the Ethiopian mountains. Finally, it is important that this model is viewed not in a static but in a dynamic way. Even minor changes of humidity and temperature influence this system and adjustment of the boundaries vertically and horizontally is followed by a gradual adaptation to the ecological and geomorphic conditions and processes. Of course, this model is not yet adequate and much basic research is still needed in order to understand in a more precise way the functioning and dynamics of mountain ecosystems (see Figure 21 below).

CLIMATE CHANGE AND ENVIRONMENTAL CONDITIONS FROM THE LAST ICE AGE TO THE PRESENT

THE LAST COLD MAXIMUM

There are a great number of multidisciplinary field studies, publications, and paleoclimatological interpretations on this topic, summarized for example in Rognon and Williams, (1977), Nicholson and Flohn (1980), Messerli and Winiger (1980), and Petit-Maire and Jamet (1989). In this paper we present an overview in time and space. Figure 2 provides a synthesis of this climatic and environmental change.

Glaciers and periglacial processes

In the Atlas system, no glaciers exist today, although there was an extensive glaciation in the past. In the massif of the Toubkal, which includes the highest summit of the Atlas, we assume the former existence of a 5-km long glacier, extending to 2,600-2,700 m. Periglacial processes were active even below 2,000 m (Menschling, 1953). There are indications of frost activity at altitudes as low as 1,000 m in Morocco, and even lower on the Mediterranean coast; for instance, frost occurred on the Cyrenaica of Libya until 12,000 B.P. (Hey, 1963; Couvreur, 1965; Coque, 1969). In the mountains of the Sahara nivation and periglacial features are found even below 2,000 m.
FIGURE 5. Present distribution of the absolute number of species in the western Sahara (compare with Figures 11 and 15; from Lauer and Frankenberg, 1979.
Number of species found in areas of 6,400 km²:
1. >160 2. 81-160 3. 41-80 4. 21-40 5. < 21

(Figure 7). Frost weathering and resultant debris transport occur in the Hoggar at heights of 1,100-1,400 m (Rognon, 1967), and in the Tibesti above about 1,800 m (Messerli, 1972). Rock glaciers can be observed in the Hoggar and in the Tibesti above 2,000 m, indicating very intense frost activity, perhaps even permafrost. Three conclusions emerge: first, the low-altitude periglacial processes, and especially the rock glaciers, indicate a distinct change of climate and environment. We assume there was a strong depression of the winter temperature, probably more than 10°C, caused by a seasonal southward shift of polar air masses, and this brought the necessary humidity especially to these mountain areas. The summer temperatures, with a depression of 6-8°C, were much more influenced by relatively dry conditions. This seasonal differentiation of the mean altitudes of the isothermal lines can be seen in the lower section in Figure 2. Second, it is important to differentiate the seasonal climatic conditions to explain these processes and their paleoclimatological and meteorological interpretation. Third, the differing heights of periglacial features in the Hoggar and Tibesti point to significant variation between the two massifs; Figure 2 demonstrates how the isotherms rise from the Hoggar to Tibesti towards the tropical and diurnal temperature regime of the Ethiopian mountains.

In the Ethiopian highlands we find a completely different situation, with a progressive increase in the extent of glaciation from very small ice caps in the north (Hurni, 1989) to extensive glacier-covered plateaus in the south (Messerli et al., 1977). In the Simen Mountains the lowest glacier may have descended to 3,760 m, and most terminal moraines ended between 4,000 and 4,200 m (Figure 8). In the Bale Mountains, valley glaciers 10 km long ended between 3,100 and 3,200 m and the area covered by ice exceeded 600 km². The lower limit of periglacial activities in the Simen Mountains may have been between 3,000 and 3,500 m, and in the Bale Mountains 3,000 m, or even lower. The lower periglacial limits in the Sahara are 1,000 m lower than in Ethiopia and this relates to the shift from a seasonal to a diurnal climate. Also, for this reason, Jebel Marra (3,042 m), at
Vegetation cover and dominant morphodynamic processes

- Vegetation cover <50%
  - Frost activity = dominant morph. proc.

- Vegetation cover >50%
  - Water erosion (areal and linear) = dominant morph. proc.

Figure 6. Limiting climatic parameters for vegetation cover and morphodynamic processes in African high mountains (Messerli and Winiger, 1980).

SN1 Sierra Nevada (Monachil 1,000 m)
SN2 Sierra Nevada (Mulhacen 3,478 m)
A1 High Atlas (Amizmiz 1,000 m)
A2 High Atlas (Ouarzazate 1,135 m)
A3 High Atlas (Toubkal 4,165 m)
S11 Sinai (Elat Mo)
S12 Sinai (Mt. Catherine 2,621 m)
H1 Hoggar (Tamanrasset 1,376 m)
H2 Hoggar (Assekram 2,706 m)
T1 Tibesti (Bardai 1,020 m)
T2 Tibesti (Trou au Natron 2,706 m)
S1 Simen (Debarek 2,860 m)
S2 Simen (Geech Camp 3,600 m)
S3 Simen (Ras Dashan 4,620 m)
B1 Bale (Goab 2,740 m)
B2 Bale (Dinshu 3,200 m)
B3 Bale (Tullu Dimtu 4,450 m)
B4 Bale (Rira valley below 3,000 m)
K1 Mt. Kenya (Nanyuki 1,945 m)
K2 Mt. Kenya (Met. station 3,048 m)
K3 Mt. Kenya (Top hut 4,770 m)

Latitude approximately 13° North, the same as the Simen Mountains, has neither recent nor fossil periglacial features (Mensching, 1982).

The glaciation of the high mountains of East Africa, is characterized by great differences between Ruwenzori, Mt. Kenya (Figure 9), and Kilimanjaro. The terminal moraines on Mt. Kenya are found as low as 3,100 m (Mahaney, 1989), while those on Kilimanjaro are much higher, lying between 3,500 and 3,600 m (Messerli and Winiger, 1980). Periglacial processes on Mt. Kenya had a lower limit similar to that of the Bale Mountains, showing again that the Bale Mountains and Mt. Kenya had rather similar climatic conditions during the last Ice Age. It is interesting to note that the retreat of the glaciers at the end of the cold phase could be dated at several places in the East African mountains at about 14,000 B.P., absolutely comparable to the Würm-Weichselian of Europe (Zinderen Bakker, 1969).

A comparison of the dominant periglacial processes of the last cold period (frost activity and weathering, solifluction, rock glaciers) with those for which data are available from the Alps to the mountains of the tropics, is illustrated in Figure 10; this indicates that periglacial processes are no longer active in the Saharan uplands. This is not due to the present temperature regime (Messerli, 1972, 1979) but to the lack of a necessary moisture supply. If moisture were increased at the same time as temperature decreased, as was the case during the last Ice Age, two effects would ensue: the present belt of freeze-thaw activity would become more active and its lower limit would be lowered following the drop in temperature. Thus, the response of desert mountains to colder and wetter conditions differs from that of the mountains on both margins of the Sahara. It is significant that all the mountains, even those in northern Africa, experienced fundamental changes in their ecosystems: their vegetation and forest belts were lowered by 1,000 m or more.

The Ecological Conditions

Figure 2 is a very theoretical reconstruction of an upper timberline for this last cold period. There are a few indications from pollen analysis from Mt. Kenya, for
FIGURE 7. The northern Tibesti, central Sahara, on the eastern side of Mouskorbe (3,376 m). Nivation occurs at 3,200 m with debris from the upper slopes.

FIGURE 8. Ras Dashan, (4,620 m), the highest mountain in the Simen massif of Ethiopia, with a very large moraine on the northwest-facing slopes at 4,000 m.

FIGURE 9. Mount Kenya (5,199 m); view from the Lewis Glacier at 4,800 m to the U-shaped Teleki Valley floor at 4,000 m.
At present: lower limit of free solifluction

Last Glacial Period (cool-humid optimum): lower limit of periglacial processes

**FIGURE 10.** The lower limit of periglacial processes at present and in the late Pleistocene (the last glaciation).

Example, showing that the area around Sacred Lake at 2,400 m supported *Artemisia* and an open vegetation until 10,600 B.P., whereas today there is humid montane forest (Coetzee, 1964; Zinderen Bakker, 1969). This depression of the upper timberline and all vegetation belts by about 1,000-1,100 m, similar to the lowering of the periglacial belt and the equilibrium line of the glaciers, is evidence of a temperature depression of 6–8° C, eventually combined with increasing aridity. This is a rather conservative estimate and takes into account the difficulties in determining a gradient which depends on the assumed humidity.

Lauer and Frankenberg (1979) used a model based on the reconstruction of the climate of 18,000 B.P. and the relationship between the present vegetation and the climate to calculate the vegetation cover of the last cold maximum (Figure 11). Even if this period were dry, a slight increase of humidity and a 30 percent reduction of the potential evapotranspiration due to the temperature depression can be assumed and this modified the vegetation cover and the number of species compared with today. The Atlas Mountains and the northern part of the Sahara have a higher number of species per unit area and, accordingly, the biomass and the vegetation cover are somewhat higher. This implies that the mountain areas below the periglacial belt played a very important role in the survival and preservation of the plant species and vegetation in general.

**The Lowlands and Plains**

The southern Sahara and the Sahel from Mauritania to the Sudan were extremely arid (Figure 12). The precipitation was less than today and sand dunes covered an area that extended further south almost to the latitude of Djamena and Niamey. The zone of the rainforest was reduced; in its place was a continuous open savanna vegetation that included both the northern and southern hemispheres of Africa. For instance, in northeastern Zaire, where rainforest exists today, pollen analysis indicates that open grassland existed before 14,000 B.P. (Brook, 1989). Lake sediments in the present-day humid tropics also show very arid conditions (Rognon and Williams, 1977; Messerli, 1980a; Nicholson and Flohn, 1980). Figure 12 shows the fundamental change of climatological and, as a consequence, of ecological conditions throughout Africa during the last 18,000 years. A tropical aridity which severely affected biomass production is partly synchronous with the glaciation of the northern hemisphere which reached a maximum between about 20,000 and 14,000 B.P.

**THE HUMID PHASES OF THE HOLOCENE**

At this time, new elements appear, including lakes with sediments that can be dated, a denser vegetation reflected in pollen analysis, terraces as the result of different fluvial processes, and various types of soils in different altitudes and climatic zones (Figures 13 and 14).

From about 12,000 to 10,000 B.P. climatic conditions changed rapidly and there were evident differences between the Mediterranean region and the tropical highlands and lowlands. In the mountains of the Sahara, reinforced fluvial processes occurred after 16,000 B.P.; in the Middle Atlas Mountains the first scattered evergreen oaks were established by 14,000 B.P. (Lamb et al., 1989),
while in other areas of North Africa more arid conditions prevailed until the beginning of the Holocene.

For northern Africa some contradictions still exist. On the one hand, there are indications of dry conditions, such as deflation, and dune formation, proving that limited runoff occurred before 6,000 B.P. On the other hand, after 8,500 B.P. forests of oak trees, Junipers, and other species existed in the Middle Atlas (Lamb et al., 1989). Many Caspian civilization sites have been found in eastern Algeria and southern Tunisia and also along the Atlantic coast from Morocco southwards to 19° N, where Neolithic man had settled prior to 10,000 B.P. and remained throughout the Holocene until 2,000 B.P. with an optimum between 3,000-4,000 B.P. (Nicholson and Flohn, 1980; Petit-Maire, 1987). In the mountains of the Sahara, from the Hoggar, the Tassili, and the Air, to the Tibesti, lacustrine sediments and paleosols of this period can be found up to the highest elevations (Figure 15). From the high plateaus and summit region of the Tibesti radiocarbon dates of 8,500 B.P. have been derived for lake sediments and 6,600 B.P. for paleosols. This must have been a morphodynamically stable episode with deposition of finer-grained and well-sorted alluvium, indicative of a denser vegetation cover with soil formation where today extremely arid conditions can be found (Messerli, 1972).

In the mountains of northern Ethiopia a deep andosol is found, covering periglacial horizons. Quite stable conditions were necessary for its formation, with a steady, sufficient supply of moisture (Frei, 1978; Hurni and Staehli, 1982). In the mountains of the equatorial zone also, more humid conditions, with corresponding vegetation, are indicated from pollen analysis (Livingstone, 1975).

The Ecological Conditions

Figure 16 shows the vegetation at 5,500 B.P. (Lauer and Frankenberg, 1979). Morocco, Algeria, and Tunisia were completely outside the floristic region of the Sahara. It must be assumed that the mountains of the central Sahara had a Mediterranean type of vegetation in their upper belts. The relicts of *Cupressus depreziana* in the Tassili Ajjer and the endemic species such as *Olea laperrini* in the Hoggar and Air are present-day proof of this. In the Tassili Ajjer at about 1,600-1,800 m we found a most impressive cypress with a circumference of 9.4 m and a

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**Figure 11.** The distribution of the absolute number of species in the western Sahara at about 18,000 B.P.; from Lauer and Frankenberg, 1979. Number of species found in areas of 6,400 km²

1. > 300  2. 161-300  3. 81-160  4. 41-80  5. 21-40  6. < 21
Present-day circulation patterns

Circulation patterns 8000 BP

Circulation patterns 18'000 BP

FIGURE 12. Climate change and circulation patterns since 18,000 B.P.; from Messerli, 1980 a.
FIGURE 13. Sinai, Djebel Catherina (2,642 m) with a small church at the summit. The profile in the foreground shows deposits below the desert surface, formed by rare occurrences of sheet flood erosion (about 10 days with over 0.1 mm of precipitation and an annual mean of less than 100 mm). The dark soil horizon was most probably formed during more humid conditions in the Holocene; this is similar to the paleosols in the Hoggar and Tibesti.

FIGURE 14. Tassili Ajjer, Ouadi Tamrit. Cupressus dupreziana, an endemic species of the Tassili and in the past also of the Hoggar; about 150 isolated trees remain today at an altitude of 1,600-1,800 m; they occur in the sandy alluvium of small rivers.

FIGURE 15. Tibesti, central Sahara. Air photograph from Emi Koussi (3,415 m), the highest mountain of the Sahara. View from west to east over the caldera (diameter 10-12 km) with the highest point on the right-hand side, in the southernmost part. The younger crater, Era Kohor, is 300-500 m deep and has a salt lake in the center. Lake sediments with diatomites in the bottom of the caldera provide evidence of the more humid conditions of the Holocene. Published with permission of the IGN Paris, Nr. 4007.
height of 18–20 m (Figure 14). A much younger tree with a circumference of 2.4 m was cut 1.5 m above the ground and the core of the stem was sampled: the central 10 cm gave a $^{14}$C age of 1,640 ± 80 B.P. (Messerli and Kienholz, 1974). In the caves of the Tassili, sediments with pollen content that corresponds to cultural developments and rock paintings were dated prior to 3,000 B.P. (Delibrias et al., 1957). Cypresses grew in the late Holocene from Mediterranean Tunisia to the region north of Chad and Niger where, due to increasing aridity, they died out and survived only in river beds at higher altitudes, such as in the Tassili Ajjer.

The tropical savanna vegetation extended northwards, where *Acacia radiana*, for example, occurs on the steppes of southern Morocco and Tunisia. Figure 16 shows, together with the absolute number of species, the fundamental changes occurring, especially in the southern part of the arid zone, where the dominating humid air masses originated (Figure 12). Of special significance is the richness of species in the mountains where orographic factors provided increased humidity. Whether the central western Sahara was so arid is still an open question and depends on the time period. For instance, in northern Mali, between 22° and 23° North, where today the annual average precipitation is 5 mm and evaporation rates are among the highest (4,000 mm), a series of paleolakes was discovered and radiocarbon-dated. The following scheme was established: beginning of the humid phase 8,800 B.P.; climatic optimum 8,300–6,700; change after 6,700, with lowering lake levels and increasing salinity and lakes drying up after 4,500, with the last brackish water recorded at 4,000 B.P. These processes must be due to important local precipitation effects (Petit-Maire, 1987) showing clearly that even this central part experienced significant changes of climate and vegetation cover.

**The Lowlands and Plains**

A first humid phase reached a maximum between 9,000 and 8,000 B.P. Particularly in the equatorial region and in the southern Sahara there are indications of very many high level lakes: lakes Victoria and Turkana had
overflows to the Nile, Lake Chad covered today’s extremely arid deserts and drained into the Benue Niger, and even the lakes in the Kenyan and Tanzanian Rift Valley system had very high levels. A second humidity maximum probably occurred between 6,000 and 5,000 B.P. and a last very weak one at 3,000–2,000 B.P. The available data contain uncertainties and contradictions due to variations in space and time, and there are difficulties of data interpretation. For these reasons, they will not be dis-

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**FIGURE 17.** The distribution of elephants (upper map) and rhinoceros (lower) in the humid Holocene; from Mauny, 1956.
strates that the climatic and environmental conditions of the Holocene were very different from those of the present.

While the increase of precipitation in the northern Sahara and in the Mediterranean zone was quite modest, especially at the start of the Holocene, it reached impressive values in the southern part. Soil formation in today’s extremely arid sand desert of Bilma (18 mm annual precipitation) demanded an annual rainfall of about 500 mm (Vökel, 1989). Without discussion of the pedogenetic problems and the probable climatic conditions (higher cloud cover, reduced temperature, less evaporation, no strict seasonal distribution of rainfall), nevertheless, the order of magnitude of this climate change and its consequences can be outlined. The neolithic human population required much better resources than are available today and the campfire sites, cattle bones, and rock paintings in the mountainous areas provide insights into the pastoral land-use system of this time (Gabriel, 1978). The reconstruction of the migration of large wildlife is also fascinating. Figure 17 shows the expansion of the range of elephant and rhinoceros from their zone of origin in the tropics to the Mediterranean coast. The highest original density and biological optimum for tropical mammals must have occurred between 4,000 and 3,000 B.P., immediately before the collapse to more arid conditions (Delibrias, 1977). In the southern region this critical threshold of aridification was exceeded at about 2,000 B.P., some time later than in the central and eastern Sahara. This time period must have been catastrophic for humans and animals, far more so than events in this century. Only the mountains remained as moist islands, where plants and some wildlife species could survive and where a very sensitive ecosystem still produced the necessary resources for a well-adapted human culture. This is very relevant to present-day conditions: if we over-exploit today’s resources, such as soil and water which derive from another environment and which have been formed under a different climate, they are lost for ever.

CLIMATE CHANGE: LONG-TERM AND SHORT-TERM PROCESSES

Figure 12 is a reconstruction of atmospheric patterns, seasonally differentiated, in three time steps: today, at 8,000 B.P., and at 18,000 B.P. This simplified presentation is based on a vast and sometimes contradictory literature. The meteorological explanations and interpretations have been discussed by Fairbridge (1972), Rognon and Williams (1977), Nicholson and Flohn (1980), Messerli (1980a and b), and Petit-Maire and Jamet (1989). This paper concentrates instead on the climate change and its ecological consequences. Compared with present-day conditions, we assume that at 8,000 B.P. the Intertropical Convergence Zone was located further north, so that humid tropical air masses reached the southern border of the Atlas Mountains or even the Mediterranean coast. In the winter season, we assume that some precipitation linked to the polar front still influenced the northwestern Sahara and pockets of cold air reached as far as the central Sahara (Petit-Maire, 1987). By 18,000 B.P. there was a totally different situation with a very weak monsoon flow in the summer that gave rise to distinct aridity during the maximum cold period. The winter season was dominated by the southward shift of the polar front with modest precipitation and snowfall in the mountains of North Africa and the Sahara.

Of interest are seasonal and altitudinal differentiations. At 18,000 B.P., paradoxically, the mountains of the Sahara had snowfall and frost activity during the winter season, although surrounded by extremely arid lowlands where eolian processes prevailed because the modest winter precipitation had no effect on landforms and vegetation in the lower areas. The processes at high altitudes were determined by the winter climate, and the lowlands and plains were dominated by the dry and radiation-intensive summer climate. The sediments of a permanent, deep lake in the “Trou au Natron” on the Toussidé (3,265 m) in the Tibesti Mountains is of interest. Although the surrounding deserts below 800 m experienced extremely arid conditions, the presence of the lake is a further example of the effects of altitude on localized precipitation (Faure and Faure-Denard, 1989).

The situation at 8,000 B.P. is characterized by much weaker differentiation between summer and winter conditions and also between highland and lowland environments. In large areas of contemporary desert the paleosols and lakes required summer and winter precipitation for their formation (Vökel, 1989). From the Mediterranean coast to the equator there occurs a remarkable change in the hydrological regime.

If conditions at 18,000 B.P. and 8,000 B.P. for the entire African continent are compared with those of today fundamental changes that have occurred in the recent earth’s history are evident. Once more it is shown that the world in which we live is not a static environmental system but an extremely dynamic one full of climatic risks. This is all the more evident when we consider that important changes, such as a warming of 7 °C in South Greenland, occurred at the beginning of the Holocene within a period of less than 100 years. This implies that future changes could also proceed according to a non-linear process and as a relatively sharp reaction after passing a certain threshold value (Dansgard et al., 1989).

Present-day oscillations or change (Figure 18) should be assessed against this background because it is not yet known if they are short or long-term processes. Moreover, we must determine whether droughts, low levels in lakes and rivers, decreasing groundwater tables, increasing salinity, reactivated dunes, destroyed soil, and degraded
vegetation, are natural or man-made phenomena, or both, and if they are the results of dominant, short-term processes, or weak, long-term processes.

The first example is the variability of precipitation in the arid zone, as occurred at Agades at the foot of the Air (Figure 18). How are we to interpret the oscillations with two catastrophic dry periods between 1969–1974 and 1981–1985? Has this been a negative trend since 1960, or is it a normal phase of lower rainfall which will change again? Is it a natural process or is it influenced by human activities? In many cases we do not know if lower groundwater tables consisting mostly of fossil water could be partly recharged by higher precipitation and better runoff conditions (Dodo, 1989).

The second example relates to glacier fluctuations in the East African tropical mountains. For the Lewis Glacier on Mt. Kenya, changes of area and volume can be determined since 1890 (Patzelt et al., 1984). It is interesting to note that moderate losses from 1890 to 1920 were followed by a strong and uninterrupted retreat up to the present (Figure 9). In this respect, the Lewis Glacier behaves as all other equatorial glaciers do. Compared with alpine glaciers, its development was similar up to 1950. In the following years, however, the glaciers of the Alps gained mass and advanced while the Lewis Glacier experienced its strongest losses from 1974 to 1983, most probably due to a decrease of precipitation (Hastenrath and Kruss, 1982; Patzelt et al., 1984; Berger, 1989). Again, we do not know yet how to interpret this phenomenon: is it a long-term or short-term process; is it a natural one; and to what extent did human activities play a role?
Interaction between climatic fluctuations and use and management of resources during more than 2,000 years are shown in Figure 19. The results of a research project in the central Tunisian steppes by Mensching and Ibrahim (1977) demonstrate a first phase of desertification through over-cultivation during the Roman era when the land was systematically colonized and brought under the plow. Then followed a phase of relative soil conservation and vegetative regeneration with the more nomadic land-use system of the Arabs. The second phase of desertification began in colonial times with the intensification of resource use and has lasted until today. Climatic change intervened in this most interesting cultural and historical process and can be seen especially in the increasing aridification before, and probably during, the Roman period (Hempel, 1988). This scheme not only shows the complex interaction between natural and human disturbances but also underlines the importance of relatively weak but long-lasting processes that are augmented slowly. It is precisely the damage that is not even registered during a decade or a generation, such as soil erosion of one or more mm/year, that is most dangerous. Continuous overuse without adaptation of the management system extracts a very high price. Even after 2,000 years the results of climatic change and human intervention can be seen on karstic surfaces and the bare rocky slopes of the Mediterranean and North African mountains which were once covered with soil and vegetation, formed in the more humid Holocene. Is the same process—over-use of the resources by increasing population, reinforced by climatic oscillations in recent decades—now taking place south of the Sahara, on Jebel Marra for instance,
Migration from the High-lands to the Lowlands

Migration from the Low-lands to the Highlands

Sensitivity of mountain ecosystems: vulnerability to human impact

Alps Mediterranean Mountain Ranges Hoggar Simen Mountains Mt. Kenya

5000 m N S N S
4000 m
3000 m
2000 m
1000 m

FIGURE 20. Highland-lowland interaction from the Alps to the equator, illustrated by the examples of migration and water resources; from Messerli and Winiger, 1988.

or in the mountains of Ethiopia: (Mensching, 1981; Hurni, 1988)?

Resource management in Africa concerns not only land but also, and especially, water. From the Mediterranean to the Sahelian and arid East African regions there is much more information on fossil groundwater formed in alternating sequences during the late Pleistocene before 20,000 B.P. and during the Holocene since 10,000 B.P. (Sonntag et al., 1979; Jungfer, 1990). One typical example of groundwater with insufficient recharge due to overuse is the valley of the Souss between the High Atlas and the Anti Atlas in southern Morocco where the continuously decreasing groundwater supply is creating serious problems for farmers. On the other hand, highly developed systems of water harvesting on level terraces below runoff-producing slopes are found in the arid Anti Atlas. Here plant species and densities are adapted to moisture availability and show an excellent utilization of scarce mountain land and water resources (Reij et al., 1988).

Figure 20 is a simplified and schematic depiction of the mountain profile from the Alps south to the equator showing that the use of land and water resources is strongly dependent on economic factors in the surrounding lowlands, as has been argued by Bencherifa (1983, 1988) for the High Atlas of Morocco. Outmigration, with underuse and collapse of an adapted traditional land-use system, and immigration, with overuse of land and water resources, can have damaging consequences. Moreover, it must be emphasized that mountains in subtropical and tropical zones have a more favorable natural potential than the surrounding lowlands, either because of increased precipitation in arid regions or decreased humidity and temperature in the equatorial areas.

But mountains are extremely sensitive to past and future climatic change. Figure 21 shows a simplified model of changing environmental processes. Many mountain areas, such as those of North Africa and northern Ethiopia, have been populated and used for over hundreds or even thousands of years. The man-made landscapes existing today are far different from the natural ecosystems. We agree with Naveh (1982) when he concludes that the conservation of Mediterranean landscapes, for example, can only be ensured by continuation of the agro-pastoral functions under which these landscapes evolved. This will not be successful, however, if land-use intensification leads to a loss of soil and productivity, as can be observed in parts of the Atlas and the Ethiopian mountains, because these man-made ecosystems have such a reduced buffering capacity that they become susceptible to even the smallest climatic fluctuations.

The situation in the mountains of the extremely arid zone is very different. The anthropogenic impact is relatively weak (except for urban and touristic areas, such
Figure 21. Anthropogenic and natural environmental changes which should be differentiated in space and time and from highlands to lowlands. Reversibility means the capability of an ecosystem to restore its original state after a disturbance or a change. Irreversibility means the absence of this capability (Gigon, 1983; Littmann, 1988).

C: Climatological conditions  S: Soil type and soil formation
H: Hydrological conditions  G: Geomorphic processes, hazards
V: Vegetation cover and diversity

as Tamanrasset) and has no significant effects in cases of climatic change. Again, the mountains of East Africa are very different, being partly preserved as national parks with ecologically more or less intact altitudinal belts. They have a certain buffering capacity in times of climatic fluctuation; the vertical range of ecosystems, the density of vegetation cover, and type and number of species may change but the basic conditions for regeneration will not be destroyed easily.

For all mountains the same tenets are valid: in a time of general global warming, as it is predicted and as several indicators begin to prove, mountains will primarily react through adjustment of altitudinal belts. Plants and animals cannot migrate to another latitude, they can only move to a higher altitude.

In this context the key elements must be defined and the stabilizing or destabilizing effects of the processes of climatic change must be understood if the resource systems are to be preserved. Parks and wildland, especially in mountain regions, can serve as benchmark areas for monitoring change; they can also provide refuges for plant and animal species that may prove to have direct economic uses and that, more importantly, form part of the vast and still inadequately understood web of connections among living things and their environment (Ledec and Goodland, 1988). Forty-seven percent of the surface of Africa is climatically unsuitable for crop production, 54 percent has a growing period of less than 120 days, only 19 percent of the continent’s soils have no serious fertility limitations, water resources are limited, and the population is rapidly increasing (Okingbo, 1990). The natural resources must be utilized in a sustainable manner, with the realization that in the tropics mountains and highlands are most favorable zones. Promotion of conservation-oriented land-management systems for different environments is needed, especially to preserve the soil as the “living membrane” of the landscape. Moreover, methods must be developed for identifying vulnerable landscapes, ecological zones must be determined, and models devised to assess the potential impact of climatic change in relation to desertification, erosion, ecological factors, and resources (Stortenbeker et al., 1989). There is also a need for basic data on climatically sensitive processes so that these assessments are reliable. Perhaps the African Mountain Association could coordinate these efforts. When we consider once more how dramatically the climate, the environment, and resource availability have changed over a period of 20,000 years throughout Africa
and how destructive were the climatic oscillations of the last decades in many parts of Africa, then the need for a much broader scientific engagement in "natural-human highland-lowland interactions" becomes evident. In December 1985, the first African Environmental Conference took place in Cairo, organized by UNEP in cooperation with the United Nations Economic Commission for Africa (ECA) and the Organization of African Unity (OAU). Here, the African Ministers resolved that the continent's resources must be conserved and that to prosper, the continent must be self-sufficient in food and energy. We must now move towards a planning policy that sees environmental degradation as the root cause of economic decline and that makes environmental rehabilitation the sine qua non of development assistance (Tolba, 1986). This is particularly true for African mountains and highlands in a time of rapid global change.

REFERENCES


