ELSEVIER

Palaeogeography, Palaeoclimatology, Palaeoecology 120 (1996) 5–24

PALAEO

On the connexion of vegetation dynamics with climatic changes in High Asia

Georg Miehe

Faculty of Geography, University of Marburg, Deutschhastr. 10, D-35032 Marburg, Germany

Received 1 January 1993; revised and accepted 19 April 1995

Abstract

Within the scope of research on environmental changes in High Asia indications of desiccation and thermal oscillations are described. They refer to different periods and are caused by different climatic factors. Distribution patterns of forest constituents with disjunctions in the Central and Eastern Himalayas are explained with changes in monsoonal rainfall presumably during the Holocene.

In Southern Tibet the plant relicts of one of the younger Holocene phases of higher humidity ("*Kobresia pygmaea* age") have been widely destroyed by the Himalaya-föhn, giving way to semiarid alpine steppe on stone pavements.

Field observations of a recent intensification of gelifluction processes in the southeastern part of the Tibetan Plateau is in accordance with a cooling period between the late 1950s and the late 1970s.

The obviously decreased vigour and lacking regeneration of the climax vegetation in the alpine belt becomes conceivable under the presumption that the respective cover of alpine turf is a relict of the climatic optimum which slowly but increasingly deteriorated since then.

A decrease of plant vigour at climatically sensitive vegetation borders (upper treeline, drought limit of forests, transition zone between alpine Cyperaceae mats and the free gelifluction belt, transition zone between humid alpine mats and alpine steppe) gives evidence of diminishing winter precipitation during the last 30 to 40 years in the Karakorum.

1. Introduction

Climatic and environmental changes in High Asia have attracted attention since the first scientific explorations of the 19th Century. The extended sequences of ancient shorelines around the lakes of High Asia give evidence of long-lasting desiccation interrupted by phases of higher humidity which obviously decreased in intensity during the Holocene. During the last 30 years investigations in the Quaternary and Holocene carried out by Chinese joint research expeditions (see Beug, 1987; Gasse et al., 1991; Hövermann and Süessenberger, 1986; Li Tianchi, 1988; Sun and Chen, 1991) revealed a sequence of oscillations from which humid phases around 9900 ± 420 and 6420 ± 420 yr B.P. were identified in West Tibet. In the Qaidam depression and neighbouring mountain areas humid phases have been recognized around 9000 and 4000 yr B.P. The younger environmental history of High Asia is thus characterized by an increasing desiccation, at least a decrease of the maxima in the humidity oscillations.

The up to now most detailed information about the climatic history of the past 2000 years resulted

SSDI 0031-0182(95)00031-3

from dendrochronological analysis undertaken by Wu and Zhan (1991) who drew the conclusion that there was a cold period in the 1st Century AD on the Tibetan Plateau (no further specificat ion). In the 2nd and 3rd century AD it became warmer and temperatures were 1°C higher than today. In the 3rd to the 5th Century AD temperatures were 1°C lower than today but from the 10th to the 12th Century a warmer period followed. The 13th Century is regarded as distinctly cooler, and the period between 1750 and the early 19th Century is described as cool and wet. A second period of wet and cool conditions was detected from tree rings between the end of the 19th Century and the 1930s. For the past 30 years a desiccation is stated in Tibet. At the southeastern periphery of the Tibetan Plateau, in the Hengduan Shan, a dry-warm trend starting with the beginning of the century has been derived which is thought to represent an important trend in the climatic changes of the whole area (Wu and Zhan, 1991, p. 548). However, statistical evaluation of temperature data revealed that the period between 1951 and 1980 was significantly cooler in the eastern half of High Asia (Böhner, 1993).

In the vast areas of High Asia where neither forests nor climatic stations provide quantitative data, the vegetation should be consulted as an indicator of present and past growing conditions: the vigour of plant species at their cold- or drought-determined distribution limits, and changes in the competitive position of such species in present plant communities offer valuable information on environmental changes. The only precondition for the climatic interpretation of successions in plant communities is the knowledge of the present natural (undisturbed) zonal vegetation in the respective area.

In this paper, the climatic interpretation of findings from phyto-ecological fieldwork at the southern and northwestern periphery of High Asia is introduced. The most indicative vegetation parameters are:

—changes of dominant zonal plant formations within the alpine belt (most prominent at the present distribution limits of closed Cyperaceae mats)

—changes in the transition zone between the upper limit of closed alpine Cyperaceae turfs and the free gelifluction belt

—changes of the vigour and regeneration of common tree species near their upper (cold) and drought limits of distribution.

Additionally, patterns of disjunct plant distribution areas provide valuable information about more long-ranging climatic changes. They will be introduced first, by means of some examples from the Himalayas.

2. Disjunct areas of plant species in the Himalayas

Patterns of separated distribution areas of plant species give evidence of environmental changes during the geological past. If it is possible to exclude anthropogenic or zoogenic seed dispersal and distribution gaps which are merely due to a lack of records, it can be assumed that the wider the distance is between the exclave and the main distribution area of a species, the longer the separation dates back. In the Himalayas several patterns of disjunct plant distributions are known (Stainton, 1972), and further progress in Himalayan plant chorology will bring a larger number to light.

In the context of humidity changes in High Asia, two plant distribution patterns in the Eastern and Central Himalaya are illuminating:

1. In the cloud forest belt of the southern declivity of the Himalayas, phanerophytes like *Vaccinium sikkimense* and *Maddenia himalaica* are widespread from Southwest China to East Nepal (Stainton, 1988, according to herbarium collections of K (Kew, Great Britain) and BM (British Museum, Great Britain), see Fig. 1). Further towards the west, the only records are known from the southern slope of Annapurna Himal and from the Helambu area (Central Nepal). Both declivities receive higher rainfall than the surrounding mountain groups (approx. 4000–6000 mm/yr). This small disjunction of 250 km can be explained with a decrease of rainfall which fell short of the required minimum within the distribution gap between the eastern border of the continuous distribution area and the exclave. It is conceivable that the zone of East Asiatic Subtropical

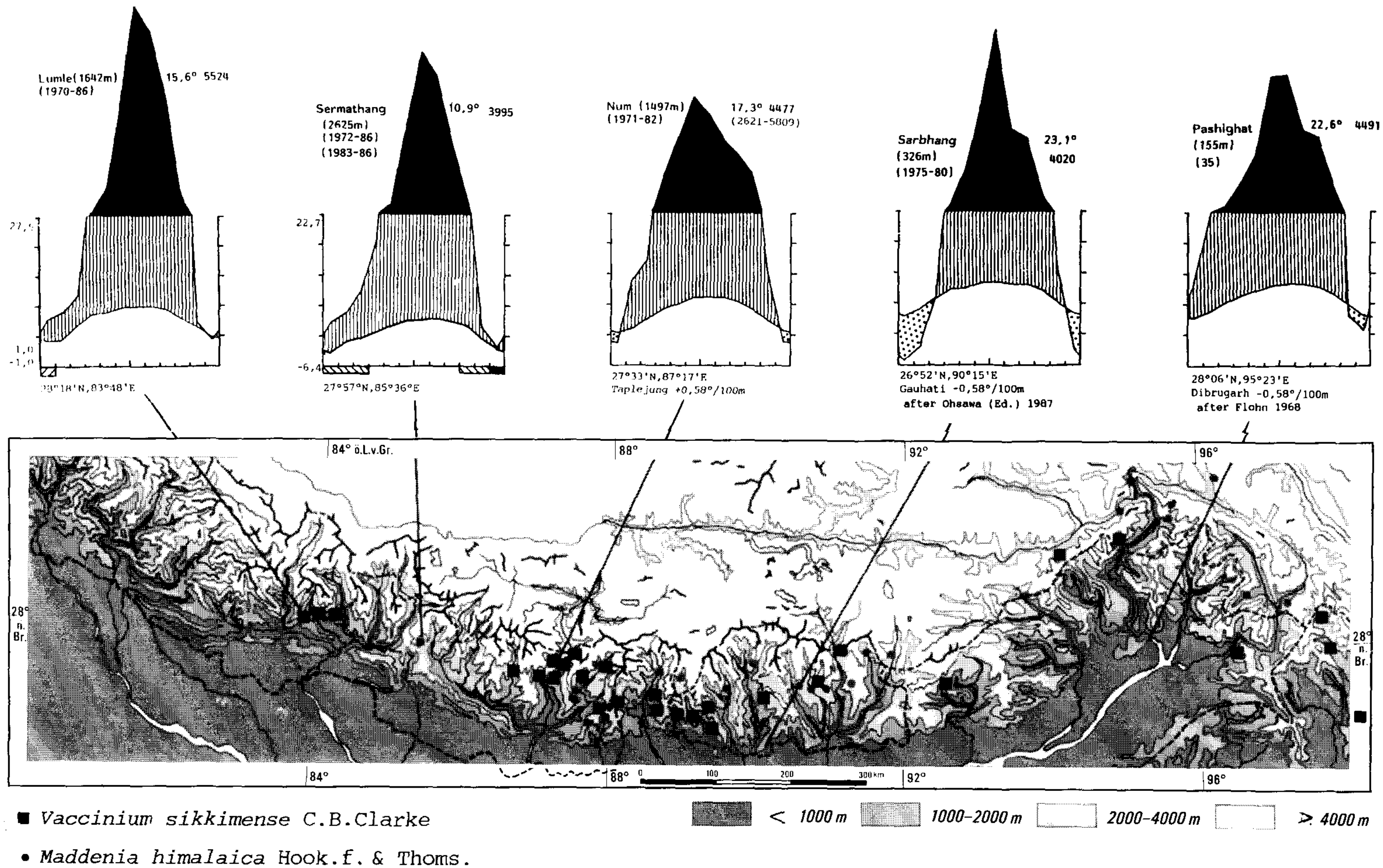


Fig. 1. Records of perhumid montane East himalayan phanerophytes with distribution gaps in Central Nepal indicating a decrease of rainfall in the southern declivity of the Himalayas (after Miehe, 1990, changed, climatic diagrams drawn according to Walter, 1955; data, if not indicated otherwise, after Climatic Records of Nepal. Map redrawn from *The Times Atlas* (Anonymous, 1981), changed.

Lauraceous Forests, which was squeezed into a narrow belt during the formation of the Tibetan Plateau and its mooving towards the south-east, in agreement with the general dynamic of the plateau, had once extended more to the northwest. The records of *Vaccinium sikkimense* thus mark the minimum westward spread of perhumid lauraceous forests in the southern declivity of the Himalayas.

2. Another disjunction occurs in the distribution area of phanerophytes in sub- to semihumid coniferous forests of the Inner Valleys in the moderate rain shadow of the Main Himalayan range. This distribution pattern was first described by Stainton (1972) in the context of climatic changes as "East Nepal–Sikkim Gap": Plants of northwest Himalayan distribution have their easternmost records in the rain shadow of the Annapurna Himal (Manangbhot) and in the upper reaches of the Trisuli Ganga (around Gyirong and in the Langtang valley); they are absent from the Inner Valleys of East Nepal and reappear in the valleys of Western Bhutan and Eastern Tibet. The width of the distribution gap is 350–700 km. If we compare the available rainfall data at the eastern border of the main distribution area with those from the Inner Valleys of East Nepal, it is evident that the humidity in the latter locations is considerably higher (see Fig. 2). In contrast to the cloud forests of the southern declivity, the Inner Valleys are not only separated from each other by deep traverse gorges and north/south-running mountain ridges: except the Khumbu valley, which is surrounded by very high ridges and separated from the highlands to the north, most of the Inner Valleys are tributaries of the Himalayan longitudinal valleys which dissect the Main Himalayan Range and originate from the highlands of Southern Tibet. This orogenetic pattern supports the hypothesis that the actually isolated occurrences of those sub- to semihumid phanerophytes had been linked together in a closed belt of semihumid South Tibetan forests. The former existence of such forests has not been proven by palynological analyses yet, but it can be concluded from results of palynological research on the Northwestern Plateau (Li Tianchi, 1988; Gasse et al., 1992) that the precipitation was 150–300 mm/yr higher during periods of higher humidity (9900±420 yr B.P.). If this can be confirmed, the climate of Gyangze (271 mm/yr at present) would once have been roughly equivalent to the present climate of the *Juniperus indica* forests of Manang (443 mm/yr, see Fig. 2). Consequently, the desiccation of Southern Tibet during the younger Holocene would have extinguished this coniferous forest zone, or split it into those disjunct relict occurrences respectively, which are nowadays recorded from the more humid parts of a formerly continuous distribution area.

3. Föhn-induced successions from Cyperaceae mats to alpine steppe

Indications of environmental changes presented here are derived from successions of plant communities which have a certain importance for the pastoralist economy in High Asia. The deterioration of the natural resources which can be observed in most parts of the pastoral landscapes of High Asia are easily connected with the grazing impact. Other factors than human interference have up to now not been considered, despite the fact that from other parts of the Old World desert belt, it is well known that the human impact is superimposed and reinforced by climatic changes.

The findings which are interpreted here refer to summer grazing pastures of the alpine belt in the rain shadow of the Himalayas (35°05′N/75°32′E, 28°34′N/85°45′E, 28°21′N/86°05′E, 28°50′N/87°35′E, 28°50′N/90°15′E) between the northwest Himalayas of Pakistan and the southeastern part of the Tibetan Himalaya in China.

On the Deosai-Plateau, situated to the north of the mountain chain framing the Kashmir Valley, alpine forb-rich steppes at 4000 m a.s.l. on a 0.5–1 m thick loess cover are being replaced by alpine cushion and rosette plant communities (see Fig. 3). These grow on open morainic substratum underlying the loess cover which is removed along deflation cliffs. The cliffs occur only in southerly exposures, most of them facing southwest. They are devoid of plants, even algae, lichens or mosses are absent. The cliffs are exclusively found on open hillsides exposed to southerly winds; they do not

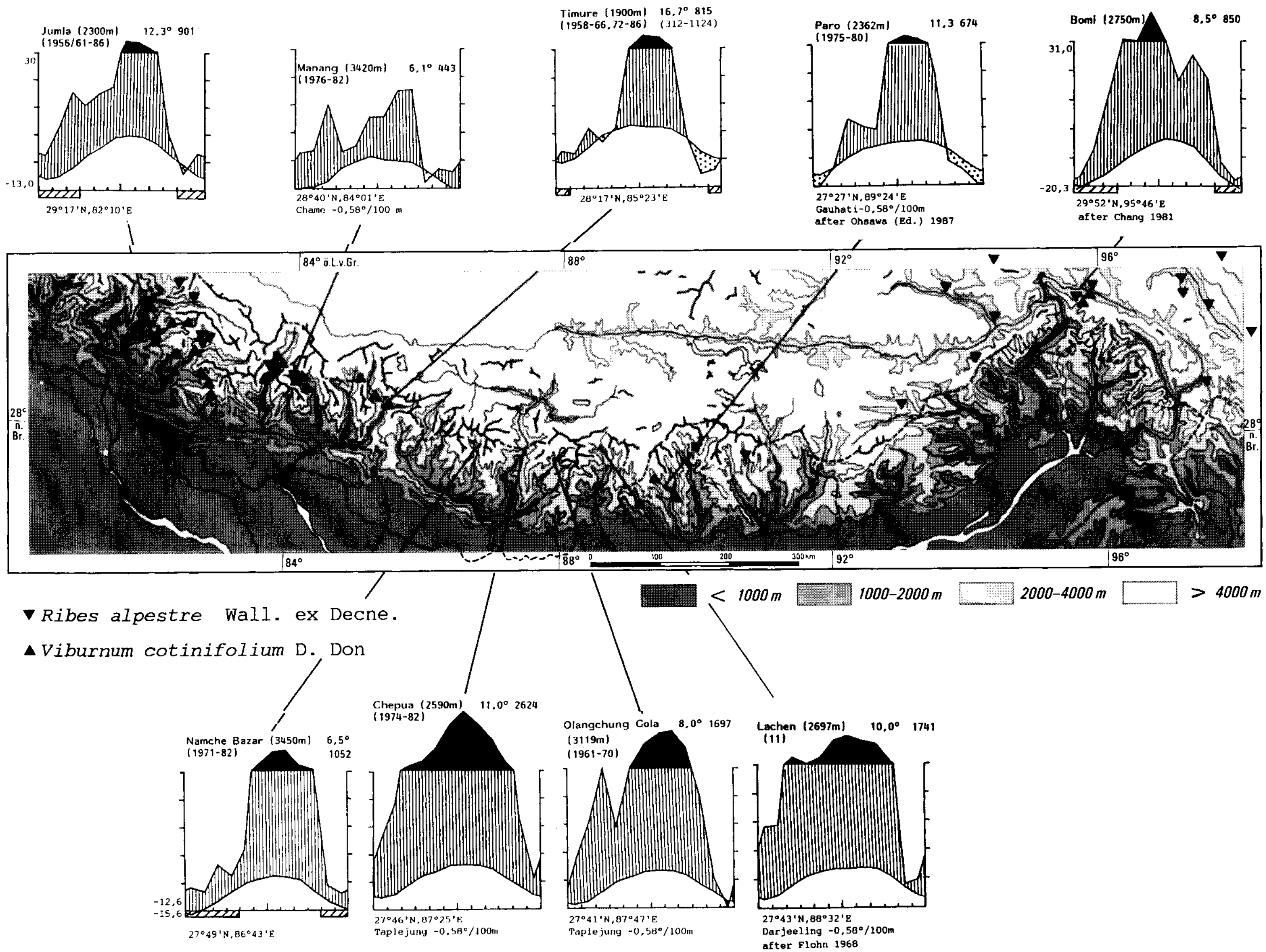


Fig. 2. Records of semihumid montane inner himalayan phanerophytes with the "East Nepal–Sikkim Gap" according to Stainton (1972) indicating an increasing rainfall on the southern side and desiccation in Southern Tibet (after Miehe, 1990, changed; climatic diagrams drawn according to Walter, 1955; data, if not indicated otherwise, after Climatic Records of Nepal. Map redrawn from *The Times Atlas* (Anonymous,1981), changed.

Fig. 3. Deosai-Plateau, 35°05′N/75°32′E, 4050 m a.s.l., July 14, 1991: The "climax" of forb-rich steppe on a loess cover (*1*) is increasingly replaced by pioneer plant communities on the morainic stone pavement (*2*) at the southern foot of the foehn-corraded deflation cliff (*3*).

occur on slopes sheltered from southerly winds. At the foot of each cliff, morainic stone pavements spread towards the south, being colonized by a diffusely scattered alpine pioneer community consisting of cushion plants (*Androsace* spp., *Draba* spp., *Sibbaldia parviflora*), carpets of *Bistorta affinis*, *Oxytropis tatarica* and rosettes of *Lagotis crassifolia*, *Saussurea roylei* and *Pedicularis* spp. The above mentioned forb-rich steppe grows on the intact loess cover preserved on the leeward side of the cliffs. It is constituted of 15–30 cm tall bunchy *Kobresia tibetica* and accompanied by *Elymus* spp., *Alopecurus* spp., *Nepeta linearis*, *Geranium pratense*, *Pulsatilla wallichiana*, *Rhodiola fastigiata*, *Pedicularis bicornuta*, *Rumex rumicifolium* and other herbs and represents the presumed climax vegetation. The beginning of this change from forb-rich steppe to cushion plant communities is not known yet, but will possibly be reconstructed and dated in the course of the palynological analysis (undertaken by H.-J. Beug, Göttingen). Under the present conditions it can be observed that the corrasion of the loess cover usually starts once the loess blanket is injured in windward position. This can be caused by cattle (yak) chafing their horns, or by erosion along snow melt water channels in late spring and early summer after unusually high winter snow fall (most channels are obviously only watered episodically). Chafing places and melt water channels in the loess cover on leeward sides are tending to be flattened by solifluction of the water-saturated loess and finally colonized by plants, whereas in wind-exposed locations vertical cliffs are created by southerly winds under fair weather conditions when the loess is dry.

In the alpine belt of Southern Tibet, situated in the rain shadow of the High Himalayas, a similar succession of plant communities can be observed (see Figs. 4–6), although the precipitation pattern

Fig. 4. Southern Tibet, 28°50′N/87°35′E, 4680 m a.s.l., August 28, 1984: Relicts of turf with *Kobresia pygmaea* (dot) are only preserved from the föhn-corrasion in the wind-shelter of rock outcrops (black arrow). On the surrounding slopes the turf has been corraded and alpine steppe plants have colonized the open substratum. On the leeward side the turfs are exfoliated by needle-ice (white arrow).

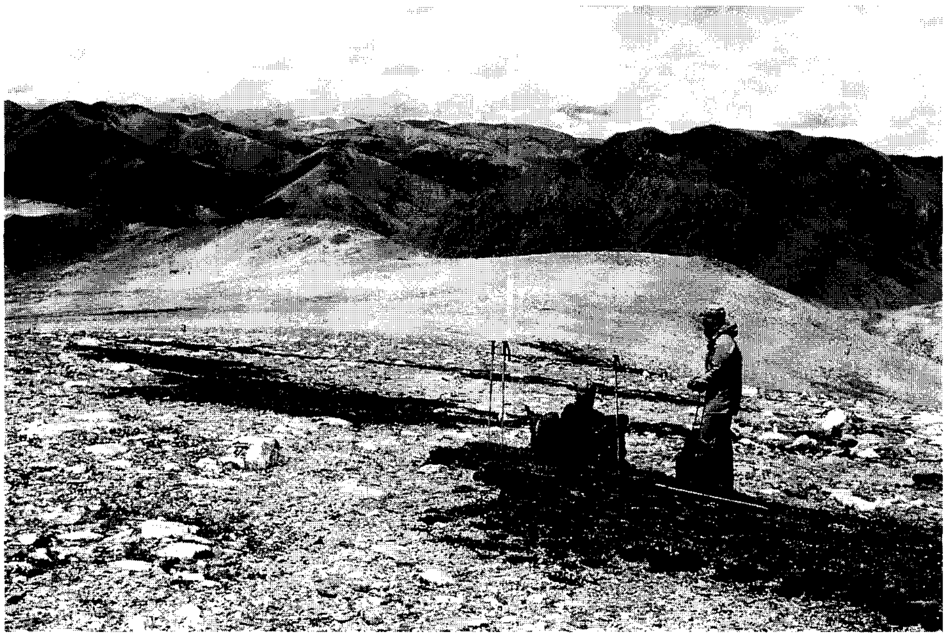


Fig. 5. Southern Tibet, 28°11′N/86°05′E, 5100 m a.s.l. September 2, 1984: SW–NE oriented föhn-corraded relicts of *Kobresia pygmaea* turfs surrounded by open morainic substratum and stone pavements colonized by alpine steppe plants: As the turfs are not confined to extrazonal habitat factors (e.g. water surplus) they should have once covered the whole slope and wider areas of Southern Tibet under more humid conditions.

Fig. 6. Southern Tibet, 28°21′N/86°05′E, 4300 m, September 6, 1984: Deflation pavement with alpine steppe plants: plate-shaped cushions of *Oxytropis densa* (black star) and *Astragalus orotrephes* (encircled with black interrupted lines) with tiny tufts of *Stipa purpurea* (black arrow) and *Carex montis-everestii* (white arrow). Compass-diametre 6 cm.

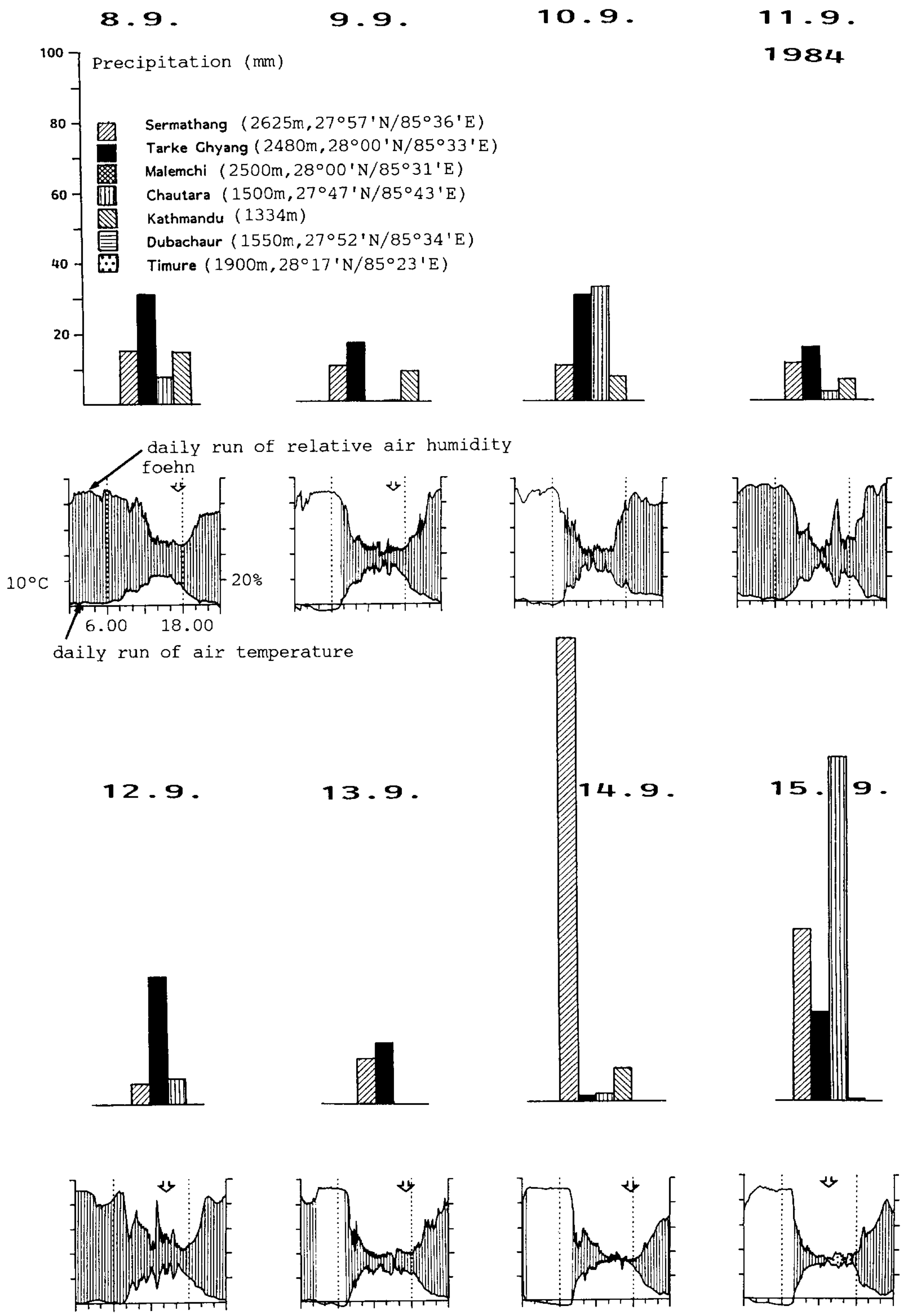
differs considerably (summer rainfall in Southern Tibet in contrast to dominant winter snowfall plus summer rains on the Deosai Plains). In altitudes between 4500 and 5200 m a.s.l. the slopes are largely covered today by sparse alpine steppe (i.e. "high cold steppe" sensu Wang Jinting, 1988; compare Fig. 6) consisting of flat cushions (*Androsace tapete*, *Arenaria bryophylla*), plate-shaped cushions (*Astragalus orotrephes*, *Oxytropis densa*, *Saussurea graminea* v. *ortholepis*), rosette plants (*Thalictrum alpinum*, *Oreosolen wattii*, *Saussurea taraxacifolia*, *Incarvillea younghusbandii*) and tiny graminoides (*Stipa purpurea*, *Carex montis-everestii*). Yet, there are scattered patches of narrow, c. 10 cm thick turf strips which emerge from the alpine steppe (see Fig. 4). These alpine mat patches have an active deflation cliff on their southern side which is completely devoid of plants, as the deflation cliffs on the Deosai Plateau. The leeward margins of the turfs are colonized by crustose lichens, mosses and phanerogams of the surrounding alpine steppe. Up to now, no reasonable explanation for the alpine steppe/turf-pattern has been found except the one that the turfs are relicts of a formerly closed cover of *Kobresia pygmaea* mats, as they are described to form the actual zonal vegetation of the southeastern Tibetan

Plateau (Zhang, 1988, see Fig. 8). If we presume that closed Cyperaceae mats had indeed been replaced by alpine steppe, it is still to be considered whether this environmental change is caused by climatic factors or by human interference, i.e. grazing impact. The alpine steppes of Southern Tibet are part of a pastoralist landscape; the impact of grazing by yaks, sheep and goats and of trampling and chafing is evident. Especially chafing by yaks opens the closed turf layer and may initiate turf exfoliation by needle-ice. Yet, this impact is not connected exclusively with animal husbandry, but applies to wildlife grazing (yaks) as well. Another way of turf layer destruction is initiated by the burrowing action of *Ochotona* and marmots. For the discussion whether the destruction of the turf layer is initially caused by chafing or similar interference and then continued and extended by needle-ice-induced substrate movement or other factors, the following findings are important: the relict strips or patches of *Kobresia pygmaea* mat on alpine turf have a longitudinal shape with mostly SW–NE orientation. Apart from this feature, they are irregularly distributed and grow under the same habitat conditions as does the surrounding alpine steppe: the presence of the mat patches cannot be attributed to any (extrazonal) habitat advantages such as water surplus, more favourable substratum etc. The only correlation between the occurrence of these mat fragments and any habitat factor is established by the exposure to the prevailing summer wind direction: turf relicts in the prevailing alpine steppe are mostly found on windward (southerly) slopes, whereas leeward slopes may still be completely covered with alpine *Kobresia* mats.

The active cliffs of the turf patches are strictly facing the windward side, i.e. the south. The other margins of the turf patch may temporarily (e.g. after unusual moisturing of the substratum during periods of bad weather) be affected by needle-ice, but this type of turf exfoliation (Troll, 1973) is not dominant. Southerly winds were always observed together with a cloud wall on the Main Himalayan range and coincided with noticeable rainfall records registered by the Department of Irrigation, Hydrology and Meteorology of His Majesty's Goverment of Nepal at climatic stations in the southern declivity of the Himalayas. The simultaneity of dry southerly winds on the northern side of the Himalayas (i.e. Southern Tibet), the cloud wall on the main ridge and rainfall on the southern side of the Himalayas suggests classifying these winds as föhn. The comparison of rainfall records from Nepal with simultaneous thermohygrograph measurements in Southern Tibet shows that the higher the rainfall is on the southern side of the Himalayas, the stronger is the aridity of the northern side (see Fig. 7). This may lead to the conclusion that the aridity of the alpine steppe of Southern Tibet is linked with high monsoonal rainfall of the southern declivity of the Himalayas.

In addition to the exposure-dependent occurrence of alpine mat relicts and their possible climatic correlation, there are further arguments against an entirely grazing-induced destruction of the turf. The proper grazing impact is of only negligible importance because *Kobresia pygmaea* has its main biomass close to the surface (below 1 cm) and only the leaf tips and the fruits are in reach of the grazing animals. The dense rhizomes of the sedge are not affected by trampling. Thus it seems probable that grazing has a minor impact on the turf destruction. Furthermore, it is important to know that *Kobresia pygmaea*, which has built the turf once, is actually neither recolonizing the windward cliffs nor the leeward margins of the open substratum around the turfs. Moreover it is typical that *Kobresia pygmaea* does not form a closed Cyperaceae carpet on those turf patches any more: the competitive position has obviously

Fig. 7. Daily diagrams of the microclimate (after Ellenberg, 1979, changed) of alpine steppes of Southern Tibet (28°34′N/85°45′E) at 5020 m a.s.l. during early post-monsoon and daily rainfall of the southern declivity of the Himalayas in Nepal. The aridity of Southern Tibet can possibly be explained with high monsoonal rainfall on the South side causing stronger föhn effects on the northern side. After thermohygrograph measurements (unsheltered 20 cm above ground) kindly provided by J.-P. Jacobsen 1984 and records of the Department of Irrigation, Hydrology and Meteorology, HMG of Nepal, Kathmandu, and N. Bishop, Massachusetts, unpublished.


8.9.
9.9.
10.9.
11.9.
1984
Precipitation (mm)
100
80
60
40
20
Sermathang (2625m,27°57'N/85°36'E)
Tarke Ghyang (2480m,28°00'N/85°33'E)
Malemchi (2500m,28°00'N/85°31'E)
Chautara (1500m,27°47'N/85°43'E)
Kathmandu (1334m)
Dubachaur (1550m,27°52'N/85°34'E)
Timure (1900m,28°17'N/85°23'E)
daily run of relative air humidity
foehn
10°C
20%
6.00
18.00
daily run of air temperature
12.9.
13.9.
14.9.
15.9.

decreased and plants of the alpine steppes (e.g. *Androsace tapete* cushions) and crustose lichens have invaded the open turf. Vigorous and completely closed, nearly monospecific *Kobresia* carpets are actually restricted to water surplus habitats along streams and in flushes. Those Cyperaceae mats are heavily grazed, but grazing and trampling damage is not evident.

From these findings it may be concluded that Cyperaceae mats of *Kobresia pygmaea* had once established themselves in zonal habitats of Southern Tibet under a climate which provided a water supply similar to that one which is today only found in extrazonal (water surplus) habitats. Thus the turf patches in the alpine steppe of Southern Tibet are indicators of a climatic period of higher humidity, which was proposed to be called "*Kobresia pygmaea*-age" (Miehe, 1988). It seems reasonable to conclude from the fact that the turf relicts are actually destroyed by the Himalaya föhn that they had been built under contrary climatic conditions, i.e. in a period when the föhn did not have the importance it has today. As the present föhn is connected with the high rainfall on the southern declivity of the Himalayas, i.e. the Indian Summer Monsoon, it may be concluded that the monsoon must have been remarkably weaker during that time in which the *Kobresia pygmaea* turfs were being built.

It must be expected, however, that the present three main vegetation belts encountered on the Tibetan Plateau do not have a constant position. On the contrary, it is probable that their extent is subjected to the desiccation of the Tibetan Plateau in the same way as the size of the Tibetan Lakes. If this is true, we must presume that the vegetation belts of the Tibetan Plateau have shifted considerably during the Holocene as it is already known from other parts of the Old World's deserts. Hence the hypothesis can be set up that during the desiccation of the Tibetan Plateau since the oldest phase of higher humidity (9400 ± 185 yr B.P. according to Beug 1987, 9900 ± 420 and 6420 ± 420 yr B.P. according to Gasse et al., 1992) the present alpine deserts evolved from alpine steppes and the alpine steppes expanded towards the southeast into the *Kobresia pygmaea* mat-zone (compare Fig. 8). Further research on the oscillations of the drought periods and the age of the superimposing human interference is needed, especially in the fields of palynology and dendroclimatology.

4. Successional changes at the lower limit of the free gelifluction belt

The following observations from the lower limit of the free gelifluction belt refer roughly to that

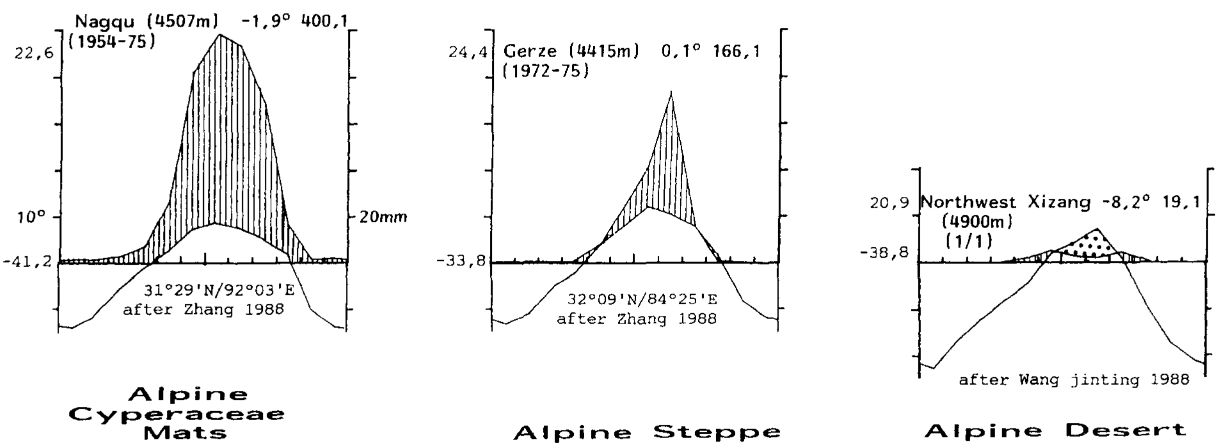


Fig. 8. Climatic diagrams from the vegetation zone of closed Cyperaceae mats (*Kobresia pygmaea*, Nagqu, Eastern Tibet) from the alpine steppe zone of Central Tibet (Gerze), and alpine desert zone demonstrating the hypothetical humidity decrease in the course of the environmental change in Tibet.

area where turfs are going to be replaced by stone pavements and alpine steppes. While the environmental change from Cyperaceae mats to alpine steppe can be explained with the High Asian desiccation, the changes at the upper limit of the alpine belt are presumably connected with thermal oscillations. It is yet unknown how these two climatic features interfere.

The altitudinal belt of scree slopes moved by gelifluction processes has its lower limit in the Himalayas between 3800 m a.s.l. in the northwestern part (Nanga Parbat) and between 4800 and 5500 m a.s.l. in the southeastern Inner Valleys and Southern Tibet. On many slopes the border between open debris and the plant communities of the alpine belt is not clear-cut, but there is a transition zone of interlacing scree and alpine turf outposts. This ecotone is highly sensitive to climatic changes: when plant growth is favoured during warm summers, creeping flat cushions are able to invade and stabilize the front of gelifluction lobes. Debris which is no longer moved by gelifluction, is being colonized by crustose lichens. On the contrary, when the frequency of frost occurences increases in colder summers, the alpine cushions are overrun by gelifluction lobes and the lichen cover is going to be destroyed. The latter case can actually be observed in the southeastern quarter of High Asia (see Figs. 9–13): the highest outposts of the alpine mats, constitued of various cushion plants and interspersed rosettes (e.g. *Arenaria polytrichoides, Sibbaldia* spp., *Bistorta affinis, Saussurea wernerioides, Rhodiola coccinea, Cortiella hookeri, Saussurea gnaphalodes)* are partly overflown by the scree or moved into a vertical position in which they dam the scree from the upper slope (see Fig. 9). Scree slopes whose debris had been colonized during the past by crustose lichens are moved again and the lichen cover is destroyed (see Fig. 10). A similar change is evident at the upper limit of closed alpine turf (see Fig. 11, 12); here the scree is either overrunning or ploughing the complete Cyperaceae cover. On other slopes gelifluction lobes between strips of vegetation originate from rocky areas where an obviously intensified physical weathering is delivering more frost debris than before (see Fig. 13). This most recent generation of gelifluction lobes is overflowing an older, now lichen-covered inactive generation of lobes, which had come to a standstill some 20 m below the recent front of the active lobes.

Fig. 9. North of Dhaulagiri, 28°55′N/83°33′E, 5000 m a.s.l., August 7, 1977: Cushion outposts of *Arenaria polytrichoides* (arrow) and *Bistorta affinis* (white dot) are moved by intensified gelifluction at the upper limit of the alpine belt.

It is questionable whether these findings can be explained by an increasing number of frost events in summer, i.e. by a decrease in summer temperature, or by an intensified downmelting of the permafrost (W. Golte, pers. comm., Jan. 14, 1991), i.e. higher summer temperatures. If warming is taken into consideration, it is difficult to explain, how the highest outposts of vegetation have developed during the more unfavourable, colder past. Moreover, the intensification of the scree movement should show a distinct difference between sunny exposures and shady slopes in this case. Yet, the increase in gelifluction is found independently from the exposure to the sun. Therefore, it is more probable that the intensified scree movements are caused by a higher number of night frost occurrences, i.e., a decrease of summer minimum temperatures.

Indications of an increase in frost activity are not limited to the transition zone between the alpine and the free gelifluction belt, but they extend into the proper alpine belt (see Figs. 14–16): the closed alpine turf cover is patchwise disintegrated into strips where the open sandy to silty substratum is freely moved by gelifluction. The strips are surrounded by cliffs of turf which are hollowed

Fig. 10. Langtang valley, 28°13′N/85°37′E, 4780 m a.s.l., July 9, 1986: Transition zone between the closed Cyperaceae mats of the alpine belt and the free gelifluction belt between 4900 (lower line of triangles) and 5000 m a.s.l. (upper line). Here the gelifluction is moderated by vegetation strips, whereas slopes with boulders are covered only by dark crustose lichens (white rhombus) and indicate as well that they remain inactive. In contrast, gravel and sand have been recently moved by gelifluction (black dots) tending to overflow the vegetation outposts.

Fig. 11. Southern Tibet, 28°50′N/87°35′E, 4620 m a.s.l., August 28, 1984: Frost heaves have cracked the cover of closed *Kobresia pygmaea* turfs. The open morainic substratum is sparsely colonized by gelifluction-adapted root-deformed phanerogams of the free gelifluction belt.

Fig. 12. Southern Tibet, 28°50'N/90°15'E, 5240 m a.s.l., November 11, 1984: Closed alpine Cyperaceae mats of *Kobresia pygmaea* are overflown by scree from the free gelifluction belt (white arrows); the upper limit of the alpine belt is pushed downwards.

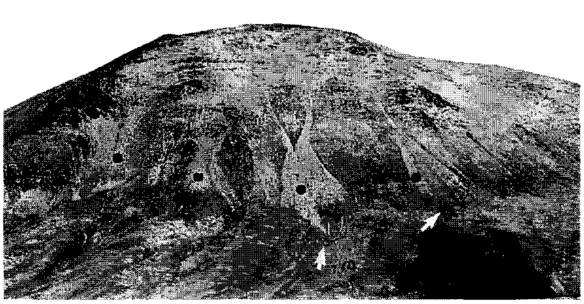


Fig. 13. Southern Tibet, 28°50'N/87°35'E, 4620 m a.s.l., August 28, 1984: A recent generation of gelifluction lobes (black dots) is overflowing an older lichen-covered inactive generation of gelifluction lobes (black triangles) which in a subrecent period of intensified frost weathering have buried the uppermost closed Cyperaceae turfs (arrow).

out at the base. The patches are distributed over all exposures and are most common on the steep inner slopes of lateral moraines. The protecting cover of alpine turf might have been opened or removed initially by natural causes (frost heaving, polygonal desiccation cracks, sliding of the water-saturated top-soil whilst the deeper soil remained frozen, rock-fall), by human impact (fire-clearing of the *Rhododendron* heathlands, uprooting of shrubs, cutting of sods) or by cattle (chafing of yaks). In none of the valleys, where those open patches inmidth of alpine pastures occurred, a recolonization by plants, i.e., a permanent restabilization of the surface, was observed. Under the present climatic conditions the vegetation is not vigorous enough to rebuild the vegetation cover. Obviously the gelifluction processes are at present stronger than the plant growth. Photos taken by O. Polunin (made accessible by courtesy of Mrs. Lorna Polunin, Godalming, UK) in summer 1949 in the Langtang valley of Central Nepal indicate that the extent of the patches of open substratum has not changed considerably in the past 37 years (until 1986, see Fig. 16). From the fact that the patches have neither been recolonized nor extended conspicuously it can be concluded that a period of stronger gelifluction dates back more than 40 years. In the Khumbu Himal (see Fig. 15) photos taken by E. Schneider in November 1955 (Hellmich, 1964) show a similar constancy over at least 27 years.

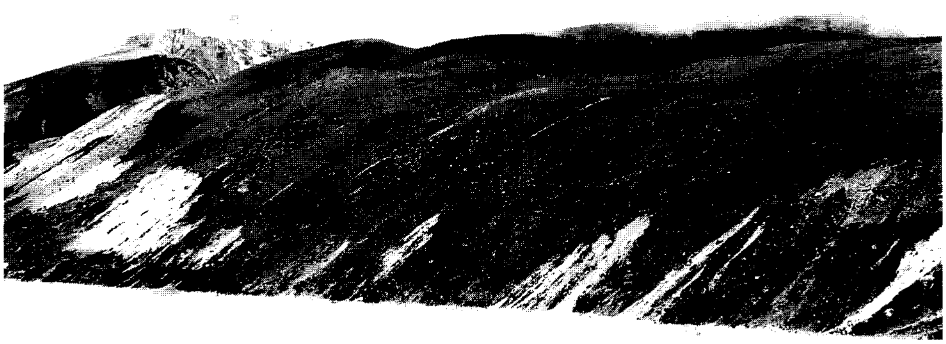


Fig. 14. Khumbu Himal, 27°57'N/86°42'E, 4750 m a.s.l., September 18, 1982: The closed Cyperaceae mats on alpine turf have been patchwise destroyed and are only recolonized by gelifluction adapted rosette-plants *(Gentiana urnula, Eriophyton wallichii)*.

Fig. 15. Khumbu Himal, 27°59′N/86°41′E, 5320 m, October 5, 1982: Patches of open morainic substratum (1) on the steep inner side of a turf-covered lateral moraine have not been extended markedly since 1955 according to photos of E. Schneider.

Fig. 16. Langtang valley, 28°12′N/85°36′E, 4480 m a.s.l., June 27, 1986: Strips of open mylonite widen succesively along the 50 cm turf exfoliation cliff with sods (arrows) breaking off the cliff. The cliffs have not noticeably changed their shape between 1949 (photos of Oleg Polunin) and 1986. The gelifluction of the open mylonite in spring and autumn is seemingly too strong to allow a recolonization of a closed plant cover.

Whatever the time span of stronger gelifluction processes might be, it is conceivable that the present so-called "zonal" closed layer of alpine turf might be a relict of a climatic period which was more favourable for plant growth. If the European Climatic Optimum reveals to be valid for these parts of High Asia too, it seems reasonable to connect the built-up of those alpine turfs with this climatic period. Up to now this is, however, purely speculative, even though not without a certain plausibility: it is estimated that during the Climatic Optimum the temperature was 3–4°C higher on the Tibetan Plateau than today (Li Tianchi, 1988). If the present upper limit of the alpine belt is not considered as reflecting the present climate but as being a relict of warmer climatic conditions with elevated altitudinal belts, it becomes understandable that open substrate patches inmidth the present turf cover are moved by gelifluction processes as if they are situated in the "proper" gelifluction belt.

It is proven that the high alpine turfs have considerable age. A turf of 25 cm in thickness from the upper Langtang valley at 5120 m was ^{14}C-dated between 15 and 20 cm below the surface at 3655 ± 175 yr B.P. (by courtesy of M. Geyh; pers. comm., H.-J. Beug). If we assume that this age is representative for this altitudinal belt, we may conclude that the present upper limit of the closed alpine turfs had been widely established in the Climatic Optimum, being slowly and patchwise destroyed under deteriorating thermic conditions. With these presumptions it is not surprising that the substratum of open patches 500 m below the upper limit of closed turfs is moved by gelifluction as in the free gelifluction belt instead of being recolonized by plants: these turf patches are in fact situated within the proper free gelifluction belt at present! If the actual upper limit of alpine turf at 5000 m resulted from the favourable thermal conditions of the Climatic Optimum being 3–4°C warmer, the real present border should be approx. 500 m lower.

Findings of intensified gelifluction are not only restricted to parts of Southern Tibet and valleys of the eastern Inner Himalaya. They are also described from Eastern Tibet (Hövermann and Lehmkuhl, 1993) and have recently been found on scree slopes of Western Tibet (34°10′N/80°25′E). In the latter area, screes move downslope and overrun the alpine steppe of *Carex moorcroftii*. In the mountain areas to the Northwest (Kunlun, Karakorum, Hindukush) as well as in the northnortheast (Qilian Shan, pers. comm., J. Hövermann, Jan. 5, 1993) intensified gelifluction processes are not clearly evident. The correlation with data from climatic stations is difficult because the stations are usually located in the extrazonally dry centre of the valley bottom, 2000–3500 metres below the lower limit of the gelifluction belt. In extended parts of the periphery of High Asia (with the exception of the Northwest) it seems, however, plausible to explain the observation of intensified gelifluction and the connected slight depression of the alpine belt with the recent temperature depression in the period between 1951 and 1980 (Böhner, 1993).

5. Recent humidity changes in the Karakorum

In contrast with the environmental changes in Southern Tibet the indications for a dessiccation found in the Karakorum, in the northwest of High Asia, seem to refer to a relatively short and recent period and appear to be caused by different climatic factors.

Like in other semiarid high mountain areas, rainfall data from the concerned national meteorological services are of little value for the assessment of the general humidity: the periods of complete and continuous measurements are too short, and the data are from stations located in the most unrepresentative part of the mountains, the dry and hot valley bottom. Everyone travelling in semiarid high mountains experiences that even during seasons of bad weather, when the higher slopes and glaciers are covered with heavy rainfall or snowstorms, the valley bottom receives only traces of precipitation, or the amounts of rainfall remain within the range of inaccuracy of the rainfall measurements (S. Miehe et al., in press, Fig. 1). Hence, the rainfall data recorded at the bottom of hot and dry valleys are not appropriate for a reliable statistical evaluation. This applies especially to the deeply dissected Karakorum, where Gilgit provides the longest complete sequence of climatic measurements (S. Weiers, pers. comm., Dec. 30, 1992). Consequently, we have to rely on other data if the focus is on recent humidity changes: besides the evaluation of tree ring analyses, the vigour of the plant cover provides valuable information, in particular at vegetation borders which are highly sensitive to climatic changes, as outlined by the examples given above. Such observations should be cross-checked with information about weather and climate given by local farmers and shepherds. Even though there is a great portion of uncertainty in the conclusions from qualitative data such as revealing from simple observation, the latter seems to be the only feasible technique for present research on recent climatic changes in remote mountain areas.

In the following, possible indications of recent climatic changes in the Karakorum are summed up from the preliminary results of two 3-month expeditions (1990/1991) to North Pakistan. The main features analysed in the Karakorum are:
—the vigour and regeneration power of trees at the limit of their distribution area,
—the vigour and dynamic status of closed alpine Cyperaceae mats in the vicinity of their drought limit and in the transition zone towards the free gelifluction belt.

5.1. Observations in the upper montane forest belt

At the upper treeline of the sunny slopes in all forested parts of the northern areas, it was evident that all living mature trees of *Juniperus turkestanica* are smaller than the trunk remains of burnt or naturally died individuals of the same species in the same location. As this is a general feature in the northern areas of Pakistan and not restricted to single groves it is not simply a matter of the age structure of a certain juniper grove. Obviously the growing conditions have become less favourable.

Mature outposts of all forest tree species of the Northern Areas of Pakistan at the arid periphery of their distribution area are without any regeneration in zonal habitats:
—In the northernmost forests of the west-Himalayan spruce *Picea smithiana* (north- and west-flank of Rakaposhi, see Fig. 5) there are neither seedlings or young trees nor browsed small specimens in the proper spruce belt (this does not agree with observations by G. Braun (pers. comm., Tübingen, April 11, 1992) in the Pisann area). Young spruce trees are at present found in the birch-forests only, 300 m higher up. This up-slope movement of the regeneration of *Picea* is most probably not caused by changes in temperature but by a decrease in humidity: the belt of mature spruce forests has become too arid for the seedlings and young trees.
—At the northernmost locality of *Pinus wallichiana* (west of Ishkoman) mature trees in zonal habitat of north-facing slopes are vigorous and fruiting, but seedlings or young trees are confined to water surplus habitats, i.e. along streams and around springs. A possible explanation is that the topsoil humidity, which is on zonal slopes merely offered by the net precipitation, has become too low or discontinuous for the establishment of young trees, whereas the mature trees reach the ground water table.
—On the eastern side of the Panji Pass (Ishkoman), the foot of south-facing scree slopes carry over-mature forests of *Betula utilis*, which is quite unusual for the area because *Betula* is, like *Picea smithiana*, only found on the shady slopes. These groves are lacking any regeneration today and even browsed smaller trees are absent. The birches are vigorous. It seems again imaginable that the mature trees reach the ground water, but in those times the slope has been colonized by *Betula*, there should have been sufficient water even for seedlings and young trees, and the ground water table did not sink faster than the birch roots grew.
—Even the most drought-resistant species of the Karakorum forest trees, *Juniperus turkestanica*, is affected by the desiccation at the arid periphery of its distribution area: in the Shimshal valley, between the Shimshal Pass and Shimshal proper, gnarled, isolated, fruiting juniper trees can still be found in euarid Chenopodiaceae dwarf-shrublands, but young trees are confined to extra-zonal habitats along streams. The mature trees in the zonal habitats of open slopes are relicts of a more humid period. Similar field observations and ideas were noted by Hartmann (1983) from Ladakh.

5.2. Observations of habitat changes in the alpine belt

—At the northern (dry) distribution limit of zonal humid alpine Cyperaceae mats of *Kobresia capillifolia* (above Atabad, between Karimabad and Gulmit, see Fig. 17; semihumid sequence type of altitudinal vegetation belts in S. Miehe et al.) the closed mats have apparently become less vigorous and are actually affected by needle-ice and deflation on sunny slopes.

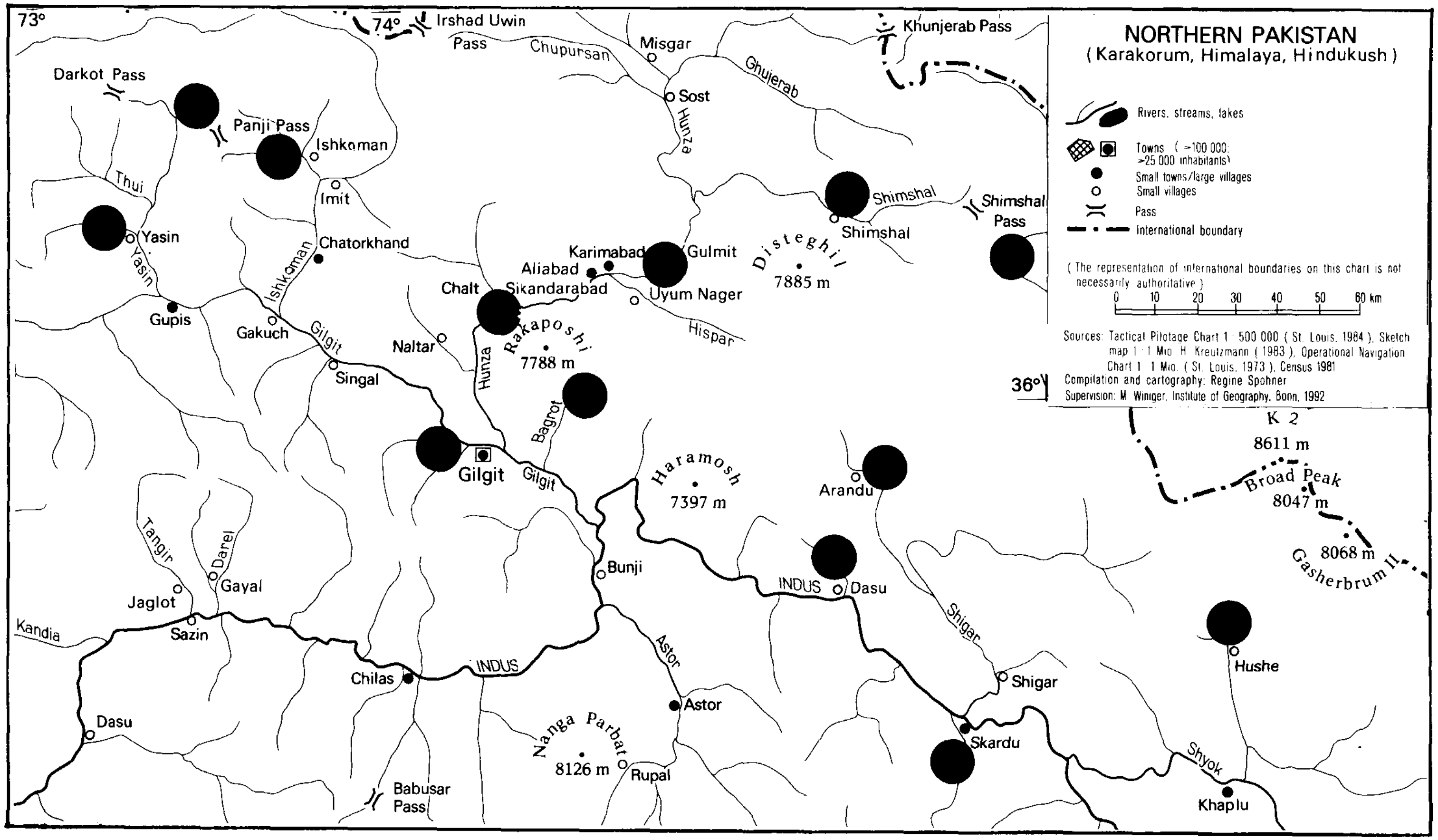


Fig. 17. Areas where interviews related to weather and climate (black dots) with farmers and shepherds of the northern areas of Pakistan have been made during the 1990 and 1991 fieldwork.

—At the arid periphery of the Karakorum (transition zone between Karakorum and Kunlun, sub- to euarid sequence type) humid alpine Cyperaceae mats are confined to (extrazonal) water surplus habitats like flushes. Even there they do not form dense carpets any longer, but have become open and tend to be colonized by species of the alpine steppe.

—In the western transition zone between Karakorum and Hindukush (north of the Panji Pass, see Fig. 17), dark alpine soil, as it is usually built by and found under humid alpine Cyperaceae mats, is actually covered by open alpine mats rich in graminoids and matted hemicryptophytes (S. Miehe et al., Fig. 5), with which steppe soils of light brown colour are connected. Obviously the Cyperaceae have disappeared and species of subarid alpine mats have invaded the ancient soil built by Cyperaceae during a more humid period.

—At the southern margin of the Karakorum (southwest of Gilgit, see Fig. 17) a disturbance of the equilibrium between the upper limit of the alpine mats (S. Miehe et al., Fig. 3) and open frost debris of the free gelifluction belt can be stated: gelifluction lobes are overrunning the highest outposts of alpine turf on sunny slopes only; on the opposite shady slopes, an intensification of periglacial movement is not evident. This is astonishing because periglacial dynamics at the lower border of the periglacial belt are caused by nocturnal frost events which are independent of slope exposure to the sun (Kuhle 1982). This contradiction can be explained with the following hypothesis: the shady slope remains snow-covered in late spring while on the sunny slope, the snow has already melted and the soil is unprotected against frost. It might be concluded that a recent shortening of the snow cover duration gives way to an intensification of periglacial processes on sunny slopes. Moreover it has to be considered that the recent trend of warming which was found in the West of High Asia (Böhner, 1993) might strengthen these features.

5.3. Supplementary observations and interviews

Additional indications of recent climatic changes were found west of the Panji Pass (see Fig. 17): small water courses of springs are surrounded by large sinter-accumulations, the only plausible explanation of which is the presumption that the springs had been much more abounding before.

On the shady slope of the Neobar, in the vicinity of Gamelti, east of Darkot, marginal irrigation terraces had to be abandoned due to decreasing supply with melt water from snow patches of the higher slopes: perennial snow patches diminished and disappeared in the past 30 to 40 years according to farmers' information. This information was confirmed and supplemented in several interviews with farmers and shepherds in the entire study area of North Pakistan (see Fig. 17): winter precipitation (i.e. snowfall) has considerably decreased during the past 30 to 40 years. Obviously the most recent period of desiccation in the northwest of High Asia is caused by a change of circulation in winter. The field observations should be extended to the west where the dominance of winter precipitation and its changes are by far more essential for agriculture and vegetation than in the Karakorum proper with its additional summer/autumn rains.

6. Conclusion

Research in vegetation ecology of High Asia revealed that in the majority of the mountain regions the deteriorating human impact of grazing and removal of woody perennials is increasing. During field work preferably in the alpine belt it has become evident, however, that the decrease of natural resources by human impact is superimposed by climatic changes: Disjunct distribution patterns of phanerophytes of the perhumid cloud forests of the southern declivity of the Central and Eastern Himalayas and the semihumid conifer forests of the Inner Valleys indicate changes of the monsoonal rainfall connected with the desiccation in Southern Tibet.

In the rainshadow of the Himalayas alpine pastures of closed Cyperaceae mats are going to be replaced by stone pavements with alpine cushions and open short grassland. This alpine steppe advances against turfs of *Kobresia pygmaea* along with corrasion of the turfs by the Himalayan föhn.

It is yet unknown during which of the humid periods in the Holocene of High Asia the *Kobresia pygmaea* turfs were built. This younger period of higher humidity in High Asia is suggested to be designated as "*Kobresia pygmaea* age". Actually the alpine desert of the Northwest Plateau (Aksai Chin) obviously advances against the alpine steppe belt, and the latter advances against the alpine Cyperaceae turfs in the southeast quarter of the Highlands. This environmental change is part of the general climatic trend of Central and High Asia during the last 8000 years.

The extension of arid environments interferes in the southern and eastern parts of the Tibetan Plateau with a younger trend of cooling which was deduced from intensified gelifluction and a recent descent of the free gelifluction belt into the closed Cyperaceae mats of the alpine belt. Intensified gelifluction processes are in accordance with a recent thermal trend of cooling, at least during the period between the late 1950s and the late 1970s (Böhner, 1993).

Scattered patches of open substratum which are freely moved by gelifluction and have not been recolonized by vegetation at least during the last 40 years, even though they are surrounded by turf cliffs of closed alpine Cyperaceae mats, lead to the following hypothesis: the present extent of the alpine mats is a relict of the Climatic Optimum; since then the alpine turfs have been destroyed patchwise and their upper limit was pushed downwards in dependence of the morpho-dynamical sensitiveness of the substratum. Not the alpine turfs, but the patches of open substratum are in accordance with the present climate.

In the Karakorum findings from the arid periphery of the forest tree species and the thermal and drought limits of humid alpine Cyperaceae mats revealed a recent loss of vigour of forest regeneration in the first case. The same applies to the Cyperaceae mats which retreat against frost-moved debris on sunny slopes at their upper limit and against alpine steppe species invading the turfs at their drought limit. Interviews with farmers and shepherds indicated that a decrease of winter precipitation during the last 30 to 40 years occurred which should have contributed to these youngest features of desiccation in the northwest of High Asia.

The reconstruction of the climatic history of the Holocene and the historical past is up to now bound to the results of ^{14}C-dated palynological research, dendrochronology and the statistical evaluation of climatic data. The statistical approach to the problem of humidity changes failed in the Karakorum, due to the unfortunate locations of the climatic stations. Yet, it is hoped that research on humidity changes is no longer necessarily bound to the availability of climatic data. In the remote mountain areas ecologically sensitive transition zones between vegetation belts and formations, e.g. the upper treeline, the drought limit of forests, the upper border of the alpine belt and the transition zone between alpine mats and alpine steppe provide information which might be valuable for the progress of research in climatic changes.

Acknowledgements

Fieldwork in the Karakorum and neighbouring mountain areas was carried out 1990, 1991 and 1992 together with Dr. S. Miehe, Prof. Li Tianchi and Prof. Xu Daoming in the framework of the Pakistani-German "Culture Area Karakorum" research project of the German Research Council (Speaker: Prof. Dr. I. Stellrecht; Chairman of the Physical Geography Section: Prof. Dr. M. Winiger). The reconnaissance in Southern Tibet was made during the Sino-German Joint Expedition 1984 (Leaders: Prof. Wang Wenying, Prof. Dr. M. Kuhle), financed by the German Research Council, the Max-Planck-Gesellschaft and Academia Sinica. Stimulating contributions of Prof. Dr. H.-J. Beug, Dr. J. Böhner, Prof. Dr. J. Hövermann, and Dr. F. Lehmkuhl are kindly acknowledged. Most of the plant names refer to determinations of Dr. B.W. Dickoré ("Flora of the Karakorum"). To all the author wishes to express sincere thanks.

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