CLIMATE PATTERN, SNOW- AND TIMBERLINES IN THE ALTAI MOUNTAINS, CENTRAL ASIA

With 9 figures

MICHAEL KLINGE, JÜRGEN BÖHNER and FRANK LEHMKUHL

Zusammenfassung: Klimaverhältnisse, Schnee- und Waldgrenzen im Altai Gebirge, Zentralasien

In den dünn besiedelten Gebieten Zentral- und Hochasiens besteht nur ein weitmaschiges Netz von meteorologischen Messstationen. So muss bei einer flächenhaften Analyse der klimatischen Verhältnisse über große Gebiete hinweg interpoliert werden. Ein hervorragender Ansatz zum Schließen dieser Informationslücke erschließt sich aus der räumlichen Verbreitung von unterschiedlichen geoökologischen Landschaftseinheiten, die an spezifische klimatische Parameter gebunden sind.

Mit Hilfe eines räumlich hochauflösenden, relief-parametrisierten Klima-Analysemodells können geoökologische Grenzen und Höhenstufen, wie z.B. Gletscher-, Wald- und Wüstenregionen ausgewiesen werden. Die Validierung des Modells erfolgt durch empirisch ermittelte Proxydaten, die auf der Basis von topografischen Karten, Luftbildern, Geländeuntersuchungen und Literaturangaben gewonnen werden. Auf diesem Wege können auch klimatische Grenzwerte bestimmt werden, die das räumliche Muster von Vegetationsgesellschaften und klimageomorphologischen Formungs- und Prozessregionen bedingen.

Das Untersuchungsgebiet befindet sich im nördlichen Zentralasien und erstreckt sich vom Altai-Gebirge im Westen bis in das Changai-Gebirge im Osten. Dieser Bereich liegt an der Grenze zwischen der sibirischen Taiga im Norden und den Steppen und Wüstenregionen im Süden. Hier bildet die Gebirgswaldsteppe einen Saum zwischen dem borealen Waldgürtel und den zentralasiatischen Trockengebieten. Diese Landschaftseinheit wird durch die ausschließlich auf nordgerichteten Hängen verbreiteten Lärchenwälder (*Larix sibirica*) geprägt. Die Südhänge werden von Gebirgs-Steppenvegetation eingenommen. Die geringere solare Einstrahlungssumme auf den nordexponierten Hängen reduziert die Evapotranspiration an diesen Standorten. Tiefe Luft und Boden-Temperaturen begünstigen das Auftreten von diskontinuierlichem Permafrost. Das führt zu einer besseren Wasserversorgung im Boden und die genügsamen Lärchen können trotz Jahresniederschlägen von unter 200 mm/a gedeihen.

Während die obere Waldgrenze allgemein durch niedrige Sommertemperaturen geprägt ist, wird im zentralasiatischen Trockengürtel die untere Begrenzung des geschlossenen Waldes durch geringe Niederschlagssummen hervorgerufen. Die Anzahl von verschiedenen Baumarten wächst ähnlich wie die vertikale Mächtigkeit des Waldgürtels mit der Zunahme der Niederschläge.

An der westlichen Abdachung des Altai-Gebirges steigt die obere Waldgrenze steil von 1.000 auf 2.000 m an. Im zentralen und südlichen Altai liegt sie in einer relativ konstanten Höhe zwischen 2.400 und 2.600 m und erreicht stellenweise bis zu 2.800 m. Im nördlichen Altai, im Sayan und im östlichen Khan Khukhiyn-Gebirge liegt die obere Waldgrenze unter 2.200 m. Die untere Waldgrenze steigt stetig von 800 m im Westen und Norden bis auf 2.220 m im trockenen Zentrum des Altais an. Demgegenüber weist sie im südlichen Altai einen steilen Anstieg von 1.500 m im Südwesten auf 2.500 m nach Nordosten hin auf. Weiter im Osten, im Changai-Gebirge, nimmt die Höhenlage der unteren Waldgrenze von 2.250 m im Südwesten auf 1.250 m nach Nordosten wieder ab.

Die klimatischen Schwellenwerte der Gletscherschneegrenze entsprechen denen der Waldgrenzen. Die Höhenlage der klimatischen Schneegrenze wird im Altai-Gebirge durch die Abnahme der Niederschläge nach Südosten hin gesteuert. Die klimatische Schneegrenze steigt von 2.600 m im Nordwesten auf über 3.800 m im Südosten des Altais an. Über dem zentralen Altai ändern die Isochionen ihren breitenkreisparallelen Verlauf in eine meridionale Richtung. Die Variationen der Gletscherschneegrenze in Relation zur Hangexposition und zu den orographischen Einstrahlungsverhältnissen innerhalb der einzelnen Gebirgsstöcke weisen deutlich auf die zyklonalen Hauptniederschlagsrichtungen hin. Sie geben aber auch Auskunft über lokale Niederschlagsverhältnisse. Der überwiegende Anteil feuchter Luftmassen wird advektiv aus Westen herangeführt. Im südlichen Altai zeigt sich ein dominanter Feuchtigkeitstransport aus südwestlichen Richtungen.

Summary: In the sparse populated areas of Central and High Asia, where climate measurements are rare and spatial climate data has to be interpolated from few meteorological stations, the geo-ecological environments provide detailed information about climate patterns. With the help of a high-resolution spatial climate-analysing scheme the potential area of geo-ecological zones, like glaciations and forests, can be outlined. Comparing these results with empirical collected geo-information from topographic maps, air photos, fieldwork and literature creates an instrument to evaluate the model and to estimate the climate patterns, which control the variation of geomorphologic features and vegetation associations. In a further step the past and future ecological environments can be delineated by these climate parameters.

The investigation area in the Altai and Khangay Mountains borders the Siberian taiga in the north to the desert and steppe regions of Central Asia in the south. A typical character of the boundary zone between the woodland and steppes in this region is, that the forests, exclusively constituted of larch trees (*Larix sibirica*), are restricted to the northern side of the slopes.

The minor solar radiation input on the north facing slopes arouses less transpiration than on the southern slopes, where mountain steppe occurs. Low annual air temperatures effect the development of discontinuous permafrost. This leads to better soil water supply and larch trees are able to grow at sites with less precipitation than 200 mm/a.

While low summer temperatures mainly control the upper timberline, the lower closed forest boundary is limited by the amount of precipitation. The number of tree species and also the vertical extension of forests in the Altai and Khangay Mountains increase with more precipitation. The upper timberline in the Altai rises steeply from 1,000 m to 2,000 m at the western border. Above the central and southeastern Altai and in the Khangay Mountains it remains in a relatively constant elevation between 2,400 m and 2,600 m. At several places it reaches more than 2,800 m. In the northern Altai, the Sayan and in the eastern Khan Khukhiyn Mountains the upper timberline remains below 2,200 m. The lower forest boundary steadily rises from 800 m in the west and north to 2,200 m in the dry centre of the Altai. It steeply rises from 1,500 m in the southwest to 2,500 m in the northeast of the southern Altai. In the Khangay the lower forest boundary declines with the increasing precipitation from 2,250 m in the southwest to 1,250 m in the northeast.

The climatic indications of the snowline coincide with those of the timberlines. In the Altai Mountains the altitude of the snowline is predominantly controlled by the decrease of precipitation to the southeast. The snowline rises from 2,600 m in the northwestern part to more than 3,800 m in the southeast and changes its latitudinal course into a longitudinal direction above the central Altai. The variation of the snowlines in regard to the slope aspects of one mountain system provides information for the local precipitation distribution and points to the main direction of wet air masses. Although most of the precipitation in the Altai is coming from western directions, in the southern Altai a huge quantity of precipitation is also coming from the southwest.

1 Introduction

Different zones of geomorphologic environments and vegetation units can provide evidence for climate conditions in high mountain environments, where empirical climate data are rare. This is especially important for sparse populated regions of Central and High Asia, where meteorological stations are predominantly situated in basins close to settlements and measurements of a short period may often be uncertain. The climatic significance of vegetation units and of zones with common geomorphologic features and processes, expressed in the upper or lower limits of their distribution, are discussed by TROLL (1973 a, b), HÖLLERMANN (1985), and HOLTMEIER (2000).

This paper focuses first on the spatial distribution pattern of glacier-snowline and timberline as indications for the climatic conditions of mountain environments in the Altai and Khangay Mountains. Secondly, the spatial distribution of glaciers and forest is presented in an environmental modelling.

The distribution of modern forests and glaciers in the entire Altai Mountains was derived from different sources, like topographic maps, air photos, field observations, literature, and data offered from the Internet. Geo-ecological parameters, as the glacier-snowline and the timberline, provide information for climatic conditions in high mountain areas. Glaciers are controlled by climate and topography. Especially temperature and precipitation are determining the elevation of the glacier-snowline. While the lower boundary of closed forest is controlled by humidity (more than 300 mm/a), the upper timberline is caused by low summer temperatures and can be estimated by mean July temperature of about 10 °C. The vegetation cover in southern Siberia and western Mongolia has strongly been influenced and changed by human activities since Neolithic times. For example, in the 18th century huge forested areas in the western Altai had been cut for the mining industry in the Kolywan district. They did not recover before Peter Sangin found the resources of coal in the Altai Mountains in the 19th century (BUCHHOLZ 1961). Therefore the natural distribution of forest could have changed, and thus can cause misinterpretations of the climate signal.

The geo-climatic proxy-data can be derived from different vegetation characters or climate induced geomorphologic indicators, as they occur in glacial, periglacial, steppe, and desert environments (BÖHNER a. LEHMKUHL 2003). In order to detect their climatic determinants and to obtain suitable climate transfer functions, e.g. for climate reconstruction purposes, a GCM-forced downscaling and climate regionalization scheme was developed. This model links climatic observations of the meteorological station network to large-scale circulation patterns (represented by NCEP/NCAR T62 reanalysis series) by semi-empirical and statistical approaches. Under consideration of advanced terrain parameterisations, the climate regionalization approach yields spatial climate estimates (long term monthly and annual means of temperature, precipitation, evapotranspiration, radiation) for Central and High Asia in a regular grid spacing 1 x 1 km (BÖHNER 2003 a). This enables the calculation of limiting climatic conditions for the timber- and snowline distribution and an estimation of the spatial distribution of different geomorphologic process regions and vegetation units in Central Asia.

2 The study area

The study area includes the Russian, Mongolian, and Chinese Altai and the western part of the Khangay Mountains (Fig. 1). The investigations concentrate first on the entire Altai, and second on the Khangay between 82° and 102°E, and 46° to 52°N. The Altai Mountains are located south of the West-Siberian lowlands and north of the Dzungarian and the Gobi deserts. In the northeast, the Altai Mountains are linking to the Sayan Mountains, and in the southeastern part they extend into the Gobi Altai. The dry basin of the "Valley of Great Lakes" is located in western Mongolia between the Altai in the west and the Khangay in the east. The rivers of the western and northern parts of the Altai Mountains (Russian Altai) drain towards the Arctic Ocean by the rivers Irtysch, Ob, and Jenissei. In contrast, the eastern and southern parts (Mongolian Altai) have internal drainage systems towards the basins of Central Asia. The southern side of east-west trending Khangay Mountains drains to the endorëic basins of the Gobi Desert. At the northern side the Selenga and Orchon Rivers flow into the Lake Baikal. This area has a connection to the Arctic Ocean via the Angara and Jenissei Rivers.

The mountain ranges rise from 2,000 m in the northwestern Altai to elevations of more than 4,500 m in the Central part of the Russian Altai (Belucha). However, the Mongolian Altai only reaches lower elevations. The highest summit is the Tavan Bogd with 4,370 m at the boundary of the four countries China, Mongolia, Kazakhstan and Russia. The western forelands of the Russian Altai are below 200 m, whereas the lowermost intramontane basin in western Mongolia, the Uvs Nuur Basin, has an elevation of about 760 m. The western Khangay Mountains are about 3,500 to 3,700 m and reach their highest elevation at the Otgon-Tengor Uul with an altitude of 3,905 m.

The main geological structures in the Altai trend in N-S, WNW-ESE, and NW-SE directions. However, in

Fig. 1: The investigation area of the Altai and Khangay Mountains in northern Central Asia.
Das Untersuchungsgebiet im nördlichen Zentralasien.

the western part of the investigation area the tectonic structures are also W-E oriented. While steep eroded valleys are predominating the relief in the western and southern Altai, in the eastern Altai intramontane basins including widespread alluvial fans divide the various, mostly isolated mountain systems. The barriers of the Altai ranges capture the precipitation of wet air masses coming with the westerlies. This results in vast dryness east of the Altai in the Valley of Great Lakes.

A high temperature range, with winter temperatures below –30 °C, characterises the present extreme continental climate. The high-pressure cell of Siberia causes this in wintertime. It controls the climate in this region producing autochthonous cold and dry weather situations with temperature inversion and cold air in the basins. Most of the precipitation, transported by the westerlies, occurs during the short summer between June and August (Barthel 1983; Lydolph 1977). In contrast to the eastern Mongolian Altai, where the winter is a very dry period, in the western Russian Altai precipitation even occurs in wintertime as a result of a few westerlies. The northwestern parts of the Altai receive precipitation of more than 800 mm per year (KOMITET GEODESII I KARTOGRAFII CCCP 1991). Rainfall decreases to 300 mm in the southeastern ranges and to less than 50 mm in the Basin of the Great Lakes in the east. The daily maximum temperatures reach up to 40 °C in summer and the daily minimum temperatures are about 50 °C in wintertime (Barthel 1983). According to the data of the climate stations, the mean annual air temperatures (MAAT) are between 6° and 7 °C in the mountainous regions, about 0 °C in the Basin of the Great Lakes and between 4–6 °C in the basins of the south.

3 Methods

The distribution of glaciers was derived from fieldwork, topographic maps, and air photos. The elevation values for the calculations of the glacier-snowline were taken from the topographic maps 1:100,000. For selected areas of the Mongolian Altai glaciers were mapped from air photos. In addition, glacier data offered by the World Glacier Inventory in Boulder, Colorado, is available for the Russian Altai (Hoelzle a. Haeberli 1999). This data set was proofed on its accuracy by topographic maps and wrong positions and aspects of glaciers had to be corrected.

The snowlines of 2,050 Glaciers from forty-four extensively glaciated areas and from ten minor glaciated peaks were calculated by a simplified method (Louis 1954). The glacier-snowline (or equilibrium line altitude = ELA) can be estimated from the arithmetical average of the altitude between the highest peak in the catchment area and the lowest margin of the terminal moraine. This method (Toe-to-Summit method = TSAM, cf. Benn a. Lehmkuhl 2000) provides a very useful and rapid method where mass-balance data is unavailable. However, Gross et al. (1976) showed that, for the European Alps, the TSAM method produces ELA-values, which are approximately 100 m too high. In contrast, for modern glaciers of the Turgen-Kharkhiraa, the northernmost mountain range of the Mongolian Altai, the calculated values fit well with estimated snowlines on glaciers observed in the field and visible on aerial photos (Lehmkuhl 1998; Klinge 2001). The TSAM method is likely to encounter problems where the highest summit is unrepresentative for the catchment area as a whole and contributes little to glacier accumulation. Because this method does not yield the real glaciological ELA of an individual glacier, Benn and Lehmkuhl (2000) suggest terming this snowline value "Glacier Elevation Index" (GEI).

In this study, the individual glaciers were classified into eight different aspects (Fig. 2). For every aspect of a specific mountain system the average mean snowline elevation was calculated, which is named GEI_A. The average mean of these eight aspects represents the local "climatic" snowline (GEI_L) of a specific mountains system. Due to the large number of data the influences of relief on the calculated snowlines is minimised. As the snowline is a climatic indicator of an exponential relation between precipitation and temperature (e.g. Böhner a. Lehmkuhl 2003; Benn a. Lehmkuhl 2000; Lehmkuhl 1995; Jenny a. Kramer 1996; Rost 1998), this detailed analysis provides useful records on climatic conditions in this high elevation (Klinge 2001).

The deviation (GEI_D) of the average snowline of one direction class GEI_A from the "climatic" snowline GEI_L, the average of all eight directions, represents a "local" snowline curve, which describes the climatic environment in a regional scale. From 44 mountain systems a "normalised" snowline curve is resulted from the average mean values of the "local" snowline deviations GEI_D in each direction class. Shown by Klinge (2001), this "normalised" snowline curve (Fig. 2) is highly correlated to the solar radiation input in regard to relief, slope aspect and the main direction of precipitation transported from the west. This "normalised" curve itself can be compared to each "local" snowline curve calculated for each aspect of a specific mountain system (Fig. 3). The differences between these two values indicate relatively drier or wetter climatic conditions on a more local scale.

In addition, the distribution of wood-covered area and forest has been mapped from the topographic maps 1:100,000 and 1:200,000 (Fig. 4). Air-photos and fieldwork proof an accurate indication of woods in these maps. Three classes were differentiated: forest on every slope, forest exclusively in northern directions and areas of no forest. Sites at the valley bottoms beside the rivers, which are influenced by groundwater and where trees like poplar (*Populus spec.)* and widow (*Salix spec.)* grow, were excluded.

Five hundred and eighty points at the upper timberline and the lower forest boundary were chosen to represent the spatial distribution of forest in the Altai and western Khangay Mountains. The upper timberline and the lower forest boundary are determined from closed forests, because individual trees are not indicated in these maps and the aim was to describe a general climatic phenomenon of the upper tree line.

In order to describe the comprehensive distribution of the timberlines, the data was interpolated by using a geographic information system (Fig. 5, Fig. 6). Three-dimensional surface data and maps were created for three different levels: the upper timberline, the lower forest boundary and the glacier-snowline. Comparing these levels, maps and data of three altitudinal distances can be calculated: the vertical extension of forests (Fig. 7) and the altitudinal distance between the snowline and the upper timberline or the lower forest boundary (Fig. 8).

4 *Results of empirical investigation*

In the Altai Mountains present glaciers occurs at the highest peaks above the main planation surface in the centre part of various mountain systems. Beside plateau-glaciers and cirque-glaciers, many isolated ice-patches occur. In the eastern part of the Altai valley glaciers are rare, whereas many of them occur in the western part of this mountain, the Russian Altai. In the Khangay a glacier is exclusively represented at the highest peak Otgon Tenger Uul. Information about the recent snowline in the Altai Mountains is given by KLINGE (2001) and KOTLJAKOV et al. (1997).

According to the decreasing precipitation the "climatic" (overall) snowline GEI_L rises 1,200 m from 2,600 m in the northwestern Altai to more than 3,800 m in the south-east (Fig. 3). In the central Altai the snowline changes its latitudinal (W-E) direction into a longitudinal direction, which is caused by the rain capture of the western mountain ranges. In contrast to the general course of the "climatic" snowline, the "local" snowline curves GEI_D give information about the local precipitation origins. In the northwestern part of the Russian Altai the glaciers terminate relatively high in northern directions and are relatively low in southern directions. In this region a large proportion of rainfall comes from southeastern directions. The lower mountains in the northwestern edge of the Altai capture much of the precipitation coming from northern directions. In the

direction class	number of individual	GEI_D m
N	607	-86
NE	456	-72
E	216	-23
SE	158	27
S	107	116
SW	109	80
W	105	13
NW	278	-56
total	**2036**	

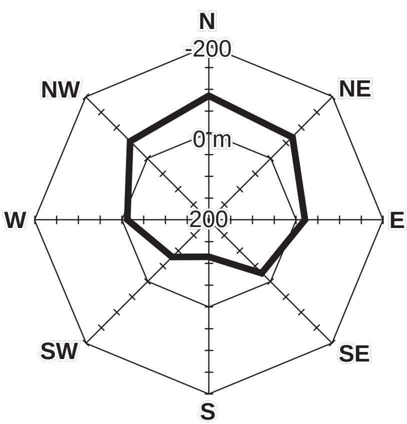

Fig. 2: The mean deviation GEI_D of the average aspect snowlines GEI_A from the local snowline GEI_L as the average of 44 glaciated mountains systems in the Altai. This snowline curve represents the background for the comparison with the regional snowline curves in Fig. 3.

Diese Kurve zeigt die im Durchschnitt von 44 Gebirgsgruppenvergletscherungen ermittelte Abweichung der lokalen, orographischen Schneegrenzwerte (GEI_D) einer Expositionsklasse (GEI_A) von der klimatischen Schneegrenze (GEI_L) als dem jeweiligen Mittelwert aller Expositionsklassen eines vergletscherten Gebirgsstockes im Altai. Auf der Basis dieser mittleren Verteilungskurve erfolgt die Analyse von unterschiedlichen lokalen Schneegrenzverhältnissen in Abb. 3.

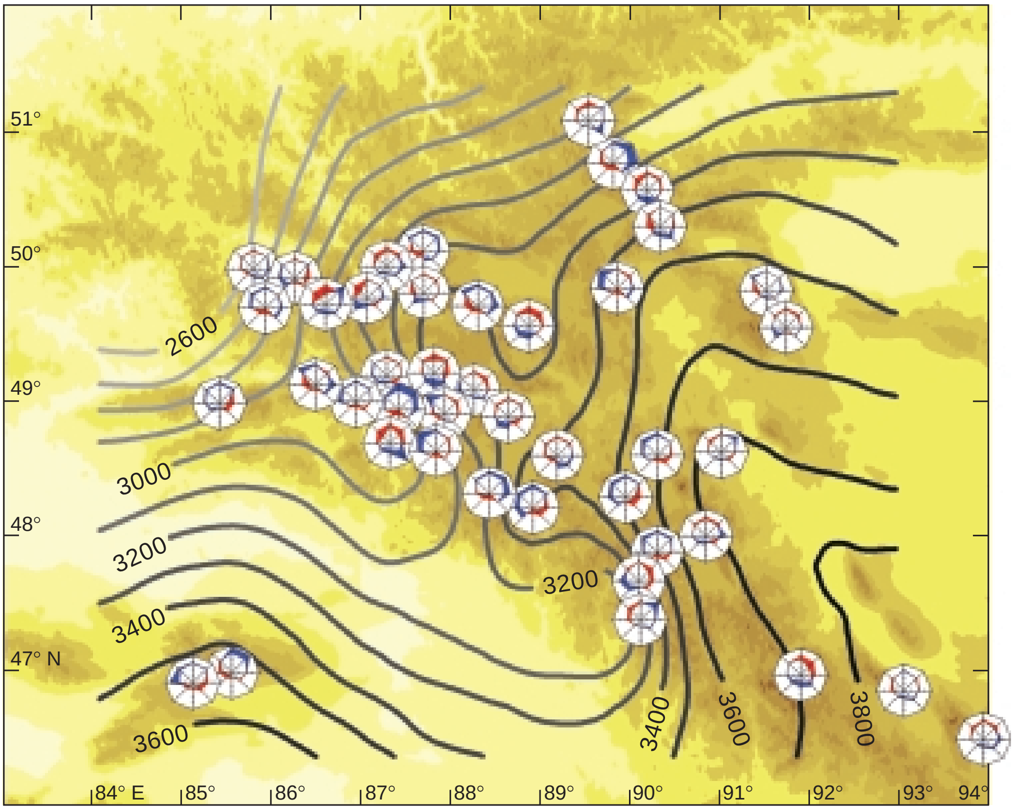

Fig. 3: The recent glacier-snowline in the Altai Mountains. The diagrams indicate the local snowline variations GEI_D of single mountain systems. Blue areas represent lower and red areas higher snowlines than the average snowline curve.

Die rezenten Isochionen im Altaigebirge. Die Diagramme zeigen die lokalen expositionsabhängigen Variationen der Schneegrenzen GEI_D in den einzelnen Gebirgsstöcken. Blaue Flächen weisen auf niedrigere und rote Flächen auf höhere Schneegrenzwerte als in der durchschnittlichen Verteilung hin.

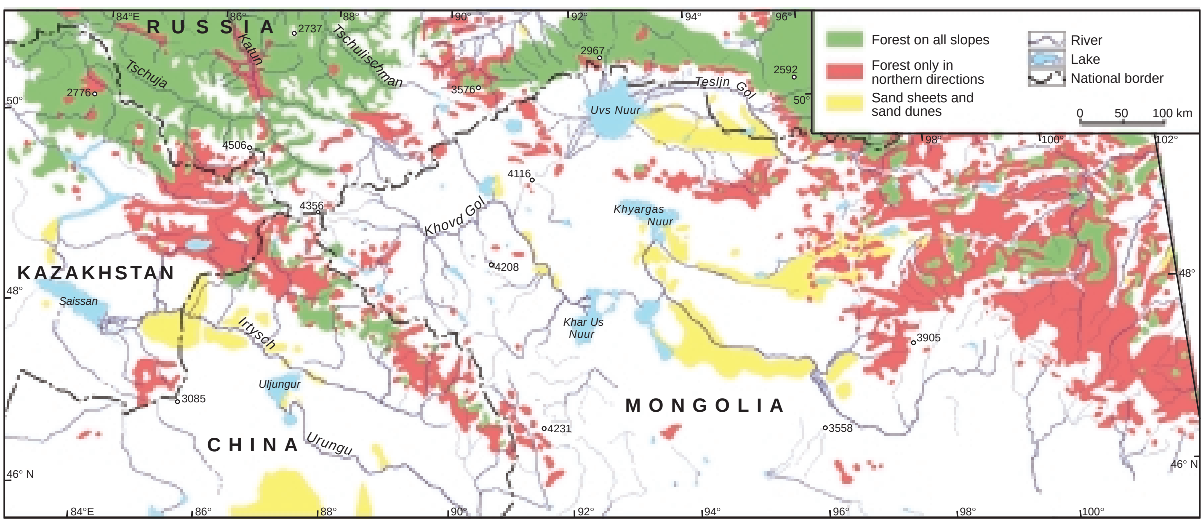

Fig. 4: The distribution of forest in the Altai Mountains and western Mongolia.

Die Waldverbreitung im Altai und in der Westmongolei.

neighbouring southwestern mountain ranges the directions of lower glacier termination face each other. The west-east trending tectonic valley of the Buchtarma River, a tributary of the Irtysch River, leads the wet air coming from the west deep into the central mountains. In the southern part of the Mongolian Altai the northern aspects have higher and the southern aspects have lower snowline values GEI_D with regard to the mean value. This points to relatively dry northern slopes in the rain-shadow of the central Mongolian Altai. The main precipitation in these mountain systems is coming from southern directions. This phenomenon may be caused by the so-called Amu Daryo Cyclone (LYDOLPH 1977).

The vegetation of the Russian Altai is described by BUSSEMER (1999), GORODKOV (1955), KOMITET GEODESII I KARTOGRAFII CCCP (1991) and KUMI-

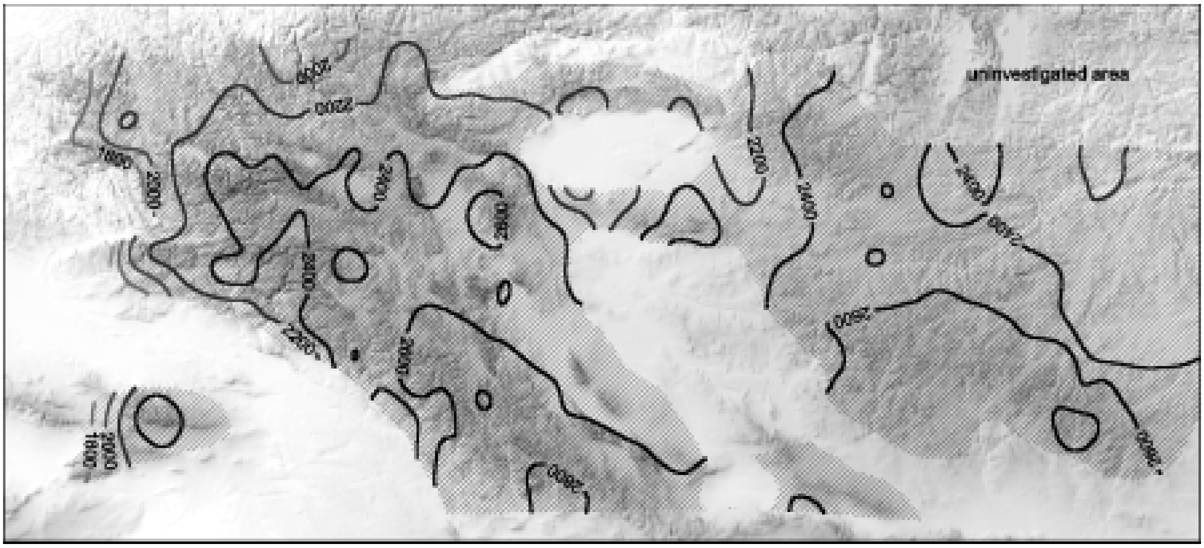

Fig. 5: The upper timberline in the Altai Mountains and western Mongolia.
Die obere Waldgrenze im Altai und in der Westmongolei.

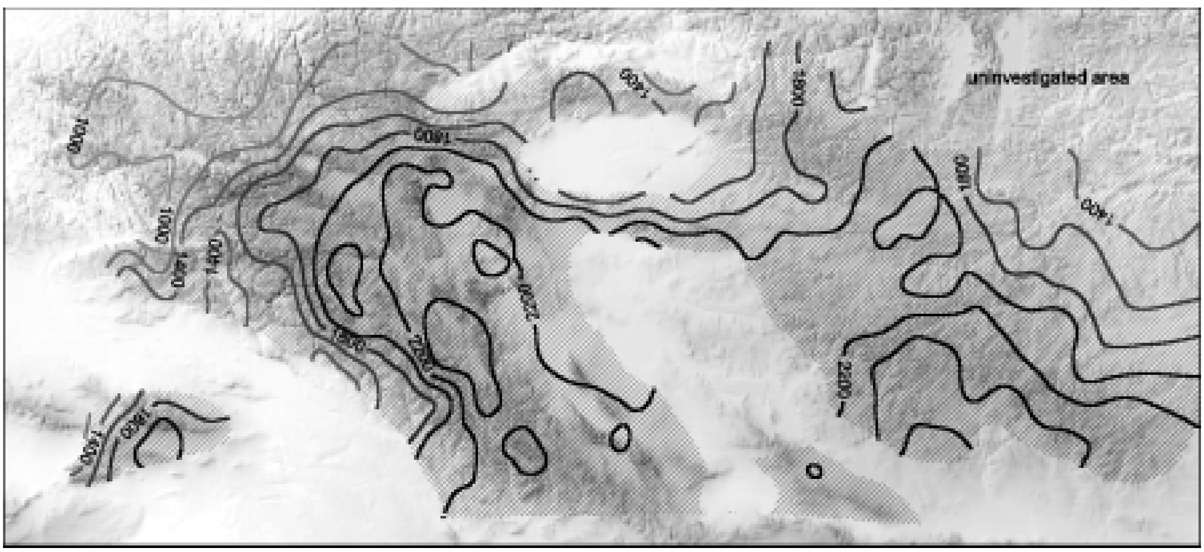

Fig. 6: The lower forest line in the Altai Mountains and western Mongolia.
Die untere Waldgrenze im Altai und in der Westmongolei.

NOVA (1960). Information about the distribution of vegetation zones in Mongolia is given by HILBIG (1995) and by the ACADEMY OF SCIENCES OF MONGOLIA a. ACADEMY OF SCIENCES OF USSR (1990). The vegetation belts of the Chinese part of the southern Altai and the northern Tian Shan are shown by ANONYMUS (1990), CHANG (1984), CHEN (1987), FICKERT (1998) and WALTER a. BRECKLE (1994).

In the moister regions of the northwestern Altai all slope aspects are covered with forest. Coniferous trees like pine (*Pinus silvestris*), stone pine (*Pinus sibirica – Pinus cembra)*, fir (*Abies sibirica)*, and spruce (*Picea obovata)* spread. Fir forests are mainly distributed in northeastern Altai (BUSSEMER 1999). Spruce forests can be seen along the rivers on floodplains and on the first terrace almost everywhere in the northern Altai, while they are

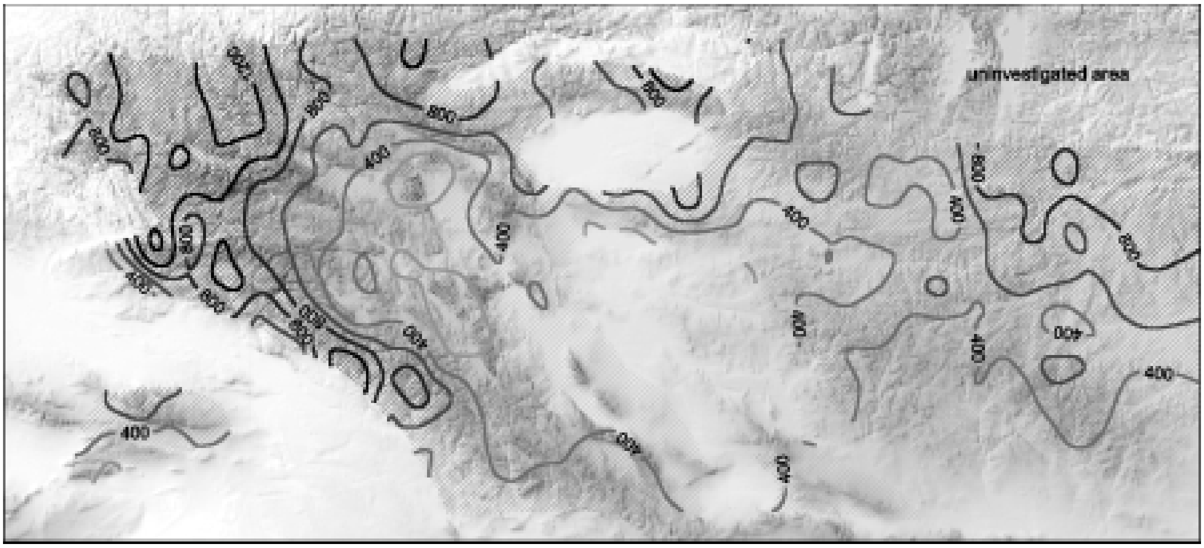

Fig. 7: Altitudinal extension of forest.
Die vertikale Ausdehnung der Waldstufe.

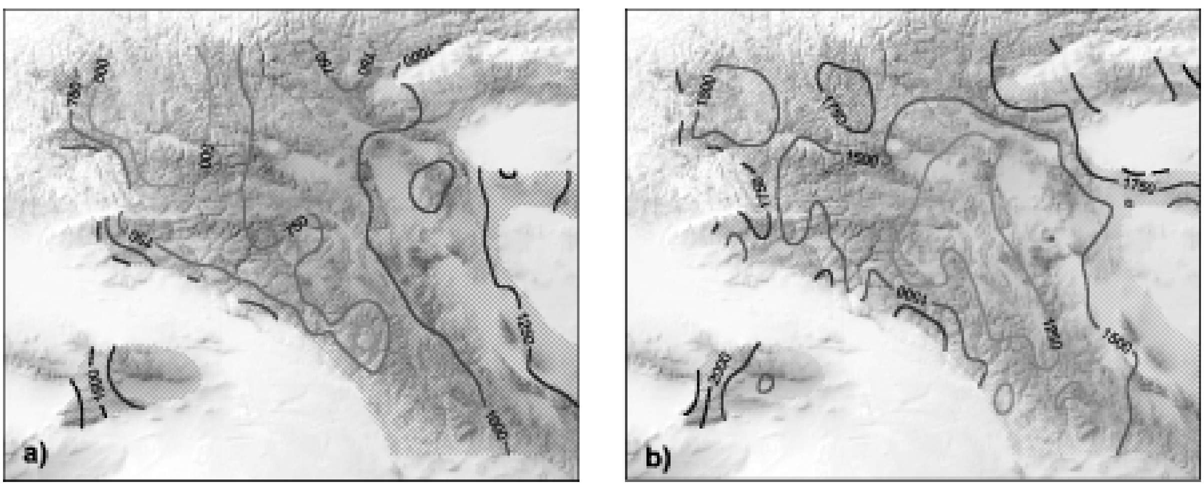

Fig. 8: The vertical distance between the snowline and the upper timberline (a) and lower forest line (b) in the Altai Mountains.
Der vertikale Abstand zwischen der Schneegrenze und (a) der oberen Waldgrenze bzw. (b) der unteren Waldgrenze im Altai.

absent in the central Altai. North of 50°N stone pine forests usually occupy the upper part of the forest belt and represent the timberline. In the northern Altai, forests of exclusively larch trees on north facing slopes and mountain steppe on the south side occur in the lower forest belt in the main valleys, the intermountain basins and the forelands. In the upper parts of the mountains the forests occur on every slope and the tree communities change to stone pine mixed with larch.

Larch dominates in the southern Russian Altai and in the Mongolian Altai. In the northwestern edge of the Chinese Altai, where the annual precipitation is between 500 and 800 mm, spruce, pine and fir also occur in a belt of 1,000 to 1,300 m (CHEN 1987; ANONYMUS 1990). Locally there are also leaf trees, like poplar (*Populus tremula)* and birch (*Betula pendula)*. In the centre part of the Chinese Altai the precipitation decreases to between 400 and 600 mm. Here, in a forest belt of 800 to 1,000 m vertical distance, beside larch trees only spruce and few stone pine trees are distributed.

At the eastern and southernmost parts of the Altai the larch forests decrease to small areas (TRETER 1996, 2000). Remnants of larch forests can be found in the central Altai, south of Turgen-Kharkhiraa and in the north of Tsambagarav Uul, in the southeastern Altai, north of Sutay Uul and in the Gobi Altai, south of the town Altai (Fig. 4). South of this place, in the Gobi Altai near the settlement Bayan-Sair, macrofossils of larch, fir and spruce were dated by radiocarbon analysis to 2.5 and 4.3 ka BP (TARASOV et al. 2000). In contrast, results from palynological peat investigations at the southern side of the Turgen-Karkhiraa showed that the recent expansion of larch forest was not much more denser during Holocene times (SCHLÜTZ 2000).

North of the Khan Khukhiyn Mountains, which are located south of the Uvs Nuur basin, and in upper part of the dune field 300 km east of the lake Uvs Nuur larch trees occur (Fig. 1). North of the Uvs Nuur basin, in the Sayan Mountains mixed coniferous taiga is widespread distributed. HILBIG (1995) divides between the upper forest belt with mixed taiga and the lower forest belt of exclusively larch forest. In the northern Khangay the upper forest belt with larch and stone pine trees is represented. The lower forest belt reaches more to the south and is also distributed in several places on the southern side of the main water divide of the Khangay Mountains. As observed by fieldwork at several places and shown by BARSCH et al. (1993), where larch trees reach the summits from the north side, they can stretch over the ridge and occupy the highest parts of the southern slopes.

The main character of forest at the outer limit to the dry steppe and desert regions of Mongolia is, that trees are restricted to the north-facing slopes. The south-facing slopes are covered by mountain-steppe (HILBIG 1995; MURZAEV 1954; TRETER 1996, 2000). Larch trees exclusively occupy these north-facing forest sites, south of approximately 50.5°N. The solar radiation in

Fig. 9: The potential glaciated area (white), forested area (light green) and forested area on permafrost (dark green) calculated by the climate regionalization scheme.

Die auf der Grundlage des relief-parametrisierten Klimaanalyse-Modells ausgewiesenen potentiellen Gebiete mit Vergletscherungen (weiß), Waldstandorten (hellgrün) und Waldstandorten auf Permafrost (dunkelgrün).

relation to the slope-aspect influences different soil-temperatures and soil-water supply, which is caused by less transpiration in the northern aspects (KASTNER 2000; LEHMKUHL a. KLINGE 2000; TRETER 1996). Discontinuous permafrost and solifluction processes occur. However, the dependence of forest distribution on the aspect or radiation income in the semi-arid regions may possibly result from the lower risk of freeze-drying due to the reduced vegetation period in northern slope aspects.

With a digital terrain model and GIS-based evaluations of remote sensing data MAYER and BUSSEMER (2001) showed that these larch stands occupy a narrow range of relief positions, which points to their strong dependence on the specific geo-ecological environment of these sites. On the basis of tree-ring analyses, vegetation mapping and soil criteria TRETER (2000) proofed that the recent forest areas in the Turgen-Kharkhiraa serve as refuges for larch trees and they move periodically into the surrounding meadow steppe areas. Triggered by humid climate phases or pasture pressure the larch forests expand or retreat in a limited range (SCHLÜTZ 2000). The dark para-tschernosem soil and the comparable herb-layer species between the meadow steppe and the larch forests underline this character of a forest movement zone (SOMMER a. TRETER 1999). Recently, an expansion of larch forest, forced by a rejuvenation phase, occurs at the upper and lower boundaries, and leads to a depression of the lower timberline in the northeastern Altai of up to 250 m vertical distance during the last 150–170 years (TRETER 2000). With regard to the plant communities HILBIG (1987, 2000) states that the forest steppe is totally influenced by human activity and the natural vegetation would be closed forest.

At the western border of the Altai Mountains the upper timberline increases steeply from 1,000 m to 2,000 m (Fig. 5). More cloudiness coming along with more precipitation causes colder conditions. Above the central and southeastern Altai and in the Khangay Mountains the upper timberline lies in a relatively constant elevation between 2,400 and 2,600 m and reaches more than 2,800 m at several places. This fact proves a relatively constant temperature level. In the northern Altai, the Sayan and in the eastern Khan Khukhiyn Mountains the timberline is below 2,200 m.

The lower forest boundary steadily rises from 800 m in the west and north of the Altai to 2,200 m in the dry central part of the Altai (Fig. 6). In the southern Altai the lower forest boundary steeply increases from 1,500 m in the southwest up to 2,500 m in the northeast. In the Khangay Mountains the lower forest boundary increases with a steady gradient from 1,250 m in the northeast to 2,250 m in the southeast. This phenomenon coincides well with the climatic conditions and underlines that the ascent of the lower forest boundary is predominantly controlled by the increase of aridity.

The vertical extension of the forest belt in the Altai increases from less than 400 m in the dry southeastern part to more than 1,200 m in the north and to more than 1,000 m at the southwestern side of the crest line in the southern part (Fig. 7). In the dry central Altai and in the Khangay the altitudinal extension of forests varies between 200 and 600 m.

The glacier-snowline is controlled by both, temperature and precipitation. In order to proof, which is the main climatic parameter leading to regional differences in snowline altitude, it is necessary to compare the snowline with the timber and forest lines, because the upper timberline is mainly controlled by temperature and the lower forest line by precipitation. This test only makes sense for the Altai region due to the extensive glaciation.

The vertical distance between the snowline and the upper timberline varies between 500 m in the moister regions and more than 1,000 m in the drier regions (Fig. 8a). This fact points to the main influence of precipitation on the distribution of glaciation. The altitudinal distance between the snowline and the lower forest boundary is approximately 1,500 m in the glaciated regions of the Altai Mountains (Fig. 8b). In the central Altai the distance decreases to less than 1,000 m and in the southern Altai the altitudinal distance reaches 1,750 m. These differences are mainly caused by extraordinary variations of the lower forest boundary. The forests inside the valleys react stronger to the local spatial distribution of precipitation, which is predominantly governed by relief. The glaciations, which occur on top of the mountains, are influenced by rainfall distribution in a more regional scale.

5 *Environmental modelling*

As concluded above, the spatial distribution of glaciation and timberlines clearly reveals moisture and thermal variations as their major controlling determinants in large to regional scales. Based on the assumption, that the spatial distribution of these climate-sensitive environments is controlled by quantifiable, but specific climatic threshold functions, an environmental modelling concept for late-Quaternary climate reconstruction and potential future climate impact assessments was developed, capable to predict the (e.g.) potential distribution of forest-stands, permafrozen grounds and glaciation on the basis of gridded climate data.

The necessary spatial high-resolution climate data input was estimated from GCM-Data (General Circulation Model), DTM (Digital Terrain Model) and available climate observations. To bridge the spatial-scale gap between the broader resolution grid data output of Global Circulation Models and the demands for an adequate topoclimatic data input for environmental modelling purposes, the regional climate modelling work used an improved GCM-forced (NCEP/NCAR and ECMWF reanalyses data) downscaling scheme. Available climatic observations of Asia's meteorological network (time series of monthly values and additional long term means from more than 400 stations) were linked to large-scale circulation patterns (represented by NCEP/NCAR T62 reanalysis series of six discrete troposphere layers and the surface layer in daily and monthly resolution) by semi-empirical and statistical approaches. The regionalization scheme consists of advanced relief and surface parameterisations (BÖHNER 2003 a). The model domain covers Central and High Asia in a regular grid of 3,000 x 4,000 grid-cells spacing 1 km^2.

Based on these spatial high-resolution topoclimatic estimates (temperature, precipitation, radiation, evapotranspiration), climatic determinants of the recent spatial distribution of climate-sensitive environments (glacial and periglacial environments, forests) were exploited. The empirical data base for the glacier distribution model consist of point-data of geo-referenced snowline altitudes from areas all over Central and High Asia as well as geo-referenced positions of terminal moraines and its corresponding catchment areas, delineated from topographic maps. The spatial distribution of forests was digitised as point-data from topographical maps on the basis of their upper and lower limits in regard to the geographic position and slope aspect.

With respect to the aimed environmental change modelling, simple climatic threshold functions were estimated, defining critical climate values for the regionalization of the considered environments by means of multiple regression analyses (for details s. BÖHNER a. LEHMKUHL 2003). The application of these distinct threshold functions for the entire model domain yields a spatial high-resolution regionalization of the potential current distribution of glacial and periglacial environments as well as for the forest distribution, only to be validated by a critical comparison with mapped geomorphic regions. The distribution of forests (light green), forests on permafrost sites (dark green) and the glaciated area (white) is represented in figure 9.

For the spatial distribution of the ELA, a critical annual mean temperature threshold $T_{(G)}$ is determined by the predictor variables precipitation P (mm/a), annual temperature range A (K), annual mean shortwave radiation R (J/cm^{2}d) and the potential climatic water balance W (mm). The resulting term, which substitutes the heat and moisture conditions at the ELA, was determined to be

$$T_{(G)} = 2.92\ln(P) - 2.98R - 0.12A - 18.74 \text{ and } W>0.$$

The recent climate conditions at the ELA in the Altai were calculated with mean annual air temperatures (mean July temperatures) between −14.0 and −6.4 °C (between 1.0 and 8.4 °C). The annual precipitation rate amounts about 370 to 1,420 mm.

To enable a direct deduction of paleoclimate information from terminal moraines, independent from the choice of a certain ELA approximation, a statistical glacier distribution model was developed additionally. Based on the ELA threshold function, weighted mean climate catchment parameters (s. BÖHNER 2003 b) with alternative weightings were computed for the terminal moraine positions of selected mountain ranges. To obtain a climatic threshold function, that predicts a critical annual mean temperature $t_{(cc)}$ of the catchment area of each grid cell, the natural logarithms of catchment areas (in km^2) were found to be the best weighted estimation. The computed glaciated area fits well with the observed distribution of recent glaciation in the investigation area (Fig. 9).

Although non-zonal forest distributions such as gallery woods, which depend on favourable water budgets in the valley grounds, are not considered in this investigation, the climatic determination of forest borders still turned out to be a problem due to the assumed intensive anthropogenic influences on forest distribution. Nevertheless, based on natural forested areas and refuges, thermal as well as hygric determinants allowed an estimate of the potential forest distribution. The following equation considers that low temperatures are generally limiting tree growth at the upper timberline (expressed by the temperature threshold value $T_{(F)}$) and the lower forest boundary in the arid regions of Central Asia outside valley floors is determined by moisture conditions.

$$T_{(F)} = 5 - 0.35A, P > 330R - 200 \text{ or } P > 350.$$

As reported by PUSACHENKO and SKULKIN (1981, cited in WALTER a. BRECKLE 1994) larch trees are adapted to cold and dry environments with less precipitation between 100 and 300 mm during the vegetation period. On the basis of the processed climate data and the digitised actual distribution of larch forests, which are exclusively occupying north-facing slopes, it is resulted that these trees are able to grow on sites with lower annual precipitation (partly below 200 mm), where permafrost soils occur and the total solar radiation input is less than 1,500 J/cm^{2}d. The mean annual air temperatures at the upper timberline locally decrease to less than –9.0 °C in peripheral settings of the intramontane basins with its characteristic huge annual temperature range. The precipitation rates amount less than 200 mm at locations with discontinuous permafrost, often in northern aspects with mean annual radiation income of less than 1200 J/cm^{2}d.

The forested area in the mountains (Fig. 9) computed by the equation term represented above coincides in many places with the mapped forested area, which is shown in figure 4. In the Khan Khukhiyn Mountains the forest area is resulted smaller than it is. In contrast, at several places in the southeastern Altai no existing forests on frozen ground are indicated on the southern mountainside. On the southern side of the Khangay Mountains the modelled forested area reach more to the south than it really does. At a few places larch forests occur at sites with only 70 mm/a precipitation. These sites may receive additional water supply from the upper parts of the slopes. The limit between the area of forests on frozen ground and without frozen ground does not automatically coincide with the border between forests on every slope and exclusively on north facing slopes.

The main difference between the synthesised and the real situation is visible at forest sites, which are displayed on the pediments of the western forelands. At these plane landscapes, which may probably be potential forest areas, the steppe vegetation dominates and hinders trees to grow up. Observed in the fields and shown by GORODKOV (1955), pine trees are able to grow on the slopes of the erosion lines, which cut this flat in a southwest-northeast direction.

6 *Conclusions*

The climatic indications of the timberlines coincide with those of the snowline. The altitude of the snowline in the Altai Mountains is predominantly controlled by the decrease of precipitation towards the southeast of the investigation area. The compositions of different trees species as well as the vertical distance between the lower forest boundary and the upper timberline decrease in the same direction. At several places in the southern Altai, where the local snowlines indicate that the main precipitation is coming from southern directions, even the forest-belt has a large altitudinal extent and beside larch other tree species like fir, stone pine and spruce occur.

The modelled spatial distribution of glaciation and forests in the Altai and Khangay fits sufficient with the actual situation. The area of potential forest distribution derived from climate parameters can be overestimated, because none-climatic impacts, such as the competition of plant associations or soil water supply, are not taken into account. Although a serious human impact into the vegetation by cutting and burning trees has to be considered, the clear correlation between climatic conditions and timberlines verify that the principles of forest distribution in the Altai and Khangay mountains are still predominantly influenced by climate.

In summary, the distinct climate patterns, which control the distribution and variation of geomorphologic features and vegetation associations, can be estimated with the high-resolution spatial climate-analysing scheme. This circumstance provides an instrument to reconstruct paleoecological environments and paleoclimatic conditions and enables a prognosis of the impacts on the environments under perturbed future climatic conditions (BÖHNER a. LEHMKUHL 2003).

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