MOUNTAIN PERMAFROST WORKING GROUP REPORT

Mapping, Modelling and Monitoring of Mountain Permafrost: A Review of Ongoing Programs

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INTRODUCTION

For its second 5-year period of activity, the Working Group on Mountain Permafrost of the International Permafrost Association (IPA) during the Sixth International Conference on Permafrost held in Beijing, China, 1993, envisaged international coordination and cooperation with regard to mapping, modelling and monitoring of mountain permafrost in order to reach a more complete view in space and time of present conditions and potential future developments (Haeberli, 1994). High priority was given to the development of the monitoring component as part of the newly established Global Geocryological Database (GGD; Barry and Brennan, 1993; Barry *et al.*, 1995) and the formation of Global Climate Observing Systems (Townshend *et al.*, 1995; Cihlar *et al.*, 1997). The schedule for the corresponding steps to be undertaken comprised:

(1) the development and circulation of a questionnaire (see Appendix) about existing programs in 1994;

(2) the compilation of an inventory/overview on the basis of the results from the questionnaire in 1995; and

(3) the delivery of actual data into GGD during 1996/97.

The present review represents the result of step (2). It briefly introduces the basic concepts used, comments on the programs in the participating countries, makes reference to selected publications, and points to the first trends becoming visible from the data bases. These activities complement the stated purpose of the Working Group on Mountain Permafrost which is to "improve the exchange of information on, describe the state of knowledge about, and stimulate research activities concerning permafrost at high altitudes and in rugged topography, especially at low latitudes".

The new PACE project which aims at establishing an important baseline for monitoring mountain permafrost along a north-south transect in Europe is also briefly described. A selective collection of rock glacier inventories and related research activities at different levels of detail concerning study locations in Antarctica, Argentina, Austria, Bolivia, Chile, Greenland, Italy, Kazakhstan, Norway, Romania, Spain and Switzerland can be found on the IPA/CAPS CD.

This product contains (1) metadata documenting investigators, research activities and research sites, (2) data samples: rock glacier inventories, averaged values from inventories, rock-glacier flow velocities, detailed maps, photos, BTS-measurements, etc. Dramis *et al.* (1997) present a collection of observational material from the Alps. The CAPS CD also contains the metadata and first 5-year data from the Circumpolar Active Layer Monitoring (CALM) network. CALM complements the monitoring programs described in this report. Since our work began the IPA circum-arctic permafrost map has been published and illustrates at a scale of 1:10,000,000 the major location of mountain permafrost occurrence in the Northern Hemisphere (Brown *et al.*, 1997).

CONCEPT

Changes in - often relatively warm/thin - mountain permafrost are assumed to take place along vertical profiles with depth at individual points in the form of:

(1) changes in active layer thickness, thaw settlement, frost heave in supersaturated material at the permafrost table as an immediate response (time scale: year(s));

(2) disturbance of temperature profiles within the permafrost, i.e., between the permafrost table and the permafrost base, as an intermediate response (time scale: years to decades and centuries);

(3) displacements of the permafrost base as a definitive response (time scale: decades to centuries or even millennia).

As a consequence of, and interacting with such changes, 3-dimensional dynamics of complex landscapes may induce:

(4) modification of permafrost distribution patterns, involving

(5) adjustment of geomorphic, hydrological and glaciological processes such as permafrost creep, frost heave, thaw settlement, thermokarst, erosion and slope instability on thaw-destabilized slopes, runoff variations in time, drainage pattern evolution, snow cover metamorphism, and avalanche formation.

Potential parameters and techniques considered for long-term monitoring programs can be listed as follows:

Depth to the permafrost table	(shallow) borehole temperatures geophysical surface soundings
Vertical temperature profile	(deep) borehole temperatures heat conduction theory (supersaturated permafrost)
Permafrost base displacements	difficult; precise borehole temperatures
Permafrost distribution patterns	BTS method (thick winter snow cover) geophysical soundings shallow drilling with soil temperature measurements
Thaw settlement and frost heave	geodesy and precision photogrammetry analysis of vector and strain-rate field

Landscape phenomena	aerial photography (small-scale infrared): - vegetation cover on rock glaciers (flow activity), scree slopes (rockfall activity) and debris flow traces (frequency of occurrence) - size and water level of thermokarst lakes - extent of perennial ice patches - drainage patterns
Hydrological processes	discharge measurement (winter maintenance!) snow monitoring (extension to permafrost sites)

Monitoring and modelling efforts are closely interrelated: results from long-term monitoring - as they become available - can be used to calibrate models of transient response at individual points (for instance, heat conduction, melting and thaw settlement in material with variable ice content, etc.). Calculations for individual points can later be combined with spatial simulations of surface permafrost conditions in order to simulate typical transient effects at depth for extended areas. In a further step, such model simulations must be tested and further developed by applying appropriate sounding methods at characteristic sites indicated by model simulations. They could then hint at especially sensitive areas and help in assessing how representative are results from long-term monitoring at a restricted number of sites. In fact, our state of knowledge and preparedness with regard to assessing, and hopefully mitigating, potential effects of realistic warming scenarios, essentially depends on the establishment of adequate long-term monitoring programs.

PROGRAMS IN INDIVIDUAL COUNTRIES

Argentina

The program is part of a larger plan to study present and past geocryologic features in the provinces of Mendoza and San Juan. Present conditions are being studied in two different periglacial areas: two basins with permafrost in rock glaciers (El Salto rock glacier and Morenas Coloradas rock glacier) and another one with seasonally frozen ground and permafrost in the region of the cryoplanation surface of the Pampa de los Avestruces. Data are being collected at locations between southern latitudes 30°-34°, longitudes 69°-70° and elevations up to 5,500 m a.s.l. by continuous recording of standard air temperature, continuous ground temperature recording down to 5 m (thermocouple installations in holes made by inserting steel pipes in the thawed active layer or seasonally frozen ground). They also include snow precipitation, wind (foehn effects), relative moisture, radiation, as well as information on ground-ice, active layer thickness, and soil moisture content.

Rock glacier monitoring by D. Barsch (University of Heidelberg) also continues in the Andes of Mendoza. This long-term program includes photogrammetry and seismic measurements of the active layer thickness. The sites are Morenas Coloradas, El Salto (Mendoza) and Agua Negra (San Juan).

Austria

Based on several local and regional studies, the knowledge about the existence and spatial pattern of mountain permafrost in the Austrian Alps has greatly increased during the last two decades. In fact, it is now possible to summarize the main characteristics of the vertical and horizontal distribution in a monograph (Lieb, 1996). The mapping of mountain permafrost was based on various methods - BTS-measurements and mapping of rock glaciers were of greatest importance. Rock glaciers were mapped over the whole of the eastern Austrian Alps using aerial photographs. In this way an inventory containing different criteria such as the lower limits of all the rock glaciers was produced.

Special studies on mountain permafrost were carried out and are continuing at several test sites using geophysical and geodetic methods. The two most important study areas are the Hochebenkar, Oetztal Alps, Tyrol (Haeberli and Patzelt, 1983), where a good map of permafrost distribution and thickness of the active layer has been produced, and the inner Dösen Valley, Hohe Tauern, Carinthia (Lieb, 1996; Kaufmann, 1996). In the Dösen Valley, research projects on high mountain permafrost started in 1993 as multidisciplinary cooperation of the Department of Geography at the University of Graz, the Department of Applied Geodesy and Photogrammetry at the Graz University of Technology, the Department of Geophysics at the University of Leoben and the Institute of Applied Geophysics at the Joanneum Research Leoben. A map of permafrost distribution and first results of seismic and georadar measurements are already available.

A useful baseline now exists for long-term monitoring of mountain permafrost changes. In the case of Hochebenkar, a series of geodetic surveys allows the observation of the changes in the surface velocity of the rock glacier. In Dösen Valley, a series of maps, compiled by V. Kaufmann at Graz University of Technology, form the basis for a comparison with older aerial photographs and for high-precision photogrammetry to examine future variations in rock glacier permafrost. Borehole drilling and measurements have not been undertaken so far in Austria but are planned for the next few years.

Canada

Ground temperature cables and weather stations were first put in place in alpine permafrost at Plateau Mountain in 1974 (Harris and Brown, 1978), and since then, the network has been extended northwards along the mountains. Continuous temperature observations have been obtained and studies carried out on related features such as ice caves, patterned ground, block slopes, rock glaciers, etc. There is a close relationship between the elevation of the lower limit of continuous permafrost and the winter snow cover (Harris, 1986). At Plateau Mountain, the snow blows off the top, resulting in permafrost at a much lower elevation than at Sunshine Ski Area, with its 2 m snow cover (Harris, 1981). The latter is unusual, and is marked by the only major development of alpine meadows in this part of the Rocky Mountains (Harris, 1995).

The long-term air temperature records at the summit of Plateau Mountain (2,500 m a.s.l.) exhibit a 2°C decrease in mean annual air temperature between 1975 and 1985. This was followed by an increase in variability but no noticeable warming. Several cold air drainage events have occurred since 1985, but none were recorded in the previous decade. This cooling in air temperature between 1975 and 1985 was accompanied by an increase in the freezing index (sum of the negative daily temperatures in a year), while the thawing index remained fairly constant. Comparison with other stations suggests that permafrost in the entire range of mountains is experiencing relatively constant thermal conditions. This fact represents a sharp contrast to the rather dramatic mass losses of glaciers in the same region and during the same time interval (IAHS (ICSI)/UNEP/ UNESCO, 1994). The only exception is at Marmot Ski Area at Jasper, but even there, the mean annual air temperatures for 1991-1994 are similar to those from 1979-1985. The ground temperatures on top of the mountain continue to decrease, although the lower limit of permafrost has risen about 10-15 m. Part of this change may be due to interference in the ground temperature regime by the ski operation. Areas of moisture movement through the ground cause the biggest changes in ground thermal regime (Harris, 1992), and removal of snow by increased strength of westerly winds probably accounts for the continued ground cooling at individual sites.

Mountains also occur in many parts of the eastern Canadian Arctic but they have been little studied. Continuous cold permafrost (<-10°C) prevails in many of these areas and small glaciers are cold-based. Debris flow and slushflow activity in the Sawtooth Mountains on Ellesmere Island were recently examined (Lewkowicz and Hartshorn, 1998) and these sites were visited during the High Arctic Symposium and Field Trip in 1996 (see report by the Periglacial Processes and Environments Working Group).

China

Due to the pervasive influences of permafrost change on the environment and on civil engineering, efforts have been made by Lanzhou Institute of Glaciology and Geocryology to monitor permafrost changes during the past 30 years in the Qinghai-Tibet plateau and the Tianshan Mountains (Wang, 1993; Cheng *et al.*, 1993, in press; Jing *et al.*, 1993). Long-term observations include borehole temperature measuring, moisture dynamics of the active layer (neutron probe), permafrost creep (inclinometer system), movement of rock glaciers, block streams, solifluction and gelifluction, permafrost thaw settlement and frost heave along the highway, vegetation change and other permafrost-related data (DC electrical soundings, radar, remote sensing). Five *in situ* observation fields, more than 20 boreholes along the Qinghai-Tibet highway, and five boreholes near the Tianshan glaciological station, were chosen for the purpose of long-term permafrost monitoring.

In the past 20 or 30 years, permafrost degradation on the Qinghai-Tibet plateau occurred to varying degrees in several districts of different frozen ground types. The evidence includes increases in ground temperatures, contraction of permafrost areas, a decrease in permafrost thickness, disappearance of permafrost, enlarging taliks, etc. Mean annual ground temperatures showed increases of 0.1 to 0.3°C on average in the plateau and permafrost degradation is especially strong in regions near the permafrost lower limits and in regions with little ice in the sediments. In regions where the deposits are rich in ice, the ground temperatures increased more slowly or even remained unchanged. For example, the borehole JXG near the northern lower limits showed a rise of the permafrost base by some 35 cm per year and the ground temperature at depths between 10 and 20 m rose by 0.5° to 0.8°C during the past 20 years. On the other hand, borehole temperatures in the Fenghuoshan where the sediments are rich in ice, have risen only by 0.1 to 0.2°C. Based on the data available, ground temperatures below a depth of 30 m generally increased slowly or even show no obvious change.

The five boreholes used for temperature measurement in the Tianshan have been measured for three years now and do not show obvious changes, probably because of the relatively short record.

France

A great number of resistivity soundings were carried out on active and relict rock glaciers as well as on other permafrost bodies, especially in the Southern Alps (Evin and Assier, 1983; Evin *et al.*, 1991; Fabre and Evin, 1990). Attempts are also being made to monitor the long-term evolution of selected rock glaciers (Francou and Reynaud, 1992).

Germany

Germany has a very limited permafrost area, restricted to the highest regions of the German Alps (Zugspitz-Area, around 2,900 m a.s.l.). Permafrost has been detected occasionally in the course of railway construction work (cf., Ulrich and King, 1993). A 6 m borehole has been drilled in the course of a new cable car construction at the top of the Zugspitze. The site is disturbed by the construction activity. It will be measured regularly in the future. It is planned to drill a 30-60 m deep borehole on Zugspitze at an undisturbed site for long-term monitoring within a project supported by the Ministry of Research and Development.

Mountain permafrost research in Germany focuses on discontinuous mountain permafrost in the Swiss Alps and long-term monitoring is mainly done by the Universities of Giessen and Heidelberg. Long-term observations include shallow borehole temperature measurements, photogrammetry and geodetic surveys of permafrost creep at selected rock glaciers as well as a systematic inventory of geophysical data (refraction seismics, DC resistivity soundings, BTS mapping). An important rock glacier site is Macun (Upper Engadin, Swiss Alps), studied mainly by Barsch and Hell (1976). This rock glacier will be resurveyed at intervals of two to five years; the last surveys were undertaken in 1989, 1992 and 1994. The results show a decrease in flow velocity during the last 25 years. Other rock glacier monitoring sites are located at Albana and Val Sassa and regular surveys at longer intervals are planned there.

Another important research area with geophysical data inventory is the Zermatt area (King, 1990, 1996). Geophysical research and data collection started there in 1983 and continues in order to supply field data for checking results from modelling permafrost distribution patterns. The models will be developed in cooperation with Swiss colleagues.

Rock glacier monitoring also continues in the Andes of Mendoza (cf., text for Argentina).

Italy

Several hundred BTS and shallow ground temperature measurements (STG) were done in the Valtellina area in combination with detailed geomorphological surveys including ^{14}C-dating of buried soils and peats for chronological analysis of the glacial and periglacial evolution of the area. The BTS and STG measurements showed a good correlation not only among themselves but also with the thickness of the active layer as evaluated by means of geoelectric prospecting (Calderoni *et al.*, 1993; Guglielmin and Tellini, 1993; Guglielmin *et al.*, 1994). More than 60 vertical DC resistivity soundings have been carried out on rock glaciers (both active and inactive) and other landforms which - according to measurements of BTS, STG and spring water temperatures - were hypothesized to be characterized by the presence of permafrost. Vertical electric soundings also allowed the identification of different internal structures in relation to the age of the investigated phenomena. Detailed phytosociological surveys carried out in the same area, allowed correlations to be made between vegetation, duration and thickness of snow cover, and the depth of the permafrost table. In addition, mapping of permafrost using satellite remote sensing techniques, furnished relevant and accurate results (Antoninetti *et al.*, 1993). This method will contribute to future monitoring of permafrost variations.

A complete automatic meteorological station was installed in September 1993; the results of the first two years of observations are presently under examination. The meteorological station automatically records wind direction and speed, air temperature, snow cover temperature at different heights, snow cover thickness, rainfall, and incident and reflected solar radiation. Furthermore, it is also capable of measuring soil temperature at different depths (0, 30, 50, 150 and 300 cm) at two different points in the La Foppa I rock glacier and in a nearby tardiglacial moraine in Val Vallaccia overridden by the same rock glacier.

Relict permafrost has been recently found at elevations between 2400 and 2700 m a.s.l. on the Maiella Mountain (Central Apennines) by means of BTS measurements in rock glaciers and surrounding terrain.

Japan

Mountain permafrost was found in the early 1970's in two volcanic regions, Daisetsu Mountains (around 2,000 m a.s.l.) in northern Japan and Mt. Fuji (the summit, 3,776 m a.s.l.) in central Japan, by means of shallow drilling and ground temperature measurements (Fujii and Higuchi, 1978). In the Daisetsu Mountains, this pioneering work was followed by a wide range of studies including the analysis of core materials, long-term monitoring of ground temperature, simulation of permafrost degradation since the Last Glacial period and photogrammetry of palsa formation (Sone *et al.*, 1988). This volcanic permafrost is of special interest in view of the high geothermal activity. Both, climatic change and volcanic activity control the permafrost development. In fact, permafrost in Mt. Fuji is quite young, considered to have grown after an eruption which took place several centuries ago. The sporadic distribution of permafrost on non-volcanic high mountains in central Japan (the Japanese Alps, around 3,000 m a.s.l.) is indicated by a certain number of rock glaciers, which may be active or inactive, and by mountain hut construction encountering frozen ground. Preliminary BTS and seismic measurements suggested that permafrost underlies at least one rock glacier. A permafrost monitoring program has just started at three localities in the Japanese Alps. This program includes long-term monitoring of ground temperature, electrical resistivity measurements, and geodetic and photogrammetric surveys. Automatic recording of freeze-thaw processes (rock weathering, soil heaving and solifluction) also continues near the lower limit of permafrost (Matsuoka, 1994).

Kazakhstan and Central Asia

The focus here has been on monitoring thermal conditions within permafrost and the study of the rock glacier activity and solifluction processes. Most of these geocryological studies have been carried out in the catchment of the Bolshoy Almatinka river near Almaty (Zailysky Alatau Range, Northern Tien Shan). This territory has been proposed as a test region for monitoring cryogenic phenomena. In addition to monitoring activities, maps at scales of 1:1,000,000 and 1:500,000 have been compiled showing permafrost distribution within the whole of the Tien Shan and Pamir mountain chains. According to these maps, the areas of continuous, discontinuous and island permafrost have been determined as 83,000, 76,000 and 110,000 km^2 for the investigated region.

A special geocryological map of the Almatinka test region has been compiled at a scale of 1:25,000. In this region, 10 active rock glaciers are being geodetically observed. Solifluction processes and the development of icings are also documented. Two boreholes are being monitored with respect to permafrost temperature. The first borehole in the Northern Tien Shan of Kazakhstan is at 43°05'N/76°52'E and at an altitude of 3,350 m a.s.l. At this site, permafrost thickness was about 40 m in 1975. Since then, the temperature at 15 m depth increased from -0.6°C to -0.2°C in 1993. The second borehole in the Inner Tien Shan of Kirghizstan is at 41°51'N/78°12'E and at about 4,100 m a.s.l. At this site, permafrost thickness is estimated at 100 to 300 m and the temperatures at 25-20 m depth have increased by an average of 0.1°C between 1987 and 1992.

Some of the research material of the last years has been summarized by Gorbunov *et al.* (1995), Gorbunov *et al.* (in press), and Gorbunov and Seversky (in preparation).

Norway

There is no borehole monitoring in mountain permafrost in Norway at present. One 10 m borehole was measured in the Jotunheimen, southern Norway, from 1982 to 1986 (Ødegard *et al.*, 1992), but the cable was then damaged and the borehole closed. At this site at an altitude of 1,851 m a.s.l, mean annual ground temperature was estimated to be -2.1°C to -2.3°C at the top of the permafrost. There are plans to reactivate this borehole as well as to drill some new holes at other sites in the same area for long-term monitoring of ground temperature. On Svalbard there are a few 10-15 m boreholes with automatic logging of ground temperatures, related to construction at Longyearbyen and Sveagruva. The measurements at Sveagruva are conducted by the Norwegian Geotechnical Institute (NGI). There are plans to drill deep boreholes on Svalbard for long-term ground temperature monitoring.

In 1995 a program to monitor shallow ground temperatures related to different geomorphological features (solifluction, ploughing blocks, nivation), was initiated at Finse in southern Norway. The site has a mean annual air temperature of -2° to -3°C and is marginal to mountain permafrost. This monitoring program is part of the PhD work of Ivar Berthling, University of Oslo, Department of Physical Geography, and focuses on solifluction and ploughing block dynamics.

New field data on mountain permafrost distribution have been collected from the mountain massifs of Jotunheimen and Dovrefjell in southern Norway. DC resistivity soundings and measurements of the bottom temperature of winter snow cover (BTS) confirm extensive permafrost occurrence at high altitude (Ødegard *et al.*, 1996). At Dovrefjell the permafrost limit occurs at about 1,450 m a.s.l.

(Ødegard, 1993). From resistivity soundings the permafrost thickness has been estimated at some 40 to 60 m at 1620 m a.s.l in a flat area near Snøhetta in Dovrefjell. The BTS data correlate well; measurements in 1992 and 1993 along the same profile showed a good replication of BTS-measurements.

Preliminary results from a site further east, Tron (1,666 m a.s.l.), indicate permafrost above 1,600 m a.s.l. So far, however, the data is too limited to establish an east-west gradient of permafrost distribution in southern Norway.

Based on a calculation of areas with mean annual air temperatures <-4°C, the area of discontinuous mountain permafrost in southern Norway is estimated at about 4,000 km^2. This value is corrected for the area covered by glaciers (about 1,600 km^2) and low altitude valleys within the mountain massifs. More BTS and resistivity soundings will allow further interpretation of the data in Geographical Information Systems (cf. Hoelzle *et al*, 1993), making possible more detailed knowledge of permafrost distribution patterns.

Switzerland

The area underlain by permafrost in the Swiss Alps is roughly estimated at about 2,000 km^2 (Keller *et al.*, in press) or somewhat more than the total glacierized area (about 1,300 km^2, IAHS (ICSI)/UNEP/UNESCO, 1989). During the past 25 years, attempts were made to establish systematic long-term observations on mountain permafrost in the Swiss Alps (Haeberli *et al.*, 1993). Emphasis is on discontinuous permafrost and the observations are made in a collaborative effort of VAW/ETH Zurich and the Universities of Bern, Fribourg, Lausanne and Zurich. Long-term observations include borehole temperature and deformation measurements (Hoelzle *et al.*, in press; Vonder Mühll *et al.*, in press), high-precision photogrammetry of permafrost creep (Kääb *et al.*, in press) and thaw settlement/frost heave on selected rock glaciers, systematic inventory of geophysical data (refraction seismics, DC resistivity soundings, gravimetry: Vonder Muehll, 1993), BTS-mapping (Hoelzle *et al.*, 1993), runoff measurements (Tenthorey, 1992), and periodically repeated analyses of infrared air photos with respect to vegetation cover, thermokarst phenomena, drainage patterns, debris flows, etc.

The two drill sites Murtèl-Corvatsch and Pontresina-Schafberg are of the greatest importance. The 60 m deep borehole on the Murtèl rock glacier was drilled in 1987. Core analyses and borehole geophysics showed that permafrost underneath the 3 m thick active layer is extremely supersaturated and the ice content amounts to almost 100% down to a depth of 28 m. Between 28 m and 58 m the pores of the coarse blocks are ice-filled (structured permafrost). Temperatures at 10 m increased from -2.3°C (1987) to -1.4°C (1994) but decreased intermittently due to thin snow cover in the winters of 1994/95 and 1995/96. Between the depths of 52 m and 58 m, seasonal temperature variations around 0°C are observed in a talik. Total permafrost thickness is estimated at about 100 m. The two drill holes at Pontresina-Schafberg reached depths of 65 m and 37 m and remained within permafrost. 10 m temperatures in 1994 were -0.5°C and -1.0°C. Parallel development of borehole temperature at both sites (Murtèl and Pontresina-Schafberg; Stucki, 1995) indicates that recent warming of permafrost temperature is not a local but a regional phenomenon. Monitoring of rock glacier flow by photogrammetric and geodetic methods extends back to 1932 (Messerli and Zurbuchen, 1968; Barsch and Hell, 1976) and is presently being carried out in cooperation with German colleagues (cf. text for Germany). The rock glaciers Gruben, Gufer, Réchy, Furggentälti, Murtèl, Muragl and Suvretta are being photogrammetrically monitored at intervals of about 5 years (Kääb *et al.*, in press).

The last decade has brought a strong increase of borehole temperatures in the permafrost of the Upper Engadin and accelerated thaw settlement on Gruben rock glacier. The energy flux involved in permafrost degradation is about one order of magnitude smaller than the energy flux reflected by glacier melt.

USA

Permafrost is present at higher elevations of the contiguous United States, in both the western and eastern mountain ranges (Péwé, 1983), throughout the mountains of Alaska and on isolated peaks in Hawaii. However, no coordinated, systematic studies are underway to map, monitor or model mountain permafrost. In Alaska, a long-term borehole monitoring program by Osterkamp and Romanovsky (1996) includes several boreholes in the Brooks Range and adjacent mountains where active rock glaciers have been studied (Ellis and Calkin, 1979). The borehole at Chandalar Shelf (3100 m a.s.l.) is 61 m deep and has been measured annually since 1985. The CAPS CD contains data from these locations. These sites are now part of the Circumpolar Active Layer Monitoring (CALM) network. A digital map of permafrost in Alaska is available at <http://agdc.usgs.gov/data/usgs/erosafo/permafrost/metadata/permafrost.html> at a scale of 1:2,500,000.

In the contiguous United States, several areas have a long history of observations. Niwot Ridge in the Front Range of the Rocky Mountains, is one site of the Long Term Ecological Research (LTER) program at which hydrologic and snowbed studies are active. Williams *et al.* (1996) report on a continuous climate record since 1951 at this site and show a decline in mean annual temperature, an increase in annual precipitation amount, and a decrease in mean daily solar radiation for the summer months. The changes in climate at Niwot Ridge are not synchronous with lowland warming in the Great Plains to the east and serve as a reminder that climate in alpine areas is driven by local conditions and may be out of phase with regional and global climate trends. Nel Caine and Hillary Hamann are working on snow hydrology and permafrost-related problems on and near Niwot Ridge.

The Galena rock glacier in Wyoming is the site of renewed intensive field investigations including a 13 m borehole in which temperatures and displacement will be measured. Future plans include extending the current borehole to bedrock and drilling additional boreholes at various locations on the rock glacier. A special issue of *Geografiska Annaler* is in preparation which reports results of the 1996 Chapman conference on geomorphic and climatic significance of rock glaciers including the Galena rock glacier.

Periglacial patterned ground has been investigated in the White Mountains of California since 1991 (Wilkerson 1995). Patterns range from large-scale sorted polygons, nets, and stripes, to small-scale hexagonal patterns located within active frost boils from 3900-4150 m a.s.l. Landforms near the summit of White Mountain Peak (4150 m a.s.l.) are highly active at all scales. At present, air and surface temperatures are recorded at 3800 m. A drill is available for boring to 30 m so that thermistors can be installed starting in summer 1998. Other sites in Wyoming and Utah have been the subject of recent investigations: Nicholas and Garcia (1997) on fossil rock glaciers in the La Sal Mountains; Konrad and Clark (1998) on the use of rock glaciers in the Sierra Nevada, California to reconstruct Neoglacial climate.

Periglacial investigations are now in progress in Hawaii. Hallet and Werner are conducting a coordinated and theoretical study of sorted stripes that are exceptionally well-developed on certain slopes above 4000 m on Mauna Kea. Continuous monitoring of surface heave, near-surface temperature, and moisture, and manipulative studies of sorted stripes are being employed to examine the evolution and recovery of altered plots in an effort to test their theoretical model (Werner and Hallet, 1993).

Other investigations are conducted outside the U.S., for example in the Himalayas where remote sensing techniques, digital elevation mapping and ground penetration radar are being used in the Nanga Parbat (8125 m) region to investigate frozen debris-covered slopes. Related studies focusing on mass movement will be reported in a 12-paper special issue of *Geomorphology* (J. Shroder, editor, in press).

THE PACE PROJECT IN EUROPE

A major new three-year research project with full title "Permafrost and Climate in Europe: Climate Change, Mountain Permafrost Degradation and Geotechnical Hazard" (acronym PACE) has been funded under the European Union Environment and Climate Program by the EU and the Swiss Government, and commenced in December 1997. The primary objectives are :

(1) to establish a framework for monitoring global climate warming by detecting changes in permafrost ground temperatures in the mountains of Europe;

(2) to develop methods of mapping and modelling the distribution of thermally sensitive mountain permafrost, and predicting climatically induced changes in this distribution; and

(3) to provide new, process-based methods for assessing environmental and geotechnical hazards associated with mountain permafrost degradation.

Thus, the PACE Project will establish a Europe-wide, long-term, mountain permafrost monitoring program based on a transect of instrumented boreholes from Janssonhaugen, Svalbard (Norway) in the north to Veleta Peak in the Sierra Nevada, Spain, in the south, including intermediate sites at Kebnekaise in northern Sweden, Juvasshytta in Jotunheimen, Norway, the Zermatt area and on Schilthorn in Switzerland, and the Stelvio Pass, Italy. The application of a range of geophysical techniques to the mapping and characterization of mountain permafrost will also be explored in order that rapid and reliable methods of detecting mountain permafrost may be developed. New approaches to numerical modelling of mountain permafrost distribution will be based on energy balance transfer functions and digital terrain models. Scaled centrifuge modelling of thaw-induced slope instability processes will be undertaken in order to investigate trigger mechanisms related to permafrost degradation. These related research activities will be integrated to provide improved methodologies for mountain slope hazard assessment associated with future climate change.

The PACE Project is co-ordinated by C. Harris at the University of Cardiff, United Kingdom and the Project Partners are Justus Liebig University, Giessen, Germany; The Third University of Rome, Italy; University Complutense, Madrid, Spain; The University of Oslo, Norway; Stockholm University, Sweden; the University of Zurich, Switzerland; The Federal Institute of Technology, Zurich, Switzerland; and TerraDat (UK) Ltd of Cardiff. Work on borehole drilling and instrumentation is led by L. King (Giessen), geophysical exploration by D. Vonder Mühll (ETH Zurich) and Terradat UK, geomorphological and related mapping of permafrost by F. Dramis (Rome) and J.L. Sollid (Oslo), numerical modelling by W. Haeberli and M. Hoelzle (Zurich), geotechnical centrifuge modelling by C. Harris (Cardiff) and M.C.R. Davies (Dundee) and hazard assessment by C. Harris (Cardiff).

The research undertaken by the PACE Project will develop a common European approach and provide an integrated interdisciplinary program of mountain permafrost research. Data will be contributed to the IPA Geocryological Database and the CALM project.

SUMMARY AND CONCLUSIONS

The first systematic overview of long-term monitoring programs related to mountain permafrost provides information from 11 countries. Additional information can be expected from Russia, Sweden and others. With respect to measured parameters, information is available or is planned (p) to be collected on borehole temperature in the Andes of Argentina (p), the Canadian Rockies since 1974, the European Alps since 1987, in Scandinavia for 1982-86 and (p), on Svalbard (p), in the Kazakh/Kirghiz/Chinese Tien Shan since 1975 and on the Qinghai-Tibet Plateau since 1962. In most of these regions, rock glacier flow is being monitored and maps/geophysical soundings exist at selected sites.

The most important signal becoming visible by now is from borehole temperatures and covers the past few years to decades. With the exception of the Canadian Rockies, where the seemingly constant thermal conditions in perennially frozen ground sharply contrast with the simultaneous mass losses of nearby glaciers as observed within the framework of worldwide glacier monitoring, warming of permafrost temperatures is pronounced in the European Alps (0.9°C during 1987-1994), the Kazakh/Kirghiz Tien Shan (0.4°C during 1975-1993 in Kazakhstan, 0.1°C during 1987-1992 in Kirghizstan) and in Qinghai-Tibet (0.1 to 0.8°C between the 1970's and the 1990's). Warming rates reported from these mountain permafrost sites vary over more than an order of magnitude (0.005 to 0.13°C per year) and average a few tenths of a degree C per decade or a few degrees C per century. Such values are roughly an order of magnitude higher than mean atmospheric warming during the past about 150 years or so. The longest and most detailed records relating to rock glacier flow are available in the European Alps. They indicate characteristic climate-induced thaw settlement at rates of about 0.01 to 0.1 m per year with flow velocities remaining fairly constant or decreasing slowly.

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