CONSIDERATION OF PERMAFROST AND PERMAFROST DEGRADATION IN NATURAL HAZARDS ASSESSMENT

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ABSTRACT

Knowledge and awareness about permafrost and the effects of climate change on permafrost phenomena and related hazards is fragmented and differs throughout the Alps. Due to the gap in objective data about permafrost distribution and permafrost response and the lack of a common strategy for dealing with this topic, the Autonomous Province of Bolzano/Bozen initiated an Alpine Space 2007-2013 project and set up a competent partnership. 14 project partners and more than 20 observers from governmental organizations, universities and research institutes worked together to reach the objectives of the project "PermaNET – Long-term permafrost monitoring". This article summarizes the most relevant outcomes of the PermaNET project for natural hazards assessment and management.

Keywords: permafrost, climate change, natural hazards assessment, rockfall, debris flows, rock glacier

INTRODUCTION

Permafrost is defined as soil or rock at or below the freezing point of water for two or more years. Due to this direct relation to temperature, permafrost is highly sensitive to climatic changes. Permafrost degradation and related natural hazards potentially affect traffic routes, tourism areas, infrastructures and settlements. So far, data on permafrost are spatially inconsistent and a map of the permafrost distribution in the entire Alpine Space does not exist. Furthermore, the relevance of subsurface ice content in rock glaciers and scree slopes for the hydrologic regime of alpine watersheds to be considered in water resources management is unknown. Searching for an objective and scientifically sound way to consider permafrost in natural hazard management reasonably, the Autonomous Province of Bolzano/Bozen found that a commonly accepted strategy to tackle the emerging impacts of climate change in risk prevention and territorial development does not exist.

In common natural hazards and risk management practice the effects of permafrost and permafrost degradation on the intensity and frequency of rockfall, landslides and debris flows are either neglected or overestimated. Especially the mass media and environmental organizations spread and force the assumption that permafrost degradation influences directly and in all cases intensity and frequency of natural hazards. But, decision makers and stakeholders need to be provided with objective and consolidated information about this topic to manage the consequences of climate change impacts on permafrost and the related natural hazards in a sustainable way. Due to the gap in objective data and the lack of a common strategy, the Autonomous Province of Bolzano/Bozen initiated an Alpine Space 2007-2013 project and set up a competent partnership. 14 project partners and more than 20 observers from governmental organizations, universities and research institutes are working together to reach the objectives of the project "PermaNET – Long-term permafrost monitoring".

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One aim of the PermaNET project was to develop a common strategy for dealing with permafrost and related natural hazards under changing climatic conditions. Therefore, project aimed to enforce good governance practices on the base of a common knowledge, of a jointly developed data base and of a commonly accepted strategy.

METHODS

The first step of the project was the setup of a network of permafrost monitoring sites in the Alps. All metadata of the key permafrost monitoring sites in the Alps were collected and compiled into a database. In regions without or with large gaps of monitoring sites new key monitoring sites were set up. The monitoring network consists of instrumented boreholes, continuous temperature measurements, repeated measurements of soil or slope movements and repeated geophysical measurements. The database of the permafrost monitoring sites has been published on the project website (www.permanet-alpinespace.eu) and is queryable by location or by type of measurement. To ensure the comparability of the data from different monitoring stations, a handbook with guidelines, standards and technical requirements for setting up new monitoring stations has been elaborated (Schoeneich et al. 2011). Furthermore, recommendations for building up permafrost monitoring networks have been compiled (Paro et al. 2011).

In a second step, an inventory of all permafrost evidences has been compiled. All direct observations such as ice lenses, ice in rock fractures or ground ice are compiled into a single database for the whole Alps. Indirect evidences for permafrost like rock glaciers or perennial snow patches are also mapped and considered in the inventory. The inventory contains for instance more than 4000 rock glaciers from nearly all parts of the Alps (Cremonese et al. 2011).

A new model for calculating the potential distribution of permafrost in the Alps has been developed and evaluated on the basis of the permafrost evidences inventory explained above. This model provides the base to generate a map of the permafrost distribution of the entire European Alps (Böckli et al. 2011).

In a further step, information about the thermal and geomorphic permafrost response to present and future climate change in the European Alps was compiled to highlight recent permafrost changes and possible future impacts of climate change to permafrost environments through case study sites in the Alps (Kellerer-Pirklbauer et al. 2011). Furthermore, different methods for monitoring slope movements and rock falls in permafrost areas were tested and evaluated. The most promising techniques for permafrost detection and monitoring of related hazards are compiled in a handbook (Deline et al. 2011). A state of the art report on the effects of climate change to permafrost and related natural hazards was elaborated (Schoeneich et al. 2011b). All possible effects of permafrost and permafrost degradation on natural hazards were pointed out, illustrated by a number of examples and well documented events and sites. Based on these steps, common recommendations for the consideration of the effects of climate change on permafrost and resultant natural hazards were formulated (Mair et al. 2011).

PERMAFROST AND CLIMATE CHANGE

High altitude and high-latitude regions are generally recognized as being particularly sensitive to the effects of climate change. A large proportion of permafrost in the European Alps, for instance, is at or close to melting point and is therefore very sensitive to atmospheric warming. Permafrost reacts to climate warming in different ways. Possible thermal and geomorphic effects of present and future climatic changes are manifold and the possible thermal reactions of permafrost include:

- Increasing ground temperature and therefore permafrost warming;
- Thawing of permafrost with three effects: reduction in the spatial extent of permafrost areas, thickening of the seasonally unfrozen layer, and increasing ground-water circulation and pressure;
- Changes in the number and characteristics of freeze-thaw cycles.

Possible geomorphic permafrost reactions include:

- Changes in the rate of rock glacier displacement (vertically and horizontally);

- Changes in displacement mode of rock glaciers (from creep to initiation of basal sliding or even collapse);
- Changes in cryogenic weathering;
- Changes in the volume and extent of unstable slopes;
- Changes in frequency and magnitude of mass movement events such as rockfalls, rock slides or debris flows.

More than 10 different study sites distributed over the entire European Alps in Austria, Switzerland, France and Italy were described and analysed in detail. In a first step, present and future climate change was analysed and modelled focusing on frost-, ice-, and freeze-thaw days between the two climate periods 1961–90 and 2021–2050 in the Greater Alpine Region/GAR. Second, the results of the climate change analysis were combined with the data from the study sites by analysing the recent thermal and/or geomorphic evolution of a relevant landform and its possible future response to predicted climate change. The study reveals the range of possibilities how permafrost is reacting in a warming climate, three examples are briefly presented here. For details see Kellerer-Pirklbauer et al (2011).

Example 1: Rockfalls in the Mont Blanc Massif

A total of 139 rockfalls have been documented between 2007 and 2009 in the central area of the Mont Blanc massif, 53 of them were precisely dated. Among them, 51 rockfalls occurred during the hottest months of the year and 38 occurred after a period of increasing mean daily air temperatures of at least two days (Fig. 1). Important is the observation that the hotter the summer, the higher the elevation of the rockfall scar. This indicates for the future that rockfalls will occur at higher elevations not affected earlier with implication to people and infrastructure at the new areas of rockfall release, transport and deposition.

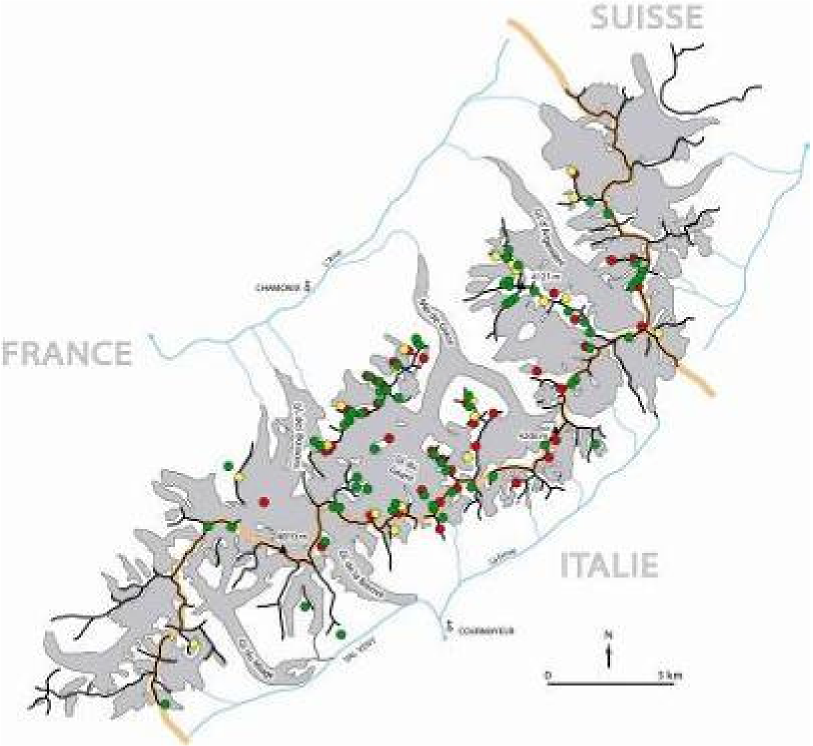

Fig. 1 Documented rockfalls in the Mont Blanc massif in 2007 (red dots), 2008 (yellow dots) and 2009 (green dots).

Example 2: Rock glacier velocities in Central Austria

Active rock glaciers are creeping phenomena of permafrost. Their movement is strongly related to climatic conditions and consequently to ground temperatures. As shown by different studies, the movement pattern of the monitored rock glaciers in the European Alps correlated with each other during the last years to decades. At the Dösen Rock glacier in Central Austria for instance, two peaks of high surface creep were detected in 2003-2004 and 2008-2010 (Fig. 1). The velocity pattern indicates that this rock glacier reacts more quickly after a cool period with deceleration. In contrast, the rock glacier needs more time to react to warmer periods with acceleration of the movement related to the inertia of the rock glacier system towards ground warming and velocity changes. This indicates for the future that predicted climate warming will first cause an increase of the creep velocities of rock glaciers. However, in a later stage this will lead to inactivation of many presently active rock glaciers. Some degrading rock glaciers may even entirely collapse and are consequently sources for natural hazards.

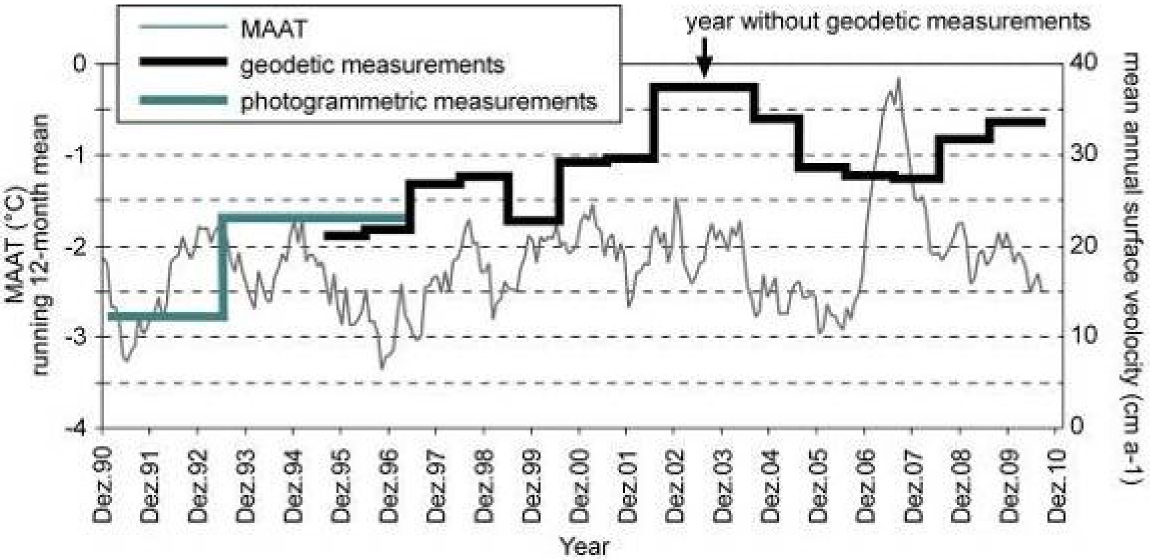

Fig. 2 Mean annual air temperature/MAAT (running 12-month mean) and horizontal surface creep at the Dösen Rock Glacier between 1990 to 2010.

Example 3: Soil subsidence and effects to tourism infrastructure in the Ortles area

If massive ground ice is melting, the soil in flat areas is sagging and subsiding. The case study from the Upper Sulden Valley, Ortler Mountains, Italian Alps showed the geomorphic response of flat or gently inclined areas covered by debris in a high-mountain ski resort outside of rock glaciers. The subsidence of the surface due to the melting of the ground ice lies in a dimension of 4 meters in 20 years (1996-2006). The foundation of a pillar of the "Madritschjoch" skilift moved sideward and disarranged the position. The pillar had to be adjusted several times since 1992 until the foundation of the pillar was re-constructed. The measured soil subsidence is accompanied with geomorphic signs in the landscape such as thermokarst phenomena (Fig. 3) or with increasing surface temperatures. In steeper areas, geomorphic signs of slope movements are found in areas with probable presence of permafrost. The subsidence of surface is relevant for ski infrastructures and must be handled with some technical effort.

Fig. 3 Soil subsidence in the vicinity of pillar no. 12 of the ski lift "Madritschjoch" and re-adjustment of the position. Note the inclined foundation of the pillar.

PERMAFROST AND RELATED NATURAL HAZARDS

Permafrost and permafrost degradation can influence intensity and frequency of natural hazards. Its four chapters deal with rock glaciers, debris flows, rockfalls, and local ground movements and their effects on infrastructure. Each chapter summarizes present knowledge about these processes and their relationship to the climate change, and is illustrated by several recent case studies in the Alps. These case studies show the variety of effects on infrastructures in high mountain areas.

The most important consequences of permafrost degradation to infrastructures are slope movements and rockfall processes. All surface movements can cause damage to infrastructures built on the moving terrain. Small movements can be accommodated by adapted design, but the potential accelerations induced by climate warming could challenge even these measures. In any case, building on permafrost induces additional construction and maintenance costs, and reduces the lifetime of infrastructures. The slope movements with the highest flow velocities are rock glaciers. Observed rock glacier dynamics show climatically-induced variations in velocity. In most cases only moderate velocity changes occur, related to annual changes of the mean annual ground surface temperature: an increase in ground temperature induces an acceleration of movements, and inversely. In some cases, a very strong and non-reversible acceleration, up to decameters per year, was observed. This can generate rockfall activity at the rock glacier front, and progression or even rupture and collapse of its front (Fig. 4).

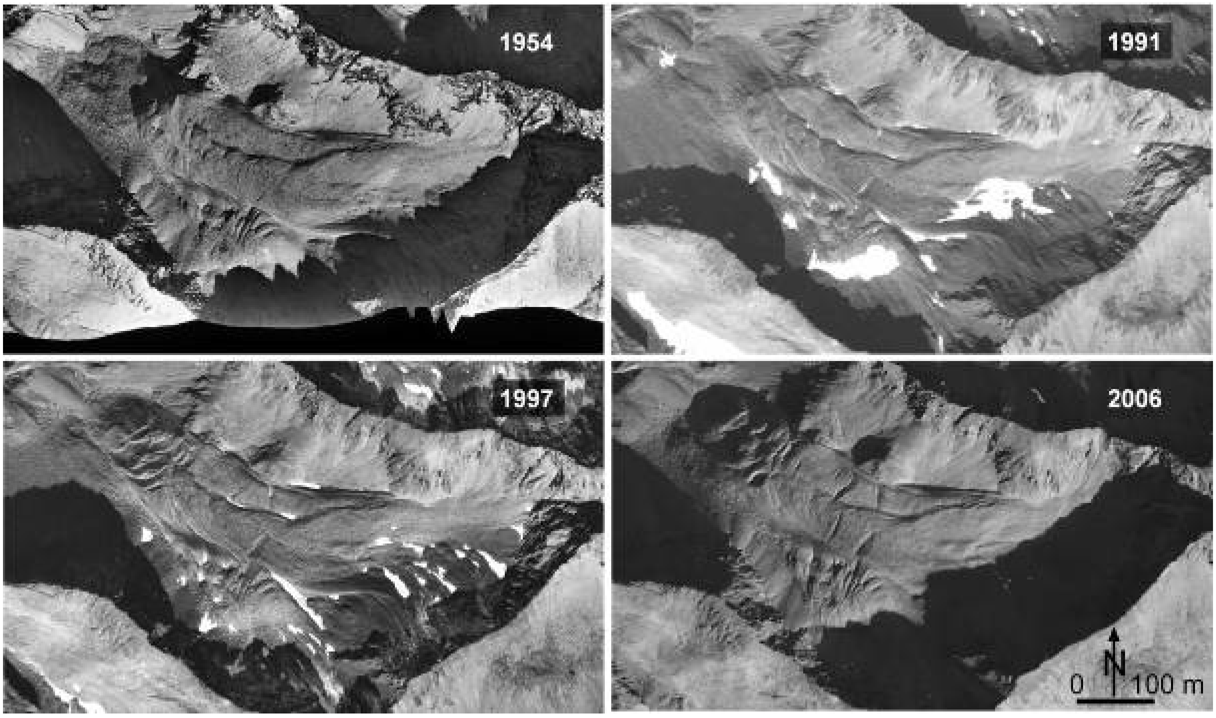

Fig. 4 Aerial photographs of the Hinteres Langtalkar rock glacier (Austria) between 1954 and 2006. Formation of crevasses and disintegration through active sliding processes since 1994 at its frontal part (cf. Avian et al. 2005). Aerial photographs by Austrian Federal Office of Metrology and Surveying (BEV), orthophotographs courtesy of V. Kaufmann and R. Ladstätter.

Rockfalls generate risks for mountaineering activities in the Alps and infrastructure like cable cars, mountain railways and roads, or ski resorts. Rock avalanches can threaten valley inhabitants at long distance from the source area. Climatically-driven degradation of rockwall permafrost is probably one of the main triggers of recent, present and future rockfalls (Deline & Ravanel 2011, Fig. 5).

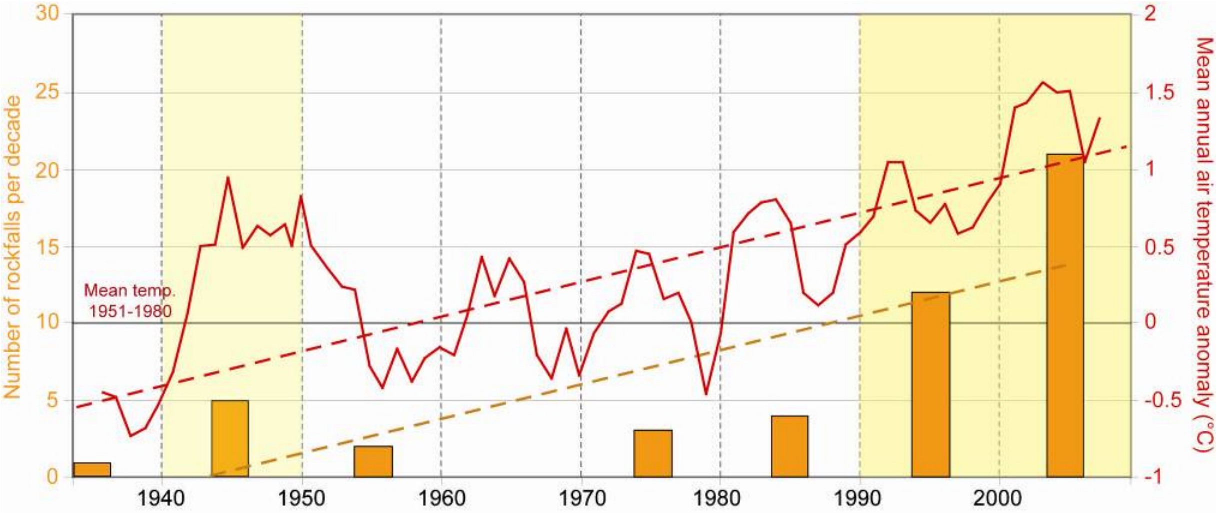

Fig. 5 Comparative evolution of climate in Chamonix (1040 m a.s.l.; data: Météo-France) and rockfalls (number per decade) in the North side of the Aiguilles de Chamonix and in the West face of the Drus (Mont Blanc massif, France).

Where rock glacier fronts are located on the upper rim of steep slopes, secondary processes can mobilize the released debris downslope. This and rockfall activity in permafrost areas can increase, for instance, the debris supply and thus the volume of debris flows. Permafrost can influence debris flow activity in different ways, mainly by increasing the debris supply to the torrential system, but also by influencing the water runoff characteristics. However, the influence of permafrost on debris flow activity depends mostly on the specific characteristics of the torrent catchment. The melting of ice in permafrost soils or scree slopes in the course of active layer thickening can lead to the loss of internal ice as stabilising binding material. This can lead to the increased availability of erodible material, to the subsidence of soils in flat areas and to slope movements in inclined slopes. In steep slopes, permafrost influences hydraulic conductivity and overall slope stability. In summertime, the active layer is often saturated because of the characteristics of the permafrost table as aquiclude. Thus, infiltration capacity is low and superficial runoff is high. The permafrost table can act as a slide horizon for landslides in the active layer. Consequences of this can be the sliding of debris cover, the settling of debris and related slope movements or landslides. The melting of ground ice contributes to the formation of thermokarst phenomena and thermokarst lakes with subsequent lake outburst floods.

The described processes related to permafrost and permafrost degradation do not influence hazard situations over wide areas. However, in single cases they could have a remarkable influence on hazard and risk situations. The first step in each planning activity is to refer to the permafrost distribution map. If the map shows a possible presence of permafrost at the study site, the use of permafrost detection methods as described in the PermaNET handbook is recommended. If permafrost is to be considered, special monitoring methods support the analysis of the processes. In order to evaluate operational approaches for detection and monitoring of slope movements and ground temperature in permafrost areas, six method sheets were established about dGPS (differential global positioning system), GPR (ground penetrating radar), DInSAR (satellite-based differential radar interferometry), ERT (electrical resistivity tomography), TLS (terrestrial laser scanning), and terrestrial photogrammetry. Basic principles of each method are summarized, before listing their possible applications, and the main results, opportunities and limitations; each sheet is completed with references and illustrated with some figures. Comparisons between some pairs of these methods were realized (Ravanel & Curtaz 2011).

CONCLUSIONS AND RECOMMENDATIONS

The interdisciplinary and integrated approach of compiling the existing knowledge about permafrost in the European Alps resulted in many valuable products that can be used in natural hazard management practice and in territorial planning (Mair et al. 2011).

The main outputs of the PermaNET project were

- the Alpine Space permafrost monitoring network and related handbooks,
- the inventory of permafrost evidence,
- the map of permafrost distribution in the Alps,
- guidelines for the consideration of permafrost in risk management.

The permafrost monitoring network extends the knowledge database of the thermal state of permafrost in the European Alps and allows the monitoring of the future thermal response of permafrost to climate change. On the one hand, this long-term monitoring network allows the ongoing signal of global warming to be recorded. On the other hand, it provides fundamental data for assessing the consequences of climate changes to permafrost and related natural hazards. The elaborated permafrost distribution datasets provide a decision base for interpreting observed changes in the landscape. For the planning sector, the permafrost inventory and the map provide a decision base for choosing adequate methods for detailed field investigations. If the map indicates the possible presence of permafrost at a specific location where problems with ground movements exist or where infrastructure is planned, the elaborated handbooks for permafrost detection and monitoring could provide the basis for deciding what techniques should be used.

Summarizing the main findings of PermaNET, the following recommendations are formulated:

1. The knowledge about permafrost and the effects of climate change on permafrost phenomena and related hazards is fragmented and on different levels of development within the Alps. The assemblage

of all experience and measurements into one knowledge base provides a sophisticated decision base and led to the development of a consistent map of permafrost distribution in the Alps. To further extend the knowledge base it is essential to continue the interdisciplinary and transnational collaboration.

2. Permafrost phenomena and permafrost degradation show a high spatial variability of occurrence through the Alps. The state of the art reports of PermaNET provide a collection of different aspects of the topic. Permafrost phenomena and related natural hazards (including the effects of climate change) should be considered in natural hazard and risk management in a common way throughout the Alps. Natural hazards related to permafrost and permafrost degradation are locally restricted to specific cases and should neither be overestimated nor neglected. The phenomenon has to be studied on the site and in detail before making conclusions or decisions in risk management. Some conclusions are valid for many locations: (i) infrastructure upon an active rock glacier and its frontal area should be avoided; (ii) a security zone should be observed below a rock glacier; (iii) trails crossing rock glaciers or passing down below its front should be regularly checked.

3. For all planning tasks in the high mountain environment it is important to know if permafrost occurrence is possible, and if so, what the possible effects on the planned activity are. A raised awareness of the existence of mountain permafrost and its possible adverse effects on economic activities is helpful for improving the efficiency and sustainability of investments. All stakeholders are invited to make use of the elaborated permafrost map, and to add their own observations to the permafrost evidence inventory. With this support, the databases will be extended and the knowledge of permafrost distribution will grow.

4. In case of slope deformations in permafrost areas, slope monitoring techniques are crucial tools for risk assessment and risk prevention. Their use must be encouraged. Adequate time is required for analysing the problem in detail. Monitoring of slope movements in permafrost areas require specific methods and must meet specific needs. It provides hints for choosing the appropriate monitoring technique.

5. In order to exchange experiences, to expand the data series and to foster harmonization, it is necessary to continue the transnational permafrost monitoring network of researchers and practitioners. National environmental authorities are recommended to support the further development of this network of persons and institutions and to financially support the maintenance of the monitoring stations. The effects of climate change to permafrost can only be quantified through long-term monitoring of the evolution of permafrost over a wide area.

REFERENCES

Avian M., Kaufmann V., Lieb G.K. (2005). Recent and Holocene dynamics of a rock glacier system: The example of Langtalkar (Central Alps, Austria). Norwegian Journal of Geography 59, 149-156.

Boeckli L., Brenning A., Gruber S., Noetzli J. (2011). A statistical permafrost distribution model for the European Alps. The Cryosphere Discuss. 5[3], 1419-1459.

Cremonese E., Gruber S., Phillips M., Pogliotti P., Boeckli L., Noetzli J., Suter C., Bodin X., Crepaz A., Kellerer-Pirklbauer A., Lang K., Letey S., Mair V., Morra di Cella U., Ravanel L., Scapozza C., Seppi R., Zischg A. (2011). Brief Communication: "An inventory of permafrost evidence for the European Alps". The Cryosphere 5[3], 651-657.

Deline P., Ravanel L. (2011). Chapter 3.9: Case studies in the European Alps – Rockfalls in the Mont Blanc massif, French-Italian Alps. In: Kellerer-Pirklbauer A., Lieb G., Schoeneich P., Deline P., Pogliotti P. (eds.). Thermal and geomorphic permafrost response to present and future climate change in the European Alps.PermaNET project, final report of Action 5.3

Deline P., Ravanel L., Krainer K., Gay M., Curtaz M., Bodin X., Sailer R., Krautblatter M. (2011). PermaNET Permafrost long-term monitoring network. WP6 Permafrost and Natural Hazards.

Method sheets for permafrost mapping and detection approaches (www.permanet-alpinespace.eu/products.html).

Kellerer-Pirklbauer A., Lieb G., Schoeneich P., Deline P., Pogliotti P. (eds.) (2011). Thermal and geomorphic permafrost response to present and future climate change in the European Alps.PermaNET project, final report of Action 5.3 (www.permanet-alpinespace.eu/products.html).

Mair V., Zischg A., Kellerer-Pirklbauer A., Deline P., Schoeneich P., Cremonese E., Pogliotti P., Lang K., Tonidandel D., Krainer K., Gruber S., Böckli, L. (2011). PermaNET - Long-term Permafrost Monitoring Network. Synthesis report. INTERPRAEVENT Journal series 1, Report 3. Klagenfurt.

Paro L., Guglielmin M., Schoeneich P. (2011). PermaNET Permafrost long-term monitoring network. WP4 Monitoring network. Handbook to establish alpine permafrost monitoring network (www.permanet-alpinespace.eu/products.html).

Ravanel L., Curtaz M. (2011). WP6 Permafrost and natural hazards, Action 6.1 Comparison of methods. Terrestral laser scanning and terrestrial photogrammetry. (http://www.permanet-alpinespace.eu/archive/pdf/WP6_1_tls_tp.pdf)

Schoeneich P., Pogliotti P., Hausmann H., Krainer K., Lang K. (2011). PermaNET Permafrost long-term monitoring network. WP4 Monitoring network. Guidelines for permafrost monitoring (www.permanet-alpinespace.eu/products.html).

Scheoneich P., Dall'Amico M., Deline P., Zischg A. (2011b). PermaNET Permafrost long-term monitoring network. WP6 Permafrost and natural hazards. State of the art report (www.permanet-alpinespace.eu/products.html).