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Plenary Lecture
Relazione ad Invito

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CLIMATE CHANGE AND GLACIAL/PERIGLACIAL GEOMORPHODYNAMICS IN THE ALPS: A CHALLENGE OF HISTORICAL DIMENSIONS

ABSTRACT: HAEBERLI W., *Climate change and glacial/periglacial geomorphodynamics in the Alps: a challenge of historical dimensions.* (IT ISSN 1724-4757, 2005).

In the Alps, there is a long tradition of scientific research on glaciers and on landscapes formed by perennial surface ice. Investigation of problems connected to high-mountain permafrost is much newer. The interest in both, however, has risen considerably during recent years. This is primarily due to their close relationship with climate change. Glaciers and permafrost do indeed react sensitively to changes in atmospheric temperature because of their proximity to the melting point. As a consequence, climatic changes during the 20th century have caused pronounced effects in the glacial and periglacial belts of mountain areas. Fast if not accelerating changes in ice conditions of cold mountain areas now increasingly influence the appearance and perception of alpine landscapes, the seasonality of melt-water runoff, the intensity of erosion and sedimentation, the stability of high-altitude slopes and the general hazard situation. To anticipate and mitigate such consequences of climate change represents a challenge of historical dimensions to the fields of glacial and periglacial geomorphology.

KEY WORDS: Glaciers, Permafrost, High mountains, Climate change, Natural hazards.

RIASSUNTO: HAEBERLI W., *Cambiamenti climatici e geomorfodinamica glaciale/periglaciale nelle Alpi: una sfida di dimensioni storiche.* (IT ISSN 1724-4757, 2005).

C'è una lunga tradizione di ricerca scientifica sui ghiacciai e sui paesaggi perennemente coperti da ghiaccio nelle Alpi. Le ricerche su problemi riguardanti il permafrost di alta montagna sono invece più recenti. In entrambi i campi, comunque, l'interesse è notevolmente aumentato negli ultimi anni. Ciò è soprattutto dovuto alle loro strette relazioni con i cambiamenti climatici. Ghiacciai e Permafrost sono, infatti, molto sensibili ai mutamenti della temperatura dell'atmosfera, data la loro prossimità al punto di congelamento. Di conseguenza, i cambiamenti climatici del 20° secolo hanno prodotto consistenti effetti sulle fasce glaciali e periglaciali delle aree montuose. Rapidi se non accelerati cambiamenti delle condizioni del ghiaccio nelle aree montane fredde stanno ora influenzando in maniera crescente l'aspetto e la percezione del paesaggio alpino, la stagionalità dello scorrimento delle acque di fusione glaciale, l'intensità dell'erosione e della sedimentazione, la stabilità dei versanti di alta montagna e una generalizzata situazione di rischio ambientale. Anticipare e mitigare tali conseguenze dei cambiamenti climatici rappresenta una sfida di dimensioni storiche nei campi della geomorfologia glaciale e periglaciale.

TERMINI CHIAVE: Ghiacciai, Permafrost, Alta Montagna, Cambiamento climatico, Rischi naturali.

INTRODUCTION

Investigations of questions related to glacial and periglacial geomorphology in the Alps has a long and important research tradition. The deciphering of landforms and traces in the landscape created or affected by glaciers and frozen ground have revealed the often dramatic evolution of our planet. In the 19th century, the detection of the ice ages led to intense ideological discussions about the creation of the world, the stability of its climate and the evolution of living conditions on earth (Haeberli & Zumbühl, 2003). Since then, decades of intensive worldwide research have helped to create a comprehensive basis of scientific knowledge about landscape evolution through time in the Alps and their forelands (Castiglioni, 2004) as influenced by glaciers and frozen ground.

Such an advanced state of knowledge now constitutes an important instrument in dealing with new challenges of historical dimensions and increases our ability to cope with aspects related to future glacial and periglacial processes and landforms. These new challenges are primarily generated by increasing human activity which uses but also affects, more and more, environments in high mountain regions as well as their surrounding lowlands and which induces changes lasting over time scales spanning from years to decades, centuries, millennia and sometimes beyond (Watson & Haeberli, 2004). The disappearance of

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glaciers and the degradation of permafrost in the highest parts of the mountains, under the influence of accelerating climate change, illustrate the situation perfectly (Haeberli & Beniston, 1998).

THE ALPS WITHOUT ICE?

Environmental impacts on mountain systems from ongoing and potentially accelerating climate change are especially pronounced in regions around and above the timberline. In these areas the effects related to snow and ice are illustrated with extraordinary clarity and reflect the increase in atmosphere/earth energy fluxes. Such climate-induced effects influence landscape appearance, natural hazards, the water cycle and the living conditions of plants and animals (Beniston, 2000). Accelerating rates of change could lead to increasingly difficult combinations of stresses involving growing levels of anthropogenic pressure, landscape alteration or increasing vulnerability of infrastructure with respect to natural and economic hazards.

Many mountain ranges have lost significant proportions of their glacier mass during the past 150 years and are quite likely to become almost entirely deglaciated during the coming decades. It has been estimated that warmer temperatures could cause more than 90% of the Alpine glacier volume to disappear by the end of the century (Haeberli & Hoelzle, 1995). The new satellite-based glacier inventory for the Swiss Alps points to an even faster ice loss than was previously estimated (Paul & *alii*, 2004, cf. tab. 1). Such disappearances of glaciers may deeply affect – and within short time periods – human perceptions of high-mountain landscapes and their recreational value. The extreme summer heat of 2003 caused an overall loss of glaciers in the European Alps ranging from 5 to 10% of the remaining ice volume (Table 1; cf. Frauenfelder & *alii*, in review) and has been a (first?) strong indication of what average climatic conditions in the second half of the 21st century could mean to icy mountain peaks. Due to the growing predominance of vertical thinning over horizontal retreat, many glacier tongues have slowed down their flow and have started to downwaste and collapse rather than to retreat (fig. 1). This is a process change which could become widespread during the coming years and decades.

TABLE 1 - Analysis of glacier inventory data in the European Alps (model results and best estimates after Haeberli and Hoelzle, 1995; updated with Paul & *alii*, 2004; application of realistic - not extreme - climate scenario).

Glacierized surface area 1970/80	2909 km^2
Glacier volume 1970/80	100 km^3
Sea level equivalent 1970/80	0.3 mm
Mean mass balance 1850-1970/80	– 0.25 m/year
Mean mass balance 1980-2000	– 0.65 m/year
Mean mass balance 2003 alone	– 2.5m
Loss in glacierized area 1850-1970/80	40%
Loss in ice volume 1850-1970/80	50%
Loss in glacierized area 1980-2000	20% of 1970/80
Loss in ice volume 1980-2000	25% of 1970/80
Loss in ice volume 2003 alone	> 5% of 2000
Loss in ice volume 1970/80-2025	> 50% of 1970/80
Loss in ice volume 1970/80-2100	> 90% of 1970/80

FIG. 1 - Downwasting and collapse of ice at the tongue of Steingletscher, Sustenpass area, Swiss Alps. Foto E. Peguiron, September 2004.

Large areas above the timberline have, so far, remained perennially frozen to great depths. Mountain areas, especially those with dry-continental climatic conditions and reduced glacier extent can contain abundant masses of subsurface ice in talus cones and moraines. Ice can also fill cracks and fissures in bedrock that has below freezing ambient temperatures. The existence of such ground ice strongly depends on climatic conditions and influences slope stability as well as the availability of near-surface water. Scientific research about these phenomena however, is rather young and long-term monitoring has only recently been established in the Alps. The response of mountain permafrost to climatic changes takes place in the form of ice melt at the permafrost table (direct response, time scale: years), the disturbance of temperature profiles within the permafrost (delayed response, time scale: decades to centuries) and displacements of the permafrost base (final response: time scale: centuries to millennia). Preliminary interpretation of temperatures measured in 100 m-boreholes drilled in the European mountains for long-term permafrost monitoring (fig. 2) indicates decadal to secular ground warming at a rate which is comparable to atmospheric warming (Harris & *alii*, 2003). With continued or even accelerated future atmospheric temperature increases, lower-altitude limits of permafrost occurrence in mountain areas could rise by several hundred meters. Due to the slow diffusion of heat into the ground, the response of permafrost to climate change involves a large inertia but would then last for very long time periods. Corresponding processes deep inside mountain slopes are not only difficult to observe but even more difficult, if not impossible, to keep under control. A new «science of transient stages and strong disequilibria» must help to deal with such developments.

CONSEQUENCES FOR GEOMORPHIC PROCESS DYNAMICS AND HAZARD POTENTIALS

Glacierized and perennially frozen mountain areas would be among the most heavily affected parts of the world in the event of accelerated future warming. Shrinkage of mountain glaciers and permafrost degradation will affect snow cover evolution and the water cycle in high mountain regions and adjacent lowlands. The disappearance of perennial ice above and below the earth surface further influences the seasonality of discharge by reducing meltwater production in the warm season and by increasing the permeability of frozen/thawing materials. Together with the shrinking of glaciers, changes in ground thermal conditions of perennially frozen slopes can lead to pronounced changes in hazard conditions (Haeberli & Burn, 2002). On slopes steeper than about 25 to 30°, stability problems can develop in freshly exposed or thawing non-consolidated sediments. Debris flows of various magnitudes may result under such conditions, especially during snowmelt and events of heavy precipitation. The formation and disappearance of ice-and moraine-dammed lakes generally accompanies marked changes in glacier extent (Chiarle & Mortara, 2001; Haeberli & *alii*, 2001), and steep hanging glaciers which are partially or entirely frozen to their beds could become warmer and less stable (Huggel & *alii*, 2004b). Steep mountain slopes with warming permafrost and/or decreasing backpressure from glaciers progressively melting down could destabilize and cause major rock falls (Davis & *alii*, 2001; Deline, 2001;

FIG. 2 - Drilling a borehole on Stockhorn (Zermatt) for long-term monitoring of mountain permafrost. Foto W. Haeberli, July 2000.

FIG. 3 - Rock fall in 2003 at Piz Murtèl, Corvatsch area, Upper Engadin, Swiss Alps. Foto R. Strebel, 11 August 2003.

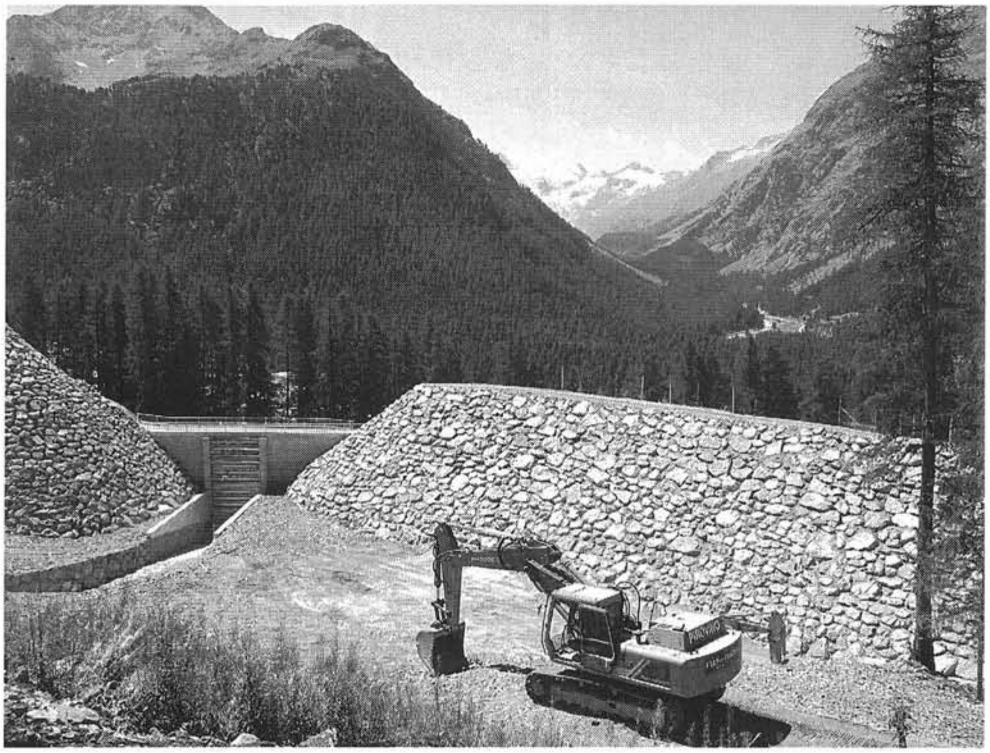
Dramis & *alii*, 1995; Dutto & Mortara, 1991; Evans & Clague, 1988; Haeberli & *alii*, 1997, 2002). A number of small as well as large events from corresponding areas have been documented and analysed (fig. 3; Haeberli & *alii*, 2003; Noetzli & *alii*, 2003; Gruber & *alii*, 2004).

PROTECTION AND MITIGATION: THE NEED FOR TRANSDISCIPLINARY COLLABORATION AND INTERNATIONAL KNOWLEDGE EXCHANGE

The general tendency in high mountain areas influenced by a scenario of accelerated future warming would be an upslope shifting of hazard zones with considerable changes in the involved processes and a widespread reduction in the stability of formerly glacierized or perennially frozen slopes (Haeberli & *alii*, 1997). A fundamental problem arises thereby, with the fact that conditions are developing far beyond historical experience and even Holocene precedence. The concept of «paraglacial landform succession» may greatly help in understanding the growing disequilibria and intensified transient conditions which are induced by continued atmospheric warming and ice disappearance (Ballantyne, 2003). For those directly involved with such changes, the main challenge would be to adapt to high and accelerating rates of environmental evolution. Empirical knowledge must be increasingly replaced by improved process understanding, especially concerning runoff formation and slope stability. For practical purposes, robust computer models treating complex changes in space and time have to help with the design of hazard mitigation measures at high altitudes.

The application of modern know-how and technologies (high-resolution satellite imagery combined with geoinformatics) is now possible even in remote mountain areas (Huggel & *alii*, 2003, 2004a; Kääb 2000, 2002; Kääb & *alii*, 2003) and is used to prepare the necessary assessments concerning high-mountain environmental conditions such as mountain permafrost distribution (Etzelmüller & *alii*, 2001) and hazards such as the formation of dangerous ice- and moraine-dammed lakes. The improvement of basic knowledge about environmental conditions and threats in high-mountain areas, however, depends on appropriate monitoring programs. Flexible planning concepts must be applied as based on a combination of systematic monitoring and robust modeling. Only appropriate observations will provide the knowledge base necessary for assessing the developments in reality and, statistically calibrated numerical spatial/gray-box models (rather than sophisticated deterministic models as applied in detailed scientific process studies) must help with anticipating consequences and possible future scenarios. The approach must be to establish an integrated observation and information system as a decision basis for planning, mitigation and adaptation, which includes continuously upgraded information from modeling and visualization. This goal can only be reached within the framework of a transdisciplinary collaboration involving a combination of indigenous knowledge, international knowledge exchange and the application of advanced technologies (The Royal Swedish Academy of Sciences 2002).

FIG. 4 - Protection dam against snow avalanches and debris flows from warming permafrost, Pontresina, Upper Engadin, Swiss Alps. August 2003.



CONCLUSIONS AND PERSPECTIVES

The destiny of icy peaks in cold high-mountain areas is, and will continue to be, among the first and most easily recognized signals from the evolution of global climate and climate-sensitive environments. Future generations may ask whether or not we understood this «writing on the wall» but the fundamentally important message lies in how we react to it. Not only snow and ice in cold high-mountain areas but also living conditions within and around such climate-sensitive parts of the earth would greatly benefit from corresponding reductions in greenhouse gas emissions. Besides the potential of avoiding most serious consequences concerning water supplies, hazards, agriculture and tourism, such measures could help to, at least, partially preserve the specific characteristics and unique attractions of these landscapes with their cultural, historical and mythological value which reaches far beyond physical aspects alone. The protection of icy peaks from climate change and its consequences will be among the first and best visible proofs of success or failure (Watson and Haeberli, 2004). In the meantime, the best-available knowledge and techniques concerning processes, environmental impacts and hazards, as related to glacial and periglacial geomorphodynamics, should be developed and applied (fig. 4) in order to mitigate unavoidable problems which are already occurring now and will, most probably, intensify in the near future.

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