GEOMORPHOLOGICAL IMPACT OF CLIMATE CHANGE ON ALPINE GLACIAL AND PERIGLACIAL AREAS

EXAMPLES OF PROCESSES AND DESCRIPTION OF RESEARCH NEEDS

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ABSTRACT

The alpine glacial and periglacial environment is a sensitive indicator of climate change, and is promptly reacting to atmospheric warming. Several instability processes which have been recently reported from high altitude alpine areas can reasonably be considered as first effects of accelerated climate change on cryospheric systems and can thus also represent significant terrestrial indicators of climate change, besides their significant socio-economic, environmental and hazard impacts. These phenomena are, in many cases, poorly documented, as they often occur in remote, uninhabited areas. This paper presents a review of geomorphological processes, distinguished by typology, that have been documented, mostly in the Italian Alps, since the beginning of the 21th century. The impacts of these processes on natural resources and hazard have been discussed; suitable investigation techniques and research needs for process understanding and monitoring have been analysed. This information is essential in order to build reliable scenarios for glacial and periglacial areas evolution and to supply technicians and decision makers with effective tools to improve hazard assessment and natural resources management.

Keywords: Italian Alps, cryosphere, climate change, natural hazards, resources management

INTRODUCTION

The alpine glacial and periglacial environment is a sensitive indicator of climate change, and is promptly reacting to atmospheric warming (Kääb et al., 2007a). Its sensitiveness is both due to glaciers and permafrost occurrence, and to an air temperature increase in the 20th century in the Alps, which has been twice that on a planetary scale (Brunetti et al., 2006). Glaciers respond in a straightforward and clearly visible way to temperature and precipitation variations and are thus recognized as the best terrestrial indicator of climate change (McCarthy et al., 2001). In the Alps, general glacier retreat started at the end of the Little Ice Age (LIA): following the last temporary advance in the period 1970-1986, glacier shrinkage has been continuous, but a marked acceleration has been observed since 2003 (Mercalli et al., in press). Permafrost response, on the contrary, is more complex and delayed and process understanding is still poor compared to glaciers, due to the difficulty of making direct observations. Permafrost behaviour under climate forcing has thus to be inferred not only from direct measurements (e.g. borehole temperature series, Harris et al., 2001b) but also

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from a variety of indirect indications (e.g. rock glacier speed, Kääb et al., 2007b). European mountain permafrost temperatures are generally only a few degrees below zero, so a slight air temperature increase can cause widespread permafrost degradation (Harris et al., 2001a).
In this contest, some instability processes which have been recently reported from high altitude alpine areas can reasonably be considered as the first effects of accelerated climate change on cryospheric systems and can thus also be used as significant terrestrial indicators of climate change (Evans and Clague, 1994; Ballantyne, 2002). These phenomena are, in many cases, poorly documented, as they often occur in remote, uninhabited areas This paper presents a review of geomorphological processes, distinguished by typology, that have been documented, mostly in the Italian Alps, since the beginning of the 21th century. The aim of the review is to contribute to the assessment of present and expected geomorphological impacts of climate change in high altitude mountains and related hazards.

RECENT AND ONGOING GEOMORPHOLOGICAL PROCESSES

Lake growth at glacier margin

In the current period of marked glacier recession numerous lakes have appeared in the areas vacated by ice or on the glaciers themselves: once formed, lakes tend to expand due to thermokarst processes. The most hazardous cases are represented by the Roche Melon Glacier lake (French Alps) and the Effimero Lake on the Belvedere Glacier (Monte Rosa Group).
The shrinkage of the Roche Melon Glacier has caused significant morphological changes in the wide top plateau over the last 15 years. Around 1980, a supraglacial-marginal lake (3200 m a.s.l.) began to fill the large depression between the left side of the glacier and the north-western Roche Melon crest. During hot summer seasons 2003 and 2004, the Roche Melon lake (3200 m a.s.l.) reached a volume of about 600 000 m^3 and a freeboard of just 15 cm: because of the risk posed to the village of Bessans in case of lake outburst, French authorities decided the artificial lowering of lake stage (Jobard, 2005; Fig.1).

Fig.1: The Roche Melon Glacier supraglacial-marginal lake in 2003. Photo by A. Tamburini.

At the Belvedere Glacier a surge-type evolution caused the formation of a large depression at the foot of the east Monte Rosa wall, filled since 2001 by a supraglacial lake (Fig. 2). The lake basin (2100 m a.s.l.) reached its maximum volume (over 3 M m^3) during an anomalous heat wave in June 2002. Considering the threat of an impending glacial outburst, threatening the Macugnaga village 2.5 km downstream, rapid emergency actions were initiated by the

Fig.2: Monte Rosa east face and Belvedere Glacier. The Effimero Lake is at maximum extent in 2002. In the lower part of the image, rock fall and debris flow paths running into the lake are visible. Photo courtesy of the Italian National Civil Protection Dept.

Italian Civil Defense Department. After a modest glacial outburst occurred in June 2003, the depression has remained almost empty (Kääb et al., 2004).

Debris flows

Debris flows seem to be increasing in frequency at the margins of glaciers, in part as a consequence of general glacier retreat and exposure of large quantities of unconsolidated, unvegetated, and sometimes ice-cored glacial sediments. These sediments are easily mobilized by floods resulting from heavy precipitation, snowmelt, glacial lake outbursts, and melt of ground ice or buried ice bodies (Harris & Gustafson, 1993; Clague & Evans, 2000; Chiarle et al., 2007). A debris flow occurred in fair weather on 29 July 2005 in Val di Fosse (eastern Italian Alps). Melt of a buried ice mass triggered a debris flow of 15000 m^3 that flowed downslope for over 1 hour, cutting off a popular trail (Fig. 3). In July 2003, during dry weather, a sequence of debris flows occurred at the foot of Frébouge Glacier (Mont Blanc Massif).

Fig.3: Melting of a buried ice mass, exposed in a 20 m long detachment zone at 3000 m a.s.l, started the July 2005 debris flow in Val di Fosse. Photo courtesy of Public Works Service, Bolzano Province.

The flows deeply incised the alluvial fan and deposited about 30 000 m^3 of coarse sediment. The July 17 debris flow may have been triggered by the release of an englacial water pocket. The debris flows occurred in the following days likely developed from the failure of an ice dam formed by ice avalanching from the Frébouge Glacier front (Deline et al., 2004).

Paraglacial adjustment of moraines

Ice-core melting inside the LIA moraines or pressure reduction due to rapid glacier lowering can significantly modify the shape of the moraines (Mortara & Chiarle, 2005).
An impressive scar failure developed in the Locce Glacier frontal moraine (Monte Rosa Group), as a consequence of rapid exhaustion of a glacial surge which had extraordinarily

increased the Belvedere Glacier thickness in the period 2001-2004 (Fig. 4). In the same way, the crest of the Belvedere Glacier right lateral moraine is gradually collapsing.

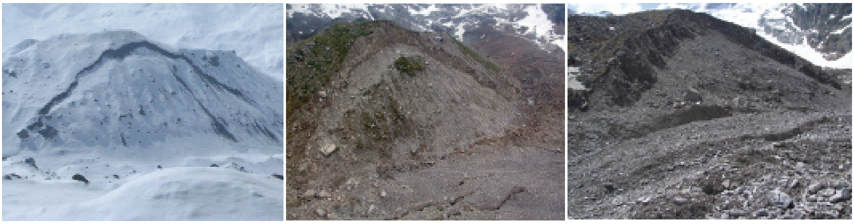

Fig.4: Evolution of the Locce Glacier moraine failure from spring 2005 (left, photo courtesy of Regione Piemonte), to summer 2006 (centre) and summer 2007 (right).

The hot summer 2003 caused the accelerated melt of the ice core of Ghiacciaio dei Forni lateral moraine, at 2600 m a.s.l. The ice core melting activates debris and mud-flows resulting in a wide instability area in the inner moraine flank, wasting approximately 40 000 m^3 of debris (Pelfini et al., 2004).

High altitude rock falls/avalanches

Large rock and rock/ice avalanches occurred in high mountain in the Alps in the period 2004-2007 (Punta Thurwieser, Italy: volume 2.6 M m^3, Fig. 5; Drus, Mont Blanc Massif, French side: volume 0,5 M m^3; Monte Rosa east face: volume some hundreds of thousands of m^3, Fig. 6), while innumerable small sized rock falls occurred during the hot Summer of 2003. At elevations higher than 3500 m a.s.l., where permafrost occurrence is most likely, massive ice with a thickness of some decimetres was sometimes exposed in the detachment zones (e.g. the “Cheminée” rock fall, 3700 m a.s.l., Matterhorn, August 2003; the “Marco and Rosa Hut” rock fall, 3600 m a.s.l., Bernina, Central Italian Alps, August 2003, Fig. 7); in other cases (Punta Thurwieser 2004 rock avalanche, 3658 m a.s.l.; Brenva 1997 rock-ice avalanche; Monte Rosa east face 2007 rock-ice avalanche, 4000 m a.s.l.; Rocciamelone 2007 ridge deformation, 3200 m a.s.l., Fig. 8, NW Italian Alps) water flowing out the rock wall was observed a few days before collapse occurrence (Cola, 2005). Both observations strengthen the hypothesis of a role of a degrading permafrost in instability development.

Fig.5: Collapse of rock pillar initiating the 24/09/2004 rock avalanche at Punta Thurwieser. Photo by J. Rozman.


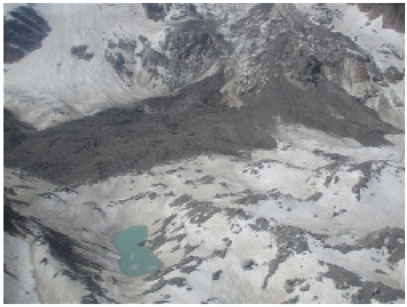

Fig.6: Detachment (left, circle) and accumulation (right) zone of the rock-ice avalanche occurred on Monte Rosa east face on 21/04/2007. The main event was preceded by small rock falls. Photos by P.Semino and M.Cucchi.

Fig.7: Massive ice outcroppig in the Marco and Rosa Hut rock fall scar (August 2003). Photo courtesy of CAI Valtellinese.

Fig.8: Western Rocciamelone crest. Since 2006, rock slope deformation became apparent, arising concern about a possible collapse. The person in the circle is for scale. Photo by P. Intropido.

Ice falls/avalanches

The degradation of the mountain slope glacial cover related with climate change has produced ice masses fragmentation, circulation of water at the ice-rock contact even at high elevation, lack of support at the foot of hanging glaciers. The ice-avalanche occurred on August 25, 2005 on the Monte Rosa east face, which has experienced in the last 20 years a drastic decrease in glaciation, is one of the largest ever recorded in the Italian Alps. An overall volume of about 1.1 M m^3 of detached ice was estimated from multi temporal aerial photo analysis (Fig. 9). A blow peak of 140 km/h was recorded by a meteorological station located near the accumulation area. The change of glacier front position on a complex topography can also affect ice stability: due to glacier retreat above a rocky step, the front of the Frébouge Glacier (Mont Blanc Massif) experienced repeated ice falls between 2002 and 2003 (Fig.10), until glacier front reached a more stable geometry (Deline et al., 2002). In 2002, the avalanche interrupted the Gervasutti Hut path.

Fig.10: Frontal view of the 18 September 2002 Frébouge ice avalanche. Photo by P. Deline.

Fig.9: The circle shows an helicopter flying in the detachment zone of the Mt. Rosa ice avalanche. The scar was about 50 m high. Photo by W. Giulietto

Glacier change

The large part of glaciers shows enhanced volume and area reduction, as confirmed by glacier mass balances (10-15 cm of ice melted per day during the hot summer 2003). The most commonly reported changes are: glacial front retreat of tens of meters/year (sometimes more than 100 m, e.g. Scerscen Lower Glacier, Central Italian Alps, Citterio et al., 2007), increase in debris cover, development of large hollows on glacier surface (e.g. Locce and Grandes Murailles glaciers, Western Italian Alps), glacier fragmentation, enhanced glacial flow. The most impressive cases are represented by recent evolution of the Brenva, Invergnan (Fig. 11), Belvedere glaciers, NW Italy, and the Lamar Serac at Punta San Matteo, Central Alps (Scotti & Cola, 2006).

Fig.11: Upper part of the Invergnan Glacier in spring 2001 (left) and summer 2003 (right). Glacier fragmentation (not observed in surrounding glaciers) proceeded until bedrock outcropping. Photos by A. Giani and A. Galluccio.

Fig.12: The Malavalle Glacier. Photo by G.L. Franchi.

Ice calving, related to glacial lake growth at the front of retreating glaciers, is another particular hazardous phenomenon which is increasing in frequency. Thermokarst processes facilitate the sudden detachment of ice lamellas which produce dangerous anomalous water waves (Diolaiuti et al., 2006). Intense calving processes facilitate the breaking of the Malavalle Glacier front, Eastern Italian Alps (Fig. 12). A sudden outburst glacial lake (discharge 1 M m^3) took place from the Malavalle ice-contact lake during the Summer 2005.

IMPACTS ON NATURAL RESOURCES AND HAZARD

Landscape evolution in glacial and periglacial areas has significant socio-economic and environmental impacts (Haeberli et al., 1997).

From the economic point of view, glacier retreat and permafrost changes induced by climate variations mainly affect water resources and tourist activities. After a period of relative water abundance due to glacier melting, in recent years glacier shrinkage, coupled with a marked snow cover reduction observed in alpine areas, is significantly affecting water supply from glacierized basins. At the Italian national scale, this water shortage is especially noticed in summer time, when hydroelectric power plants strongly rely on water supplied by glaciers. At a local scale, glacial water reduction in summer time may have heavy consequences on water supply to mountain villages and huts relying on glaciers, because of peak water demand due to tourist crowding. These problems are going to get worse and worse.

Glacier retreat and permafrost changes are likely to have an impact also on hydrological and sediment cycles, but there's still a lack of knowledge about this topic in alpine areas. Reduction in snow and glacial ice cover may lead to winter frost penetration in uncovered areas (Wegmann et al., 1998): because of reduced infiltration rates in frozen grounds, increased surface runoff can be expected and a consequent depletion of groundwater reservoirs and an increase of flood peaks. Permafrost degradation might have an opposite effect. Expected sediment budget changes are mainly related to the exposure of large quantities of unconsolidated sediments due to glacier vanishing, and to debris supply from previously frozen grounds. Modification of sediment fluxes are likely to affect engineering works along channels (e.g. defence works, hydropower basins).

Geomorphological changes involving glacial and periglacial areas are having heavy consequences also on tourist exploitation. On one side, glacier vanishing is a threat to landscape attractiveness. On the other side, due to glacier shrinkage summer skiing resorts are running into difficulties. Moreover, morphological changes are affecting climbing routes on ice (Fig.13) and trekking trails, which in some cases had to be abandoned (e.g. the glaciological path in the Forno Glacier basin, Pelfini et al., 2004).

Fig.13: North Ciarforon face, Gran Paradiso Massif, in 1920 (left) and 2000 (right, photo by SMI). The famous route on ice has been greatly modified by the strong shrinkage of the peak glacial cover.

An other important consequence of ongoing processes is an increase of natural instability and related hazards in same cases, or also a change in location, magnitude, frequency, and timing of events (Gruber & Haeberli, 2007). Climbers and hikers are most exposed to hazards arising from climate warming in high altitude mountains, as enhanced rock fall activity along many climbing routes previously considered safe has been observed in recent years, while hanging glacier stability seems decreasing. Nevertheless, large events pose also a risk to inhabitants and infrastructure in valleys prone to rock/ice avalanches or glacial outbursts. These events can reach very high velocities (up to 200 km/h), large volumes (up to millions of cubic meters) and long travel distance (up to tens of kilometres), considered also the high mobility shown by mass movements in glacial environment (Evans & Clague, 1988; Dutto & Mortara, 1992). Recent examples are represented by the 1997 Brenva rock-ice avalanche (Mont Blanc Massif, Italian side, Barla et al, 2000), or by risky conditions in 2002 and 2003 for the Macugnaga village due to Lago Effimero outburst risk.
Rock and debris mass settlement due to permafrost degradation, even if not leading to failure, may affect the stability of building foundations and structures on ice-bearing ground, like cableways or mountain huts (e.g. Capanna Carrel, Matterhorn; Lambronecca hut, Monte Rosa).

RESEARCH NEEDS FOR PROCESS UNDERSTANDING AND DEVELOPMENT OF MITIGATION STRATEGIES

Monitoring present geomorphological evolution of glacial and periglacial mountain areas is a priority, considering the rapidity of climate change, the shift of cryospheric hazard zones, the remoteness of many hazard source areas, besides the fact that changes are going beyond any previously known limit. Monitoring can be carried out by mean of field observations, ground-based instruments or remote sensing techniques.
The establishment of networks of observers formed by local, trained people (mountain guides, rescue people, hut keepers,…), coordinated by researchers or technicians, represent a low-cost, effective way to get a continuous and widespread monitoring of high altitude, remote

areas. An interesting experience in this direction started in the Valle d'Aosta Region (NW Italy) in summer 2005, in the framework of the Interreg project "PermaDataRoc" (« Elaboration d'une base de données et expérimentation de méthodes de mesure des mouvements gravitaires et des régimes thermiques des parois rocheuses à permafrost en haute montagne »). The project, leaded by Fondazione Montagna Sicura in cooperation with EDYTEM Laboratory - Université de Savoie, ARPA Valle d'Aosta and CNR-IRPI Torino, aims at testing different methodologies and techniques for investigating the relation between permafrost degradation and high mountain rock wall stability (Deline et al., 2007). In order to fill the lack of information about high altitude rock fall events, a systematic survey of present-day rock-falls/avalanches was set up, carried out by mountain guides, trained for the purpose.
An extensive monitoring of this kind allows to identify critical situations deserving a specific, accurate monitoring, to be carried out by instrumental means. The Belvedere glacial basin is a relevant example of this kind. During and after the emergency related to the Belvedere Glacier surge and Effimero Lake growth, investigations were carried out by mean of advanced techniques, in order to gain data relevant to the glacier dynamics, the lake evolution and the englacial and subglacial drainage system pattern (Tamburini & Mortara, 2005). Once the surge movement slowed down and the epiglacial lake emptied, the attention was driven towards the Monte Rosa east face, where enhanced rock-fall activity was observed since 1999 (Fischer et al., 2006). Ground based laserscanning and synthetic aperture radar, in addition to multitemporal photogrammetry, are the principal techniques adopted to survey rock wall evolution.
An other promising approach is represented by modern remote sensing techniques (Kääb et al, 2005). Digital terrain models (DTMs), derived from optical stereo data, synthetic aperture radar or laserscanning, represent valuable data sets for investigating high-mountain processes, on a regional scale. Multitemporal data, in particular, can be used for change detection and displacements measurements. The application of remote sensing techniques becomes essential in remote regions, where access is made difficult by physical and/or political reasons.
Monitoring outcomes will give valuable information for better understanding glaciers and permafrost system functioning and their reaction to climate change. Major research gaps refer to mountain permafrost evolution, and in particular to permafrost in steep bedrock (Gruber & Haeberli, 2007). An other important investigation issue relates to glacier-permafrost relationships and interactions, a this topic which has long be neglected (Haeberli, 2005).
Other important tools for process understanding and scenario development are represented by historical research on past natural instability events and geomorphological evolution (Deline 2001; Glaciorisk EU Project, http://glaciorisk.grenoble.cemagref.fr), instrumental monitoring of relevant environmental parameters like air and ground temperature (Gruber et al., 2003; Cremonese et al., 2007), laboratory tests (Davies et al., 2001), process modeling (Wegmann et al., 1998).
With reference to historical research, the main problem, as mentioned before, is represented by the lack of direct information on past instability events and geomorphological evolution, mainly due to the remoteness of investigated areas. An historical reconstruction is still possible when processes produced evident geomorphological features, but it won't allow to recognize small-sized events (also important when considering permafrost-related instability), or events involving ice/snow masses. In any case, knowledge of historical processes is only partially representative of future developments, considered that present changes are going beyond any previous known limit. Because of the lack of historical data and the novelty of present and future climatic scenarios, modeling is a key tool to investigate the response of

glacial and periglacial areas to climate change and forecast the impact of natural processes in the present climatic and environmental framework (Bottino et al., 2002; Huggel et al., 2004).
Knowledge and process understanding coming from the above mentioned investigation activities are essential to build scenarios useful for hazard assessment and natural resource planning in high elevation mountain areas, aimed at mitigation strategies able to face climatic change. Moreover, testing up-to-date investigation technologies and methodologies in high altitude alpine conditions, will supply technicians and decision makers with effective technological and methodological tools.

CONCLUDING REMARKS

The availability of a larger number of well documented case records, together with models improving, will allow, in the next future, to outline reliable scenarios for geomorphological evolution in glacial and periglacial areas under changing climate, and related problems and hazards. On the other hand, emergency conditions faced in some critical occasions gave the opportunity of testing modern investigation techniques in extreme environments. In any case, the velocity of climate change and the observation that changes in glacier and permafrost equilibrium are shifting beyond historical knowledge require a careful and continuous monitoring of ongoing and potential processes, in order to define adaptation and mitigation strategies.

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