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A surge-type movement at Ghiacciaio del Belvedere and a developing slope instability in the east face of Monte Rosa, Macugnaga, Italian Alps

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Extraordinary developments are taking place at Ghiacciaio del Belvedere near Macugnaga, Valle Anzasca, in the Italian Alps. A surge-type flow acceleration started in the lower parts of the Monte-Rosa east face, leading to strong crevassing and deformation of Ghiacciaio del Belvedere, with extreme bulging of its orographic right margin. High water pressure and accelerated movement lasted into winter 2001/2002: in places, the ice is now starting to override moraines from the Little Ice Age. In addition, but fairly independently, a most active detachment zone for rock falls and debris flows has been developing for several years now in the east face of Monte Rosa. Besides the scientific interest in these separate phenomena, both events affect the growing hazard potential to the local infrastructure and must be considered seriously.

Keywords: *Climate change, glaciers, high mountains, natural hazards, slope instability*

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Introduction

As a consequence of global warming trends, glacierized mountain areas presently undergo rapid and potentially accelerating changes. In fact, the combination of human activities and ice vanishing through melting has introduced the most striking changes in cold-mountain landscapes (Haeberli & Beniston 1998). As a consequence of such developments, permafrost degradation in fissured rock walls has long-term impacts on frost weathering and rock fall activity by reducing the strength and increasing the permeability at depths of metres to tens of metres below the surface (Matsuoka et al. 1998). At places of pronounced glacier retreat, changes in stress distribution and surface temperature in rock walls must also be anticipated (Wegmann et al. 1998). Formation and disappearance of ice- and moraine-dammed lakes generally accompany marked changes in glacier extent or thickness (Walder & Costa 1996, Reynolds 2000) and steep hanging glaciers that are partially or entirely frozen to their beds could become less stable. The general tendency in high mountain areas with a scenario of accelerated future warming would be a marked shifting of hazard zones with considerable changes in the involved processes and a widespread reduction in stability of formerly glacierized or perennially frozen slopes (Dramis et al. 1995, Haeberli et al. 1997, Barla et al. 2000, Davies et al. 2001, Giani et al. 2001, Deline in press).

The uppermost part of the Anzasca Valley (Valle Anzasca) above Macugnaga in the Italian Alps with its spectacular high-mountain scenery of Ghiacciaio del Belvedere and the gigantic east face of Monte Rosa (Figs. 1 and 2) has been affected by such processes for a long time. Most recently, some quite dramatic processes have taken place, including a surge-type movement of Ghiacciaio del Monte Rosa/Ghiacciaio del Belvedere and rock instability in the central part of the Monte Rosa east face. The present contribution briefly describes these still ongoing phenomena and provides some recommendations with respect to observation and hazard assessment. It is devoted to Johan Ludvid Sollid as a sign of admiration for his outstanding work on glaciers and permafrost in Norway and Svalbard, and as an expression of deeply felt gratitude for excellent collaboration with the Swiss partners over many years.

Background

Ghiacciaio del Belvedere is a humid-temperate, heavily debris-covered glacier fed by steep glaciers (especially Ghiacciaio del Monte Rosa as the main tributary), ice and snow avalanches as well as rock falls from the large east face of Monte Rosa. It has been investigated for many decades and was known in the early scientific literature as a classic example of a glacier with an elevated sediment bed (Monterin 1923, VAW 1983–1985, Mazza 1998).

At least seven outburst floods are known to have originated from the glacier in the past; some of these seriously threatened the Macugnaga village besides affecting the original moraine geometry. In August 1868, strong pressure exerted by water accumulated inside the glacier as a con-

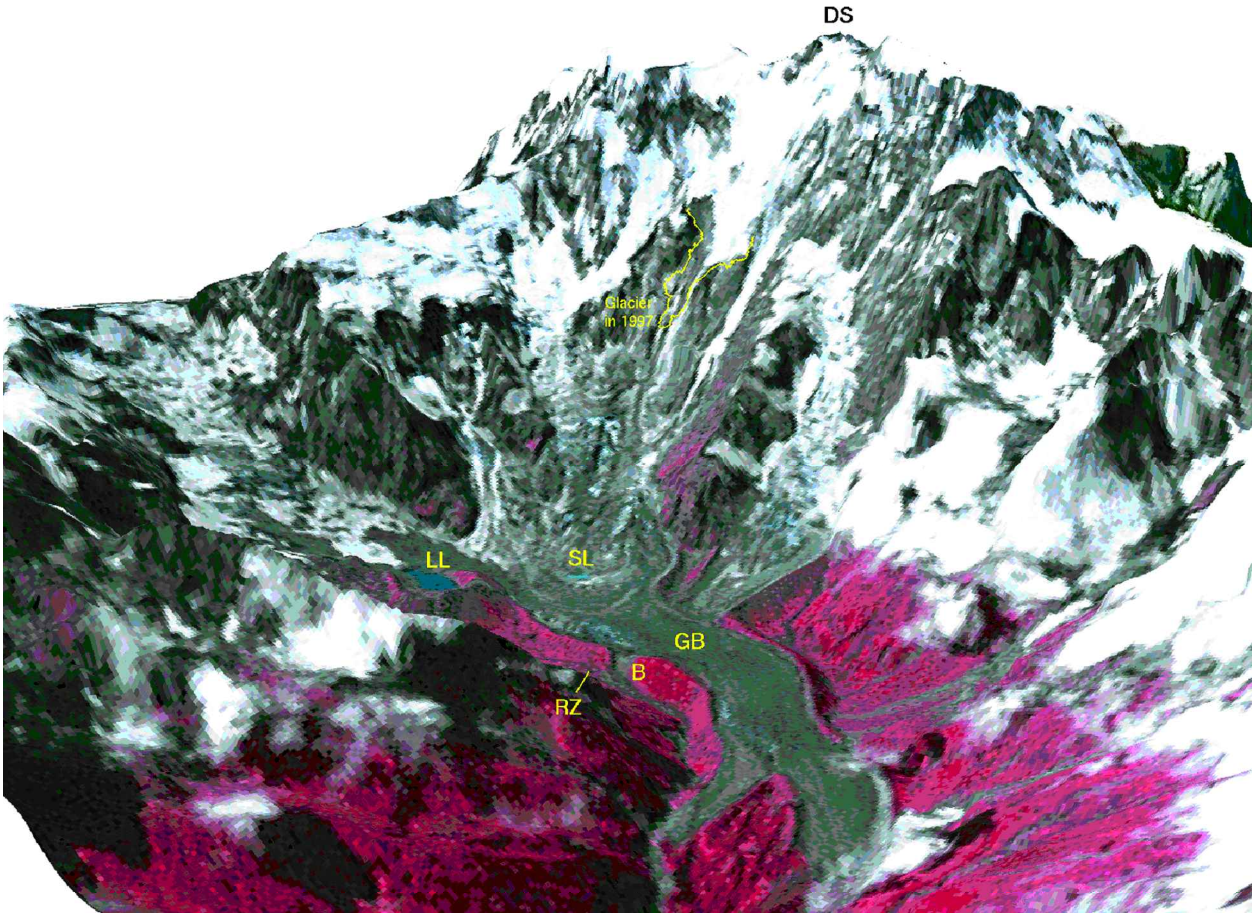

Fig. 1. Synthetic oblique perspective view of Monte Rosa east face with Ghiacciaio del Belvedere (GB). The figure is created from an ASTER false colour infrared image (band 3, 2 and 1 as RGB) acquired on 24 August 2001 and draped over a DEM with 25 m cell size. The frontal position of a steep hanging glacier in 1998 (derived from TM) is indicated (green line), SL = supraglacial lake, B = breach, DS = Dufourspitze, LL = Lago delle Locce, RZ = Rifugio Zamboni CAI. Elevation data: DEM 25 © Swiss Office of Topography (BA 024091).

sequence of prolonged rainfalls caused a sudden collapse of the right lateral moraine of the left glacier lobe. The 60–70 m wide grass plain in front of the breach was covered by boulders for *c*. 1 km^2 (Stoppani 1871). Some 30 years later, during a rainy period in August 1896, water cut two ways through the moraine and devastated meadows near Pecetto of Macugnaga (*La Voce* 1896). A water-pocket inside the glacier provoked progressive saturation of the right lateral moraine and its breaking down near the Alpe Pedriola in 1904 (Somigliana 1917). Following several days of rain in September 1922, a huge mass of water was expelled from the glacier, destroying a *c*. 100 m length of the wall constructed to defend Macugnaga. Big ice blocks were carried for *c*. 6 km to Borca (Monterin 1926). On three occasions, 13 August 1970, 2 August 1978 and July 1979, outburst floods issuing from the moraine- and ice-dammed Lago delle Locce at one of the tributaries (Ghiacciaio delle Locce), progressively widened the breach initially cut in 1904 through the right lateral moraine near Alpe Pedriola. The 1979 outburst seriously damaged the Belvedere chair-lift and flooded the valley bottom for a length of 1 km and a mean width of 150 m, almost reaching the Pecetto hamlet near Macugnaga (Tropeano et al. 1999, Chiarle & Mortara 2001).

Following the 1979 flood, prevention work (artificial lowering of the lake level at Lago delle Locce and extensive dam construction in the main torrent below the glacier) became necessary (Haeberli & Epifani 1986, Mazza 1998). In connection with this work, integrated assessments on the special conditions at Ghiacciaio del Belvedere and general glacier hazards around Macugnaga were prepared by an interdisciplinary group of experts from Switzerland and Italy (VAW 1983–1985). This work was mainly based on knowledge and experience collected in Switzerland within the framework of a working group on glacier hazards established by the federal government after the Mattmark catastrophe (Haeberli 1983, Alean 1985, Haeberli et al. 1989). It also reinterpreted the seismic reflection soundings which had been carried out at Ghiacciaio del Belvedere during the International Geophysical Year, by using results from new radio-echo and seismic refraction/reflection soundings. Furthermore, it developed a model for understanding the elevated bed and the fast intermittent growth of Ghiacciaio del Belvedere during the 1970s as a function of the sediment balance in the catchment (cf. Haeberli 1986, 1996, Maisch et al. 1999). For many years now, the so-collected material has been used as documentation for national and international excursions to the unusual and fascinating site. Especially, visits were organized every year in connection with advanced courses on glacier hazards for geoscience students of the University and ETH Zurich. The excursion in 2001 had a participation of not only specialists from France and Great Britain but also students from the Department of Physical Geography at the University of Oslo: it provided a most astonishing surprise.

A surge-type movement in progress at Ghiacciaio del Belvedere

Ghiacciaio del Belvedere developed an extraordinary change in flow, geometry and surface appearance between summer 2000 and summer 2001. In June 2001, the guardians of Rifugio Zamboni of the Club Alpino Italiano (CAI), located in the orographic right ablation valley, observed heavily crevassed and almost debris-free ice towering above the orographic right lateral moraine (Fig. 3), which was last reached by the glacier during the 19th century (= maximum stage of the Little Ice Age), and also ice filling the breach (Fig. 4) cut by the repeated outbursts of Lago delle Locce. Already in summer 2000, the lower part of the main tributary (Ghiacciaio del Monte Rosa) exhibited intense chaotic crevassing suggestive of accelerated flow conditions, and had become almost completely detached from lateral and upslope ice by an immense crevasse zone at its orographic left margin (Fig. 2). As a consequence of the accelerated flow, the surface of Ghiacciaio del Belvedere at the foot of the wall became dramatically compressed and deformed (Fig. 5). Local authorities were made aware of the phenomenon by mountain guides when a depression on this deformed surface was filled by a lake containing blue (surface) water during spring snowmelt in 2001. The general direction of the compressive strain appears to be directed mainly towards the orographic right glacier margin, accounting for the increased elevation of heavily crevassed, debris-free ice above the moraine for a distance of *c.* 1 km. Within a few months only, the thickness increase over this part of the glacier amounted to tens of metres. Photographs frequently taken until October 2001 by the guardians of Rifugio Zamboni and visiting scientists clearly show that ponds of dirty water remained between the ice and the moraine (Fig. 6) and that the glacier continued to flow at accelerated speed well into the winter of 2001/2002. After the summer season 2001, during which ablation had – to a certain degree – offset the rise in surface elevation, the ice started to override the

Fig. 2. Monte Rosa east face as seen from Battisti Pass (Colle Battisti) on 29 August 2000. Photo: G. Kleis (www.bergdias.de).

Fig. 3. View from the main entrance door of Rifugio Zamboni in summer 2001 towards the fully vegetated, orographic right lateral moraine and heavily broken debris-free ice of Ghiacciaio del Belvedere; in September 2000, the almost completely debris-covered glacier surface was still many metres lower and could not be seen from the hut. The steep tributary in the background, Ghiacciaio del Monte Rosa, is heavily crevassed in its lower but not upper part. Photo W. Haeberli, 17 July 2001.

right lateral moraine at and shortly below the breach (Fig. 7). Satellite imagery (ASTER) as well as a special airphoto flight showed that a large supraglacial lake with a surface area of *c*. 2,500 m^2 formed again in autumn 2001 (Figs. 1 and 8).

There is no doubt that Ghiacciaio del Monte Rosa and Ghiacciaio del Belvedere are presently undergoing an extraordinary flow instability with surge-type characteristics. Among the most important of these are the extreme deformation and crevassing over parts of the surface, the high water pressure as indicated by dirty ice-marginal pools, and the large ice volume displaced within a short time. As an exceptional phenomenon in the Alps, the observed surge-like phenomenon is clearly of great scientific interest. It could, however, also have hazardous consequences for the local infrastructure and tourist facilities. Thus, special attention should be paid to the following facts:

- the glacier could continue to override, or push through, the orographic right lateral moraine and the breach, causing rock and ice falls onto the access trail to the Rifugio Zamboni (Fig. 7);
- the increased ice volume of the glacier could reach the Belvedere site adjacent to the glacier snout and impact the tourist installations there (cable car, ski run, restaurant);
- the end of the surge could be accompanied by a sudden outburst of pressurized water;
- the supraglacial lake could grow and overflow during spring snowmelt and trigger a flood – possibly with a slush avalanche starting from the less inclined ice surface;
- the lateral moraine has lost its retention/deflection function with respect to major snow/ice/rock avalanches from the east face of Monte Rosa; and
- the rapidly changing ice condition in the lower part of the Monte-Rosa east face may affect the stability of ice and rocks at higher elevation within the same slope.

The regional and local authorities have been made aware of this situation and are now establishing an observational programme.

Developing slope instability in the east face of Monte Rosa

In connection with the stability aspects in the east face of Monte Rosa, the growing rock-fall activity at medium height, immediately south of Imseng Ridge (Crestone Imseng) must be mentioned. The apparent frequency of events has increased for a number of years from an extended source area (Fig. 9), the entire width of which obviously acts as a detachment zone. This extended detachment zone is at the base of a hanging glacier and not only delivers material

Fig. 4. Ice of Ghiacciaio del Belvedere penetrating the breach created by repeated outbursts of Lago delle Locce; there had been virtually no ice visible in the breach during previous years. Photo: G. Mortara, August 2001.

almost continuously during summertime, when meltwater can often be observed to trigger debris flows in the chute, but sometimes also during wintertime. Above and especially below this detachment zone, surface ice cover appears to have diminished in a rather dramatic way (Fig. 1). The possibility cannot be excluded that the steady increase in rockfall activity through the past years, the broad zone of active detachments and the continuation of instabilities during wintertime may be related to the destabilization of a larger rock mass which could trigger an event comparable to

Fig. 5. Heavily broken and deformed surface at the confluence of the steep Ghiacciaio del Monte Rosa and the much flatter Ghiacciaio del Belvedere; the fine sediment in the topographic depression indicates the position of a supraglacial lake during spring 2001 and where a new lake formed in summer and autumn 2001. Photo: W. Haeberli, 17 July 2001.

Fig. 6. Pond of muddy water at the glacier margin indicating strongly pressurized subglacial water; an enormous crevasse is visible on Ghiacciaio del Monte Rosa in the background, where the instability has its origin. Photo: W. Haeberli, 16 August 2001.

the rock fall and powder-snow avalanche at Brenva, Mont Blanc, in 1997 (Barla et al. 2000, Giani et al. 2001, Deline 2001). A major event, especially if involving large volumes of snow in winter or spring, could easily travel over distances about three times the vertical distance of fall, i.e. several kilometres in the present case.

Hazard monitoring

Observations should continue from space and airborne remote-sensing platforms supported by ground investigations. In order to visualize the impressive scenery of Ghiaciaio del Belvedere and its recent changes, a synthetic oblique perspective view was created from an ASTER false colour infrared image (band 3, 2 and 1 as RGB) acquired 24 August 2001 and draped over a DEM with 25 m cell size (Fig. 1). The supraglacial lake (SL) on Ghiaciaio del Belvedere (GB), as well as the dramatic glacier recession in the Monte Rosa east face, is visible (the green line indicates the 1998 glacier position); the position of Lago delle Locce (LL), Rifugio Zamboni (RZ), the breach from the repeated Locce outbursts (B) and the summit of Dufourspitze of Monte Rosa (DS) are also indicated. The ASTER scene is a product collected within the framework of worldwide glacier observation from space coordinated by the USGS-led project GLIMS (Global Land Ice Measurements from Space) which will use data from the new sensors ASTER and ETM+ on board Terra and Landsat 7, respectively (Kieffer et al. 2000). ASTER has 15 m spatial resolution for three bands in the green, red and near infrared part of the spectrum, and 30 m in the middle infrared. The higher spatial resolution of ASTER is able to monitor finer spatial details such as the supraglacial lake or the recession of the small hanging glacier in the Monte Rosa east face. Compilation of new inventories of Alpine glaciers is part of the ongoing GLIMS project and worldwide climate-related observation of terrestrial ice conditions (Haeberli et al. 2000, Kääb et al. in press, Paul et al. in press).

A detail from a specially arranged airphoto flight, showing the area around the supraglacial lake, is provided in Fig. 8. Space and airborne images repeated in the near future may enable surface deformation to be documented and flow fields to be derived (cf. Kääb et al. 2000). Photos are also regularly taken from the ground by mountain guides and people from

Fig. 7. Ice blocks thrown over the moraine ridge onto the access trail to the Rifugio Zamboni CAI. Photo: G. Mortara, early October 2001.

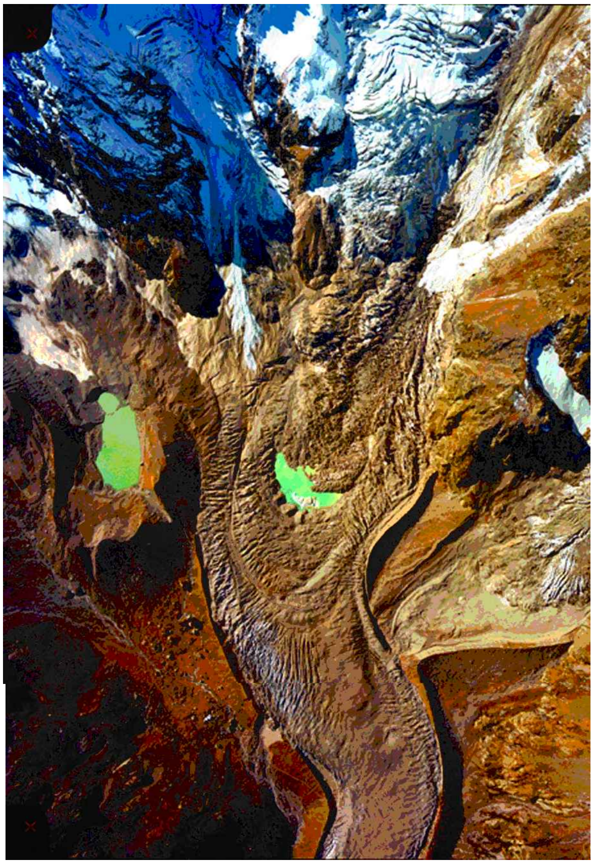

Fig. 8. Aerial view (11 October 2001, IRPI) of the central part of Ghiacciaio del Belvedere with the new supraglacial lake.

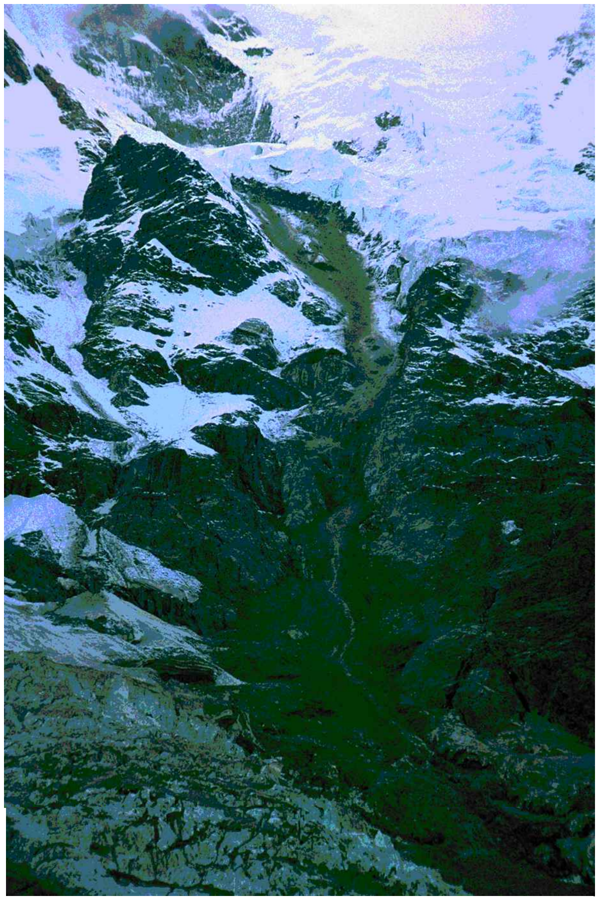

Fig. 9. Large detachment zone of rock falls and debris flows in the east face of Monte Rosa (upper central part of the image). The extremely crevassed Ghiacciaio del Monte Rosa is visible in the lower left corner of the image. Photo: W. Haeberli, 17 July 2001.

the Rifugio Zamboni. Helicopter flights have been recommended for closer inspection of the rock-fall area in the east face of Monte Rosa and automatic cameras may be used to monitor crevasse patterns, rock falls, ice/snow avalanches or floods. Changes in surface geometry are carefully observed near Belvedere and stake measurements for determination of flow velocity are planned. More detailed scientific investigations could include drilling and borehole observations. Various experiences for the assessment and management of glacier-related hazards exist, through which the monitoring efforts could be coordinated in association with the local and regional authorities (Haeberli et al. 1989, Richardson & Reynolds in press, Huggel et al. 2002, Huggel unpublished data).

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