A ~9460 - 9490 cal. yrs BP age for the Flimser rockslide based on limnogeological evidences

Deplazes, G. & Anselmetti, F.

Geological Institute, ETH Zürich, CH-8092 Zürich, Switzerland
gaudenzd@student.ethz.ch, flavio.anselmetti@erdw.ethz.ch

Limnogeologic investigations of two lakes that are located on top of the Flimser rockslide deposits provide new data on the history of this largest rockslide of the Alps. They suggest an early Holocene timing (~9460 – 9490 cal. yr BP) of the event. The Flimser rockslide is located in the Vorderrhein Valley 20 km to the west of Chur in the canton of Grisons. The rockslide mass consists mainly of Mesozoic brecciated limestone clasts of all grain sizes (from silt to huge blocks). The Flimser rockslide has been historically attributed to the Late Glacial Period. Lately, new studies i.a. based on 14C-AMS ages of wood fragments sampled from the base of the distal rockslide deposit in the Versamer Tobel (Poschinger and Haas 1997, Schneider et al. 2004), and an event layer in downstream Lake Constance (Schneider et al. 2004) have proposed, however, that the slide is rather of early Holocene age.

In this study, a new approach to investigate the age of the Flimser rockslide is presented: Recovering and dating of the oldest sediments deposited in the lakes on top of the Flimser rockslide provide a minimum age of the event. In addition, wood fragments in the rockslide deposits directly below the lake sediments present a maximum age of the Flimser rockslide. For this purpose, two small lakes, Lag la Cauma near Flims, and Lag Grond in Laax, are investigated from a limnogeological point of view. The rockslide area has created a unique and complicated hydrological situation and each lake has its own hydrologic regime (Bonanomi et al. 1994). Lag la Cauma has a subsurface in- and outflow with a water level that oscillates annually by up to 6 m. The maximal water depth of 25 - 30 m is usually reached in early summer. Lag Grond, in contrast, has a superficial out- and inflow and is characterized by a dominantly siliciclastic input. The maximum water depth is ~5.5 m.

Both lakes have been investigated with a high-resolution reflection seismic surveying campaign (3.5 kHz pinger source) so that bathymetric maps of these lakes have been made. The total sediment thickness could not be determined geophysically, likely because high gas content of the sediments prevented penetration of the seismic signal all the way to the underlying rockslide mass. Gravity short cores and long piston cores have been taken from the deepest parts of the two lakes reaching all the way down to a hard substrate.

The sediment cores from Lag Grond can be combined to one 7.3 m long composite section. The upper 5.7 m consist of dark organic-rich sediments with a variable content of authigenic calcite. These sediments are interbedded with light grey detrital layers. The uppermost of these layers can be related to the major flood that occurred in 2002. Similar layers in the lower part of the core provide a record of past flood events. The composite core section consists below 5.7 m almost purely of silt to gravel sized limestone clasts, which represent Flimser rockslide material. The top of this interval is characterized by several perfectly-graded sequences of limestone grains that were deposited in an early lacustrine environment. They likely originate from redeposition of rockslide material through turbiditic flow events in the young lake. They are underlain in the lowest part of the core by an unsorted limestone breccia, which resembles strongly the compacted and brecciated Flimser rockslide debris, as it is known from the Rhine gorge outcrops.

Two long cores in Lag la Cauma reached a hard substrate, beyond which no further coring penetration could be achieved. At the base of one of these cores, a piece of gravel sized limestone has been recovered, supporting the assumption that the hard surface represents the top of the rockslide mass. Comparing all cores of Lag la Cauma, a composite
section of ~3.9 m length can be established. Differences in sediment thickness and in the stratigraphic record between the sites can probably be explained with changing current patterns of the subsurface inflows. The sediments of Lag la Cauma are, in contrast to the ones from Lag Grond, mostly dominated by autochthonous deposits with a low sedimentation rate. Lag la Cauma sediments consist partly of very thinly-laminated sediments. Some of these microlaminae are composed of black organic-rich horizons that contrast sharply to more carbonate-rich light-coloured layers. Other parts of the cores consist of thicker-laminated lithologies with variable amounts of organic matter and probably authigenic calcite.

Seven $^{14}$C-AMS datings of wood and leaf fragments from Lag la Cauma provide a consistent downcore age trend (Figure 1). The oldest dated leaves taken 2.5 cm above the bottom of the core have an age of ~9632 – 9465 cal. yr BP. This sediment age is interpreted to be a minimal age of the rockslide, reflecting the onset of lacustrine sedimentation after the event. In contrast, a maximum age of the rockslide is provided by dating a wood fragment deposited between gravel sized limestone clasts in the lower part of the Lag Grond composite core, interpreted to be the rockslide mass itself. This sample has been dated to ~9487 – 9232 cal. yr. BP. These early Holocene ages are supported by the lack of typical glacial organic-poor deposits in both lakes.

Based on this assumed concept of maximum and minimum ages that all were calculated with a two-sigma calibration range, the time window for the Flimsar rockslide is postulated between 9460 and 9490 cal. yr BP. This matches and refines the previously suggested time windows from Poschinger & Haas (1997) and Schneider et al. (2004) (Figure 1).

**REFERENCES**


---

**Figure 1.** Comparison of new $^{14}$C-AMS ages (cal. yr BP) from Lag la Cauma and Lag Grond sediments with published ages concerning the age of the Flimsar Rockslide. All ages with error bars have been calibrated with the program CALIB REV4.4.2 (Stuiver and Reimer 1993; 95% confidence limit).
What controls deposition and incision on debris-flow fans?

1Duehnforth, M., 1Densmore, A.L., 2,3Ivy-Ochs, S., 4Allen, P.A. & 5Kubik, P.W.

1Institute of Geology, ETH Zurich, Switzerland
2Institute of Particle Physics, ETH Zurich, Switzerland
3Department of Geography, University of Zurich, Switzerland
4Department of Earth Science and Engineering, Imperial College London, UK
5Paul Scherrer Institute, c/o ETH Zurich, Switzerland

Debris-flow fans of the arid southwestern USA have been the focus of a number of geomorphic studies. While many studies have been focused on controls of fan surface segmentation or fan slopes, we still lack a general quantitative model for the driving mechanisms of large-scale fan geomorphology, including the number of depositional fan lobes and the degree of incision at fan heads. Debris-flow deposition and incision on fans is mostly attributed to either climatic, tectonic, or internal controls. It is often assumed that a climatic control produces a regionally similar geomorphic response in the landscape. But does this mean that we can exclude climatic influence in cases where adjoining landforms have a different geomorphology? If so, is this pointing to a tectonically-driven landscape or is this rather indicating intrinsic forcing?

Here, we attempt to elucidate the forcing parameters for the large-scale geomorphology of two debris-flow fans, Shepherd and Symmes Creek fans, in Owens Valley, CA. We establish a relative depositional fan chronology based on topographic elevation profiles, geomorphic parameters, and fan lobe cross-cutting relationships derived from 1 m resolution Airborne Laser Swath Mapping (ALSM) data. We combine this depositional chronology with results from absolute exposure dating of debris-flow boulders using cosmogenic \(^{10}\text{Be}\). Furthermore, we link our findings to catchment properties derived from field observations, digital orthophotos and 10 m resolution digital topographic data.

Our first results indicate that Shepherd and Symmes Creek fans exhibit variations in the number of depositional lobes, the degree of incision at the fan head and the shape of the catchment stream profile. Shepherd Creek fan has multiple depositional fan lobes that correspond to distinct periods of debris-flow deposition. The fan head is \textit{in fact} by and the catchment stream profile records glacial modification of the trunk valley with overdeepened subbasins. Today, these subbasins are partly filled with sediment. In contrast, Symmes Creek fan exhibits just one major depositional lobe, ~5 m incision at the fan head, and a smooth, concave-up stream profile.

Our observations lead us to the conclusion that the morphology of the catchment trunk valley has profound implications for the dynamics of debris-flow processes and large-scale fan geomorphology. As long as stored sediment can easily leave the catchment, there is more or less continuous deposition on the fan and no fan head incision. If sediment is trapped within the catchment, it can only reach the fan if (a) the sediment traps are completely filled, (b) the flows are high enough to overtop the trap barriers, or (c) the flows originate downstream of the traps. Trapping of sediment leads to undercapacity water flows that are able to incise the fan head, causing abandonment and switching of depositional lobes.

Our investigation shows that fan dynamics and large-scale fan geomorphology are strongly coupled to catchment properties. Even though the basic conditions of sediment delivery and mobilization might be set by climatic, tectonic, and lithologic controls, these controls may be modified by intrinsic triggering mechanisms. Therefore, we expect that systematic information on timing and controls of debris-flow deposition on fans may be derived on Symmes Creek-type fans, where sediment deposition is a direct function of sediment availability, mobilization, and transport. In contrast, on Shepherd Creek-type fans, this relationship is influenced by sediment trapping, and the fan chronology may be decoupled from variations in the external forcing.
Dynamic modelling of regional rockglacier distribution:

presentation of a prototype model

Frauenfelder, R.¹, Schneider, B.², Kääb, A.³, Hoelzle, M.¹ & Haeberli, W.¹

¹ Glaciology and Geomorphodynamics Group, Department of Geography, University of Zurich, Switzerland
² GeoTask AG, Güterstrasse 253, 4053 Basel, Switzerland
³ Department of Geosciences, University of Oslo, Postbox 1047 Blindern, 0316 Oslo, Norway

Rockglaciers are periglacial debris accumulations produced, deposited, and deformed during historical and Holocene time periods. They originate from talus (‘talus-derived’ rockglaciers, see Figure 1) and/or glacier-transported debris, mostly from lateral and terminal moraines (‘moraine-derived’ rockglaciers).

Numerous inventory studies about rockglaciers yielded information about their characteristics such as form, geology, location, etc. In addition, detailed studies on individual rockglaciers helped to build up a profound knowledge basis about these landforms. A comprehensive understanding of intra-regional variability of rockglacier occurrence is, however, still lacking.

The prototype model allows the numerical simulation of the spatial and temporal distribution of talus-derived rockglaciers. Its main goal is to help evaluate and increase knowledge about dynamics and distribution patterns of rockglaciers by detailed comparison of the model outcome with the actual occurrence of rockglaciers (cf. Bras et al. 2003, for an in-depth discussion of mathematical modelling in geomorphology). The area considered is the Upper Engadine, eastern Swiss Alps; the represented timescale is the Holocene (i.e. ~10,000 y BP to today).

Dynamic modelling builds upon static modelling by incorporating the time component (e.g. Karssenberg 2002). A dynamic model describes, thus, how a parameter system can transform from one qualitative state into another, where each qualitative state is described by a static model.

The presented dynamic model considers processes in the spatial and temporal domain and accounts for both external and internal processes, implemented by means of six modules (A to G). The external processes considered are: (A) rock-debris accumulation, (B) hydrology, (C) climate, (D) glacier extent. The internal processes are: (E) creep initiation, (F) advance rate, (G) creep termination (see Figure 2).

Technically, each DEM with a resolution sufficient to adequately represent rockglacier features – spatial resolution denser or equal to ca. 30 m – can be used as an input for the model. Whichever actual DEM is used, it portrays the topographic surface including the rockglaciers. Therefore, the rockglaciers have to be extracted from the DEM before modelling.

Comparison between field evidence and modelling results yields the following most important results: (1) Most active and inactive talus-derived rockglaciers are reproduced accurately by the model, and the extents they exhibit in nature are also shown, approximately, although deviations can be found. (2) Certain active rockglaciers are not reproduced by the modelling. Careful consultation of the inventory data reveals that (at least) some of these rockglaciers are moraine-derived forms, and thus cannot be reproduced by a model that is based entirely on the processes involved in the development of talus-derived rockglaciers. (3) In a model run for 10,000 years, the modelled rockglacier fronts do not advance into regions where relict rockglaciers are found in the inventory. Based on temperature reconstructions and relative age dating on selected rockglaciers, it can be assumed that relict rockglaciers in the area evolved as early as the Alpine Lateglacial. These findings seem to be supported by the model results with ‘virtual rockglaciers’ not exceeding the extents of active (and some inactive) rockglaciers.

Generally, it can be said that dynamic modelling enables the simulation of spatio-temporal creep processes but proves to be highly dependent on the accurate modelling of the relevant input parameters (cf. Frauenfelder 2005, for a more detailed information).
Figure 1. Schematic plot of a talus-derived rock glacier, (b, c) two examples of active talus-derived rock glaciers: (b) Muragl rock glacier in the Upper Engadine, Eastern Swiss Alps (photograph by R. Frauenfelder), (c) rock glaciers at Nordenskiöld-kysten, Svalbard Archipelago (photograph by A. Kääb).

Figure 2. Qualitative sketch of important boundary conditions for: ① the initiation (modules A–E), ② the growth (modules A–F), and ③ the inactivation/relictification (modules A, C, D, F, G) of a talus-derived rock glacier. See text for further explanations.

REFERENCES


Parameterization of snow-redistribution by avalanches for regional-scale models of mass and energy balance

1,2 Gruber, S. & 2 Hasler, A.

1 Laboratoire EDYTEM, Université de Savoie, France
2 Glaciology and Geomorphodynamics Group, Department of Geography, University of Zurich, Switzerland

The snow cover is a decisive factor of the energy and mass balance of cold mountain regions. Redistribution of snow on steep mountain slopes by avalanches often strongly alters the spatial pattern of snow deposition. Snow patches that melt late in summer below steep slopes have been shown to favour cold ground temperatures and, hence, influence the distribution of permafrost. Many small mountain glaciers obtain a significant proportion of their accumulation from avalanches originating from the rock walls surrounding them. Often, such glaciers are situated entirely below the climatic equilibrium line altitude. Additionally, redistributed snow changes the altitudinal and areal distribution of snow water equivalent and thus also affects the runoff regime in mountain catchments.

A multitude of studies and methods use morphometric attributes or model wind fields to simulate snow distribution patterns in mountains on varying scales of sophistication, spatial and temporal resolution. However, most models of snow redistribution by avalanches are far too complex to be included into regional-scale models operating on cell sizes in the order of 10-100 m.

A simple array-based algorithm that handles the task of transporting the snow from a source cell to its deposition area is introduced: The TOPMODEL multiple flow-direction algorithm (Quinn et al. 1991) is extended by a deposition function. This multiple flow-direction algorithm with deposition (MFLOWDEP) is a fast and simple way to achieve realistic transport of snow in steep topography and to improve distributed models dealing with alpine snow cover. Application in a simple degree-day model as well as analyses of the sensitivity to cell size are presented. Figure 1 provides an impression of the achieved snow redistribution. Broader application of the proposed algorithm to e.g. lahars and mudflows is possible but still in an experimental stage.

REFERENCE


Figure 1. Modelled snow accumulation below rock faces on a small glacier. Darker colours indicate high accumulation of snow. Little or no snow is indicated by light grey in steep walls.
Verifying EROSION 3D:

Model performance, effects of downscaling and input resolution


Forest Engineering Group, Department of Environmental Sciences, ETH Zurich, Switzerland
* Institute of Geography, Department of Geosciences, University of Basel, Switzerland

Objective of this study is a verification of the process-related, spatially discrete soil erosion simulation model EROSION 3D (Schmidt et al., 1992). This is achieved by opposing model calculated brook runoff and sediment yield for major erosive events of the period 2002 – 2004 to measured sampling discharge-gauge runoff and suspended sediment yield data (Weisshaidinger et al., 2005) from a 2.6 km² large agricultural watershed ('Laenenbach Valley', Plateau Jura Region, Northwestern Switzerland), as well as from two sub-catchments.

GIS supported input generation is effected using continuous meteorological and soil physical observation data, land use mapping data, as well as available official soil and digital elevation maps. Various accuracy indices, as well as linear regression, and a recurrence frequency analysis for calculated and measured data are used to indicate the calculation quality.

Methodical approach for model verification follows up a study to evaluate the suitability of erosion models for observance supervision of erosion limits defined by Swiss legislation (Hebel, 2003). The study will complement earlier validations of EROSION 3D (Jetten et al., 1999; Schmidt et al., 1999; Weigert et al., 2003).

Results enable conclusions on the model performance in general, on the effects of calibration, and of downscaling (entire catchment versus sub-catchments), as well as of a rise in input data resolution (6.25 to 3 m). Further conclusions comprise statements on the applicability of distributed, event based models such as EROSION 3D for the purpose of erosion limit obedience control, and on the applied and widely supposed validation method using point data.

REFERENCES


*Glaciology and Geomorphodynamics Group, Department of Geography, University of Zurich, Zurich, Switzerland, maisch@geo.unizh.ch

**Paul Scherer Institute, c/o Institute of Particle Physics, ETH Hoenggerberg, Zurich, Switzerland

Over the last few years the glaciological and geomorphological situation of the Upper Engadine and Bernina region, stretching from Maloja to the west and, via Albula to the north, to the Bernina pass in the east, has been mapped, earlier by project NFP31 and more recently by NFP48 within the framework of the project (“GISALP”). Besides the cartographic representation of the bare geomorphology in mosaic-like and GIS-based forms, specific analyses of the occurrence, stratigraphy and dynamics of distinct landforms were performed (i.e. alluvial fans, debris flows, rockglaciers etc.). Special attention is given to the morainic remnants of Holocene (i.e. Little Ice Age) and Late-glacial history, their paleoglaciological reconstruction and tentative placement in relative and absolute chronologies.

Although the general sequence and morphological appearance of late-glacial stadials seems to be well established (cf. Ivy-Ochs et al., subm.) direct dating of the local moraines (based mainly on the radiocarbon dating of peat bog and lake sediment chronologies) are very rare and have, so far, yielded some questionable results (ages too young). To add new data points to the absolute time scale and to bring new methodical aspects (or problems) to fruitful discussion, moraines were selected with reasonable age assignments and pre-existing radiocarbon dates from nearby peat bogs. These were at Maloja (Forno glacier), Palü and Morteratsch. Here we present only the results from the Morteratsch site (Fig. 1), which is believed to represent a clearly developed Younger Dryas situation (local stadial of “Pontresina”, assumed to be Egesen equivalents; Maisch et al. 1999). In Oct. 2002 eight rock samples (A to H) were taken from granite boulders in order to date them by exposure dating techniques ($^{10}$Be, $^{26}$Al). A, B, C and D were taken from the top of the huge and multiple morainic crests on the right-hand side of the confluence of the Morteratsch and Bernina valleys. E is an “older” control point outside the huge Morteratsch moraine and was taken from a vertical rock cliff entirely shaded from the south; F and G originate from scoured bedrock and the last site H (outside fig. 1) is located on a small but perspicuous moraine sitting on the alluvial plane 1.5 km downstream from the Little Ice Age extent. H therefore represents a younger glacier position inside the maximal extent of the Pontresina Stadial of the Morteratsch glacier.

![Figure 1. Block diagram of the Morteratsch area with sampling sites (A - H) for exposure dating](image)

The sample was crushed and sieved to yield a grain size of between 0.5 – 1 mm. The sample was leached in several steps (at a step a day) in an ultrasonic bath heated to 50°C to obtain pure quartz free from meteoritic $^{10}$Be (Ivy-Ochs 1996). The dried quartz and added $^{9}$Be carrier were dissolved in HF in a microwave oven. Be and Al were separated using cation exchange columns (Ivy-Ochs 1996). The Be was precipitated out of solution with NH$_4$OH, dried
and calcinated to BeO. The $^{10}\text{Be} / ^{9}\text{Be}$ ratio was measured using standard accelerator mass spectrometry (AMS) techniques by the PSI/ETH facility in Zurich. The surface exposure ages were calculated using a sea-level high latitude production rate of 5.1 ± 0.3 $^{10}\text{Be}$ (atoms per gram of quartz per year). Topographic shielding was calculated from a digital terrain model (DTM). We used an exponential depth profile for Be, a rock density of 2.65 g cm$^{-3}$ and an effective attenuation of 157 g cm$^{-2}$. The ages were corrected for erosion and snow cover according to (Ivy-Ochs et al., 2005).

The preliminary results (to be interpreted as minimum ages for glacial deposition) confirm at first sight the supposed late-glacial position of the morainic system in the absolute time range of Younger Dryas. They also show the subsequent ice recession and the shortening of the Morteratsch glacier over time. The oldest ages (C, D) vary in the range of 12'500 cal y BP. It is believed that sampling site E, just outside the huge lateral moraine, was glacier-covered prior to the Pontresina (Egesen) Stadial (assumption: Samedan Stadial; equivalent to Daun) Sample E yielded an exposure age in the range of 15'500 cal y BP, this very nicely supports the assumed pre-Bölling position of the glacial landscape just outside the ice margins of Younger Dryas. Samples A and B, located on top of the same ridge as C and D, seem to be comparatively younger than expected (about 2'000 years or 8'600 cal y BP). The reason for this is not yet clear but points to geomorphological processes (erosional and/or weathering) as well as to the inherent methodical problems still associated with exposure dating techniques. Overall the results obtained are very promising in regard of future direct and combined (exposure, radiocarbon) moraine dating within the late-glacial and early Holocene time window of glacial and periglacial landscape history.

**THANKS**

We are very grateful to Ivan Woodhatch, Markus Stähli, Michael Studer and Remo Zanelli for their practical help in the field and to Frank Paul for providing the necessary topographic DTM-data needed for the shielding calculation.

**REFERENCES**

Ivy-Ochs S., Kerschner, H., Reuther A., Schaefer J., Kubik P.W., Maisch, M. and Schlüchter Chr. (subm.): The timing of glaciations in the European Alps based on surface exposure dating with cosmogenic $^{10}\text{Be}$, $^{26}\text{Al}$, $^{36}\text{Cl}$, and $^{21}\text{Ne}$.  
Slope shape effects on erosion:

A laboratory study


Institute for Geological Sciences, University of Berne, Baltzerstr. 3, Switzerland
zapp@geo.unibe.ch

* USDA-ARS Southwest Watershed Research Center, Tucson, AZ, USA 85719
mneaming@tucson.ars.ag.gov

KEY WORDS
Sediment, Deposition, Drainage Networks, Soil erosion, Rainfall simulation, Rills, Optimum channel networks, Runoff

Data on soil erosion at the slope scale is almost entirely limited to experiments on uniform slopes. The objective of this research was to measure the rates and patterns of erosion on complex shaped slope elements under controlled laboratory conditions where surface morphology changes could be carefully quantified. Artificial rainfall was applied for 90 minutes to a silt loam soil in a 4 by 4 m box. Five slope shapes were formed: uniform, concave-linear, convex-linear, nose-, and head-slopes. DEMs of the surface were measured using photogrammetry after 0, 10, 20, 40, 60, and 90 minutes.

Slope shape had significant impact on rill patterns, sediment yield, and runoff production. The uniform, nose, and convex-linear slopes yielded more sediment than the concave-linear and head slopes, where sediment deposited on toe-slopes. Soil topography led to flow convergence and divergence, resulting in a non-uniform distribution of rill spacing and efficiency. Distribution of rills was related to slope steepness, and rill success was related to the contribution area of the rill. Drainage density approached a similar value for all networks during the experiments. Development of the drainage system was similar to the development of optimum channel networks, in that during the evolution of the rill network energy expenditure was reduced. This indicated that energy expenditure was a quantifiable measure of network development and self-organization.
We quantitatively illustrate that El Niño Southern Oscillations (ENSOs) have had a strong impact on sediment flux and the topographic development of the Piura drainage basin, Northern Peru. Topographic data show that the Piura drainage basin is made up of two segments. The lowermost area comprises the flat Sechura desert that extends from the Pacific coast to the border of the cordillera over a distance of ca. 110 km. The headwaters comprise the cordillera where the elevation of topography increases from 150 m to ca. 3600 m above sea level over a lateral distance of 35 km.

Pluviometric data reveal that ENSOs strongly disturb the precipitation pattern. In a 'normal' year precipitation only falls in the cordillera as easterlies bring the moisture from the Atlantic across the Amazon basin. In this case, the westerlies derived from the Pacific are a negligible source of precipitation. During these 'normal' periods the Sea Surface Temperature (SST) in the Pacific is 17°C at the coast, and precipitation rates ca. 30 mm/yr in the Sechura desert. During ENSO events (e.g., 1983, 1998), however, the SST rises up to 27-29°C along the coast, disturbing the equilibrium of the atmospheric cell configuration. As a result, precipitation rates increase to 4000 mm/yr in the Sechura desert. In the cordillera at ca. 2000 m above sea level, however, ENSOs cause a three fold increase in precipitation rates (ca. 3000 mm/yr).

Gauging stations measured a tremendous increase in water and sediment discharge due to ENSOs. During a 'normal' year, water discharge is ca. 15 m³/s in Piura (located in the Sechura desert), and sediment discharge measures ca. 179 kt/yr. ENSOs, however, have resulted in a ca. 24 and 807 fold increase in water and sediment discharge, respectively. Hence, denudation rates rise up to ca. 8.8 mm/yr during ENSO events. This tremendous increase in sediment discharge and erosion rates must be visible in the topography. Indeed, at 2000 m above sea level (which is the highest region in the cordillera that has been significantly affected by ENSOs) the morphometric properties change from high topographic roughness in the lower portions to smooth landscapes in the uppermost part. This change reflects the predominant controls of episodic precipitation (ENSO) on the landscape evolution in the lower regions, and the strong influence of seasonal 'normal' precipitation in the headwaters.
Fluctuations of mountain glaciers are among the best natural indicators of climate change (IPCC 2001). Thereby, mass balance is the direct and un-delayed signal to yearly atmospheric conditions, whereas changes in length are an indirect, delayed and filtered but also enhanced signal.

Within the framework of the EU-funded project ALP-IMP (dealing with climate change within the greater Alpine region over the past 1000 years; www.zamg.ac.at/ALP-IMP/) the World Glacier Monitoring Service (WGMS; www.wgms.ch) compiled an unprecedented Alpine glacier data set, containing one- to three-dimensional glacier fluctuation information dating back to 1850. The spatio-temporal variability of mass balance, front variation and equilibrium line altitude data is analysed for glaciers with long time series on an annual basis. Additionally, area and hypsographic changes between 1850, 1973 and 2000 are investigated based on the new digital Swiss Glacier Inventory (SGI2000; Kääb et al. 2002, Paul et al. 2002). Increasing mass loss, rapidly shrinking glacier areas and spectacular tongue retreats are clear witnesses for the atmospheric warming observed in the Alps in the last 150 years and its acceleration during the past two decades. However, on short-terms or at a regional-scale, glaciers show a highly individual variability. Glacier behaviour depends not only on the regional climate but also on local topographic effects, which complicate the extraction of the climate signal from glacier fluctuations. The latter are essential for the verification of mass balance and ice flow models, which are needed to quantify these local topographic effects.

It is important to continue the long-term glacier fluctuation series. The new methods developed in the SGI2000 could serve as a basis for glacier inventorying from space, to be integrated into the global framework of the USGS-led Global Land Ice Measurement from Space (GLIMS; www.glims.org) project and the WGMS.

Figure 1. Synthetic 3D-perspective of Morteratsch glacier, Switzerland, generated from a digital elevation model overlaid with a fusion of satellite images from Landsat TM (1999) and IRS-1C (1997) and with the glacier polygons of the SGI2000. The Morteratsch glacier retreated about 1900 m from 1860 (white) to 1973 (black) and another 300 m until 1997/99.

REFERENCES