Permafrost thaw and destabilization of Alpine rock walls in the hot summer of 2003

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[1] Exceptional rockfall occurred throughout the Alps during the unusually hot summer of 2003. It is likely related to the fast thermal reaction of the subsurface of steep rock slopes and a corresponding destabilization of ice-filled discontinuities. This suggests that rockfall may be a direct and unexpectedly fast impact of climate change. Based upon our measurements in Alpine rock faces, we present model simulations illustrating the distribution and degradation of permafrost where the summer of 2003 has resulted in extreme thaw. We argue that hotter summers predicted by climate models for the coming decades will result in reduced stability of many alpine rock walls. *INDEX TERMS:* 1823 Hydrology: Frozen ground; 1625 Global Change: Geomorphology and weathering (1824, 1886); 1630 Global Change: Impact phenomena. **Citation:** Gruber, S., M. Hoelzle, and W. Haeberli (2004), Permafrost thaw and destabilization of Alpine rock walls in the hot summer of 2003, *Geophys. Res. Lett.*, *31*, L13504, doi:10.1029/2004GL020051.

1. Introduction

[2] The summer of 2003 was ~3°C warmer in Switzerland than average 1961–1990 [*Schär et al.*, 2004] and exceptional rockfall activity has been reported [e.g., *Keller*, 2003] throughout the Alps, especially at high elevations and in north-facing slopes. In the absence of unusually strong precipitation or other plausible transient effects on slope stability the fast degradation of mountain permafrost has been hypothesized to be the likely cause for the extreme rockfall and, as a consequence, this topic received much public attention [e.g., *Schiermeier*, 2003].

[3] The temperature distribution and evolution in steep rock was largely unknown until now, even though, permafrost thaw in rock faces maybe equally consequential (in terms of natural hazards and geotechnical consequences for infrastructure) as that in debris-covered slopes. Additionally, the thermal response of rock faces to individual extreme events is fast compared to debris slopes that are often insulated by blocky surfaces [*Harris and Pedersen*, 1998] and have a high ice-content.

[4] During the last century, Alpine permafrost in Europe has warmed by 0.5 to 0.8°C in the upper tens of meters [*Harris et al.*, 2003]. The stability of steep rock slopes can be reduced due to melting of ice-filled crevices and subsequent build-up of hydrostatic pressure [*Haeberli et al.*, 1997]. Even prior to thaw, frozen rock joints have been demonstrated to destabilize with rising temperatures, entering a zone of minimal stability between −1.5 and 0°C [*Davies et al.*, 2001]. The exceptional rockfall activity during the summer 2003 is likely an indication of this rapid destabilization that takes place as an almost immediate reaction to extreme warming. This paper seeks to elucidate the effect that the summer of 2003 had on perennially frozen Alpine rock faces and the role of rockfall as an impact of future climate change.

2. Measurement and Modeling of Rock Temperatures

[5] In autumn 2002 we recovered 14 data loggers that had recorded one year of near-surface temperatures in steep Alpine rock faces (Figure 1) between the summers of 2001 and 2002 [*Gruber et al.*, 2003]. Measurement sites were chosen between 2600 and 4500 m a.s.l. trying to represent slope expositions evenly (Figure 2). Data were recorded at a depth of 10 cm every two hours. These data were used to verify an energy-balance model [*Gruber et al.*, 2004] simulating daily surface temperatures based on meteorological observations from the standard Swiss observational network operated by MeteoSwiss. The model is based on the algorithms used in PermEbal [*Stocker-Mittaz et al.*, 2002; *Mittaz et al.*, 2002] and simulates the one-dimensional energy balance at the rock surface as well as the subsurface heat conduction using daily time steps. After calculation of the short-wave net radiation and the long-wave irradiance, the turbulent heat flux and upwelling long-wave radiation are parameterized using an estimated surface temperature. The derived ground heat flux is used as upper boundary condition of a heat conduction scheme having 200 nodes, evenly spaced every 10 cm. The initial surface temperature estimate and the calculated temperature are iterated to converge to better than 0.3°C. Latent heat due to freezing/melting of pore water in the rock is included as apparent heat capacity between −0.5 and 0.0°C. The verification runs were based on daily meteorological data of the MeteoSwiss stations Zermatt, Corvatsch or Jungfraujoch. All calculations were based on the same parameters to prevent "fitting" of results: albedo: 0.28; emissivity: 0.96; roughness length: 0.3 mm; environmental lapse rate: $-0.006°C\ m^{-1}$; moisture content: 1%; volumetric heat capacity of dry rock: $1.8\ 10^6\ J\ m^{-3}\ K^{-1}$; thermal conductivity: $2.2\ W\ K^{-1}\ m^{-1}$ [based on *Čermák and Rybach*, 1982]. Due to strong topographic [*Kohl*, 1999] and transient [*Harris et al.*, 2003] effects it is unknown whether the geothermal heat flux at the lower boundary is positive or negative and therefore assumed to be zero. With the parameters above, only elevation, slope and aspect were adapted to each measurement site and the appropriate meteorological station was chosen for the

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Figure 1. Installation of a rock-face temperature data logger during summer 2001.

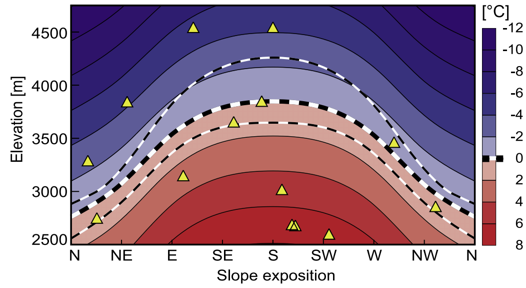

Figure 2. Mean annual surface temperatures and mean 0°C isotherm (thick dashed line) in Alpine rock faces from 1982 to 2002, modeled for the Jungfrau area and 70° slope inclination. The thin dashed lines show the highest and lowest mean annual 0°C isotherm during that period. Yellow triangles indicate the aspect and elevation of the 14 rock-wall temperature data loggers used for model verification.

driving time series of the verification run. Daily averages of measured temperatures are compared to the model results at all 14 sites. The mean annual near-surface temperature has a mean absolute difference of 1.2°C (9 series were better than 1°C and 5 series between 1.0 and 3.8°C without a bias related to elevation or aspect). The mean R^2 is 0.88 (min: 0.72; max: 0.96). This indicates that the model and the parameterizations used are reliable to simulate the surface energy balance over rock faces in complex terrain. Using this model, rock temperatures for different aspects and elevations were calculated from 1982 to 2003. Daily rock temperatures for a slope of 70°, seven elevations from 2000–5000 m and eight aspects (N, NE, …. W, NW) were simulated based on meteorological data from Jungfraujoch from 01/1982 to 12/2003. Oct.–Dec. 2003 were not yet available at the time of calculation and substituted by 2002 data. Being after the extreme summer and after the time of maximum ground heat flux, this substitution does not influence our results. The temperature profile at depth was initiated using the 1982 mean surface temperature followed by a two-year transient run with 1982 data to ensure a realistic temperature distribution at depth before the start of the 1982–2003 experiment.

3. Results and Discussion

[6] From the simulated daily temperatures, the distribution of mean annual ground surface temperatures (MAGST) for rock faces was calculated (Figure 2) and a mean 0°C isotherm derived. This mean isotherm represents the elevation that limits the presence of permafrost under the climatic conditions used for the 21-year model run. In reality, the lower limit of permafrost within rock walls is assumed to be about 1.0°C or 150 m lower than this line due to 20th century atmospheric warming [*Haeberli and Beniston*, 1998; *IPCC*, 2001; *Böhm et al.*, 2001; *Beniston et al.*, 1997; *Diaz and Bradley*, 1997]. Additionally, three zones are delineated by the two thin dashed lines: a) the zone of seasonal frost (SF-zone, MAGST > 0°C for all years); b) the zone of active permafrost (AP-zone, MAGST < 0°C for all years); and c) a transitional zone (T-zone), where only some years have a MAGST < 0°C. The interannual variation of the mean 0°C isotherm elevation is 400–550 m vertical, underscoring the necessity for a combination of measurements and models in determining the distribution of permafrost in rock walls. From the calculated transient subsurface temperature field, the progression of summer thaw or winter freezing can be extracted (Figure 3). The modeled thaw of 2003 exceeds the maximum of all previous years. The associated depth range of this anomaly and of the possible destabilization depends on site characteristics and water content [*Wegmann et al.*, 1998] in the rock but its overall pattern is not affected fundamentally. It is striking that most rock fall took place between June and August when the depth of thaw was not at its maximum but when the heat flux in the ground at somewhat shallower depths was greatest. Figure 4a shows the mean maximum depth of the 0°C isotherm (1982–2002). In the AP-zone, this is the depth of summer thaw, in the SF-zone it is the depth of winter freezing and in the T-zone it can be either one or even a signal from the previous year. In our model, the summer thaw of 2003 is 10–50 cm deeper than the maximum of the 21 previous years throughout the AP-zone (Figure 4b).

[7] In northern slopes, the depth of thaw is mainly controlled by the influence of air temperature (mostly via long-wave radiation) on surface temperatures, whereas

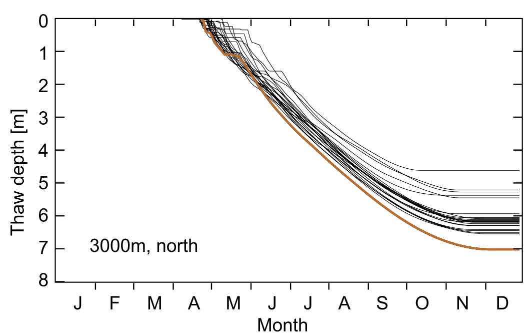

Figure 3. Summer thaw in Alpine permafrost. Depth evolution for individual years 1982–2002 (black) and 2003 (orange).

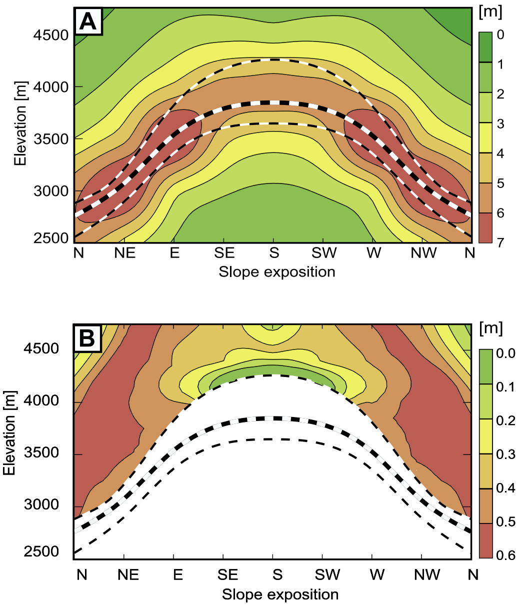

Figure 4. Depth range of freezing or thawing. (a) Average maximum annual depth of the 0°C isotherm in the ground. (b) 2003 permafrost degradation shown as the depth exceeding the 1982–2002 maximum modeled depth of thaw.

southern slopes additionally receive high amounts of shortwave radiation. As a consequence, southern slopes exhibit greater inter-annual variability of thaw depth, larger pre-2003 maxima and, therefore, a smaller 2003 anomaly. In the T-zone, the 2003 signal is less clear and may only be at its maximum in the following year due to the great depth of the active layer. The increased thaw during the summer of 2003 far outweighs the direct effect that gradually rising temperatures have on rock wall stability in the uppermost meters. The extreme frequency of rockfall in the Alps during 2003 [*Keller*, 2003; *Schiermeier*, 2003] corroborates this finding. The observed domination of events in northern slopes can be explained by the strong effect of 2003 (Figure 4b) as well as the greater extent of perennially frozen northern slopes. The 2003 thaw depth is likely to exceed previous maxima even on time scales of centuries, considering the pronounced recent global and hemispheric temperature rise inferred from instrumental records and proxy data [*IPCC*, 2001; *Mann et al.*, 1999] and its influence on Alpine ground temperatures [*Harris et al.*, 2003]. The thermal response of permafrost to atmospheric warming [*Lunardini*, 1996; *Haeberli et al.*, 1997; *Haeberli and Beniston*, 1998] generally takes place at different scales of time and depth which correspond to frequency and magnitude of the expected destabilization. Following increases in temperature, with a delay of only months or years (direct response), the active layer (uppermost meters that are subject to annual freeze/thaw cycles) thickens and thus, new volumes of rock will be subjected to critical temperature ranges. This immediate response has been observed in the summer of 2003. Then (delayed response), the temperature profile within the permafrost becomes disturbed and the lower boundary of the permafrost layer will rise (final response), both possibly causing large and deep-seated instabilities delayed by decades or centuries. Therefore, following the projected rise in mean annual and summer temperatures during the 21st century [*Zwiers*, 2002; *Stott and Kettleborough*, 2002; *Knutti et al.*, 2002; *Ohmura et al.*, 1996; *IPCC*, 2001], the locations, magnitudes and frequencies of rock wall instabilities are likely to develop beyond the ranges of historic variability.

4. Conclusion

[8] Past and modeled future climatic change is likely more pronounced in mountain areas than the global or hemispheric average [*Haeberli and Beniston*, 1998; *Beniston et al.*, 1997; *Diaz and Bradley*, 1997; *Barry*, 1992, 1990]. Thus, coming decades are expected see a well-perceptible transient response of Alpine permafrost to the projected 0.3–1.3°C rise (2020–2030) in global mean temperature [*Zwiers*, 2002; *Stott and Kettleborough*, 2002; *Knutti et al.*, 2002]. In addition to a warming trend of 5°C, a study based on regional climate models [*Schär et al.*, 2004] predicts a 74% increase in the standard deviation of summer temperatures in Switzerland (2070–2099). The extreme summer of 2003 and its impact on mountain permafrost may be seen as a first manifestation of these projections. Wide-spread rockfall and geotechnical problems with human infrastructure are likely to be recurrent consequences of warming permafrost in rock walls due to predicted climatic changes.

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