Name of research institute or organization:

Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW), ETH Zürich

Title of project:

Glacier outburst floods: A study of the processes controlling the drainage of glacier-dammed lakes

Project leader and team:

Martin Funk, Heinz Blatter, Nicholas Deichmann, Andreas Bauder, Martin Lüthi, Shin Sugiyama

Project description:

During the period of the lake formation and drainage in 2004 and 2005, detailed field investigations of the surface ice flow field, basal water pressure, dye-tracing of the water from the Gornersee to the glacier snout and passive seismicity were performed.

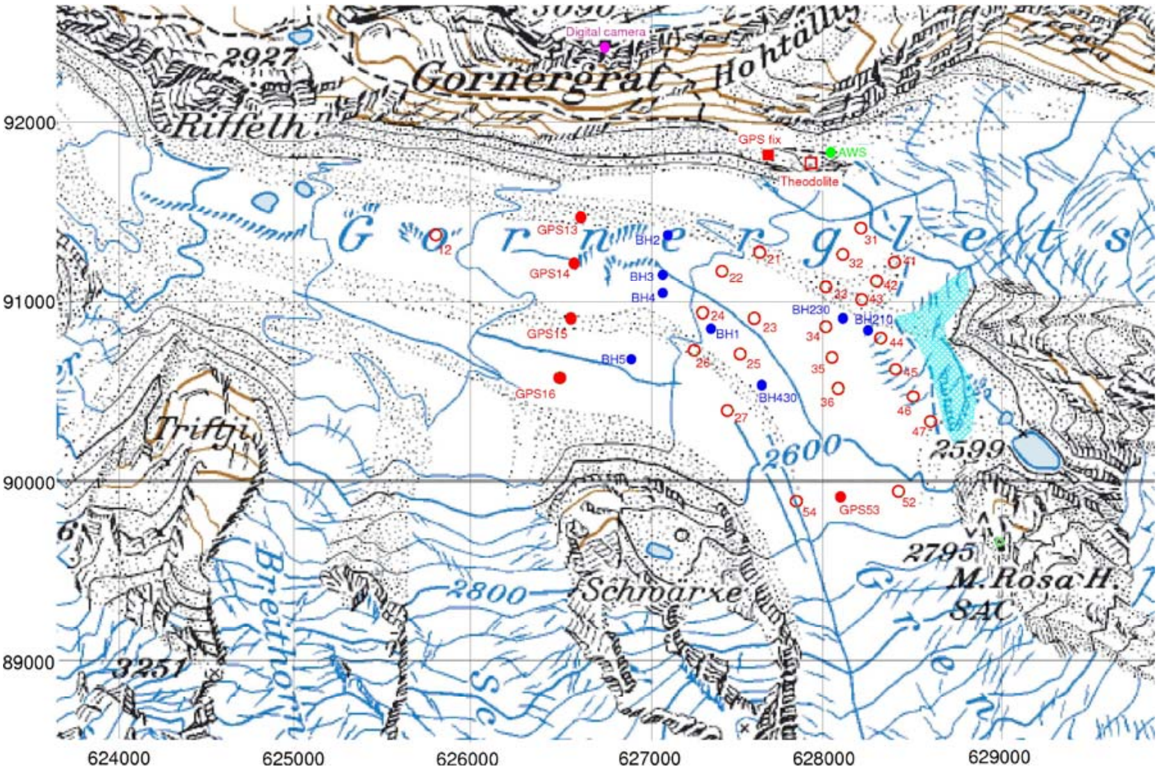

Fig. 1 Map of the study site (2005. The locations of the theodolite survey stakes, GPS-stations and boreholes are indicated by the open red circles, solid red circles, and solid blue circles, respectively. The seismicity was measured in the hatched red-areas (left 2005 and right 2004) and Gornersee is shown in light blue.

Boreholes were drilled by hot water drilling technique to measure subglacial water pressure, vertical strain and ice temperature. More than 30 stakes were installed on the glacier to survey the position every hour with an automatic theodolite with distance-meter (ATD) and with differential GPS stations. The lake level was recorded with a water pressure transducer and the evolution of the lake was monitored with an automatic digital camera installed at Gornergrat. An automatic weather station was set up on the glacier flank to measure air temperature, precipitation and humidity. In the outlet stream near the glacier terminus, temperature, conductivity and turbidity sensors were installed. Water discharge measurements in the Gornera were obtained from the Grande Dixence SA. With a network of geophones, passive seismic measurements were performed on the glacier in collaboration with the Institute of Geophysics ETHZ (Figure 1 for an overview). Our main results are:

1. Outburst of the Gornersee

In 2004, the lake started to form on May 15. The outflow first occurred at the glacier surface for roughly one day, before the water started to escape sub- and englacially on July 2. Total amount of the stored water was estimated as 4 mio m^3 from the bathymetry of the lake and from the discharge in the outlet stream. In 2005, the filling of the lake started around May 12. The drainage of the lake started subglacially on June 10 with a surface water level 18 m lower than in 2004, well before a supra-glacial outflow could occur. The stored water amounted to only 1.2 mio m^3 and the lake was empty on June 15. According to these observations it seems likely that the 2004 flood was triggered by flotation of the ice dam with a linearly rising lake outflow discharge, whereas the 2005 flood was the classical slowly rising jökulhlaup with an exponentially rising lake outflow discharge (Figure 2). However, the hydrographs of the Gornera river (presented here without melt water contribution) look very similar in both years. The striking different hydrographs of the lake outflow in 2004 and 2005 are indicative for different outburst mechanisms in both years. This "early drainage" was observed several times in the past at other glacier-dammed lakes (e.g. Mathews, 1973; Clarke, 1982; Anderson et al., 2003; Björnsson, 1992). In our case the corresponding triggering mechanisms are still not clear.

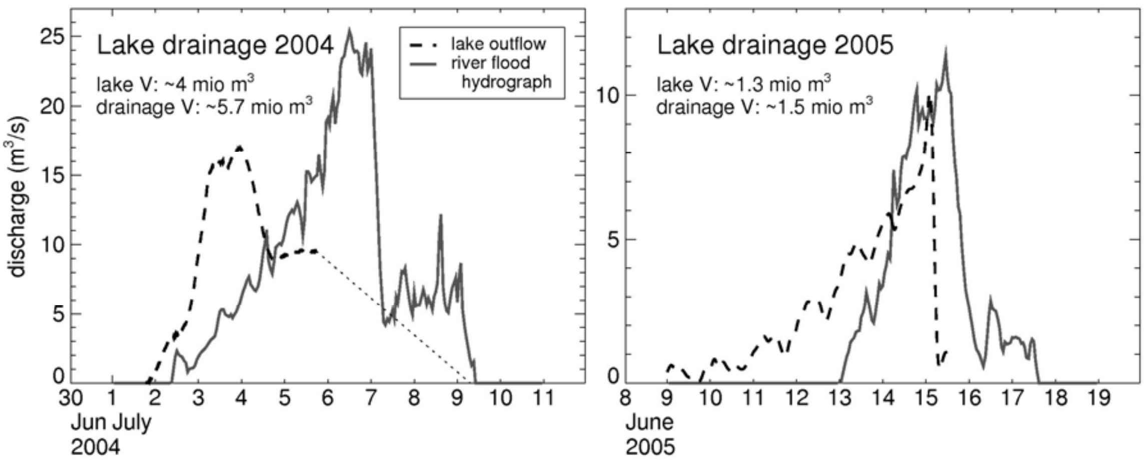

Fig. 2 Outflow from Gornersee and corresponding discharge record (in which the contribution of the glacier melt was substracted) in the Gornera river at Grande-Dixence gauging station near the glacier snout for the years 2004 and 2005. Note that after July 5 2004, no lake level records were available.

A detailed analysis of the existing hydrographs of the Gornera at the Grande-Dixence gauging station near the glacier snout has been performed (Huss et al., in preparation). Using the distributed temperature-index-model (Hock, 1999; Pellicciotti et al., in press), a reconstruction of the discharge records since 1970 could be achieved. From the difference between the modeled and recorded discharge, the former outburst events could be reconstructed in terms of water volume, timing, duration and intensity. Moreover, the results allow for inferences on the development of the Gornersee as well as insights into the subglacial drainage processes during the lake drainage.

2. Glacier flow

The glacier flow pattern was influenced by the lake outburst. In most places of the glacier, surface lifted up during the outburst and then dropped afterwards. The magnitude of the uplift is not spatially uniform across the glacier. Although the surface uplift of a temperate glacier is often attributed to pressurized subglacial water pushing up the glacier sole, it is also caused by vertical straining of ice. To determine the mechanism of the uplift, the surface vertical displacement was measured by stake surveying (differential GPS and ATD) and compared with the length changes of boreholes drilled at the same location. While the surveyed vertical uplift at the glacier surface can be attributed to vertical strain or lifting up by subglacial water pressure (or a combination of both), the length changes of deep boreholes are only the result of vertical strain. Our results show that the ice was lifted up by subglacial water pressure during the intensive lake drainage period, then it dropped as the water pressure decreased. Although the intensive uplift during the drainage was caused by the high water pressure, vertical strain rates significantly changed after the drainage and influenced the surface uplift. The change in the vertical strain rate indicates the lasting impact of the outburst on the glacier flow regime. Two distinctive flow patterns could be identified during the period of the lake drainage. The changes in the flow direction relative to the pre-event direction are opposite in these two patterns. Considering the very rapid changes in the basal conditions and corresponding stress and strain fields in the glacier, the change in the ice flow during the first half of the lake drainage is partly due to elastic ice deformation. If we assume a significant part of the change was caused by the elasticity, the flow pattern during the second half of the drainage can be understood as the rebound of the elastic deformation during the first half. The timing of the flow direction change favors this interpretation, because it coincides with the drop in the discharge from the lake. Elasticity of ice has been studied in laboratory experiments, but is normally neglected in the glacier dynamics. Since the sudden water release from the lake changes basal conditions rapidly, the glacier is expected to behave as a visco-elastic material rather than a viscous fluid. It is plausible that the elastic behavior of ice near the lake plays an important role in the triggering of the outburst. In order to better understand the observed glacier flow patterns, a three dimensional glacier flow model has been developed. A finite-element mesh with 2,145 rectangular elements was constructed based on the bedrock profile obtained by radar echo sounding carried out in spring 2004 and 2005. The model solves non-linear viscous flow of ice (Gudmundsson, 1999; Helbing, in press) with a prescribed inflow from Gorner- and Grenzgletscher and outflow downglacier as boundary conditions. The computed flow field under the assumptions of no basal sliding and no water in the lake shows reasonable agreement with measured annual flow speeds. The flow patterns at the confluence area as well as the flow direction nearby the lake are well reproduced by the model (Weiss, 2005). Two main questions raised by the flow measurements in 2004 and 2005 are, the mechanism of huge uplift and reverse movement at the lake marginal ice, and spatial variability of the speed up and uplift in the lower reaches of the glacier and their relationship with subglacial water pressure. The first question is directly related to the triggering mechanism of the outburst and the second one gives insight into the subglacial drainage process as well as the dynamic response of a glacier to basal conditions. A finer stake network is required near the lake to investigate the behavior of the marginal ice. In the lower reaches of the glacier, stake profiles across and along the glacier near stake 14 (Figure 2) will provide information to solve the second question.

3. Passive seismicity

Goal of the passive seismic measurements is to detect, localize and characterize seismic signals due to deep icequakes and link them to hydrologic processes of the glacier, particularly the lake drainage. The networks of seismometers were set up in two distinct aeras in 2004 and 2005 (Figure 1). In both years, seismic data was collected for about one month. The systems recorded between several hundred and several thousand seismic events per day producing a large amount of data. This imposes a serious challenge when analyzing the data, because those signals due to deep sources have to be identified. Since surface crevasse opening, icequakes outside the seismic network and weak signals constitute the vast majority of recorded seismograms, this is a very laborious task. So far, about two dozens of deep events were identified. In order to characterize their sources, an inversion procedure will be applied to determine their seismic moment tensors. In 2004, several surface events showed radiation patterns hinting toward double couple sources. They suggest the presence of shear fractures in the ice, which has not been observed so far. Determining their moment tensors will provide valuable insights into the fracture processes inside glacier ice.

4. Dye tracing

After the illfated tracer experiments in 2004, good data was obtained during the 2005 field campaign. A total of 30 tracer experiments were conducted before, during and after the jökulhlaup using fluorecent dyes. With these experiments the development of the hydraulic conditions inside and beneath the glacier could be probed. In particular, these three points could be recognized: Prior to the drainage, a transition from a distributed to a channelized system occurred several hundred meters upglacier from the lake, significant changes of the transit velocity and the dispersion of the tracer could be observed between the period before, during and after the lake drainage, and a substatial amount of water was stored in the glacier during the drainage. These data will provide, in the course of this project, valuable benchmarks for testing numerical models of glacial drainage.

5. Englacial temperatures

The ice temperature is an important factor with respect to the heat transfer in the drainage channels between water and ice. For this reason we performed profile measurements of englacial temperatures at BH210, BH430 and BH4 (Figure 1) during the last two field campains. We found slightly decreasing temperatures from 0 ^{o}C at the surface to 0.2 ^{o}C at 200 m depth (BH210 and BH430). In summer 2005 we installed another thermistor chain down to the bed (BH4), but the thermal equilibrium is not yet attained. Nevertheless, our former assumption of polythermal conditions seems to be verified, but then ice temperatures seem to be much higher than previously published (Haeberli, 1976). Therefore the effect of the cold ice on the subglacial drainage process can be considered as marginal.

References

Anderson, S.P., Walder, J.S., Anderson, R.S., Kraal, E.R., Cunico, M., Fountain, A.G., and Trabant, D. (2003). Real-time hydrologic observations of Hidden Creek

Lake jökulhlaups, Kennicott Glacier, Alaska. Journal of Geophysical Research, 108(F1):6003, doi:10.1029/2002JF000004.
Björnsson, H. (1992). Jökulhlaups in Island: Prediction, characteristics and simulation. Annals of Glaciology, 16:95--106.
Clague, J.J. and Mathews, W.H. (1973). The magnitude of Jökulhlaups. Journal of Glaciology, 12(66):501--504.
Clarke, G. K. C. (1982). Glacier outburst floods from “Hazard Lake”, Yukon Territory, and the problem of flood magnitude prediction. Journal of Glaciology, 28(98):3--21.
Gudmundsson, G.H. (1999). A three-dimensional numerical model of the confluence area of Unteraargletscher, Bernese Alps, Switzerland. Journal of Glaciology, 45(150):219-230.
Haeberli, W. (1976). Eistemperaturen in den Alpen. Zeitschrift für Gletscherkunde und Glazialgeologie, 11(2):203--220.
Helbing, J. (in press). Glacier dynamics of Unteraargletscher: Verifying theoretical concepts through flow modeling. Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich. ETH PhD.
Hock, R. (1999). A distributed temperature-index ice- and snowmelt model including potential direct solar radiation. Journal of Glaciology, 45(149):101-111.
Huss, M. (2005). Gornergletscher, Gletscherausbrüche und Massenbilanzschätzungen (in german with english summary). Diplomarbeit, Abteilung für Glaziologie, VAW (unveröffentlicht), ETH-Zürich. pp. 176.
Mathews, W.H. (1973). Record of two jökulhlaups. In Symposium on the Hydrology of Glaciers, volume 95, pages 99-110. International Association of Hydrological Sciences. edited by J.W. Glen et al.
Pellicciotti, F., Brock, B.~J., Strasser, U., Burlando, P., Funk, M., and Corripio, J. (in press). An enhanced temperature-index glacier melt model including the shortwave radiation balance: development and testing for Haut Glacier d’Arolla, Switzerland. Journal of Glaciology.
Weiss, P. (2005). Gletscherdynamik vor und nach der Entleerung des Gornersees im Sommer 2004. Diplomarbeit, Abteilung für Glaziologie, VAW (unveröffentlicht), ETH-Zürich. pp. 149.

Key words:

Glaciology, glacier hazards, glacier floods

Internet data bases:

http://www.vaw.ethz.ch/research/glaciology/glacier_hydraulics/gz_outburst_glacierdammed_lake

Collaborating partners/networks:

University of Oslo, Dr. T. Schuler
University of Stokholm, Dr. R. Hock
IHW-ETH, Prof. P. Burlando
University of British Columbia, Prof. G. Clarke

Scientific publications and public outreach 2005:

Conference papers

Sugiyama S., Funk M., Müller B., Bauder A., Fischer U., Weiss P., Huss M., Deichmann N., Blatter H.; Glacier dynamcis during the outburst of a glacier dammed

lake on Gornergletscher, Switzerland EGU05-A-07473; CR1-1MO3O-004, Vienna 2005

Theses

Huss, M. (2005). Gornergletscher, Gletscherausbrüche und Massenbilanzschätzungen (in german with english summary). Diplomarbeit, Abteilung für Glaziologie, VAW (unveröffentlicht), ETH-Zürich. pp. 176.

Weiss, P. (2005). Gletscherdynamik vor und nach der Entleerung des Gornersees im Sommer 2004. Diplomarbeit, Abteilung für Glaziologie, VAW (unveröffentlicht), ETH-Zürich. pp. 149.

Address:

VAW
ETH-Zentrum
CH-8092 Zürich

Contacts:

Martin Funk
Tel.: (with international prefix) +41 44 632 4132
Fax: (with international prefix) +41 44 632 1192
e-mail: funk@vaw.baug.ethz.ch
URL: http://www.glaciology.ch