Workshop on Climate Change and Mountain Risks in the European Alps — from Recognition to Management

Saas-Fee, Switzerland, August 23–27, 2021

Jointly organized by the University of Geneva, Switzerland, WSL, Switzerland, Free University Bolzano, Italy and the University of Graz, Austria

Workshop Program and Abstracts volume

(Abstracts are in alphabetical order of author name)

Workshop organizers

Markus Stoffel

Christoph Graf

Francesco Comiti

Martin Mergili

Climate Change and Mountain Risks in the European Alps
from Recognition to Management

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WORKSHOP PROGRAM

	Monday, August 23	
Afternoon	**Participants arrive in Saas-Fee**	
18:30	Icebreaker, followed by supper (around 19:30)	
	Tuesday, August 24	
09:00-09:10	Welcome by the organizers and meeting objectives.	
	SESSION 1: Cryospheric hazards - from ice to snow	
	Chairperson: Markus Stoffel	
09:10-09:30	***Mylène Jacquemart, ETH Zurich, Switzerland*** From the Alps to the World – Creating a Global Database of Cryospheric Hazards	**18**
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09:50-10:10	***Paolo Perret, Fondazione Montagna Sicura, Italy*** Ice avalanche hazard evaluation and risk management from the Planpincieux glacier (Courmayeur — Italy)	**27**
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10:30-10:50	***Peter Mani, geo7 / University of Geneva, Switzerland*** Climate change impact on rain on snow events	**23**
10:50-11:20	Coffee, tea, refreshments	
	SESSION 2: From GLOFs to floods	
	Chairperson: Martin Mergili	
11:20-11:40	***Adam Emmer, University of Graz, Austria*** Understanding patterns of GLOF occurrence in the post-LIA context: an everlasting need for updated GLOF inventories	**15**
11:40-12:00	***Simon Allen, University of Geneva, Switzerland*** Transferring learnings from the Alps to High Mountain Asia	**7**
12:00-12:20	***Isabelle Kull, Geotest, Switzerland*** Plaine Morte Glacier Lake – Lake evolution and unique adaptation strategy / measures	**20**
12:20-12:40	***Vittoria Scorpio, Eurac Bolzano, Italy*** Geomorphic catchment response to different severity storm floods: channel changes and hillslope sediment coupling dynamics	**30**
13:00-17:00	Free afternoon for outdoor or indoor activities	
17:30-19:30	**DISCUSSION SESSION: Impacts of climate change on mass movements in the Alps: What? How? When? Where?**	
	Chairperson: Markus Stoffel	
19:30	Evening meal	

	Wednesday, August 25	
	SESSION 3: From rockfall to debris flow	
	Chairperson: Christoph Graf	
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10:00-10:20	***Jan Beutel, University of Innsbruck, Austria*** Unraveling Matterhorn Rockfall Mysteries	**9**
10:20-10:40	***Christine Moos, University of Lausanne, Switzerland*** Climate change impacts on rockfall and rockfall protection forests	**25**
10:40-11:10	Coffee, tea, refreshments	
11:10-11:30	***Alberto Muñoz-Torrero Manchado & Manon Farvacque & Sandra Gorsic*** ***University of Geneva, Switzerland*** Determination of recent rockfall activity at Täschgufer using repeat hi-res imagery and field-based magnitude-frequency assessments	**26**
11:30-11:50	***Sara Savi, University of Potsdam, Germany*** Pronounced increase in slope instability linked to global warming: a case study from the Eastern European Alps.	**29**
11:50-12:10	***Perry Bartelt, SLF, Switzerland*** Climate Change, Cascading Processes and the Thermodynamics of Rock/Ice Avalanches	**8**
12:10-12:30	***Francesco Comiti, Free University Bolzano, Italy*** Scenarios of bedload transport changes in proglacial areas and downstreams channels	**14**
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17:30-19:30	**DISCUSSION SESSION: Modeling complex process chains: recent advances and research gaps**	
	Chairperson: Martin Mergili	
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	Chairperson: Adrien Favillier	
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10:00-10:20	***Martin Mergili, University of Graz, Austria*** Progress and remaining challenges in process chain modelling	**24**
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	Chairperson: Francesco Comiti	
10:50-11:10	***Michael Rinderer, Geo7, Switzerland*** Hazard assessment on the regional scale under current and future climate scenarios	**28**
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12:10-12:30	***Matthias Buchecker, WSL, Switzerland*** Pooling mental and scientific models of climate change impacts on Alpine mass movements	**10**
13:00-17:00	Free afternoon for outdoor or indoor activities	
17:30-19:00	**DISCUSSION SESSION: Management of mountain mass movements in a context of climate change**	
	Chairperson: Francesco Comiti	
19:30	Evening meal	

	Friday, August 27	
	SESSION 6: Final plenary, wrap-up, future work	
09:00-10:30	Reports from the discussion sessions (25' each)	
10:30-11:00	Coffee, tea, refreshments	
11:00-11:30	The way forward, future work and coordination of decisions taken	
11:30-11:45	Closing remarks from the organizers, farewell	
12:00	Close of the meeting	
Afternoon	**Participants depart from Saas-Fee (or prolong their stay for hiking or sightseeing…)**	

ABSTRACTS
AND
AUTHOR CONTACT INFORMATION

(In alphabetical order by author family name)

Allen, S.

Transferring learnings from the Alps to High Mountain Asia

There is a long-standing tradition in the European Alps of living with and responding to natural hazards originating from glacial and permafrost environments. In the Swiss Alps, for example, the first record of a glacier glacial lake outburst flood (GLOF) was in 1595, while casualties linked with ice avalanches are first documented in 1597. As a consequence, Swiss institutions have long been at forefront of research into these hazards, and more recently, via support of the Swiss Agency for Development and Cooperation, have played a leading role in establishing international best practices and transferring knowledge to mountain regions in the global south. In this presentation, I'll focus on two recent examples of such knowledge transfer: Firstly, the development of International Guidelines for the Assessment of Glacier and Permafrost Hazards, led by the University of Zurich, and secondly, implementation of training programs on glacial hazards and risk in India, led by the University of Geneva. The International Guidelines, developed as a product of the Joint Standing Group on Glacier and Permafrost Hazards in High Mountains (GAPHAZ) was created as a resource for international and national agencies, responsible authorities and private companies. The document, drawing heavily on experience from the Alps, provides guidance on susceptibility assessment, impact modelling, and hazard mapping for a range of catastrophic mass flows and onsite hazards in mountain environment. The training program, implemented under the Indian Himalayas Climate Adaptation Program (IHCAP), aimed to enhance local scientific skills on these same topics.

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Bartelt, P.

Climate Change, Cascading Processes and the Thermodynamics of Rock/Ice Avalanches

Co-authors: P. Bartelt[1], C. Graf[1], Y. Bühler[1], J. Munch[1] and B. McArdell[1]

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The recent avalanches in Piz Cengalo (CH, 2017) and Chamoli (India, 2021) have highlighted the role of ice entrainment and melting as a source of water that lubricates rock masses, leading the formation of secondary debris flows or even debris floods. Because the degree of melting is directly related to the initial temperature of the entrained ice-masses, the problem of ice-entrainment/melting is the key question in predicating cascading events and how a changing climate will increase the danger of extreme runout events. Using Piz Cengalo (2 mio m^3) and Chamoli (27 mio m^3) as examples, we discuss the thermodynamics of rock/ice avalanches, demonstrating some of the physical limitations of existing numerical models. We show why the total meltwater production is sensitive to initial conditions and how melting can begin at temperatures well below mean avalanche temperatures of 0C (melting temperature ice). Another important question centers around the calculated location and concentration of water in the deposition zone which facilitates the formation of secondary debris flows/floods. Our primary concern is that although thermo-mechanical models of rock avalanches with ice-entrainment exist, adequate knowledge of the initial conditions (temperature, water content) and boundary conditions (disposition of rock, ice, water and snow masses along the slope) remain largely unknown. Obtaining better estimates of this information is considered a priority in climate change research.

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Beutel, J.

Unraveling Matterhorn Rockfall Mysteries

The Matterhorn Hörnligrat observatory is one of the most comprehensive and longest operational field sites for the quantitative assessment of steep bedrock permafrost and related natural hazards worldwide. What started out with very simple measurements assessing slowly varying quantities over the years grew significantly w.r.t. the experimental complexity, the sensors used as well as the data obtained. Methods explored by the team include ground surface temperatures, conductivity and moisture, water pressure, ice pressure, optical as well as NIR imaging, crack kinematics, present weather, acoustic emission, seismic as well as different remote sensing techniques. Here we will review which technologies actually worked and delivered, which prerequisites are necessary for which sensing technology, how many datapoints are required, how much computation is necessary and approximately how much handwork is necessary to obtain meaningful results that can actually be put into context and interpreted in process studies, help calibrate simulation models or aid in natural hazard mitigation measures. Based on this analysis, I will identify where current gaps exist w.r.t the observability of the mountain cryosphere and where current efforts should focus in creating a next generation of sensing technology and adjacent methodologies. A specific focus will be given to methods that allow a quantitative assessment at scale, are robust to use and allow for a wide range of applications.

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Buchecker, M.

Pooling mental and scientific models of climate change impacts on Alpine mass movements

Research expects massive impacts of climate change on Alpine mass-movements, but there is considerable uncertainty about the related dynamics and risks. Regional stakeholders, natural hazard managers and natural hazard researchers have specific knowledge or mental models of these mass-movement dynamics (MMD) and strategies to cope with them, and this diversity presents substantial challenges in finding accepted prevention strategies. Bringing these three actor groups' knowledge together in an interactive learning process is expected to enhance region's capacity to define long-term prevention strategies to cope with future MMD. First studies have demonstrated the diversity of actor groups' mental-models of regional climate change impacts (Gaus et al., 2020) without, however, considering MMD. A recent study has furthermore confirmed expected social learning effects through interactive exchange among actors, but without involving scientists' models (Buchecker et al., accepted). Hence, we aim to test in a upcoming study a new method of co-creation of knowledge (Muccione et al., 2019) in risk management by finding out:

- How different actor groups (regional stakeholders, natural hazard managers and natural hazard researchers) conceive the problem of climate-driven regional MMD.
- To which extent an exchange of actor groups' mental and scientific models of regional MMD leads to a convergence of actor groups' mental models?
- How much participatory modelling of regional MMD contributes to reducing uncertainty of regional long-term risk prevention planning.

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Bühler, Y.

Remote Sensing Tools for Mountain Risk Monitoring and Mitigation

Remote sensing has developed into a key tool for early detection and monitoring of alpine natural hazards as well as for the planning and supervision of mitigation infrastructure. In particular Unmanned Aerial Systems (UAS) enable a flexible and accurate acquisition of valuable geodata even within inaccessible terrain such as avalanche release zones or steep rock faces. Satellite data on the other hand, allows for covering much larger regions without the need for people being even close to the area of interest.

We will present an overview on recent remote sensing applications performed at WSL/SLF. We apply UAS based photogrammetric surveys for avalanche documentation, the monitoring of avalanche release defense structures and snow depth mapping. We also show applications for the documentation of the Flüela-Wisshorn rock avalanche in 2019, which subsequently triggered a large snow avalanche. We demonstrate damage assessments of wind-storms in protection forests and the monitoring of the large and active landslide in Brinzauls/Brienz (GR). Additionally, we will present the results and evaluation of the rapid satellite mapping of two extreme avalanche periods (danger level 5) in January 2018 and 2019 in Switzerland, applying SPOT6/7 as well as Sentinel-1 and -2 data, recording approximately 25’000 individual avalanche outlines. These applications illustrate the huge potential of remote sensing technologies in high alpine terrain, initiating the discussion for future projects and applications.

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Cathala, M.

Mapping rockfall potential release areas and runout distances in the high mountain of the French Alps

High mountain environments of the European Alps have been increasingly affected by rockfalls (V > 100 m3) over the past decades, in conjunction with the atmospheric warming and the resulting permafrost degradation. These processes, and their potential cascading effects, constitute a threat for population and infrastructure, especially in the frequented massifs such as those of the French Alps.

The aim of this study is to characterize the distribution and propagation of rockfalls in order to map the potential release and deposit areas in the French Alps. To do so, we used a rockfalls database (>1000 events) that occurred in the Mont Blanc massif during the period 2007-2020. From this dataset, we analyze the topography and permafrost conditions the most prone to trigger a rockfall, considering the altitude, orientation, slope and MARST (Mean Annual Rock Surface Temperature) mapped with a statistical model. The topographic profile of rockfalls for which we know the precise deposit location is deeply analyzed to characterize the runout path according to the volume of the events. These results are then used to map potential release and deposit areas with a multicriteria approach in a GIS. These maps, combined with infrastructure or mountaineering routes, could be used to point out "hot spots" where more detailed analysis would be required to estimate the possible risks.

This work aims to provide a baseline for future researches and for decision makers in short- and long-term planning to anticipate rockfall hazards at present and in the near future.

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Cicoira, A. and Gaume J.

A material point method for alpine mass movements and process chains

Numerical modeling is an essential tool for the analysis and management of mountain risks: it allows quantitative description of the run-out distance and impact pressure of rapid mass movements and may contribute to better understand the effects of climate change on their magnitude, frequency, and dynamics. Yet, a unified model able to simulate multi-phase cascading events, including their initiation, propagation, entrainment and finally impact on structures is still missing. Hence, more detailed and physically-based models are still required to advance our understanding of gravitational mass movements and process chains and ultimately to contribute improving hazard assessment and risk management.

Here, we present a three dimensional numerical modeling approach based on a hybrid Eulerian-Lagrangian Material Point Method (MPM), finite strain elasto-plasticity and critical state soil mechanics to simulate in a unified manner the mechanical processes leading to failure and instabilities of heterogeneous materials, the dynamic behavior of the consequent mass movements, including phase transitions and interactions, as well as processes of entrainment and deposition. In order to demonstrate the potential of our approach, we investigate four real-scale cases: the 1963 Vajont rock-slide and lake outburst flood (IT), the 2017 Piz Cengalo rock-avalanche and ensuing debris flow (CH), the 2018 Wisshorn rock- and snow avalanche (CH), and the 2020 collapse of the Whymper hanging glacier (IT). Results show a good agreement with available data. Finally, we discuss the relevance and limitations of our approach and suggest improvement strategies for future applications.

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Comiti, F.

Scenarios of bedload transport changes in proglacial areas and downstreams channels

The headwaters of mountain basins worldwide are expanding at an incredibly fast pace as newly exposed stream reaches emerge from the rapidly melting ice masses. At the same time, large volumes of coarse sediments transported to rivers by glacier melt runoff are influencing downstream channel morphodynamics, posing new management challenges to society. Unfortunately, our ability to predict the most likely future changes of glacier-fed Alpine rivers is still severely limited. In fact, the following four crucial knowledge gaps hinder our understanding of how glacier recession is impacting river dynamics worldwide: i) Very poor understanding of the factors controlling coarse sediment output from glaciers, due to extremely scarce field datasets; ii) Limited understanding of how effectively coarse sediments sourced from the glacier snouts are transferred to downstream river reaches; iii) Modelling activities aimed at predicting the future fluvial dynamics greatly limited by the absence of ground-truthing datasets necessary to calibrate and validate model outputs.

In my presentation, I will address the following questions: i) What are the glacio-hydrological factors affecting coarse sediment fluxes from Alpine glaciers? ii) How important is longitudinal (dis)connectivity in mediating coarse sediment transfer within and downstream of the proglacial area? iii) How have proglacial and downstream reaches been evolving in Alpine regions since the Little Ice Age?

Finally, hypothesis - and speculations – on which will be the most likely future trends in the emerging proglacial channels as well as in the downstream river reaches will be put forward.

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Emmer, A.

Understanding patterns of GLOF occurrence in the post-LIA context: an everlasting need for updated GLOF inventories

Owing to often extreme characteristics and possibly disastrous consequences, glacial lake outburst floods (GLOFs) became well-recognized hazard in mountain regions across the globe. A variety of interrelated triggers and process chains were documented to cause GLOFs, making the prediction of future events quite challenging. Yet, our ability to predict the occurrence and characteristics of potential future GLOFs to a large extent relies on the analysis of and learning from past events (deriving GLOF susceptibility indicators). To this end, several attempts to compile regional as well as global GLOF inventories have been made in the past. Hand in hand with increasing amount and availability of high-resolution satellite products, also GLOF inventories in remote and unsettled high mountain regions are becoming more complete and more comprehensive. Recent studies pointed out surprising incompleteness of existing GLOF inventories, possibly changing our view on GLOF frequencies. In this contribution, I put observed patterns of GLOF occurrence into the context of post-LIA glacier retreat and lake evolution, discuss challenges associated with compiling GLOF inventories from documentary data sources and geomorphological imprints, and outline possibly transferable implications for enhanced GLOF hazard assessments. Further, I put these findings into the perspective of expected future retreat of glaciers and formation of new glacial lakes, with special emphasis given on the European Alps.

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Favillier, A.

Impacts of the climate change on the pluricentennial snow avalanches activity in the Queyras Massif (French Alps) derived from tree-rings

In the course of the 20th century, high-mountain regions, such as the Alps, have experienced a significant warming with temperature increase twice as much as the global average. Such warming strongly alters the cryosphere components. It induces, for example, a shift from solid to liquid precipitation, more frequent and more intense snowmelt phases or a strong decrease in the amount and duration of snow cover, especially at the location of the snow-rain transition. Such changes in snow cover characteristics are expected to induce changes in spontaneous avalanche activity. However, the IPCC special report on oceans and cryosphere (SROCC) mentions that "avalanches are one of the less understood process of the cryosphere in terms of response to warming". This research gap mainly results from the insufficient documentation of past events that relies on (1) historical chronicles, often discontinuous and focused on catastrophic events or (2) on systematic inventories limited to the second half of the 20th century which preclude a comparison from climatically distinct periods. On forested paths, the dendrogeomorphic approach was demonstrated as a reliable approach to complement to historical archives and series of systematic observation. However, a wide majority of dendrogeomorphic studies failed to identify clear links between avalanche activity and climate fluctuations due to (i) the very limited number of avalanche paths included in the reconstructions; (ii) potential non-stationarities related to e.g. increasing sample depth over time that blur the climatic. Based on the latest developments in dendrogeomorphology, we (1) developed an homogenized multicentennial (1560–2016) regional reconstruction for the Queyras Massif (French Alps) and (2) compared avalanche activity and climatic fluctuations at different time scales. At the decadal scale, our study evidences an increasing frequency of snow avalanches during the cooler and wetter decades and a more limited activity during warmer or drier periods. At the centennial scale, it shows a strong decrease of avalanche activity over the 20th century with a release probability significantly lower than in the preindustrial period. These very preliminary results suggest a climatic control of avalanche activity and a direct impact of global warming on snow avalanche frequency in the Southern French Alps.

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Graf, C.

Importance of high-quality and comprehensible basic data in integral risk management

Hazards due to natural hazard processes and the resulting risks due to the progressive development of settlements and the use of space by humans as well as the effects of climate change will be a major challenge in the future. To limit the risks, we assess natural hazard processes comprehensively and maintain the level of protection through combined measures within the framework of integral risk management.

In the integral risk management approach, hazard and risk assessment is at the center of a cycle of vulnerability reduction and mitigation through measures. The collection of robust basic data strongly determines the quality and informative value of the risk assessment. If we look at the activities and resources in the two categories, we see a strong trend toward risk assessments in recent years. At the same time, the quality of the basic data is repeatedly criticized and uncertainties with regard to the data are mentioned, but not always quantified. Hazard assessment is mainly declared as an expert opinion, based on experience, specific methods and procedures. Compared to relatively strongly standardized approaches and exact calculations in risk evaluation, we therefore often start the evaluation with a rather imperfect data basis with a more or less strong scatter or uncertainty range. By applying novel methods and technical tools, there is the possibility to replace or at least complement the strongly expert- and experience-based assessment with increased measurement-based determination. This should improve the comprehensibility and transparency of a hazard assessment and reduce uncertainties as far as possible.

This paper aims to contribute to the discussion around the role and importance of hazard assessment in the context of integral risk management.

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Jacquemart, M.

From the Alps to the World – Creating a Global Database of Cryospheric Hazards

That an increasingly warmer global climate would cause more frequent mass movements in glacierized mountain ranges has been postulated for decades. Indeed, regional analyses have shown increasingly frequent rock avalanches in various parts of the world, but comprehensive global studies are currently lacking. Here we present a framework upon which we aim to build a global, version-controlled, and machine-readable database of cryospheric hazards. By incorporating data from different existing inventories, and soliciting new data, we hope to pave the way to what will become a benchmark dataset for investigating the changing trends of cryospheric hazards at global scales. Such a database will not only allow large scale analyses, but also provide a much needed container for the numerous small to medium sized events that are recorded but not investigated in detail. Currently, these valuable datapoints go unused. In the long term, we hope to establish a network of regional observers that can contribute data to the database on a regular basis. By integrating these data into a standardized metadata framework we will facilitate data interpretation, automatic validation, and the addition of future contributions. Additionally, we will adhere to FAIR Data Principles to ensure that the compiled data will be Findable, Accessible, Interoperable, and Reusable for humans and machines alike. Combined, we believe that these efforts will help understand what the hazard landscape in the Alps, and beyond, will look like in the future.

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Kleinn, J.

Characteristics of Risk

An integral risk perspective is needed in dealing with natural hazards, especially for taking uncertainties and climate change into account in natural hazard risk analyses. Risk is always a combination of physical hazard and consequences like damages or losses. The concept of risk is difficult to grasp, partly because it cannot be directly measured and it cannot be summarized in a single number only. Nevertheless, risk has to be characterized for a number of applications, ranging from risk assessment to risk communication, stakeholder involvement and discussions on the level of acceptable risk.

The authors are presenting three characteristics of risk, which are essential for an integral view of the risk. These characteristics of risk are based on approaches commonly used in the insurance and reinsurance industry. They cover the entire range of probabilities and therefore allow an integral view of the risk. Uncertainties and future changes can easily be taken into account in this view of risk. These characteristics of risk have proven to be helpful in practical applications of natural hazard mitigation in Switzerland and have been successfully applied as a basis for decisions on the level of acceptable risk or for finding the optimal combination of mitigation measures.

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Kull, I.

Plaine Morte Glacier Lake
Lake evolution and unique adaptation strategy / measures

Co-authors: Isabelle Kull, Daniel Tobler

Plaine Morte glacier in central Switzerland is draining to the north into the touristic village of Lenk. A glacial lake is formed every year during spring and summer months. Lake drainage can occur rapidly with a flood-like discharge or during several days. Since 2011 yearly GLOFs have been registered. In 2018 the entire lake volume (2 Mio m3) drained within 24 hours with huge damages in the valley. Mitigation measures were necessary to prevent the valley bottom.

Since 2007 the lake volume has continuously increased. Modelling forecasts also indicate a further increase to 4 Mio m3 by 2050. With an increasing lake volume the peak discharges will also remain high. The analysis of the former events indicate that a maximum lake volume of 1 Mio m3 should not be exceeded. The most efficient solution was the artificial drainage of the lake through an open ice channel of 1.2 km into a nearby moulin. The structure reaches a depth of 5 - 13 m. The drainage is unique. There was no experience so far, so that the solution contained many uncertainties. The lake was partly drained successfully in 2019 and 2020. It has been shown that snow accumulation in the channel throughout the winter is a challenge for the maintenance of the channel. In 2021 a drainage system of wooden wool at the very bottom of the ice channel has been implemented to support the drainage effect through the snow. The prove of functionality will follow this summer.

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Maidl, E.

Individual risk preparedness among the general population

Building a culture of risk is an essential objective within the integrated risk management (IRM) paradigm to mitigate natural hazard events. This requires resilient communities, in which all responsible actors are recognized and aware of their role in risk management. However, previous studies indicate that risk awareness and preparedness levels are rather low within the general population. Fresh data from our panel-study among the Swiss general population provide results on factors that influence individual risk preparedness. From these results we draw conclusions how to increase most relevant social capacities in IRM.

Our baseline study (2015) showed that risk awareness and preparedness are strongly related to personal hazard experience. Interestingly, we found other influence factors that are important for awareness raising in absence of personal experience (which counts for the majority of the population). For instance, social integration enhances the effects of risk communication on the local scale. This confirms our earlier findings, according to which dialogic forms of communication are more effective than one-way information campaigns.

We emphasize that social capacity building needs to consider such factors in order to render integrated risk management strategies successfully.

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Manconi, A.

The Great Aletsch glacier terminus: a “supersite” to study long-term effects of climate change on rock slope evolution and mountain risks?

The Great Aletsch glacier is an iconic image of Switzerland, attracting every year a large number of visitors. Current models considering the evolution of temperatures due to climate change predict that in about 100 years the ice mass will entirely disappear. During this time, a substantial reaction of the adjacent slopes is expected, i.e. increasing number of rock failures in the form of single blocks, moderate mass collapses, as well as reactivation of deep-seated landslides, and possibly large rock avalanches. An example of this potential is the Moosfluh landslide, one among several mass movements located near the current glacier tongue. In 2016, we observed at Moosfluh an increase of surface velocities locally exceeding 1 m/day and causing serious concerns to the community. After the identification of surface displacements in 2010 via satellite radars, the Engineering Geology group at ETH Zurich has progressively implemented since 2013 an in-situ monitoring network, including temperature sensors, robotized total stations, GNSS, time lapse cameras, and seismic sensors. The aim of this contribution is to present selected results and ongoing research based on this monitoring network. Another goal is to trigger discussions on the possibility to identify the Great Aletsch glacier terminus as a long-term natural laboratory. Joint efforts are needed to continue acquiring, preserving, and sharing multi-parametric monitoring data in our community. The identification of “supersites” where to foster and catalyze long-lasting cooperation can be a worthwhile approach to increase our capability to understand and potentially forecast the effects of climate change on mountain risks.

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Mani, P.

Climate change impact on rain on snow events

On October 10, 2011, an extraordinary event hit the northern part of the Swiss alps. In the Gastern valley (Bernese Oberland) huge debris flows were triggered. Within a few hours in several debris flow channels about 800'000 m^3 of material was eroded and deposited in the valley bottom. Most of the starting zones of the debris flows in the Gaster valley were either until recently covered by firn or glacier ice or are in the region of permafrost degradation. But most of the material was eroded in the uppermost part of the cones, somewhat that did obviously not occur in the last few centuries or even millennia.

The event was triggered by a rain on snow event. The event was preceded by heavy snowfall which led to a thick snow cover down to low elevation. An atmospheric river brought very warm air and a lot of humidity into the area up to high elevation. Together with strong winds this led to a fast moisture penetration into the snowpack. The combination of a thick cold snowpack with high energy input led to unexpected effects which are presented in this paper.

Rain on snow events up to high elevation where they coincide with newly deglaciated areas or loose material destabilized by permafrost degradation must be expected more frequently.

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Mergili, M.

Progress and remaining challenges in process chain modelling

Simulations of gravitational mass movements in high-mountain areas are important to inform risk management. For high-frequency processes such as "ordinary" snow avalanches or debris flows, operational predictive simulation procedures are available for hazard zoning as well as for the design of technical protection measures and warning systems. This is not the case for low-frequency or even singular processes of potentially high magnitude. This contribution focuses specifically on the numerical simulation of the propagation of complex cascading landslide events as they are typical in glacierized high-mountain areas, sometimes related to climate change. The software tool r.avaflow is used for the simulations presented in this work.

Detailed back-calculations of complex process chains have become feasible, as it is shown for the events at Salkantay, Peru and Jinwuco, PR China (glacial lake outburst floods in 2020) and the 2021 Chamoli event in India. However, the gap to useful predictive simulations still has to be bridged. The following issues are discussed, partly based on the above examples:

- Even though many key components of high-mountain process chains such as entrainment, deposition, or landslide-lake interactions are increasingly well understood from a physical point of view, the appropriate application of these concepts has to build on parameters which are usually not known and cannot directly be measured. A sensible equilibrium between physical correctness and practical applicability is therefore important when simulating such processes.
- There are few events with similar mechanisms and magnitudes. Further, key parameters may vary spatially or dynamically, so that the development of guiding parameter sets remains a considerable challenge and needs more research.
- Uncertainties in the simulation results have to be considered and communicated in an appropriate way. Whereas scenario-based analyses and likelihood estimations are more or less established, the communication of uncertain results to decision-makers and the broader public remains a controversial and multi-dimensional issue.

Further inter- and transdisciplinary research & development are required to move forward in our ability to make computer simulations a more useful basis for disaster prevention related to complex cascading landslide processes in high-mountain areas.

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Moos, C.

Climate change impacts the protective effect of forests: A case study in Switzerland

Forests play an important role as natural means of protection against natural hazards, such as rockfall. Due to climate warming, changes in the protection service of these forests have to be expected. Shifts of current to more drought adapted species may result in temporary or even irreversible losses in the reduction of rockfall risk provided by these forests. In this study, we assessed how the protective capacity against rockfall of a protection forest in the Valais in the Swiss Alps may change in future, by combining dynamic forest modelling with a quantitative risk analysis. Current and future forest development was modelled with the forest model TreeMig under a moderate (RCP4.5) and an extreme (RCP8.5) climate scenario. We quantified the protective effect of the different forest scenarios based on the reduction of rockfall risk for people and infrastructure at the bottom of the slope. The forest simulations predicted a decrease in basal area of the currently occuring species (*F. sylvatica*, *P. abies*, *L. decidua*, *A. alba*) in future. The forest turned into a *Q. pubescens* dominated forest, for both climate scenarios, mixed with *P. sylvestris* under RCP4.5. With climate warming, an increase in risk is expected for both climate change scenarios. In the long-term (> 100 years), a stabilization of risk, or even a slight decline may be expected due to an increase in biomass of the trees. Future research should explore into more details the long-term effect of different adaptive forest management strategies on the protection service of forests under climate change.

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Muñoz-Torrero Manchado, A., Farvaque, M. and Gorsic, S.

Determination of recent rockfall activity at Täschgufer using repeat hi-res imagery and field-based magnitude-frequency assessments

At Täschgufer (Swiss Alps), tree-ring based reconstructions point to a high recurrence of rockfall activity, with a sharp increase in activity since the 1980s (see abstract Christophe Corona). Consequently, several dams were built on the slope to protect the village of Täsch and transportation infrastructure in the valley floor. Here we present a multidimensional approach with the aim to improve our understanding of rockfall activity in a context of climate warming and permafrost wasting – and the impacts that these changes could have on rockfall risk.

The first part of the presentation will be dedicated to the interpretation of systematic drone flights and the acquisition of terrestrial images with high-resolution Gigapan panoramas since 2016. Since April 2021, the same acquisition is realized at a monthly rhythm to analyze seasonal rockfall activity in addition to annual changes in activity. We demonstrate that the comparisons of both image sources allows the manual detection of rockfall sources and deposition even for boulders with diameters smaller thanof 0.5m. We also introduce the use of Object Base Image Analysis for the automatic detection and digitizing of rockfall source and deposition areas on the slope.

In the second part of the talk, we will introduce relationships between the magnitude and frequency of boulders released by repeatedly counting and measuring the volumes of fresh deposits in the dams. The gradual filling of the dams with rockfall material will then be used to analyze the efficiency of protective measures and the life cycle of the dams in terms of risks.

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Ice avalanche hazard evaluation and risk management from the Planpincieux glacier (Courmayeur — Italy)

Since 2013, the Planpincieux glacier, located on the Italian side of Mont Blanc massif, has been studied to analyse the dynamics of ice collapses in a temperate glacier. Several documented ice avalanches and glacial floods (1929, 1952, 1982, 2005, 2017), which, in some cases, threatened the village of Planpincieux and damaged the municipal road, have been linked to this glacier. Starting from the summer of 2019, a fast moving ice volume, partially separated by the rest of the glacier tongue by a large crevasse, has drastically increased the possibility of a new collapse with possible implications for the valley floor.

Considering the potential risk, a civil protection plan based on the combination of a constant monitoring (GbInSAR) and an early warning system (avalanche Doppler radar) was deployed.

To assess the hazard caused by ice avalanches from the Planpincieux glacier, two separate studies have been carried out at the same time, with RAMMS and r.avaflow models. The calibration of the parameters were based on the back calculation of ice avalanches from the Planpincieux glacier mapped between 2017 and 2020. The results obtained from the two different methodologies are comparable and confirm the robustness of the analyses. The outputs of the simulations were then translated into risk scenarios and safety concepts for different unstable volumes of the glacier.

With this work, we suggest a comprehensive methodology for the study and the risk management of ice avalanches in the alpine environment.

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Rinderer, M.

Hazard assessment on the regional scale under current and future climate scenarios

Regional hazard assessment is a powerful tool to analyse natural hazards on a large scale of interest and identify hots spots that need prioritization. Even if the underlaying models that are used to represent certain hazard processes are simple some include drivers that are sensitive to climate change. For that reason, these models allow to predict the effect that climate change can have on the large-scale pattern of hazard areas.
We present a set of models for bedload and large wood transport hazard assessment on the regional scale. The models are detailed enough to account for differences in runoff generation patterns and simulate runoff concentration on hillslopes and channels. The channel geometry is not depending on channel cross section data but can be determined from high resolution digital elevation models. Channel flow conditions are used to calculate bedload transport event loads. The necessary sediment potential is determined with a set of simple models that simulate rockfall, landslides, soil denudation, bank and bed erosion. Discharge and associated flow width and depth are further used to calculate large wood transport in the channel during floods. The wood potential is determined from forest inventory data.
Currently the model is developed and tested in the State of Baden-Württemberg, Germany using extreme precipitation scenarios under current climatic conditions. However, the model can account for different antecedent conditions and extreme rainfall scenarios that will likely occur more frequent under climate change conditions. We present first result and compare them with a number of extreme events that caused damage in recent years.

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Savi, S.

Pronounced increase in slope instability linked to global warming: A case study from the Eastern European Alps.

In recent decades, slope instability in high-mountain regions has often been linked to increase in temperature and the associated permafrost degradation and/or the increase in frequency/intensity of rainstorm events. In this context we analyzed the spatiotemporal evolution and potential controlling mechanisms of small to medium-sized mass movements in a high-elevation catchment of the Italian Alps (Sulden/Solda basin). We found that slope-failure events (mostly in the form of rockfalls) have increased since the 2000s, whereas the occurrence of debris flows has increased only since 2010. The current climate-warming trend registered in the study area apparently increases the elevation of rockfall-detachment areas by approximately 300 m, mostly controlled by the combined effects of frost-cracking and permafrost thawing. In contrast, the occurrence of debris flows does not exhibit such an altitudinal shift, as it is primarily driven by extreme precipitation events exceeding the 75th percentile of the intensity-duration rainfall distribution. Potential debris-flow events in this environment may additionally be influenced by the accumulation of unconsolidated debris over time, which is then released during extreme rainfall events. Overall, there is evidence that the upper Sulden/Solda Basin (above ca. 2500 m asl), and especially the areas in the proximity of glaciers, have experienced a significant decrease in slope stability since the 2000s, and that an increase in rockfalls and debris flows during spring and summer can be inferred. Our study thus confirms that "forward-looking" hazard mapping should be undertaken in these increasingly frequented, high-elevation areas of the Alps, as environmental change has elevated the overall hazard level in these regions.

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Scorpio, V.

Geomorphic catchment response to different severity storm floods: channel changes and hillslope sediment coupling dynamics

Several heavy precipitation events caused flash floods and landslides in Europe over the last years. In mountain environments, mass movements are important sources of sediment supply to the rivers.

The Stolla creek is a partly confined channel of the Dolomites (Easter Italian Alps), that was affected by an extreme flood in August 2017, and by a moderate flood in August 2020.

The geomorphic effects of the two floods were investigated with the aims to compare the channel changes induced by the two events and to assess the rule of the sediment connectivity. A multi-methodical approach was applied, including radar rainfall estimation, rainfall-runoff modeling, field surveys and comparison of multitemporal orthophotos and DTMs.

The 2017 flood was caused by rainfall with a short duration (6 hrs) and a rain rate exceeding 45 mm h^{-1}. More than 600 debris flows were triggered along the hillslopes. The Stolla channel experienced widening and bed level aggradation or incision. Although 294,000 m^3 of sediments eroded in the connected debris flows, limited volumes of sediments (< 1000 m^3) were exported to the catchment outlet.

The 2020 flood event was characterized by a lower rain rate (max 17 mm h^{-1}) and a long duration (48 hrs) and did not trigger debris flows. The moderate magnitude of the flood peak did not lead to channel widening, but only bed incision in some reaches.

The main results of this study suggest that:

- different rainfall intensities and durations controlled channel changes and sediment transport effectiveness;
- sediment supply from hillslopes played a relevant impact in channel adjustments;
- the structural connectivity strongly influenced the sediment cascade.

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Stoffel, M.

Climate warming drives rockfall activity from a permafrost slope in the Zermatt valley: implications for rockfall risk

Rockfall in high mountains is perceived to change more than other mass-wasting processes, presumably as a result of ongoing climate warming and the related, increasing degradation of permafrost. However, the systematic lack of longer-term observational records of rockfall largely hampers any in-depth assessment of how process activity may have been altered by a warming climate and its variability since pre-industrial times. Here, we present evidence that the ongoing climate warming in the Swiss Alps indeed controls rockfall activity from degrading permafrost, and that changes in rockfall frequency correlate significantly with warming air temperature. Using growth-ring records from trees impacted by rockfall, we construct the longest, continues time series of periglacial rockfall activity that is currently available. Using this dataset, we also present insights into how rockfall risk has changed since the 1880s and how it might change over the course at the 21st century.

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Evolution of mass movements at Spitze Stei (Kandersteg) – Disposition, process chain, monitoring and adaptation concept in the valley bottom

Co-authors: Daniel Tobler, Christian Kienholz, Kaspar Graf

A rock mass of 20 Mio. m3 has destabilized above Lake Oeschinen in the Bernese Oberland (Switzerland). The instability was detected in 2018 following an increase in rockfall activity in the Spitze Stei area. Large rock avalanches from Spitze Stei currently threaten the infrastructure around Lake Oeschinen. Debris flows originating from the rock avalanche deposits may reach as far as the village of Kandersteg. The possible process areas of rock avalanches and several secondary processes (e.g., flood waves, debris flows) were simulated with sophisticated models (DAN-3D, RAMMS). A monitoring program was established in 2018, relying on GPS, tachymetry, radar, camera measurements and boreholes equipped with inclinometers, thermistores and pressure gauges. Furthermore, a scenario-based hazard management for the entire process chain down to the valley bottom was implemented based on a comprehensive hazard assessment. With continuously increasing velocities of up to 15 cm/d during spring (snowmelt) and summertime, it is likely that the unstable rock mass has passed a "point of no return". Indeed, large events have been predicted to occur within the next 1-5 years. In the year of 2020 the first debris flows occurred, in 2021 they have been increasing in volume and frequency. The scenario-based hazard management involving local and regional authorities, planners, the army, and local hazard organizations will help mitigate adverse effects of these events. An emergency planning has been setup. Uncertainties in the primary process (rockslide) and the following process chain are a huge challenge for the hazard management. New concepts have to be evaluated.

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Troilo, F.

Basal Thermal regime investigations at Whymper Hanging Glacier (Courmayeur – Aosta Valley): Implications for ice avalanches risk management.

The Whymper Serac is an avalanching hanging glacier located on the top of the Grandes Jorasses on Mont Blanc Massif at an altitude of 3900-4100m. Major ice avalanches have been documented historically and since 1997 at least 5 ice avalanche events with volumes ranging from 20.000 to 150.000 m^3 have been monitored and predicted with sufficient time to set up safety measures for the protection of infrastructures and population. Monitoring of the serac has proven to be effective as long as the basal thermal conditions analyzed in 1997 continue to show negative basal temperatures. In 2020 a drilling campaign started with the installation of 3 thermistor chains on the serac, reaching the ice-bedrock interface. One of the 3 boreholes showed temperate conditions at the ice/rock interface. The realization of 3 additional boreholes equipped with thermistor chains is planned for 2021 and a series of further investigations started to better understand how the monitoring of the Whymper Serac can be continued in an effective way. New simulations of the expansion of a major event are being performed on r.avaflow software and the possibility to realize thermo-mechanical modeling using the Elmer-Ice module is underway. Multitemporal UAV photogrammetric surveys and geophysical soundings have been performed to better assess ice thicknesses and serac topography. Meanwhile, continuous monitoring of serac deformations is in place, thanks to a GB-InSAR radar, a topographical station and automated digital cameras to detect any accelerations or anomalous deformation behavior.

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Völk, M.S. and Bründl, M.

Facing Climate Change Impacts and Risks with Large Scale Hazard Modelling

Various studies show that changes in the climate system, such as temperature rise and extreme precipitation events, strongly influence gravity driven hazards. Within the framework of the research program “Climate Change Impacts on Alpine Mass Movements” currently running at the Swiss Federal Institute for Forest, Snow and Landscape Research WSL, we are developing a framework to model the risk caused by mass movements and altered by climate and socio-economic changes. In a first approach, we model avalanche and rockfall risks in Switzerland for the current climate situation. The changing hazard disposition will be modelled using the RAMMS::LSHM Large Scale Hazard Mapping method. Risks are assessed with the probabilistic, Python-based risk assessment platform CLIMADA, developed at ETH Zurich. We apply algorithms for automatically determining potential release areas, a high-resolution terrain model, and forest layers to simulate the spatial distribution of hazards for scenarios with a 30, 100, and 300-year return period. Avalanche scenarios are characterized by different 3-day increases in snow height and rockfall scenarios by various block sizes. The so-derived hazard indication maps are taken as input for different risk models such as CLIMADA and the risk tool of the Swiss Federal Railways. In these risk models, we use high resolution building and infrastructure layers to identify exposed objects and impact functions based on “EconoMe” to calculate the risk potential and to depict them in risk indication maps. These maps provide a basis for identifying risk hot spots and to support decisions regarding adaptation measures.

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