Riederalp 2016 Cryosphere Workshop

From process understanding to impacts and adaptation

Riederalp, Switzerland, March 15-19, 2016

Jointly organized by:

UNIVERSITÉ DE GENÈVE

Swiss Federal Institute for Forest, Snow and Landscape Research WSL

Workshop Program

Abstracts Volume

Cryosphere Workshop: From Process Understanding to Impacts and Adaptation

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WORKSHOP PROGRAM

(Right-hand column indicates the page of the abstract in the Abstracts Volume below)

	Tuesday, March 15	
Afternoon	**Participants arrive in Riederalp**	
18:30	Icebreaker, followed by supper (around 19:30)	
	Wednesday, March 16	
09:00-09:15	D. Farinotti, M. Stoffel, M. Beniston: Welcome by the organizers and objectives of the meeting.	
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12:00-12:20	*Erika Coppola, International Centre for Theoretical Physics, Trieste, Italy* Impact of climate change on runoff timing over the Alpine region	**5**
12:20-12.40	*Juan-Ignacio Lopez-Moreno, Institute for Pyrenean Ecology, CSIC, Zaragoza, Spain* Different sensitivities of snowpack to climate warming in different Mediterranean mountain regions	**5, 6**
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09:40-10:00	*Umberto Mora di Cella, ARPA – Val d'Aosta, Italy* Permafrost response to climate change in the Cervinia basin (Italy)	**7, 8**
10:00-10:20	*Arthur Lutz, Utrecht University, The Netherlands* Impact of climate change on the hydrology of High Mountain Asia	**8**
10:20-10:40	*Daniel Farinotti, Swiss Federal Inst. for Forest, Snow and Landscape Res., Birmensdorf, Switzerland* From dwindling ice to headwater lakes: Could dams replace glaciers in the European Alps?	**8, 9**
10:40-11:10	Coffee, tea, refreshments	
11:10-11:30	*Juan Ballesteros Canovas, Universities of Bern and Geneva, Switzerland* Glacial lake outbursts flow reconstruction in the Northern Tien Shan: implications for hazard assessment	**9**
11:30-11:50	*Silvia Terzago, Institute of Atmospheric Sciences and Climate (ISAC-CNR), Turin, Italy* Uncertainty in the representation of snowpack over the Alps in CMIP5 global climate models	**10**
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17:20-17:40	*Eddy Moors, Wageningen University, The Netherlands* Adaptation Pathways, highlighting stakeholder driven and gender inclusive processes	**12**
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09:20-09:40	*Delphine Six, Laboratory of Glaciology, University of Grenoble, France* Estimating uncertainties in mountain glacier mass balance	**13**
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10:00-10:20	*Elisa Palazzi, Institute of Atmospheric Sciences and Climate (ISAC-CNR), Turin, Italy* Elevation-dependent warming in the Tibetan Plateau-Himalayas from CMIP5 models	**14, 15**
10:20-10:40	*Markus Stoffel, Universities of Bern and Geneva, Switzerland* Proliferation of Himalayan hydropower projects increases uncertainties about exposure to glacial lake outburst floods	**15**
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11:30-11:50	*Marco Vagliasindi, Fondazione Montagna Sicura, Courmayeur, Italy* Glaciers- and permafrost-related hazard in Aosta Valley: evolution and monitoring	**16**
11:50-12:10	*Enrique Moran, University of the Balearic Islands, Palma de Mallorca, Spain* Rain-on-snow events in Switzerland: observations and projections for a warmer climate	**16, 17**
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19:30	Evening meal	
	Saturday, March 19	
	SESSION 6: Final plenary, wrap-up, future work	
09:00-10:30	Session reports from evening meetings (Sessions 2 and 5)	
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	M. Beniston, M. Stoffel, D. Farinotti: Closing remarks from the organizers, farewell	
12:00	Close of the meeting	
Afternoon	**Participants depart from Riederalp**	

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VOLUME OF ABSTRACTS

List in order of appearance of the contributions as given in the Workshop Program above

Runoff changes in mountain regions with declining snow and ice regimes (EU/FP7 *ACQWA* project overview)

Martin Beniston

The University of Geneva, Switzerland
Martin.Beniston@unige.ch

Future shifts in temperature and precipitation patterns, and changes in the behavior of snow and ice in many mountain regions will change the quantity, seasonality, and possibly also the quality of water originating in mountains and uplands. As a result, changing water availability will affect both upland and populated lowland areas. Economic sectors such as agriculture, tourism or hydropower may enter into rivalries if water is no longer available in sufficient quantities or at the right time of the year. The challenge is thus to estimate as accurately as possible future changes in order to prepare the way for appropriate adaptation strategies and improved water governance. The ACQWA project aimed to assess the vulnerability of water resources in mountain regions such as the European Alps, the Central Chilean Andes, and the mountains of Central Asia (Kyrgyzstan) where declining snow and ice are likely to strongly affect hydrological regimes in a warmer climate. Based on RCM (Regional Climate Model) simulations, a suite of cryosphere, biosphere and economic models were then used to quantify the environmental, economic and social impacts of changing water resources in order to assess how robust current water governance strategies are and what adaptations may be needed to alleviate the most negative impacts of climate change on water resources and water use.

The results from the ACQWA project suggest that there is a need for a more integrated and comprehensive approach to water use and management. In particular, beyond the conventional water basin management perspective, there is a need to consider other socio-economic factors and the manner in which water policies interact with, or are affected by, other policies at the local, national, and supra-national levels.

Monitoring climate change impact on glaciers and permafrost – an outlook based on 15 years of experience

Hans Stötter

University of Innsbruck, Austria
hans.stoetter@uibk.ac.at

The behavior of glaciers and permafrost can be used as a perfect indictor for the impact of increased energy supply under climate change conditions. Due to their individual direct and indirect coupling with atmospheric energy fluxes they show reacts on different time scales. Laser scanning technology provides a methodological framework which allows high precision and high resolution monitoring of changes in volume and mass, which gives insight in how much additional energy has been stored in the glacier or permafrost system.

Since 2001, ALS-based multi-temporal time series have been recorded on i) individual glaciers (e.g. Hintereisferner, Kesselwandferner) and rock glaciers (e.g. Reichenbachkar, Hochebenkar), and ii) area-wide glaciation (e.g. Ötztal Mountains) and area-wide permafrost pattern (e.g. Province of Southern Tyrol). The analyses of all data sets draw a clear picture of how drastically climate change impacts on high mountain environments. Besides the quantification of changes in the cryosphere, additional consequences of glacier decay and permafrost shrinkage on geomorphic processes (e.g. rock fall, debris flows) can be detected and quantified.

Glacier changes in the European Alps since 1850 using a new regional glacier model

Fabien Maussion

University of Innsbruck, Austria
fabien.maussion@uibk.ac.at

Most regional and global glacier models rely on empirical scaling laws to account for glacier area and volume change with time. These scaling methods are computationally cheap and are statistically robust when applied to many glaciers, but their accuracy considerably lowers at the glacier or catchment scale. The nearest alternative in terms of complexity - glacier flowline modelling - requires significantly more information about the glacier geometry. Here we present a new open source glacier model implementing i) the determination of glacier centerlines, ii) the inversion of glacier bed topography, and iii) a multi-branch flowline model handling glacier tributaries. Using the HISTALP dataset as climatological input we apply the model in the Alps for 1850 to present. The relatively large number of independent data available for validation in this region allow a critical discussion of the added value of our new approach. We discuss two contradictory aspects inherent to any geoscientific model development: while our model clearly opens wide-ranging possibilities to better resolve the glacier processes, this new playground is associated with an increase in complexity, the number of calibration parameters, and... uncertainty?

Mountain snow distribution and how it may change in the future

Hendrick Huwald

Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland
Hendrick.Huwald@epfl.ch

The spatial distribution of snow in the mountains is highly heterogeneous, and processes behind this heterogeneity are not yet understood quantitatively. Based on (i) increasing accuracy and spatial coverage of remotely sensed snow depth maps, which have become available recently, (ii) improved atmospheric modeling of precipitation and particle dynamics, and (iii) better distributed measurements of solid precipitation (radar), it is possible to improve the characterization of processes leading to the observed snow distributions. We present results that show the relative importance of local precipitation variability, preferential deposition of snow, and wind and gravity driven snow transport. Current evidence suggests that these processes significantly contribute to shaping the alpine snow distribution. On average snow depth and water equivalent increase up to a certain elevation showing a distinct maximum, before decreasing at ridge/summit elevations.

Additionally, we address the impact of climate change and show how much different elevations (and climate zones) in the Alps are affected by global warming as predicted by various regional climate models. Also snowmelt dynamics and runoff generation are investigated on the sub-catchment scale and related to forcing of local climatic conditions. It is concluded that above the tree-line, snow distribution and the relative importance of associated processes is not expected to change significantly, despite the fact that warming will lead to a strong decrease in snow at the mid-altitude range.

Glacier changes in Norway – A century of monitoring

Liss Andreassen

Norwegian Water Resources and Energy Directorate, Oslo, Norway
lma@nve.no

Glaciers in mainland Norway cover ~2700 km^2, 0.7 % of the land area. In this paper, I give an overview of glaciers in Norway, describe the current monitoring program, and sum up the main results. I will also discuss challenges in current and future monitoring of the glaciers. The first systematic observations of Norwegian glaciers started around 1900, when glacier length-change measurements started on a number of glaciers. Throughout the 20th century the glaciers in mainland Norway have generally retreated, although several periods of advance have also occurred. The Norwegian glaciological mass balance record is extensive. More than 40 glaciers have been observed and 10 glaciers have series longer than 20 years. Since 2007, LIDAR campaigns have been conducted on one third of the glacier area in Norway including all current mass balance glaciers. The acquired digital terrain models (DTMs) and orthophotos provide an accurate baseline for future repeated mapping and glacier change detection. Geodetic results reveal an overall mass loss from the 1960s to 2010s: a mean change of -0.24 ± 0.05 m w.e./a. for the surveyed area. The largest mass losses were found for the northernmost glacier, Langfjordjøkelen, and for continental glaciers in the interior, whereas some maritime glaciers have had periods with mass surplus. Since 2000, both geodetic and glaciological measurements show a remarked mass loss with glaciers shrinking in area, length and thickness. Comparison of glaciological and geodetic mass balance have led to reanalyzed and partly calibrated mass balance series.

Past and future evolution of the mountain snow cover

Ulrich Strasser

University of Innsbruck, Austria
ulrich.strasser@uibk.ac.at

Due to the key role that snow plays as resource for hydrology, ecology and winter tourism, the past and future evolution of the mountain snow cover is under continuous monitoring and scientific assessment since long time. For the analysis of the historical period, instruments and recordings of a multitude of measures are in use - mainly for snow water equivalent, snow height, snow-covered area and a multitude of remotely sensed snow parameters. For the future, regional climate model output is downscaled to local topographical conditions, and

used for numerical simulation of the snow cover using more or less complex representations of the relevant physical processes. Results suggest that whereas in the past, when the duration of a seasonal snow coverage has mostly receded in the forelands and valley bottoms, it is now the lower altitudes (colline zone) of the mountain ranges where the snow duration goes back most significantly. For the future, scenario simulations suggest that the snowline will further shift to the montane zone, due to the temperature increase expected with global climate change. This latter signal is very clear in comparison to the expected seasonal shifts of the precipitation regime.

The resulting new pattern and seasonal dynamics of the mountain snow cover and the respective meltwaters will have wide implications for the inhabitants of the world's mountain regions and their forelands. The presentation generalizes the results from several research projects to give an overview of methods, results and open questions from a scientific perspective.

Permafrost and climate warming: New methodological approaches to quantify the evolution of ground ice

Christian Hauck

University of Fribourg, Switzerland
Christian.Hauck@unifr.ch

Mountain permafrost is currently undergoing substantial changes due to climate change as a whole and especially due to the observed and projected air temperature increase. To evaluate the sensitivity of mountain permafrost to climatic changes and to assess its future evolution, both, climatic variables such as air temperature, radiation and timing and duration of snow cover have to be considered, as well as subsurface characteristics such as ground temperature, ice content, porosity or hydraulic properties. Current observational evidences suggest that especially the variable water/ice content in the near subsurface plays a major role, also regarding permafrost degradation and stability issues on sloping mountainous terrain. Within the recently finished project cluster TEMPS (The evolution of mountain permafrost in Switzerland), a hierarchy of different climate and subsurface models were employed to improve the process understanding of the complex interaction between atmosphere and frozen subsurface. The results were incorporated into climate impact simulations using the subsurface model COUP and downscaled outputs of various ENSEMBLES GCM/RCM chains as forcing data.

In addition, new monitoring techniques focusing on subsurface water and ice contents are developed and installed in operational networks in the Swiss Alps. The data can be used as calibration variables for permafrost models (in addition to the commonly used ground temperatures) but also as independent validation data. These methodological improvements can easily be transferred to other field sites, including polar permafrost, and different permafrost models.

Impact of climate change on runoff timing over the Alpine region

Erika Coppola

Abdus Salaam International Centre for Theoretical Physics (ICTP), Trieste, Italy
coppolae@ictp.it

We investigate the greenhouse gas-induced change in snowmelt-driven runoff (SDR) over the Alpine region using the output from two Med-CORDEX and two EURO-CORDEX regional climate model (RCM) projections (RCP8.5 scenario) at two resolutions (12km, 50km) driven by a sub-set of the CMIP5 GCMs. Comparison with the European Water Archive (EWA) observed runoff dataset (242 stations) over Alps shows a good performance by the higher resolution models in representing present day SDR, with the lower resolution simulations being less accurate in capturing the SDR timing. In the future projections all the models show a temperature increase of up to 4 degrees by the end of the 21st century throughout the Alps and this leads to an anticipation of SDR timing throughout the year that can span from 1 to 3 months depending on the model horizontal resolution. These timing changes are associated to changes in snow cover modulated by the complex Alpine topography. In fact, model resolution plays a critical role in regulating the magnitude, timing and spatial distribution of the response of snow cover and SDR to warming. Accurate simulation of changes in runoff timing requires high resolution representation of the Alpine topography, and can be important for water storage regulations concerning energy production, agriculture and domestic use.

Different sensitivities of snowpack to climate warming in different Mediterranean mountain regions

Juan Ignacio López Moreno

Institute for Pyrenean Ecology – CSIC, Zaragoza, Spain
nlopez@ipe.csic.es

Mediterranean climate is a type of subtropical climate characterized by warm to hot, dry summers and mild to cool, wet winters and a very large interannual variability. Thus, mountainous areas may accumulates an important snowpack during winter and spring that is very important to ensure water resources during the beginning of the dry season in the lowlands and to attenuate the effect of temporal variability of precipitation on river flows. At the same time these areas have been identified in global studies as hot spots in terms of climate change, with a higher than average warming and drying. To analyse the impacts of climate change on snowpack, it is necessary to consider that different Mediterranean mountains exhibit contrasting climatic conditions that may lead to noticeable differences in the partition of the snow energy balance and snowpack characteristics. These differences might cause strong differences in the sensitivity of the snowpack to climate warming process. To verify this hyphotesis we have simulated the snowpack in different mountain areas dominated by Mediterranean climate (Pyrenees, Sierra Nevada-Spain, Sierra Nevada-USA, Atlas, Chilean Andes) under different scenarios of warming and drying, being possible to quantify their sensitivity to climate change. The partitioning of the components of the snow energy balance (SEB) is clearly different amongs the analysed AMS. Net radiation is much higher in Sierra Nevadas, Atlas and Chile than Pyrenees, and they also show strong energy losses due to latent heat fluxes (high sublimation). In the Pyrenees and also in Sierra Nevadas, sensible heat fluxes are more important than Atlas and N. Chile. Different climate and SEB lead to strong contrasts in snowpack magnitude and duration and also in snow temperature, that is colder in the most semiarid mountains (thinner snowpack and with more energy losses due to sublimation) . The most semiarid mountains have exhibited a lower sensitivity to climate warming than the Pyrenees. In the most semiarid regions, the response of snowpack to climate warming will be more contrasted between aspects receiving different solar radiation. Climate Models point out Sierra Nevada (Spain) and Atlas (Morocco) as the ones that will undergone fastest warming and drying by mid of the 21st century. However, differences in sensitivity of snowpacks are expected to balance such impacts.

IPCC Special Report proposal on *Mountains and Cryosphere*

Christian Huggel

University of Zurich, Switzerland
christian.huggel@geo.uzh.ch

The IPCC is currently collecting proposals for a limited number of Special Reports to be undertaken in the AR6 cycle. Switzerland, together with several other countries has submitted a proposal for a Special Report on Mountains. Other countries (including China and the USA) have submitted proposal related to the cryosphere. While it is not yet clear how the decision taken by the IPCC Plenary will look like, merger of topics are possible, and it is likely that those topics that will not have an own Special Reports will have dedicated space in the IPCC AR6. For either outcome it will be important that the research community is well prepared, and sufficient papers are submitted in time to be considered by the SR and/or AR. For the AR5 a pre-assessment procedure done by the research community for glaciers can serve as a valid experience. The idea here is to discuss the pertinent issues that would need to be represented in a SR, and to come up with a number of actions concerning research and publications that should in particular consider current scientific gaps in these fields.

Avalanche activity response to the Little Ice Age termination in a temperate low altitude mountain range

Florie Giacona

Université de Haute-Alsace, Mulhouse, France
florie.giacona@uha.fr

Snow avalanche activity response to climate warming remains poorly documented on the long range. This work grounds on a record of 731 avalanches from the last 240 years. It results from comprehensive inventory of available historical sources referring to the Vosges, a temperate low altitude mountain range in North-East of France. Homogenization techniques are used to remove the bias towards fewer event retrievals far in the past, and a Hierarchical Bayesian approach permits extraction of the predominant temporal signal at the massif scale. The low frequency trend is consistent with main trends in different coarse long-range climate indicators and proxies: measurements from distant stations, results from large-scale climate simulations and general circulation indexes. Annual fluctuations follow the year-to-year variability of the local winter climate documented with high accuracy over the recent decades by refined snow and weather reanalyzes. All in all, the response of Vosgian

avalanche activity to combined changes in winter temperature and precipitation / snow cover characteristics documents with unprecedented accuracy a drastic drop at the little ice age termination, from a strenuous stage ~0.6 avalanches per winter and path over a large activity range, to a current residual stage below 0.1 avalanches per year and path mostly limited to highest glacial circs. The comprehensive diachronic mapping of forest cover in the whole studied region demonstrates that forest cover evolution is not the predominant cause of this major pattern of change.

Changes of the cryosphere in the Aksu-Tarim Catchment (Central Asia) and its impact on river discharge

Tobias Bolch

University of Zurich, Switzerland
tobias.bolch@geo.uzh.ch

Tarim River is the main artery for the northern oases of the Taklamakan desert in Xinjiang, China and is strongly fed by snow and ice melt. The streamflow of the transboundary Aksu River, the most important tributary increased by ~30% over the last decades. The correct assessment of the contribution of snow and ice melt to the runoff is hampered by the lack of measurements. Ice-ice permafrost bodies may also be an important source of fresh water. We therefor investigate snow and ice using remote sensing data with additional field investigations. Snow cover mapping using AVHRR and MODIS data reveal high interannual variability and a slight decrease of snow cover in lower altitudes up to 4000 m asl. and an opposite trend above. Geodetic mass balance assessments show mass loss of 0.35±0.34m w.e.a−1 on average within the catchment (glacier area: ~6500 km²) in the period ~1975-2000 and slightly less loss thereafter. The contribution to the runoff of Aksu River due to glacier imbalance has been determined at ~20%. Climate model scenarios for the 21st century were used to simulate future glacial and hydrological changes. Results show an initial further increase in river discharge until the mid-century and a decline thereafter mainly caused by the projected further glacier mass loss. Although high uncertainties exist and the projections are strongly scenario-dependent, these projections are an important basis for long-term planning and decision making with respect to the water management in the arid Xinjiang province.

Permafrost response to climate change in the Cervinia basin (Italy)

Umberto Morra di Cella

Regional Agency for Environmental Protection (ARPA, St.-Christophe, Val d'Aosta, Italy
u.morradicella@arpa.vda.it

The Cervinia basin, located on the Italian side of Matterhorn, is a privileged place for studying permafrost due to its morphological features which include, debris covered slopes, high-elevation flat plateau and steep rock walls, the whole, over an elevation range spanning from nearly 2000 to 4500 m. In this area the climate change is inducing a strong modification of permafrost conditions as witnessed by e.g. the increase of rockfalls activity and

creep velocities of rock glaciers; nevertheless, permafrost characteristics varies from debris to bedrock flanks as well as from flat to steep areas, thus, the response to climate forcings are spatially variable.

In this talk, the main results of ongoing monitoring activities in three permafrost areas with different characteristics are presented and discussed: (i) in the lower part of the basin, the creep velocity of a rock glacier overhanging the ski tracks is increasing, (ii) at higher elevation, the deep permafrost temperatures measured on flat plateau are warming and finally (iii) on the Matterhorn rock walls the active layer is thickening.

Impact of climate change on the hydrology of High Mountain Asia

Arthur Lutz

Utrecht University, The Netherlands
a.lutz@futurewater.nl

Rivers originating in the high mountains of Asia are among the most melt water dependent river systems on Earth, yet large human populations depend on their resources downstream. Across High Mountain Asia's river basins, there is large variation in the contribution of glacier and snow melt to total runoff, which is poorly quantified. The lack of understanding of the hydrological regimes of these rivers is one of the main sources of uncertainty in assessing the regional hydrological impacts of climate change. In these studies we typify contrasting hydrological regimes at large river basin scale in contrasting climates in Asia. Subsequently we analyze the hydrological impact of climate change using the latest climate model output. We use a high-resolution (1 km), fully distributed cryospheric-hydrological model including a large scale parameterization of future glacier retreat. We conclude that the average annual runoff will increase in the coming decades as a result of projected increases in precipitation in combination with sustained higher glacier melt, for years to come. A separate study focusing on the upper Indus basin, being Asia's climate change hotspot, generated hydrological projections for the entire 21st century. The analysis focuses on changes in sources of runoff, seasonal shifts and changes in hydrological extremes. We conclude that the future of the water resources in the upper Indus basin is highly uncertain in the long run, but that patterns of seasonal shifts and changes in hydrological extremes are consistent across climate change scenarios.

From dwindling ice to headwater lakes: Could dams replace glaciers in the European Alps?

Daniel Farinotti

Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf, Switzerland
Daniel.Farinotti@wsl.ch

Environments significantly influenced by the presence of seasonal snow or glaciers are hotspots regarding the impacts on water availability in response to expected climate change. With warmer temperatures, both the duration and the spatial extent of the seasonal snow cover are projected to decrease, and glaciers are expected to retreat substantially. This is anticipated to have important influences on water availability, including changes in the seasonality of runoff, as well as an overall reduction in water yields from high-mountain catchments. Here we present an estimate for the potential of mitigating projected changes in seasonal water availability from melting glaciers by managing runoff through reservoirs. We compute the water volume that, in future, is expected to be in excess during winter and spring time, and transfer it seasonally through temporary storage in order to mitigate the water deficits during summer.

For the European Alps we estimate that by the end of the century, about 1 km^3 of water from presently glacierized surfaces could be seasonally reallocated in order to mitigate expected changes. On average, the strategy could offset up to 25% of the changes in summer runoff from presently glacierized surfaces. A first order approach suggests, moreover, that the retention volume potentially available in the areas becoming deglacierized is in excess of the volume required for achieving the maximal possible mitigation by more than one order of magnitude.

Glacial lake outbursts flow reconstruction in the Northern Tien Shan: implications for hazard assessment

Juan Ballesteros Cánovas

The Universities of Geneva and Bern, Switzerland
Juan.Ballesteros@unige.ch

Glacier lakes outburst (GLOFs) are a major natural threat in the Kyrgyz Mountains. The understanding of its spatio-temporal occurrence and relation with glacier dynamism is essential for defining disaster risk reduction (DRR) strategies under climate change scenarios. In this communication, we present a tree-ring analyses aimed to reconstruct the past GLOFs and debris flow activity in the Aksay cone (Kyrgyz range), where both phenomena have operated during last decades.

A total of 96 trees, *Picea abies*, growing on the cone and main channel were sampled. Dating procedure was based on the assessment of growth disturbances (GD) in the tree-ring records, such as injuries, tangential rows of traumatic resin ducts (TRD) and abrupt growth changes. We also perform an aerial picture analyses to interpret both, the spatial pattern of past event at cone level as well as the glacier dynamic.

In total, 320 GD were identified suggesting 26 past events took place during the period 1877–2015. We observed a large process activity during 60’s, with major events in the cone in 1950, 1966 and 1968. The spatial analyses indicate two different spatial patterns at Aksay cone, suggesting dissimilar magnitude between GLOFs and DF, caused by rainfalls. Results here presented, represent the longest annual resolved GLOFs-DF in the region, and have key implication on the risk assessment in Ala-Archa valley, but also to in the entire Kyrgyz range (Northern Tien-Shan) and its relationship with glacier retreat.

Uncertainty in the representation of snowpack over the Alps in CMIP5 global climate models

Silvia Terzago

Institute for Atmospheric Sciences and Climate (ISAC – CNR), Turin, Italy
s.terzago@isac.cnr.it

Global Climate Models (GCM) still have too coarse spatial resolution to reproduce the small-scale variability of snowpack in orographically complex areas, nevertheless they are a unique tool to simulate past and future climate. The quantification of the uncertainties in GCM simulations is essential to critically analyze future climate change projections. In this work, we evaluate the representation of the snowpack over the Greater Alpine Region in the state-of art Global Climate Models participating in the Coupled Models Intercomparison Project phase 5 (CMIP5). We compare the spatial distribution, annual cycle and temporal variability of snow depth represented by the GCMs to the major reanalysis products, i.e. Climate Forecast System Reanalysis, Modern Era-Retrospective analysis for Research and Applications, ERA-Interim/Land, and 20th Century Reanalysis, highlighting common features and discrepancies. We explore the projected changes in snow depth for the XXI century in RCP4.5 and RCP8.5 scenarios. Our analysis shows that the spread among both the global climate models and the reanalyses is remarkable, indicating high uncertainty in the snow depth estimation. Nevertheless, GCMs are in overall agreement in indicating a strong decrease of the snow depth in the Alpine region especially in the second half of the XXI century.

Development and validation of a glacier mass balance algorithm to nest into the Canadian regional climate model

Marjorie Perroud

The University of Geneva, Switzerland
Marjorie.Perroud@unige.ch

This project aims at nesting the ensemble of glaciers of western and Arctic Canada in the Canadian Regional Climate Model (CRCM5) to assess interactions of glaciers in the climate system through atmospheric feedback mechanisms. A glacier mass balance model, initially developed to be driven by observed in-situ meteorological data, has thus been adapted and optimized to be run on pre-processed grids of different spatial resolutions covering western and northern Canada. Techniques to downscale meteorological fields to each high-resolution grid cell have been developed. Validation of the model is done by simulating glacier mass balance at three study sites in the Rocky Mountains where long series of data exist (Haig, Peyto and Place glaciers). The atmospheric data to drive and test the model are provided by CRCM5 fields, as well as by NCEP-NCAR reanalysis and NARR data. In order to account for the terrain characteristics (altitude, slope, aspect and shading) with an appropriate degree of accuracy, the simulations are performed on a 90 m resolution grid, consistent with that of the Canadian Digital Elevation Data (1:250000, Geobase). Other experiments have been conducted using coarser grid resolutions and resampling methods. A comparison of simulated and observed glacier mass balances will be shown, and results from a sensitivity test to evaluate the effects of the resolution on the total mass balance will be presented.

Impacts of climate change and reforestation on mountain water resources in Norway

Jan Magnusson

Norwegian Water Resources and Energy Directorate, Oslo, Norway
jmg@nve.no

In high latitude regions, the climate change signal is particularly strong, and will likely cause large changes to the water cycle in future. In several Nordic countries, the combined effect of a warming atmosphere and changes in land use have influenced the forest cover largely. Due to heavy grazing and timber production in the past, the tree line in Norway is now below its equilibrium and, consequently, forests are advancing rapidly to higher altitudes. Currently 45% of mainland Norway consists of mountainous regions without tall vegetation cover. In a long-term perspective, natural regeneration could increase the forested area by 16% in Norway. In this study, we will assess the combined effect of changes in climate and vegetation on the hydrological conditions. The focus regions of this study are vegetation-free areas, which in future will be covered by either low vegetation or forests. For the assessment of changes in hydrological characteristics, we will use conceptual as well as physically based hydrological models. Finally, our results intended for local to regional impact assessments will be compared to results obtained from global and continental hydrological projections, mainly obtained by land-surface models.

Glacier change and hazards in the Caucasus: present-day state and projections for the future

Dmitry Petrakov et al.

Moscow State University, Federation of Russia
dpetrakov@gmail.com

Glacier hazards in the Caucasus, highly glaciated mountains with altitude up to 5642 m asl., increase socio-economic stress in the region and result in numerous fatalities and economic losses. Glaciers in the Russian Caucasus have experienced an accelerating downwasting due to regional climate changes over the past decades. This trend could be explained by rapid increase of summer air temperature which is partially compensated by increase of cold period precipitation in the Central Caucasus. Such conditions have already resulted in predominantly negative glacier mass balance and accelerating glacier area loss, disappearing of ice apron and termini retreat overall in the Caucasus. For example, rate of Mt. Elbrus deglaciation increased 2.5 times in recent years. This is also true for the Djankuat Glacier which is benchmark for the region. It has lost 4 times more mass in 1998-2015 comparatively to 1968-1997. The observed and projected reduction in the extent of glacier ice has implications for glacier runoff and various geomorphic processes, including accelerating glacier lake formation and expansion, glacier related debris flows, ice-rock avalanches etc. We present case stories of some glacier hazards in the region with focus to Mt. Kazbek area. According to modelling glacier retreat in future will lead to formation of many glacier lakes with total volume an order of magnitude higher than present-day lake volume. Pattern of glacier hazard change is not uniform: in some valleys glacier hazard increases, whereas in other valleys glacier hazard decreases or remains quasistable.

Adaptation pathways, highlighting stakeholder driven and gender inclusive processes

Eddy Moors

Wageningen University, The Netherlands
Eddy.Moors@wur.nl

A novel decision approach under uncertainty is the exploration of adaptation pathways. Adaptation pathways are defined as sequences of policy actions to achieve targets under changing climate and societal conditions (see figure). Adaptation pathways encourage taking short-term actions to sustain the current management, while at the same time planning longer term adaptation that may be required in the future. Adaptation pathways therefore offer flexibility by allowing for progressive implementation (see e.g. Haasnoot, 2013). The presented research describes the design of sustainable adaptation pathways that enable the improvement of policies and practices to help vulnerable populations adapt to climate change. Findings on barriers and opportunities and adaptation turning points for single sectors are combined into integrated adaptation pathways. Both individual small scale practices and approaches to the design of large scale strategies at policy level are discussed. This research is part of the HImalayan Adaptation, WAter and REsilience (HI-AWARE) project which focuses its research on glacier and snowpack dependent river basins for improving livelihoods. The main objective is to develop climate change adaptation approaches and increase the resilience of the poorest and most vulnerable women, men, and children in the mountains and plains of the Hindu Kush Himalayas. Adaptation practices and policies that appear to have good potentials for out-scaling from a feasibility point of view are identified. For those practices and policies, up-scaling opportunities are explored. Barriers and opportunities for successful up-scaling of promising adaptation strategies are determined by potential benefits of the adaptation approaches.

Statistical modelling of glacier fluctuations

Antonello Provenzale

Institute of Geosciences and Earth Resources (IGG – CNR), Pisa, Italy
Antonello.Provenzale@cnr.it

The statistical analysis of longtime series of annual snout positions of several valley glaciers in the northwestern Italian Alps, together with a high-resolution gridded dataset of temperature and precipitation available for the last 50 years, is discussed. Glacier snout fluctuations are on average negative during this time span, albeit with a period of glacier advance between about 1970 and 1990. To determine which climatic variables best correlate with glacier snout fluctuations, a large set of seasonal predictors is considered, based on the available climatic dataset, and the most significant drivers are determined by a stepwise regression technique. This in-depth screening indicates that the average glacier snout fluctuations strongly respond to summer temperature and winter precipitation variations, with a delay of 5 and 10 year, respectively. Snout fluctuations display also a significant (albeit weak) response to concurrent (same year) spring temperature and precipitation conditions. When employed for out-of-sample projections, the empirical model displays high prediction skill, and it is used to estimate the average glacier response to different climate change scenarios (RCP4.5, RCP8.5, A1B), using both global and regional climate models. I also mention how statistical approaches can be used to parameterize glacier mass balances and subsequently applied to the development of Minimal Glacier Models for specific glaciers. The role of ensemble predictions and prediction uncertaineties are finally considered.

Hierarchical Bayesian space-time models for glaciological data

Nicolas Eckert

Institut national de Recherches en Sciences et Technologies pour l'Environnement et l'Agriculture (IRSTEA), St.-Martin d'Hères, France
Nicolas.Eckert@irstea.fr

Retreat of glaciers recorded in all mountain systems is one of the most iconic evidence of the current global warming. Yet, the rigorous extraction of a temporal signal from glaciological data remains a difficult problem. Recently, Hierarchical Bayesian modelling has become a popular option for inferring a climatic trend from a set of partially correlated time series. It allows acknowledging the non-linear nature of their response to climate covariates, separating change points and long range trends from "random" annual fluctuations in a rigorous manner. The objective of this talk is to demonstrate the usefulness of this approach for the field of glaciology with application to different data sets from the French Alps that document the ongoing glacier retreat at different spatio-temporal resolution: the worldwide longest seasonal mass balance series from glacier de Sarennes, the end of summer snowline (EOSS) of ~40 glaciers available since around 1980 from remote sensing images, and the full series of mass balance measurements made in the French Alps (*Glacioclim* observatory). The analysis in made in a time explicit framework to let the data speak as much as possible. In a second time, consistency of the inferred temporal signal with patterns of change in predominant climate drivers is demonstrated. Straightforward extensions of the framework include i) perform the local and regional variance decomposition in one single step, and ii) enlarge the modelling to composite glaciological data (mass balances, EOSS, front positions and moraine positions) taking advantages of the strength of each of them.

Estimating uncertainties in mountain glacier mass balance

Delphine Six

Laboratory of Glaciology, University of Grenoble, France
delphine.six@ujf-grenoble.fr

The surface mass balance of mountain glaciers is a crucial indicator of climate change. Understanding the surface mass balance sensitivity is required to calibrate/validate numerical models used to simulate the past and future evolutions of glaciers. In previous studies, numerous models have been developed to simulate the melt rates at the glacier surface, from empirical/statistical approaches using temperature only, to physically-based approaches including all the energy fluxes at the glacier surface. However, from numerical modelling experiments, our analysis reveals that the uncertainties in the simulated annual mass balance are largely dependent on winter accumulation uncertainties (Reveillet and others, in preparation). For this reason, new observations and numerical modeling are needed to improve our understanding of spatial distribution of winter accumulation. The climate warming is affecting the ice/rock interface temperature of hanging glaciers and could lead to avalanching glacier instabilities on steep slopes in the future (Gilbert and others, 2015). Some of these hanging glaciers could threaten the populated region below. Consequently, indicators of instabilities are needed to prevent from disasters. The risk induced by this glacier hazard is high for the populated region below and makes observation and modeling of such glaciers a priority.

Sensitivity of glacier energy balance to meteorological variability

Shawn Marshall

University of Calgary, Canada
Shawn.Marshall@ucalgary.ca

The surface energy balance processes that govern glacier melt are well understood. When local meteorological data and radiative fluxes are available (e.g., through in situ or proximal weather stations), the surface energy balance can be modelled well at a point, or for an individual glacier. However, distributed melt models using surface energy balance are notoriously difficult to implement at regional to global scales, because of the complexities of predicting meteorological fields at km-scale resolution in mountain environments. Climate models that are used for historical reanalyses or future projections simply don't resolve the topographic features, elevations, and surface conditions where glaciers reside. For this reason, most regional- to global-scale assessments of glacier response to climate change use simplified melt models, such as the temperature index approach. This is justified because temperature is more reliably interpolated over the terrain than other meteorological fields such as winds, cloud cover, and humidity. On the other hand, temperature index models are missing some important processes. For instance, they are insensitive to changes in cloud cover, which strongly modulate incoming shortwave and longwave radiation, the primary drivers of glacier melt. Moreover, melt is modelled through empirical melt factors that do not directly represent surface albedo or its evolution through the melt season. I present a surface energy balance perturbation approach that aims to overcome some of these limitations and provide an approach to distributed glacier mass balance modelling. Initial results at Haig Glacier in the Canadian Rockies indicate the sensitivity of summer melt extent to different meteorological variables and how this changes in the future.

Elevation-dependent warming in the Tibetan Plateau-Himalayas from CMIP5 models

Elisa Palazzi

Institute for Atmospheric Sciences and Climate (ISAC – CNR), Turin, Italy
e.palazzi@isac.cnr.it

We use the output of 27 Global Climate Models (GCMs) participating in the Coupled Model Intercomparison Project phase 5 (CMIP5) to investigate Elevation Dependent Warming (EDW) in the Tibetan Plateau/Himalayas in historical simulations and in future projections. The model data indicate enhanced warming with elevation in the past and an intensification of the EDW in the future decades under the high-range IPCC emission scenario RCP8.5, particularly for the minimum temperature in the cold season and for the maximum temperature in the warm season, which corroborates previous observational and model studies. However, our study suggests that the relationship between warming rates and the elevation is not linear. Two clearly distinct regimes emerge such that regions with temperatures below the freezing point show a much stronger warming than regions above, suggesting that the phase of water and/or the presence of snow play a key role. This bimodal response is very robust and it is captured by the multi-model mean as well as by all individual GCMs. The mechanisms for enhanced warming trends with elevation are investigated using a regression model which incorporates five predictors, associated with the variables that are expected to be important for the EDW: surface downwelling longwave radiation, surface downwelling shortwave radiation, near-surface specific humidity, albedo, and

orography. The albedo emerges as one variable playing a significant role, in some case more important than, in other comparable to downward longwave radiation and specific humidity that previous studies indicated as leading mechanisms for the EDW in the Tibetan Plateau region.

Proliferation of Himalayan hydropower projects increases uncertainties about exposure to glacial lake outburst floods

Markus Stoffel

The Universities of Geneva and Bern, Switzerland
Markus.Stoffel@unige.ch

The Himalaya's abundant water resources attract a growing number of hydroelectric power projects (HPP) to satisfy Asia's soaring energy demands. Ongoing construction and plans for new HPP in steep, glacier-fed mountain rivers face the hazard of glacial lake outburst floods (GLOFs) that damage hydropower infrastructure, distort water and sediment fluxes, and compromise livelihoods downstream. Appraisals of GLOF hazards remain limited to few case studies, underlining the need for a more comprehensive, systematic study. We answer to this need and use flood propagation modelling to estimate the regional exposure of Himalayan hydropower to GLOFs from >2,300 glacial lakes as potential sources. We find that 66% of HPP are on potential GLOF tracks. Up to one third of these HPP could experience GLOF discharges well above the local design floods. Plans for new HPP increasingly favor higher sites closer to glacial lakes. Sparse data on potential outburst volumes and dam-break rates in these headwaters complicate GLOF predictions, and effectively double the uncertainty about estimated peak discharges, compared to downstream reaches where simulated GLOF waves rapidly attenuate. Climate-change scenarios predicting more and larger glacial lakes thus call for a more integrative view of GLOF hazards to ensure the sustainable deployment of Himalayan hydropower.

Modelling ablation on high elevation glaciers in the semi-arid central Andes of Chili

Benjamin Brock

Northumbria University, Newcastle-upon-Tyne, United Kingdom
benjamin.brock@northumbria.ac.uk

Glaciers in the high Andes of central Chile are a vital source of dry season runoff for the populous Central Valley, but scientific studies have been limited due to difficulty of access. To improve understanding of the meteorological drivers of ablation on these glaciers, automatic weather stations (AWS) and ablation measurements have been maintained at two glaciers in the upper Olivares Valley, 50 km northeast of Santiago, since November 2012. This presentation provides an overview of typical meteorological conditions and describes the development of a new energy balance model which is used to calculate glacier melt and sublimation rates. Radiation fluxes are calculated directly from corrected radiometer measurements, while the turbulent fluxes are evaluated using the stability-adjusted bulk aerodynamic method. The model employs an iterative procedure to estimate the surface temperature through surface energy budget closure. Summer ablation is dominated by high

melt rates of on average 21-25 mm d^{-1}, with average daily melt:sublimation ratios of 28:1 during December-March. Sublimation remains low year-round, with average values of 0.8 mm d^{-1} in summer and 1.6 mm d^{-1} in winter, due to relatively low wind speeds. Shortwave radiation is the dominant source of ablation energy, while the net sensible heat flux is small due to sign reversal between day and night. Total summer ablation is between 2.5 and 3.0 m indicating that these glaciers are productive sources of freshwater, but in a state of unsustainable negative mass balance.

Glaciers- and permafrost-related hazard in Aosta Valley: evolution and monitoring

Marco Vagliasindi

Fandazione Montagna Sicura, Courmayeur, Italy
mvagliasindi@fondms.org

Glaciers- and permafrost-related risk represent a concern in civil protection and land-use planning in mountain areas. Glaciers dynamics can trigger destructive processes, such as ice avalanches, floods and debris flows. Permafrost evolution due to recent warming can also result in instability processes. Forecasting of instabilities is usually difficult due to a poor knowledge of processes and remote location of glaciers and uncertainty is enhanced by changes in climate. Aosta Valley (NW Alps, Italy) is a highly glaciarized region, since more than 50% of the territory is above 2000 m asl. About 200 glaciers are inventoried, covering 135 km2 (5% of the territory). Wide areas are also likely subject to permafrost. Settlements and infrastructures reach high-mountain environment, mainly because of tourism development. Hence, glaciers dynamics can affect settlements, thus generating risk. Regional Governement, by means of Fondazione Montagna sicura, set up a Glaciers-related Risk Monitoring Plan (GRMP), in order to inventory glaciers hazards, detect new hazards arising from glaciers evolution and survey cases involving risk. GRMP matches an historical analysis of past instability events with a geomorphologic analysis of the present glaciers state. Potential runoff areas have been evaluated and crossed with vulnerabilities, to select dangerous glaciers. A photographic survey is carried out every year to evaluate glaciers evolution and detect potential arise of new hazards. If a risk is detected, specific surveys and monitoring systems are set up. Assessment of potential instabilities related to permafrost evolution has also been done.

Rain-on-snow events in Switzerland: observations and projections for a warmer climate

Enrique Morán Tejeda

University of the Balearic Islands, Palma de Mallorca, Spain
e.moran@uib.eu

Rain-on-snow events (*ROS*) are hydro-meteorological phenomena over snow-covered regions that may have serious implications during the melting period, including intense floods. Fortunately, most *ROS* events do not have catastrophic consequences, although they remain interesting phenomena in hydro-climatic and geographic terms. In a country where snow plays a relevant economic and environmental role, such as Switzerland, our study focuses on the climatology of conditions for *ROS* to occur, during the past decades and

for a future warmer climate under A1B greenhouse gas emissions. Changes in the frequency of *ROS* events are determined by trade-off between the duration of snowpack and the amount of precipitation that falls as rain, both of which are highly affected by temperature. The main questions we aim to answer are which of the two factors have and will have a prevalence on *ROS* occurrence, and consequently what are the most plausible trends in *ROS* in the future climate over Switzerland. The results indicate that *ROS* events occur mainly during winter months at low elevations, and during summer months at high elevations. The solid/liquid precipitation ratio and the duration of the snowpack explain the spatio-temporal characteristics of *ROS* events. Observations indicate a trend for slightly fewer *ROS* events during the study period (1972-2012) due to decreasing precipitation, and a reduction in snowpack duration due to warming temperatures. However, increased warming may increase the frequency of *ROS* events in future decades, especially at high elevations. At high elevations, snowpack will be present during most of the year, but liquid precipitation will become more frequent at increasingly higher elevations.

How can we overcome the inadequacies of the degree day method for estimating future snow and glacier melt?

Mario Rohrer

METEODAT, Birmensdorf, Switzerland
rohrer@meteodat.ch

Meteodat is involved - for about two decades now - in measurement and analysis of the centennial Clariden glacier mass balance measurement series and its analysis. This unique time series offers the possibility to analyze the performance of degree day methods on a decadal scale. It was shown – inter alia with Clariden mass balance data - that degree day factors cannot be considered as constant for this long-term scale. This has implications for the interpretation of estimations of future snow-cover and glacier development based on a degree day factor model. It is discussed how shortcomings of degree-day models may be circumvented.