Task 2.1

Task Title

Morphoclimatic controls on future hydropower production

Research Partners

Swiss National Institute of Forest, Snow and Landscape Research (WSL), Center for Climate Systems Modeling (C2SM) at ETH Zurich, Chair of Hydrology and Water Resources Management (HWRM) at ETH Zurich, Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at ETH Zurich, Laboratory of Hydraulic Constructions (LCH) at EPF Lausanne, School of Architecture, Civil and Environmental Engineering (ENAC) at EPF Lausanne

Current Projects (presented on the following pages)

Task Objectives

- To significantly reduce uncertainties related to future water and sediment supply to HP plants and, by that, provide a more secure basis to HP industry to decide on long-term investments.

Interaction Between the Partners – Synthesis

- Annual meeting of all Task 2.1 partners at ETH Zürich (on 29 June, 2016)

Highlights 2016

- Study of the overall potential of new HP dams at high-alpine locations, where glaciers retreat, to store water for mitigating water shortage in late summer. This work of WSL and VAW - published in Environ. Res. Lett. – estimates that two thirds of the climate change effect on seasonal water availability could be avoided when storing water in areas becoming ice-free.
- Significant progress in mapping Swiss glacier masses (VAW), quantifying/predicting snow water operationally at the national scale (SLF) and quantifying sediment transport at the inlet of a HP dam (WSL). All these elements will be fundamentals for the upcoming synthesis on climate change impacts on HP production (phase 2).
- The extended-range hydro meteorological forecast system (WSL) is now operational and is currently being set up for specific HP plants.
- A new space-time stochastic weather generator was developed at ETHZ enabling the generation of high-resolution climate variables for the future climate, which will be an essential input to the second phase of SCCER SoE.

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Rethinking Pumped Storage Hydropower in the European Alps

Astrid Björnsen Gurung, Axel Borsdorf, Leopold Füreder, Felix Kienast, Peter Matt, Christoph Scheidegger, Lukas Schmocker, Massimiliano Zappa, and Kathrin Volkart

Pumped storage hydropower

[Look for the red numbers in the text]

Figure 1: System view of PSHP operation with environmental, economic, and social relationships. (Diagram by Valentin Rüegg and Astrid Björnsen Gurung et al.)

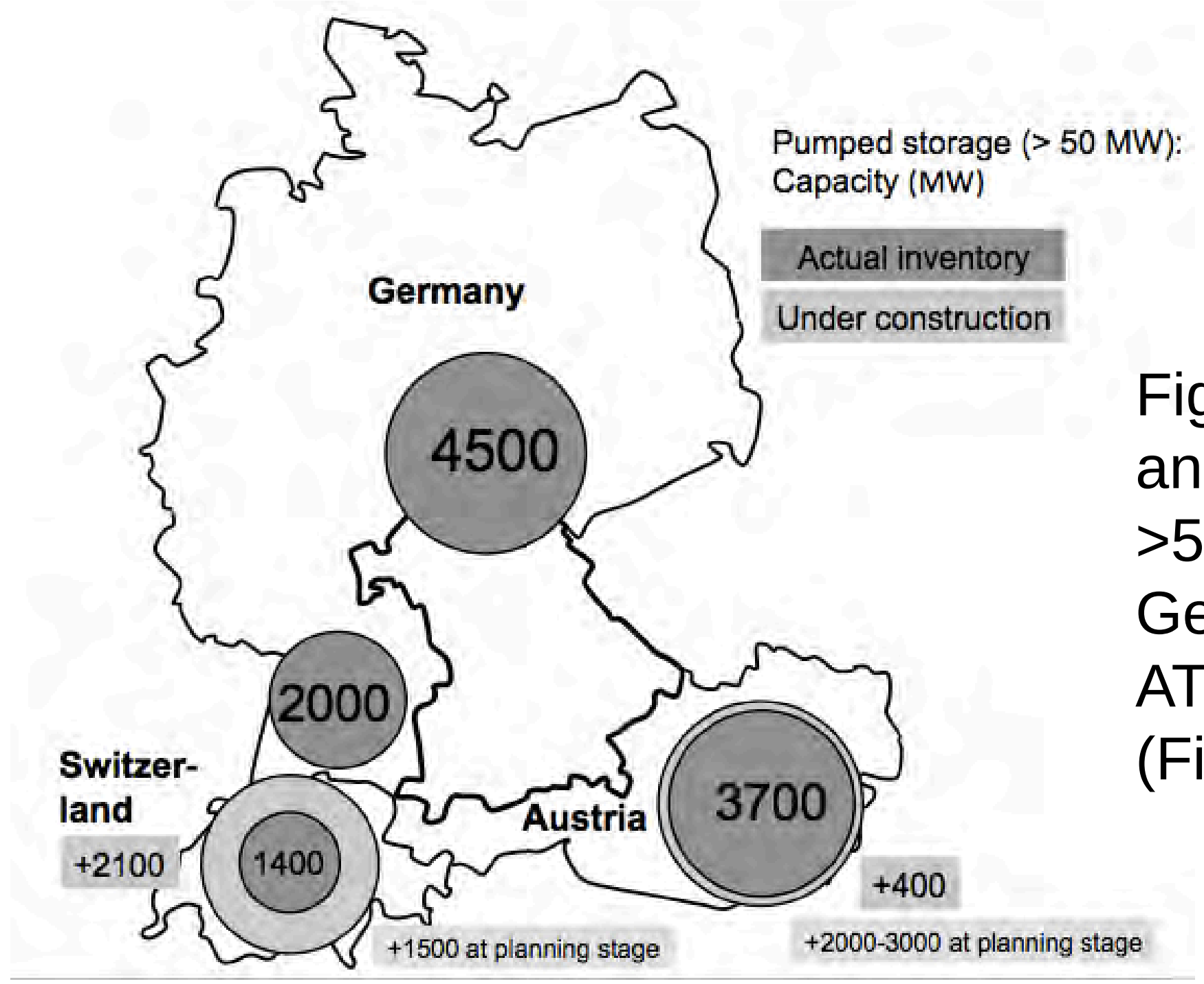

Figure 2: Actual, currently constructed and planned capacity of PSHP plants >50 MW in Switzerland, Austria and Germany. (Data CH: BFE, Piot 2014; AT and DE from PSHP operators). (Figure by M. Aufleger)

Conclusions

The present analysis has drawn from the expertise of researchers and hydropower operators from different backgrounds allowing an interdisciplinary view on PSHP. Research has a lot to contribute when it comes to alter existing management and infrastructure in favor of ecosystems and human societies. For complex systems like hydropower plants, the stimulation and production of collective knowledge with contributions from science, operators, administration and policy is imperative. In addition, it no longer suffices to investigate the impacts of the energy transition to answer the question "What will happen?" (System Knowledge). Future research needs to address the question "What do we want to happen?" or "How do we want our energy future and our way of life to look like?" (Target Knowledge). Such an approach requires the ability to find a societal consensus on where to compromise if synergies are not feasible (Transformation knowledge). An integrated assessment tool could help in this respect.

Motivation

The European Alps are well positioned to contribute significantly to the energy transition. In addition to sites with above-average potential for wind and solar power [9] , the "water towers" of Europe [1, 4, 22, 29, 33] provide flexible, low-carbon power generation as well as energy storage [7]. In the future, hydropower systems are expected to become more than mere electricity generators, serving a key role as flexible complements to intermittent power generators and as providers of large-scale seasonal and daily energy storage. Upon the decommissioning of nuclear power plants [32], the new energy systems of Switzerland and Austria will rely even more strongly on such services [Figure 2].

Energy transition on national and European scales [25,26,34] could be facilitated by expanding the capacity of pumped storage hydropower (PSHP) plants. Yet the extension of hydropower production, in particular PSHP, remains controversial, primarily due to environmental concerns [2, 8, 14, 15, 16, 19, 21, 23, 28, 30]. This poster summarizes a paper by Björnsen Gurung et al. (2016) providing a system view of hydropower production [10, 12, 13] and energy storage in the Alps. It draws on knowledge shared by researchers and practitioners during a workshop on "Sustainability Assessment for PSHP Plants in Switzerland and Austria" held in February 2015 in Bregenz, Austria.

How to support the energy transition with a system view on PSHP making the impacts on the environment, economy and society more transparent?

An assessment tool needs to be elaborated and account for:

Environmental indicators: Biodiversity [8, 16, 28], water quality [19, 20, 23], water quantity [1,4], river morphology [2, 10, 14, 21] and continuity should be valuated adequately.

Cumulative effects: The cumulated impacts of several types of power plants or impacts matter (e.g. hydropeaking [32], retained sediments [6], water temperature [20], or physical barrier for species movement [18]) and should be adequately reflected in any assessment.

Time: Reservoir volume [6, 7, 17], natural hazards [3, 4, 22, 33], hydrological regime [1] but also management and technologies change over time [3]. As they affect production, efficiency, reliability and costs of electricity [24], the sustainability assessment must take time into account.

Economic benefits: The construction and operation of power plants [27] lead to financial benefits for regional, national and international economies in varying degrees [24]. New assessment tools must make the respective share of gross value added explicit and transparent.

Multiple services and water use: Apart from electricity production [7, 12, 13], regulatory services need to be valued in the assessment. In the same vein, multiple and far-reaching economic and social benefits such as leisure [5, 11], tourism [5, 11], natural hazard prevention or water supply [29, 31] need to be weighted against environmental impacts.

Landscape: Assess visual impacts with ecological footprints [16] or with the variable 'willingness to pay' [25].

Participation: The assessment needs to stipulate processes to inform and involve local population [25] prior to the construction and during operation more strongly.

References

Björnsen Gurung A et al. 2016. Rethinking Pumped Storage Hydropower in the European Alps. Mountain Research and Development, 36(2):222-232.
Björnsen Gurung A et al. 2016. Alpine Pumpspeicherung – Quo vadis? *Wasser Energie Luft* 108(3):187-193.
Piot M. 2014. Bedeutung der Speicher- und Pumpspeicherkraftwerke für die Energiestrategie 2050 der Schweiz. Wasser Energie Luft 106(4):259-265.

Acknowledgments

This contribution was enabled by the support of the Swiss-Austrian Alliance for Mountain Research, the Swiss Federal Research Institute for Forest, Snow and Landscape Research (WSL), the Swiss Center of Competence for Energy Research "Supply of Energy," and the Vorarlberger Kraftwerke. The following experts also contributed: M. Aufleger, V. Braun, D. Farinotti, T. Grünewald, K. Jorde, P. Meier, J. Neubarth, A. Patt, C. Pfurtscheller, C. Schaffner, S. Schweizer, B. Steidl, and W. Stroppa.

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Pre- and Post-processing of Monthly Forecasts for Optimized Hydropower Production

Konrad Bogner[1], Samuel Monhart[1,2,3], Christoph Spirig[2], Mark Liniger[2] and Massimiliano Zappa[1]

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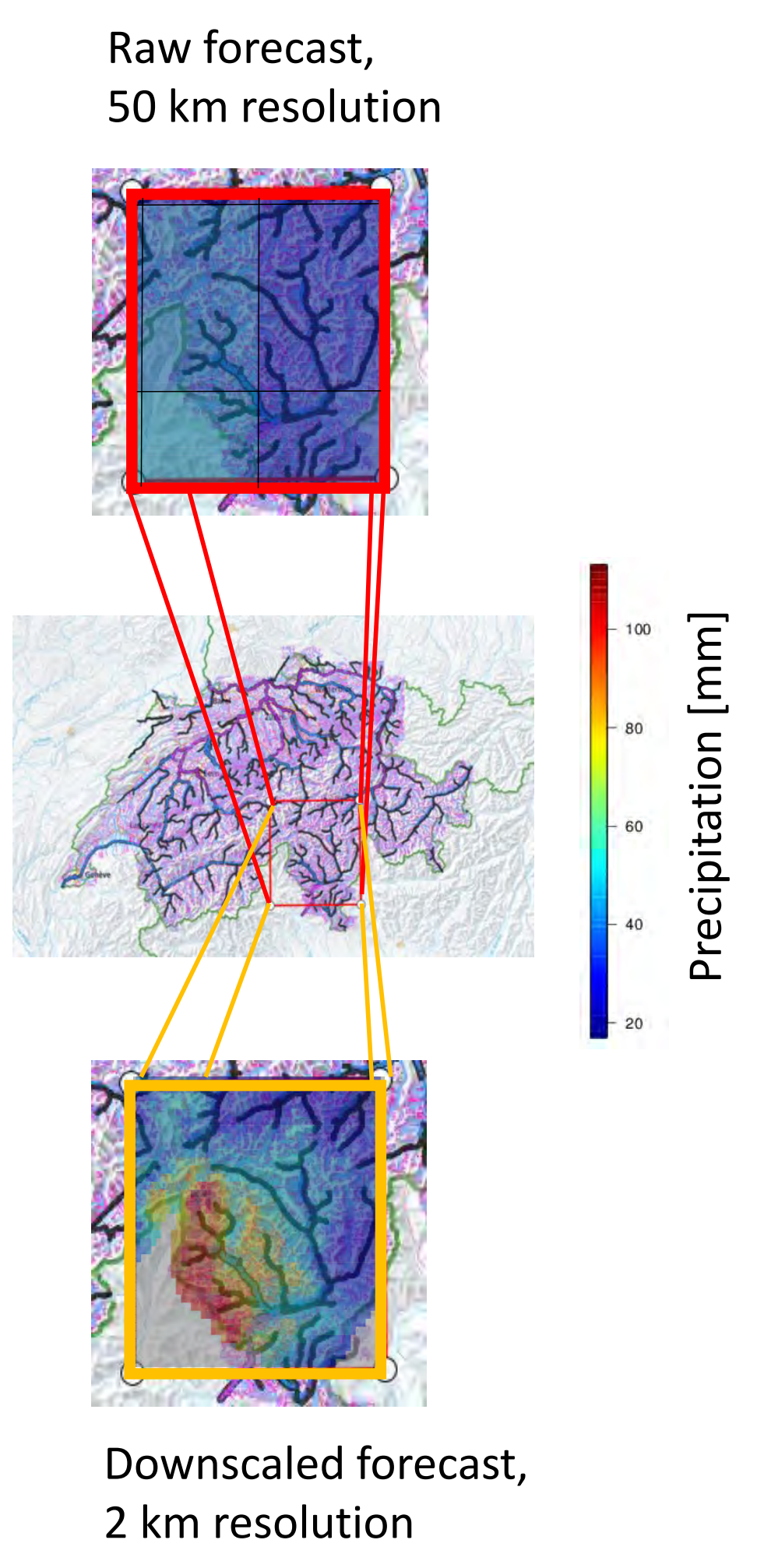
[3]ETH Zurich, Institute for Atmospheric and Climate Science, Zurich, Switzerland

Motivation

- Demonstration of the **potential of operational short to extended-range hydro- meteorological forecasts** for fine tuning the production of energy from hydropower systems through **increased intra-day to intra-week flexibility**.
- Highlighting potential benefits from **probabilistic hydro-meteorological forecasts** based on **Ensemble Prediction Systems** for the next 15 to 60 days in order to **optimize the operations and the revenues**.
- **Test case**: In quasi-operational mode the hydrological model **PREVAH** is driven by monthly weather forecasts consisting of 50 + 1 members of the **ENSemble prediction system** from ECMWF and predictions for the next 32 days ahead are calculated once per week with a spatial resolution of 200m or 500m. First results and verifications regarding statistical modifications and corrections of meteorological input data (**pre-processing**) and hydrological outputs (**post-processing**) will be presented here.

Pre-processing



Problem: Gap between meteorological and hydrological model resolutions (grid cells of 50km, resp. 500m or 200m length)

Downscaling methods: A mean debiasing and a Quantile Mapping (QM) technique have been applied to correct the forecasts.

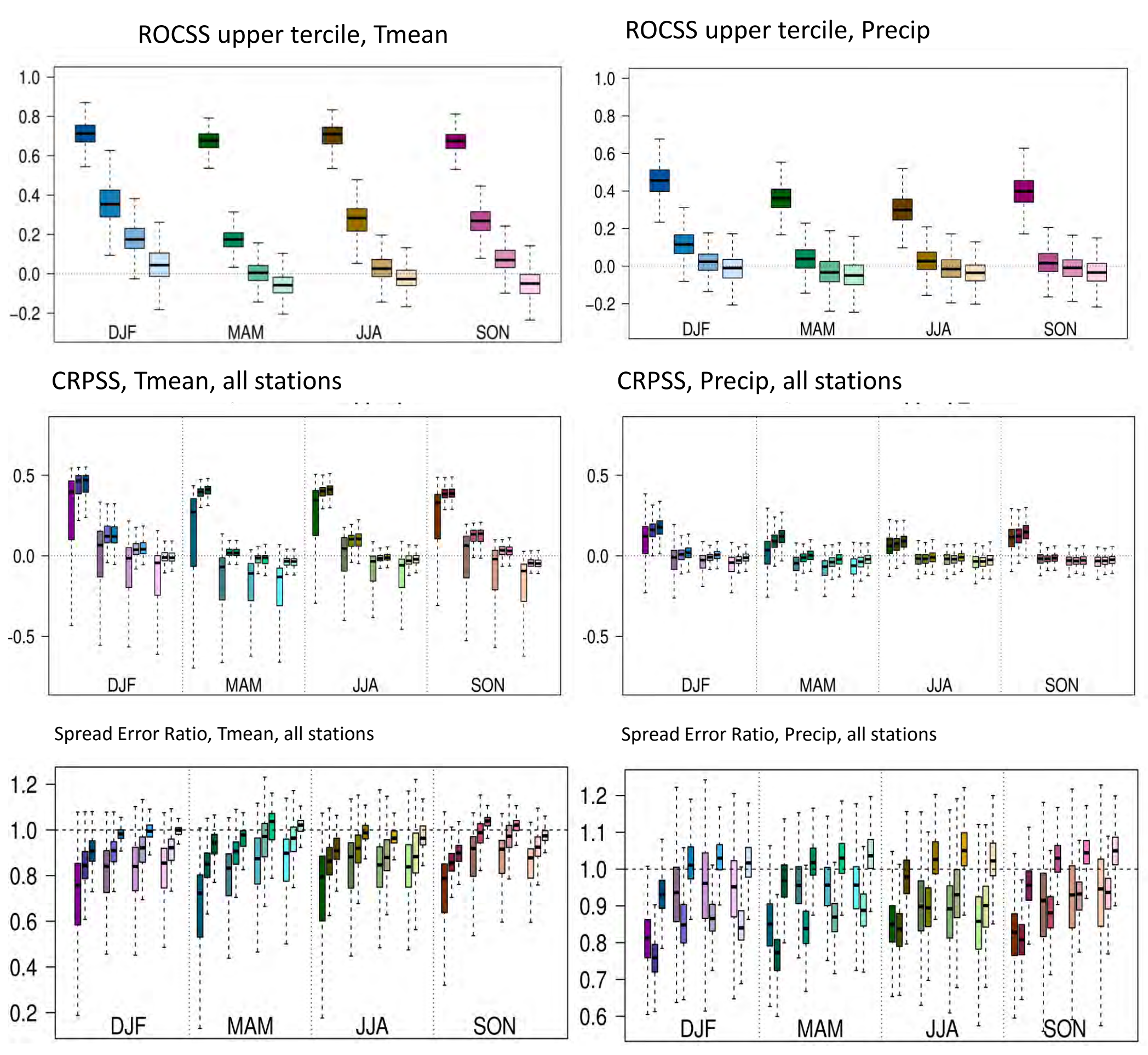
Test: Temperature and precipitation for 1000 stations across Europe.

Verification:

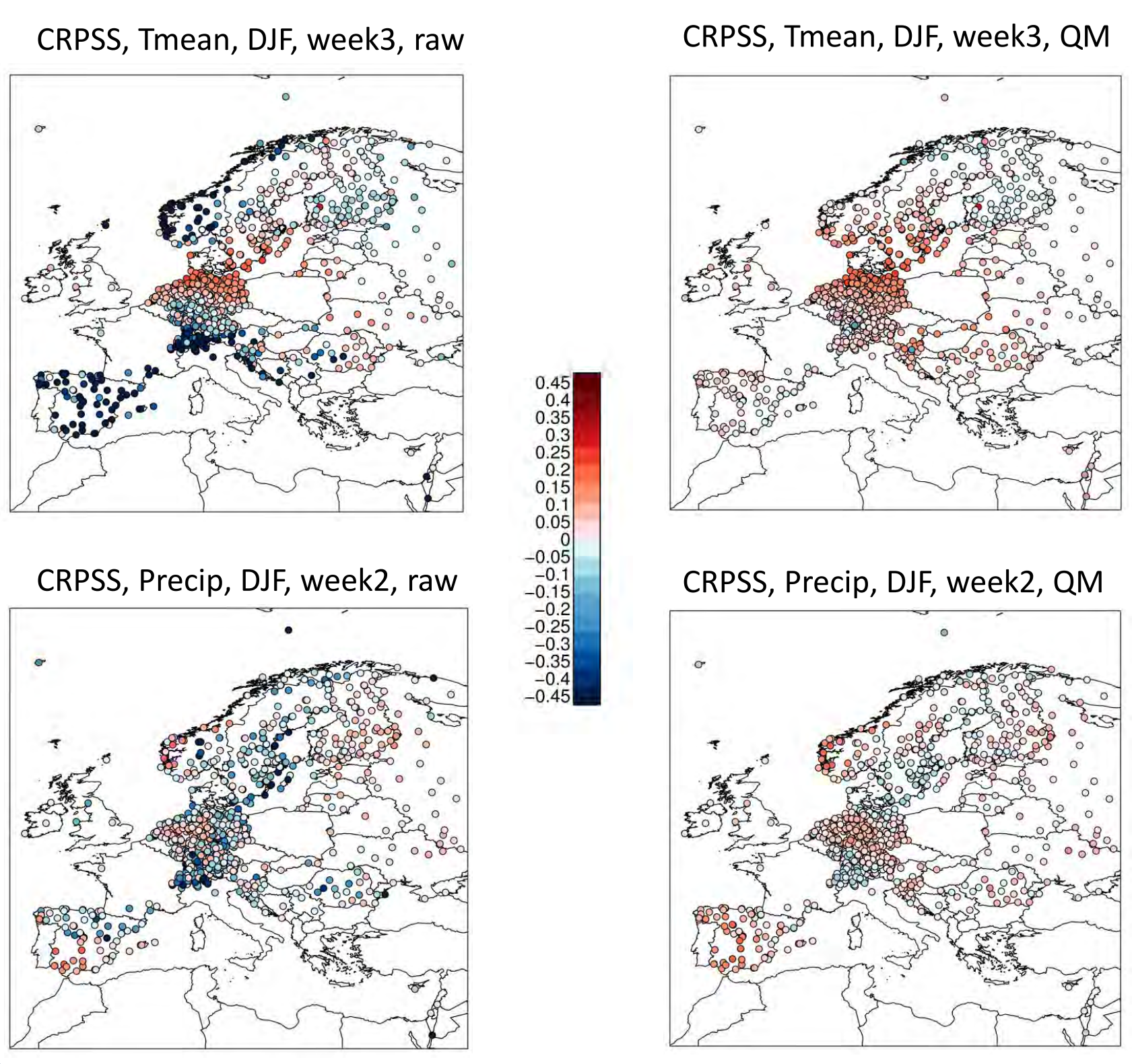
- Continuous Ranked Probability Skill Score (CRPSS), a measure for the sharpness and the reliability of the forecast.
- The Relative Operation Characteristic Skill Score (ROCSS), a measure for the discrimination of the forecast.

Furthermore, the QM approach is applied to gridded observation dataset to downscale the raw forecasts with 50km resolution to 2km resolution as hydrological pre-processing.

Results: Pre-processing



The skill of the forecasts depend on the lead time, the season and the location. The forecasts show discriminative skill (ROCSS) up to 3 weeks lead time for temperature and up to two weeks for precipitation. In terms of reliability and resolution (CRPSS) the forecast show skill up to two weeks. The QM approach outperforms the simple mean debiasing. This can be attributed to better spread correction of the QM method.

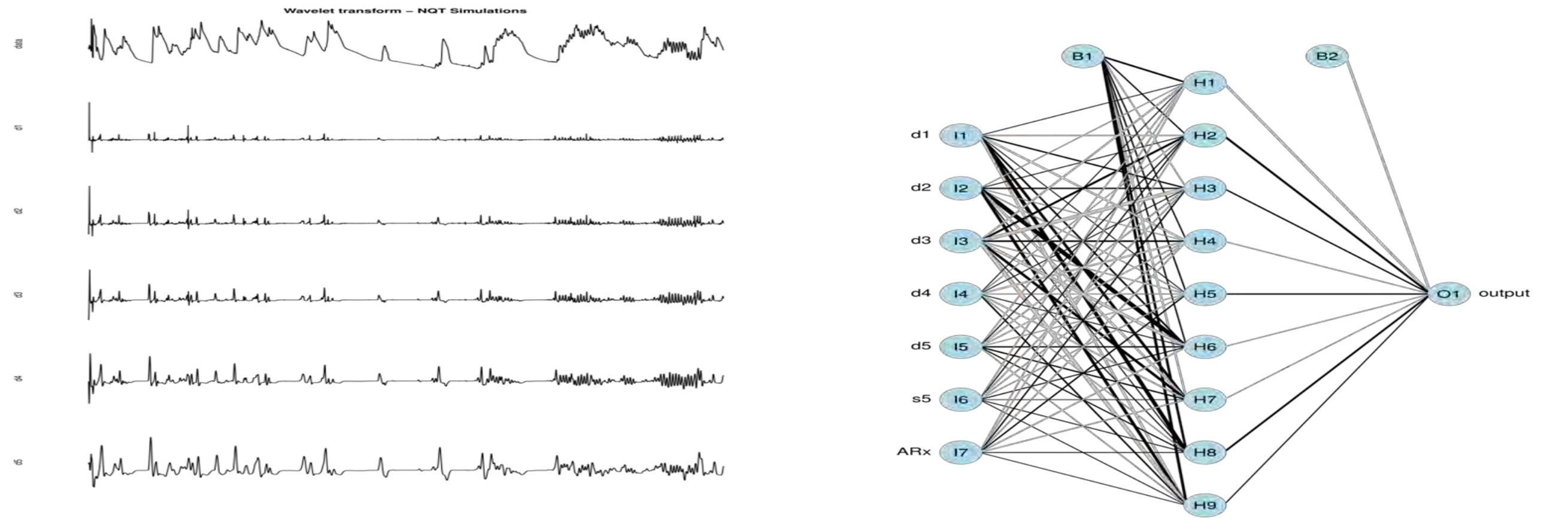


Forecasts for stations in complex terrain show lesser skill but the relative effect of the bias correction technique is larger.

Higher skill for temperature forecasts can be found in northern Europe around the Baltic Sea. This pattern is evident in all seasons but differs in strength.

Post-processing

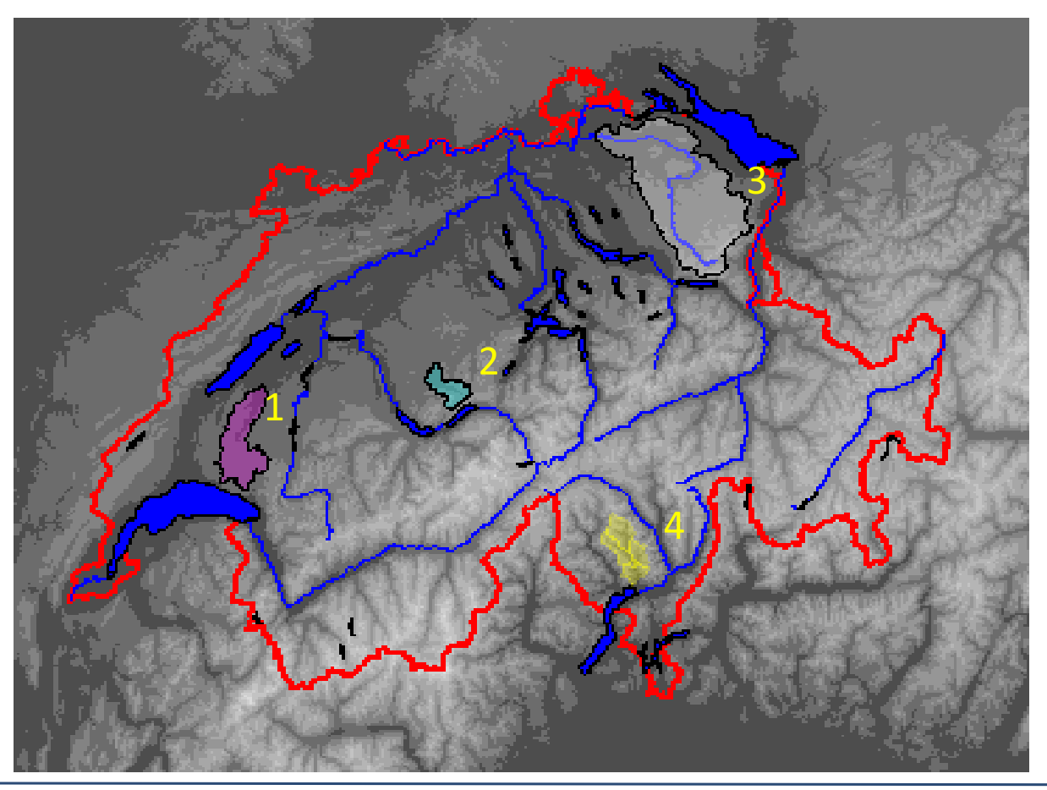
The post-processing of the outcome of the hydro-meteorological model chain is important for **improving the quality of the prediction system** and for deriving **predictive probability density functions**. Therefore different methods have been applied with varying complexity combining wavelet transformations and **Quantile Regression Neural Networks** (QRNN) and including the derivation of predictive uncertainties (Bogner et al., 2016).



Example of a Wavelet transformation of normalized stream-flows and corresponding Neural Network

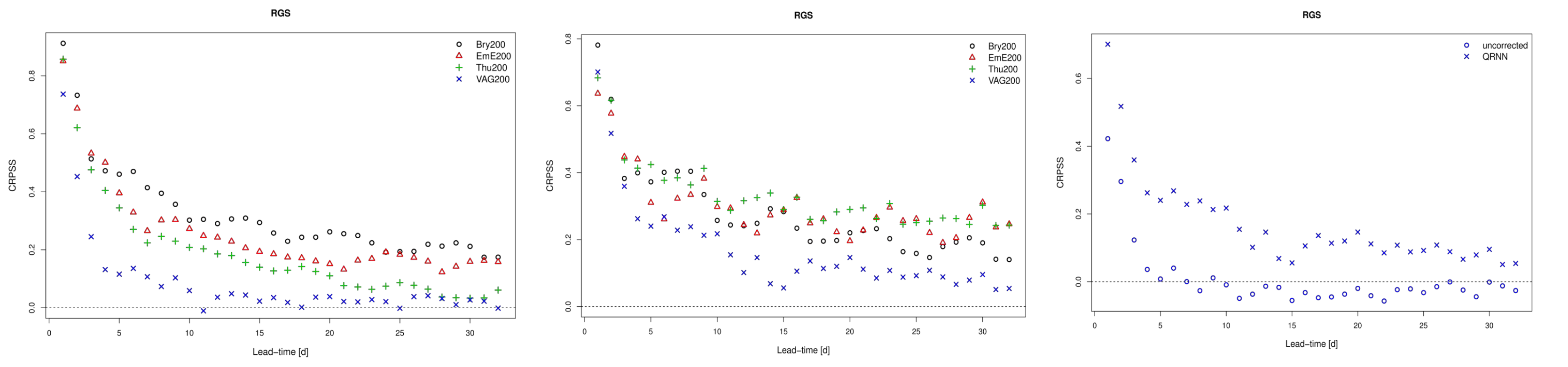
These techniques have been tested at 4 different catchments representing different geomorphological and climatological conditions with 3 years of monthly forecast.

ID	Catchment	Channel Slope [%]	Mean Altitude [m.a.s.l.]	Area [km2]
1	Broye	0.9	710	392
2	Emme	1.8	1189	124
3	Thur	0.7	770	1696
4	Verzasca	5.6	1672	392

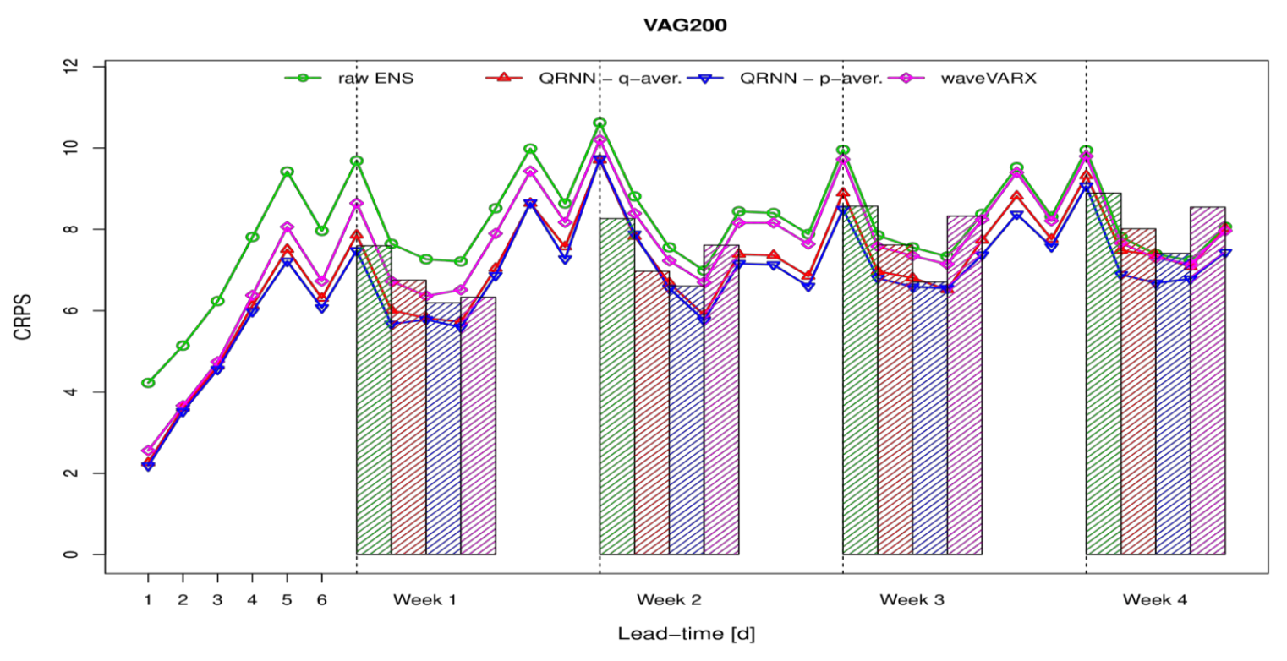


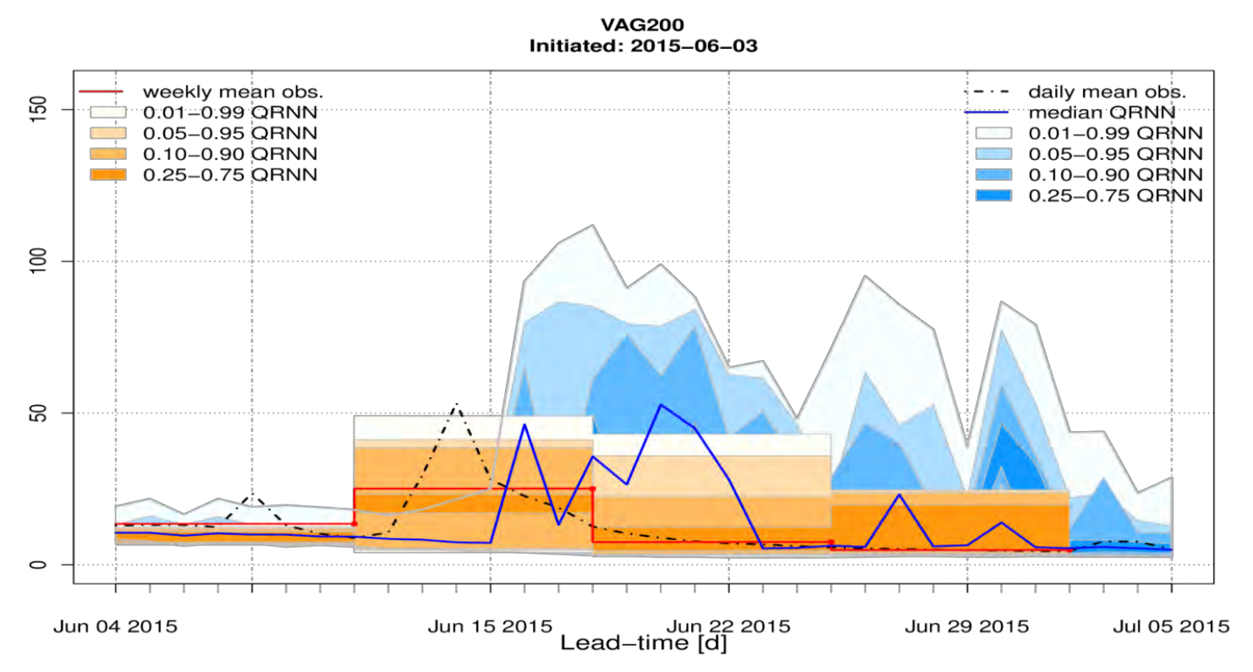
Results: Post-processing

For the verification of the quality of the hydrological forecasts different skill scores have been estimated for the four catchments. Below the CRPSS for the uncorrected ensemble is shown on the left, the QRNN corrected forecasts in the middle, and the VAG200 (on the right), demonstrating the improvements of post-processing with respect to climatological forecasts.



Besides the quality of the monthly forecasts at daily forecast horizons the weekly time aggregates will be important for certain applications as well, which have been analysed also (e.g. CRPS for VAG200 and an example of a corrected monthly forecast below showing daily and weekly aggregates)





Outlook

The upcoming step is to combine the pre- and post-processing methods in a single hydro-meteorological prediction chain. Within this setup we can analyse the effect of the pre- and post-processing steps and their combination on the monthly streamflow predictions. At next these methods will be tested at selected catchments defined by our partner from the industry, AXPO and Alpiq.

Related work:

- Farinotti, D. et al., Towards decadal runoff predictions for high-alpine catchments
- Anghileri, D. et al., Design of hydropower systems operation under current and future energy market conditions

K. Bogner, K. Liechti, and M. Zappa. Post-Processing of Stream Flows in Switzerland with an Emphasis on Low Flows and Floods. *Water*, 8(4):115, 2016.

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Generation of high resolution climate variables for hydropower studies: model calibration and validation

Nadav Peleg, Simone Fatichi, Paolo Burlando

Summary

The main objective of this project is to generate very high-resolution climate scenarios to assess the impact on hydropower production and operation along the 21st century using the state of the art global and regional climate models and greenhouse gas scenario ensemble.

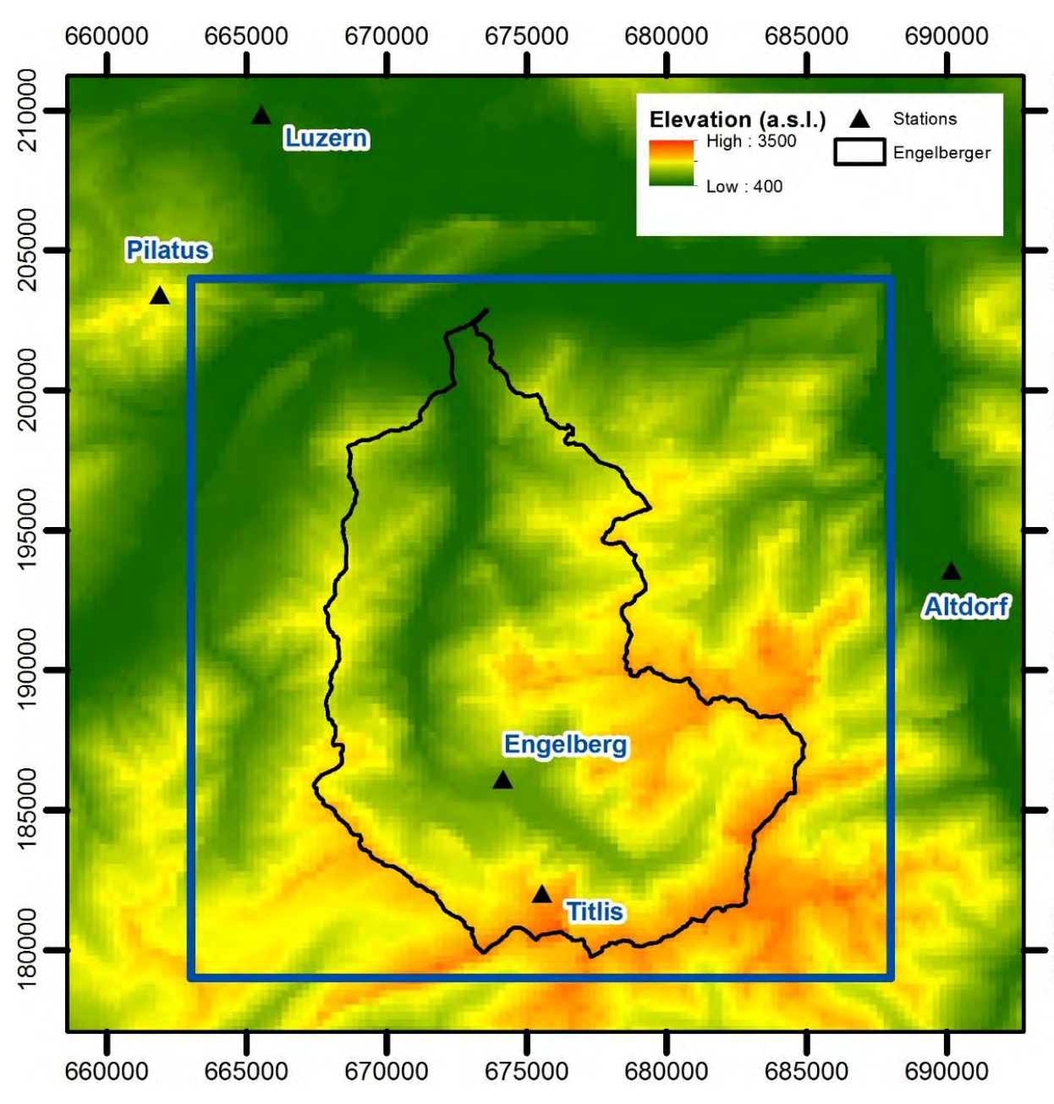
This will be done by using stochastic methods for downscaling of climate variable from regional scale to local scale, allowing to explore the uncertainties resulting from natural (stochastic) climate variability.

For this purpose, a new stochastic weather generator, **A**dvanced **WE**ather **GEN**erator for **2**-**d**imension grid (AWE-GEN-2d) was developed as part of SCCER-SoE phase 1.

AWE-GEN-2d has been developed following the philosophy of combining physical and stochastic approaches to simulate key climate variables at high spatial and temporal resolution: 2 km x 2 km and 5 min for precipitation and cloud cover and 100 m x 100 m and 1 h for near-surface temperature, solar radiation, vapor pressure, atmospheric pressure and near-surface wind.

The high-resolution climate variables reproduced by AWE-GEN-2d will serve as input to impact models addressing hydropower dynamics. Model output will be available for the SCCER-SoE partners upon request.

AWE-GEN-2d was calibrated and validated for the Engelberger catchment (right figure), a complex orography terrain in the Alps.



AWE-GEN-2d Calibration and Validation

The calibration of the different climate variables and model components requires long time series that represent the statistics of the climate variability. For this case study, AWE-GEN-2d was set to simulate the current climate (from the 1980s onward) assuming climate is stationary.

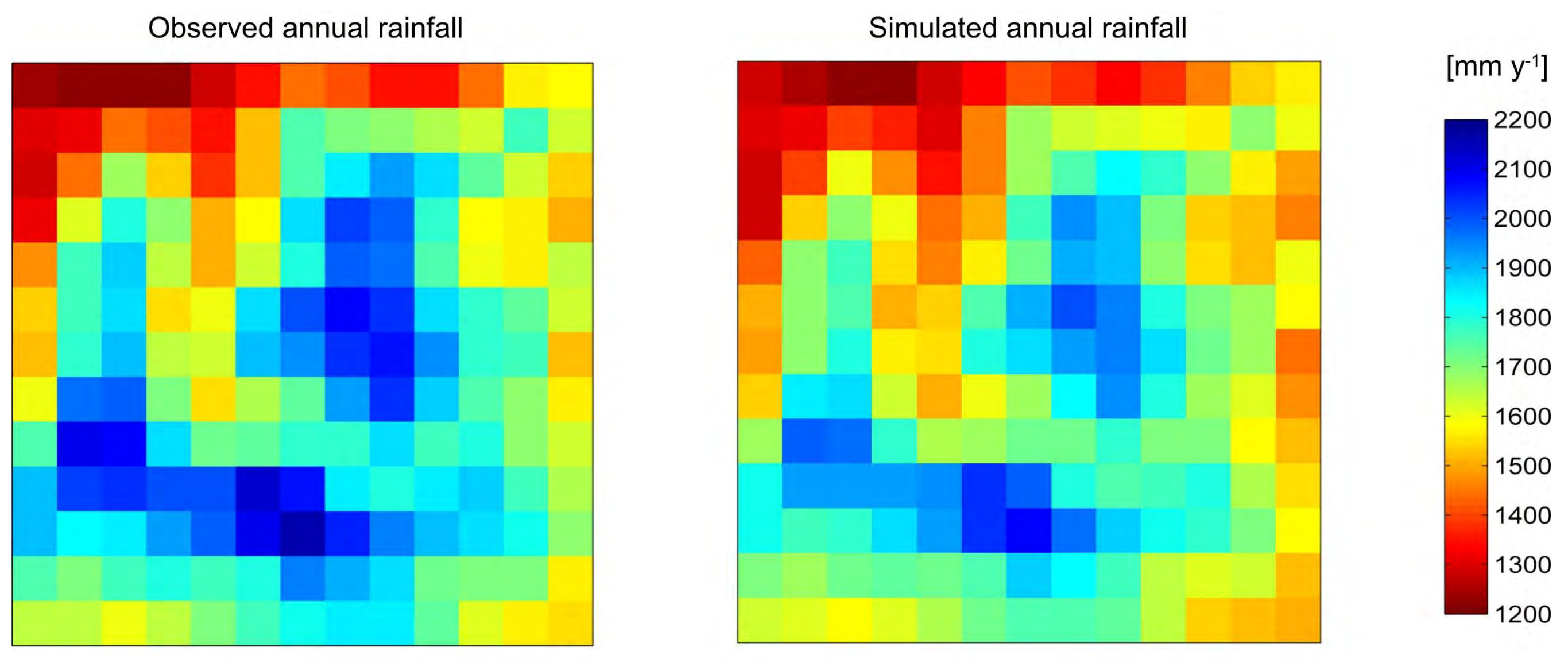
AWE-GEN-2d was tested to reproduce statistics for the above mention key climate variables. 50 stochastic realizations, each for a 30 years period, were generated using AWE-GEN-2d in order to simulate the annual and seasonal variability of the tested variables. In the following, examples for some climate variables are presented.

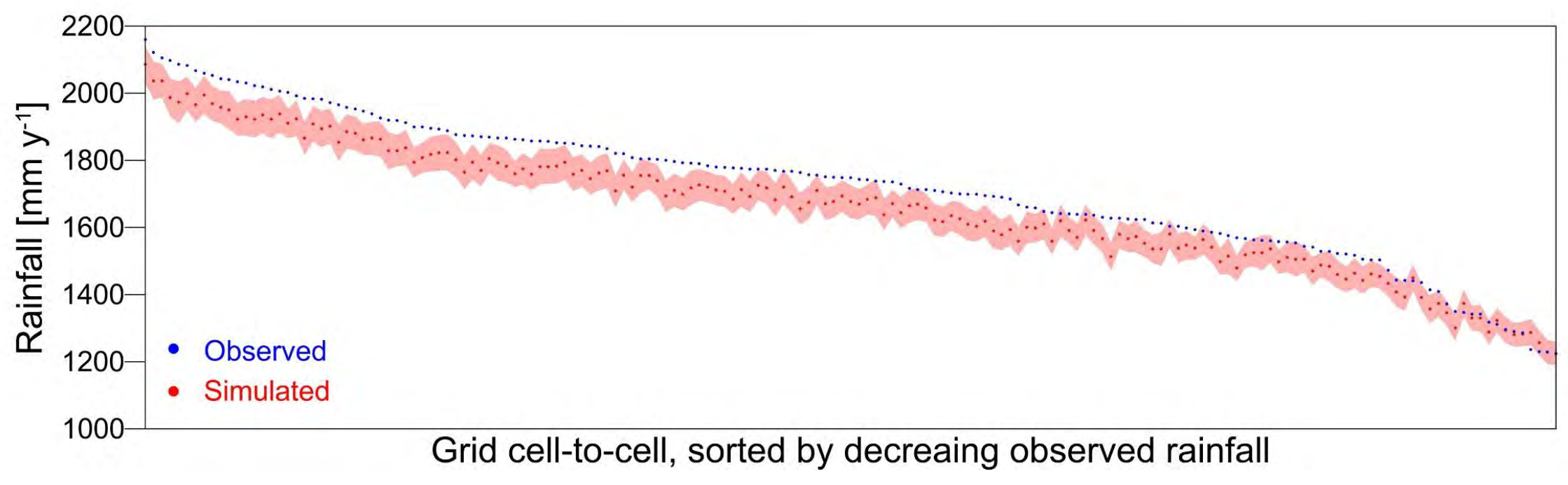
Further details regarding AWE-GEN-2d calibration and validation can be found in the referenced papers.

Precipitation

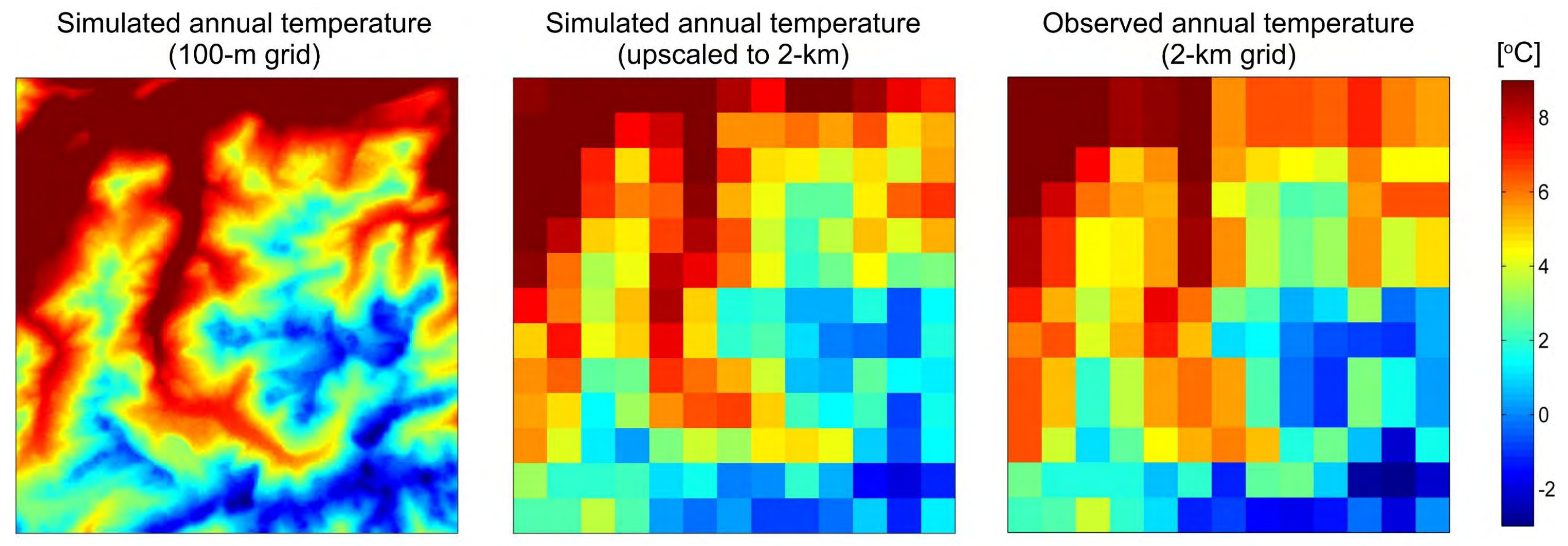
A comparison between the median observed annual rainfall (left) and the mean of the median simulated annual rainfall (right).

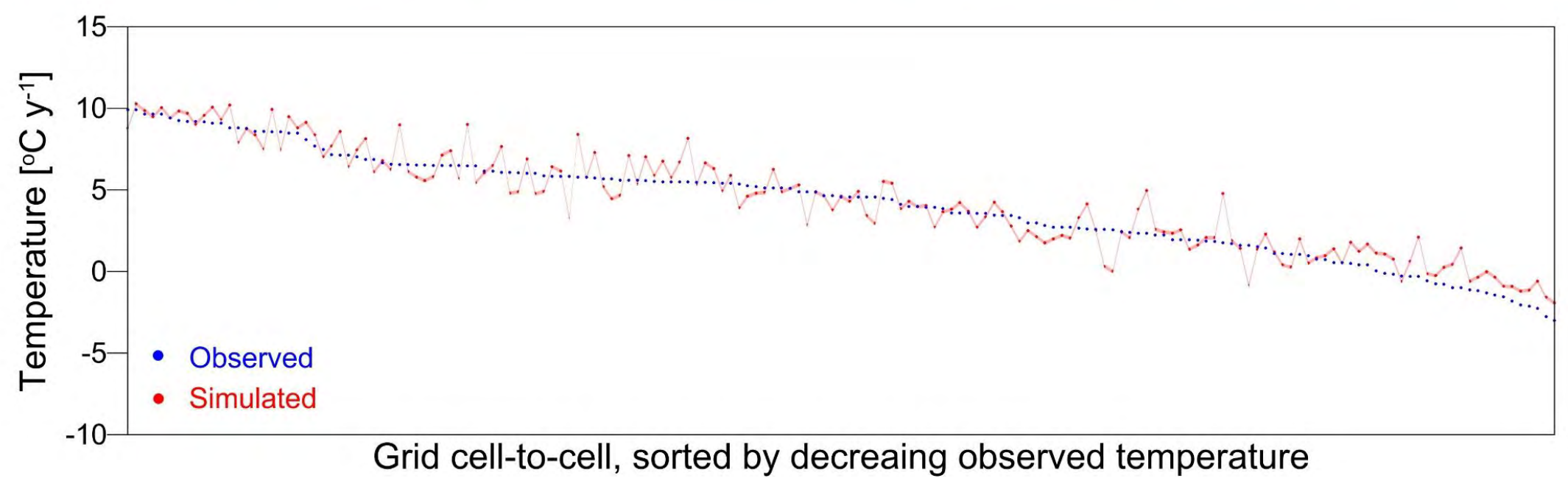
In the lower panels, a comparison is made between the observed (blue) and simulated (red) median annual rainfall for each grid cell within the domain.





Temperature

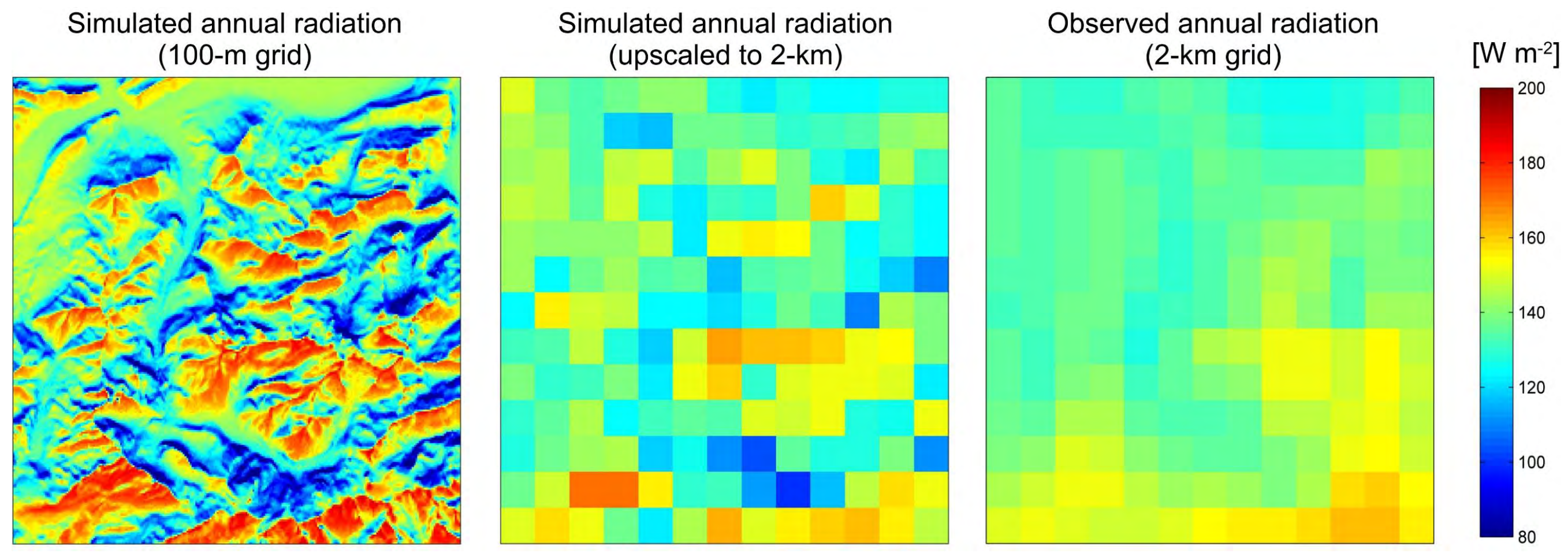




A comparison between the median observed annual temperature (right) and the mean of the median simulated annual temperature (left). The simulated grid was upscaled from 100 m resolution (left) to 2 km resolution (middle) to match the observed data.

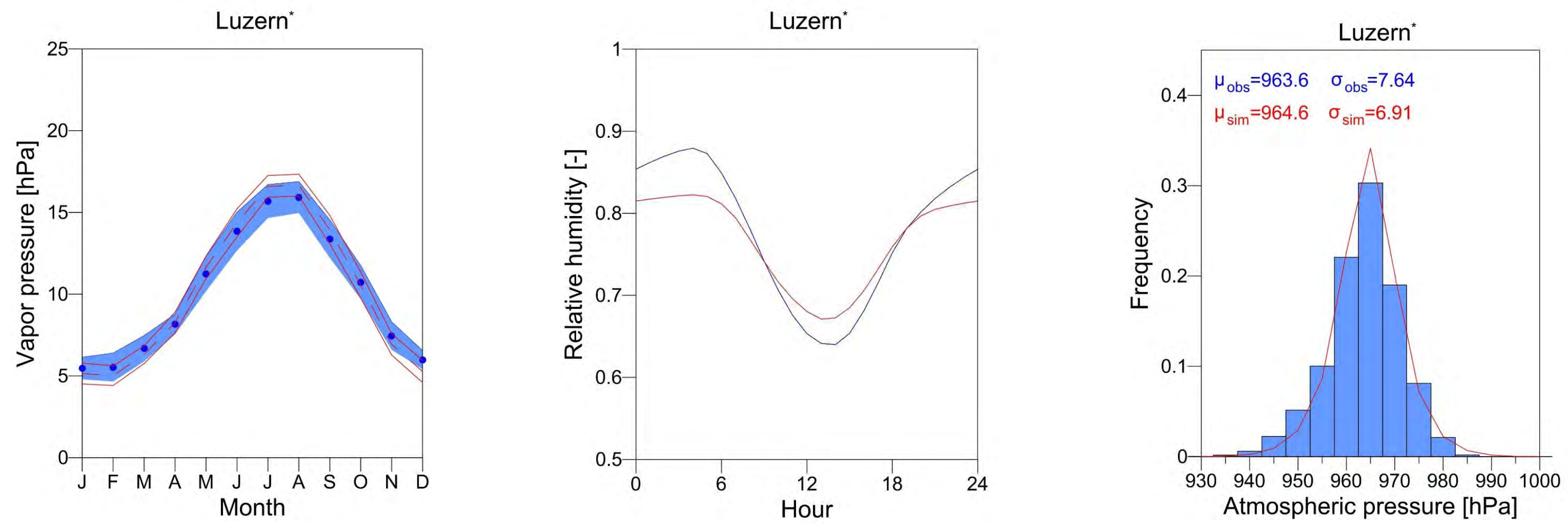
In the lower panel, a comparison is presented between the observed (blue) and simulated (red) median annual temperature for the grid cells within the domain.

Incoming Shortwave Radiation



A comparison between the mean observed annual radiation (right) and the mean of the simulated annual radiation (left). The simulated grid was upscaled from 100 m resolution (left) to 2 km resolution (middle) to match the resolution observed data.

Other Climate Variables



A comparison between observed (blue) and simulated (red) vapor pressure for every month (left), relative humidity average daily cycle (middle) and annual atmospheric pressure distribution (right) for Luzern ground station.

Outlook

Phase II

- Re-parameterizing AWE-GEN-2d for future climate projections
- Generating climate ensembles based on the latest IPCC's emission scenarios using Euro-CORDEX and CMIP5 models
- Supplying high-resolution scenarios for tasks` partners
- Analyzing the future climate scenarios to characterize the uncertainty of extreme events
- Analyzing reservoir operation sensitivity to current and future climates (with Task 2.5)

References

AWE-GEN-2d V1.0: a gridded stochastic weather generator. N. Peleg, S. Fatichi, A. Paschalis, P. Molnar, and P. Burlando. Submitted to *Geoscientific Model Development* (GMD).

AWE-GEN-2d V1.0: Technical Reference. N. Peleg, S. Fatichi, A. Paschalis, P. Molnar, and P. Burlando. GMD paper supplementary material.

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Generation of high resolution climate variables for hydropower studies: model re-parameterization for future climate

Nadav Peleg, Simone Fatichi, Paolo Burlando

Summary

The main objective of this study is to generate very high-resolution climate scenarios to assess the impact on hydropower production and operation along the 21st century using the state of the art global and regional climate models and greenhouse gas scenario ensemble.

For this purpose, a new stochastic weather generator, **A**dvanced **WE**ather **GEN**erator for **2-d**imension grid (AWE-GEN-2d) was developed as part of SCCER-SoE *phase I*. AWE-GEN-2d was calibrated and validated for the Engelberger catchment [1], a complex orography terrain in the Alps.

In *phase II*, AWE-GEN-2d will be re-parameterized for future climate projections based on the latest Intergovernmental Panel on Climate Change's (IPCC) emission scenarios (RCPs), using Euro-CORDEX and CMIP5 models. The aim is to supply high-resolution climate scenarios for SCCER-SoE tasks` partners by summer 2017.

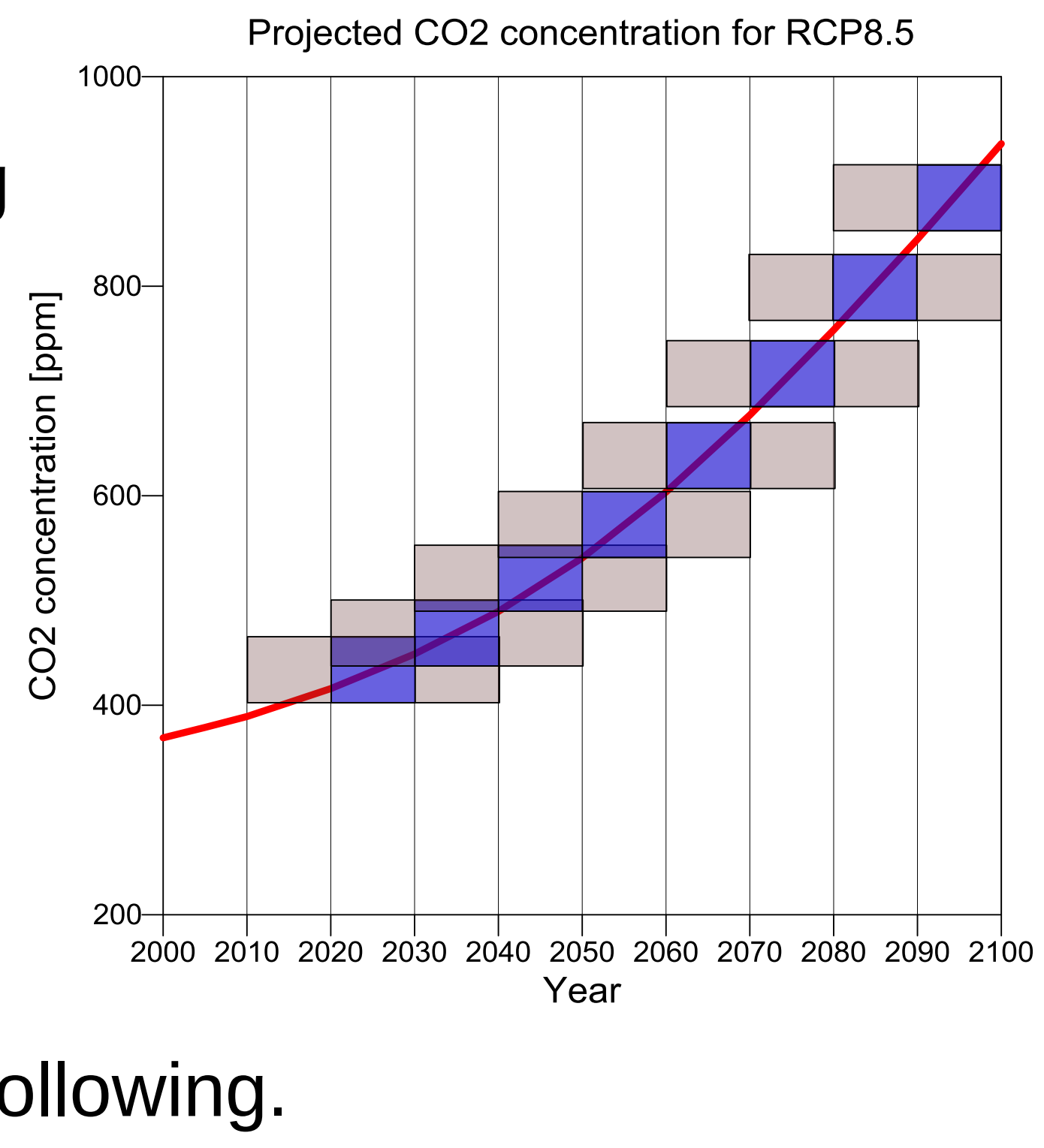
AWE-GEN-2d Re-parameterization

The method for generating future climate projections consists in re-evaluating the parameters of AWE-GEN-2d, as compared to the parameter values obtained from historical observations (HIS), using inferences from climate model outputs. The new parameter set is considered representative of the future climate.

One method is to use factors of change (FC). FC are used to quantify the projected change for several statistics of climatic variables by comparing a specific control scenario (CTS) with a specific future scenario (FUT). CTS is a period of time when both observations and climate model simulations are available, while for FUT only model simulations are available.

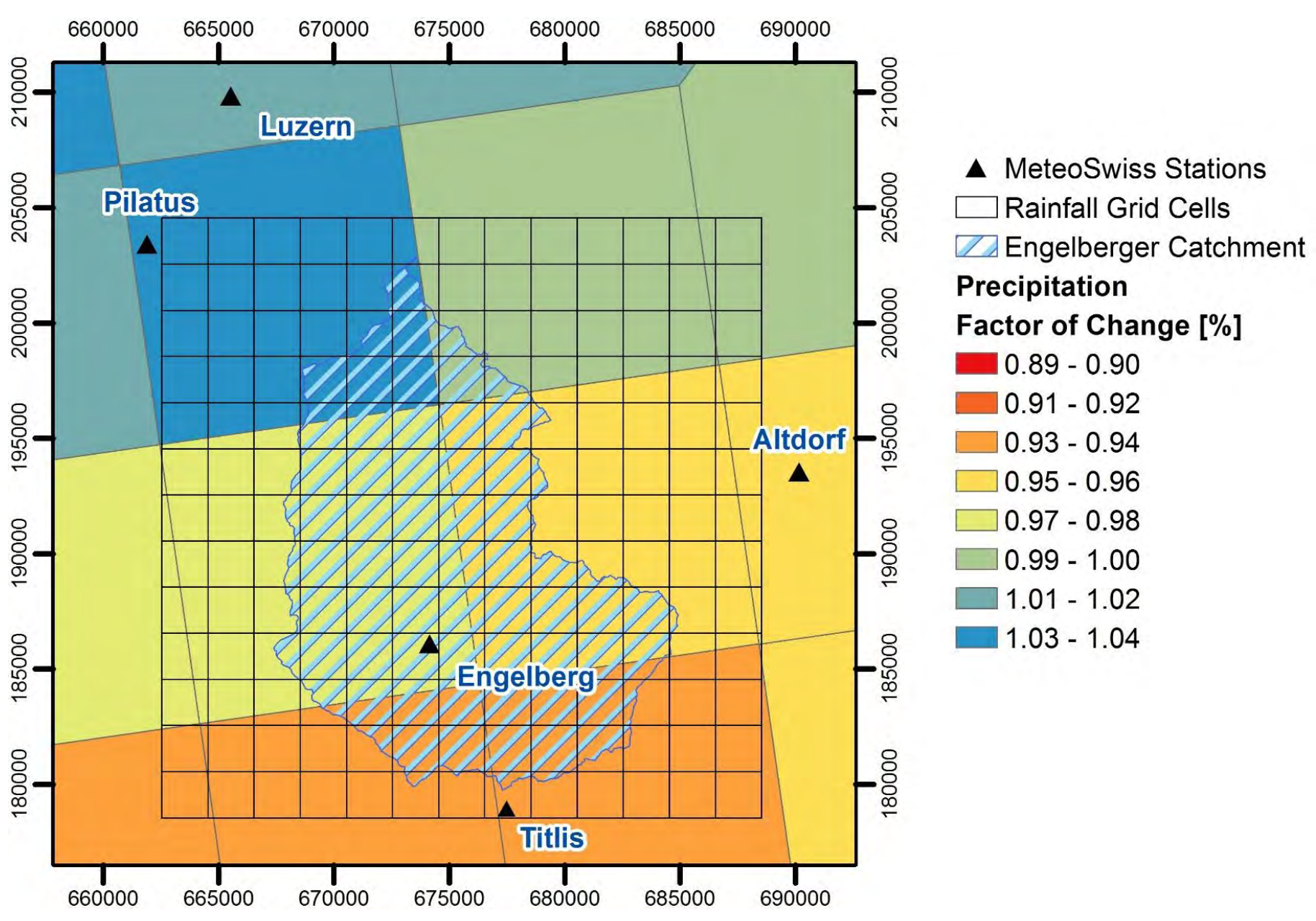
For AWE-GEN-2d, FC will be estimated only for precipitation, cloud cover and air temperature. Other simulated climate variables (e.g. incoming shortwave radiation or relative humidity) will be affected as a result of linkages with the modified climate variables. To determine the FC, a set of 16 daily regional climate models (from Euro-CORDEX project) will be used.

AWE-GEN-2d will be used to simulate the climate variables for the 21st century period (2020—2100). This will be done by applying a decadal moving window for which the statistics from the climate models will be estimated on a 30- years period basis (see figure at the right).



Besides of the FC, other methods will be applied for the regional climate model downscaling and stochastic simulations. Examples for some of the planned re-parameterization methods are given in the following.

Precipitation



An example for the estimation of precipitation FC on a grid cell basis is given in the right (from a single climate model, RCP8.5, month of June and for the period of 2036-2065).

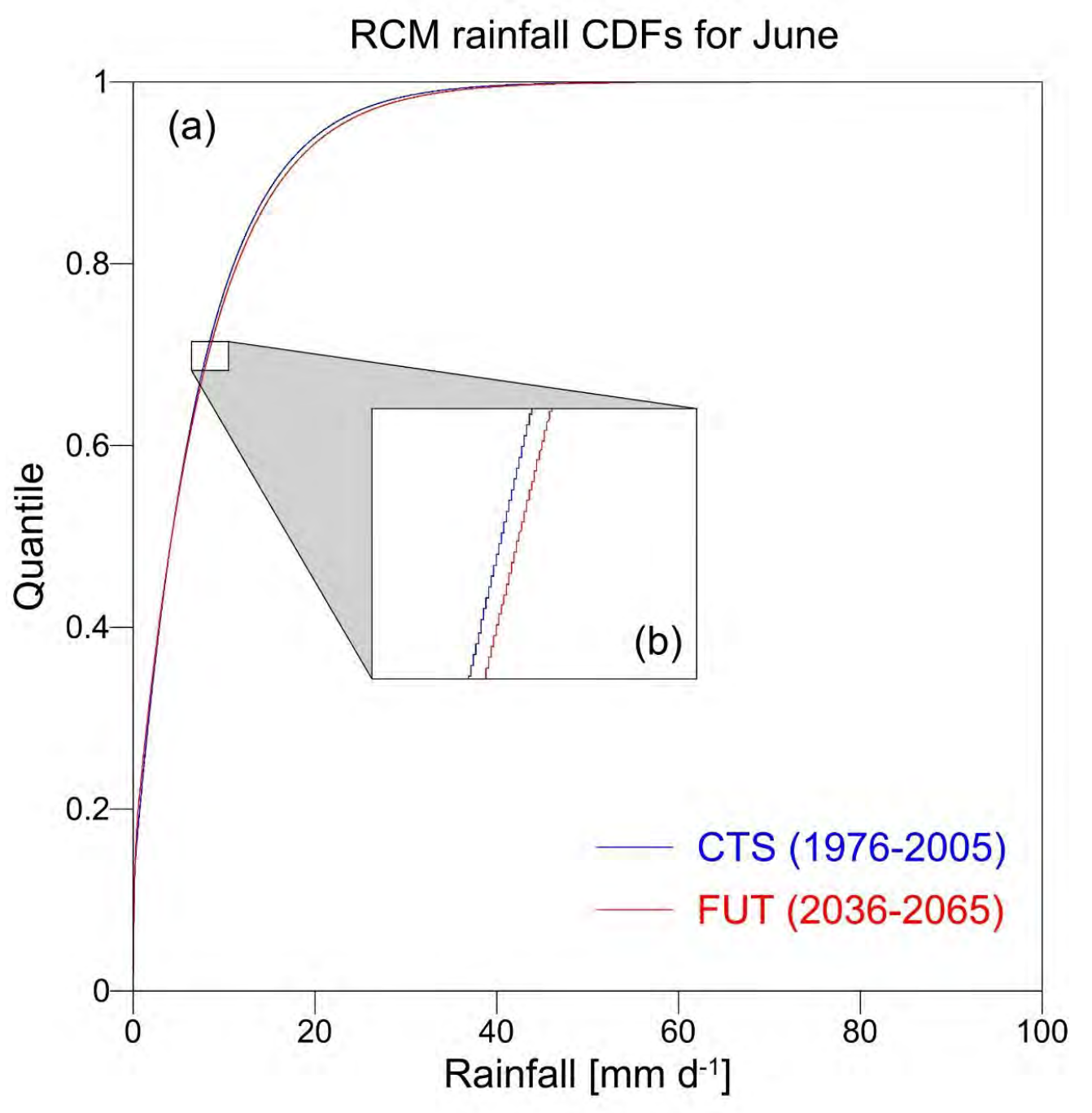
Precipitation FC is presented as FUT/CTS. This will allow to re-parameterize the observed rainfall for any given grid cell, enabling the calculations for the future rainfall occurrence and rainfall intensity filters needed by AWE-GEN-2d and the estimation of the future storm arrival process.

Re-evaluating Rainfall Intensity

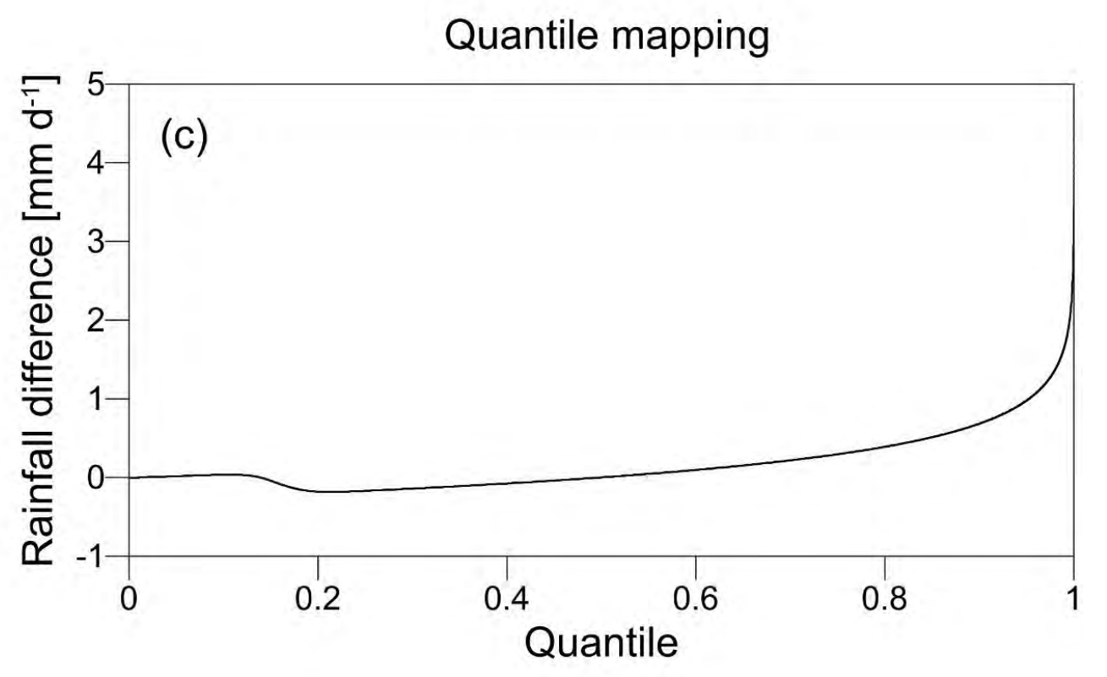
In additional to the FC method, a quantile mapping (QM) method will be applied to re-parameterize rainfall intensities.

An example for the re-evaluation of daily series of rainfall using QM over a single grid cell is presented in the following figs.

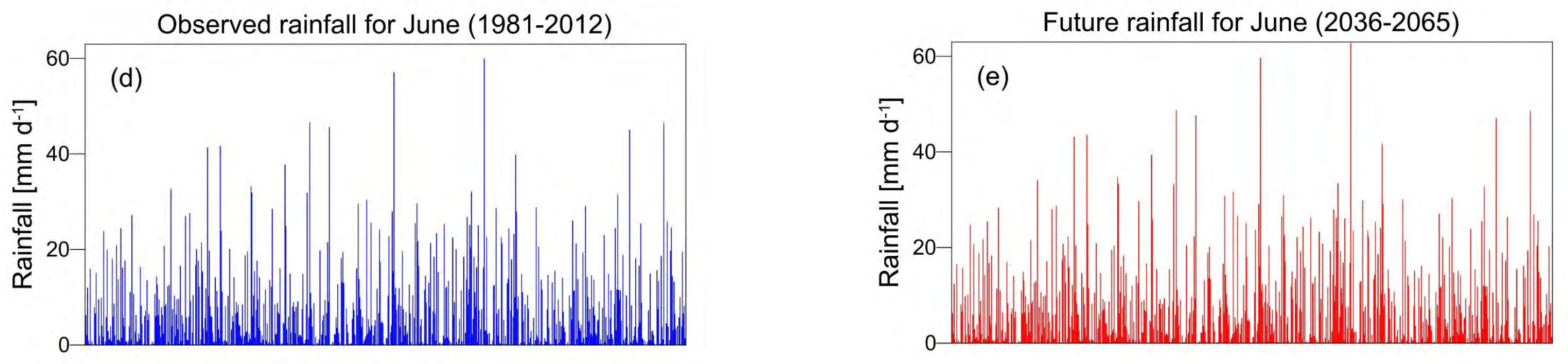
First the quantile difference between CTS and FUT is calculated for each climate model and for every grid cell (a and b).



Than QM is applied (c) to estimate the required correction to HIS.



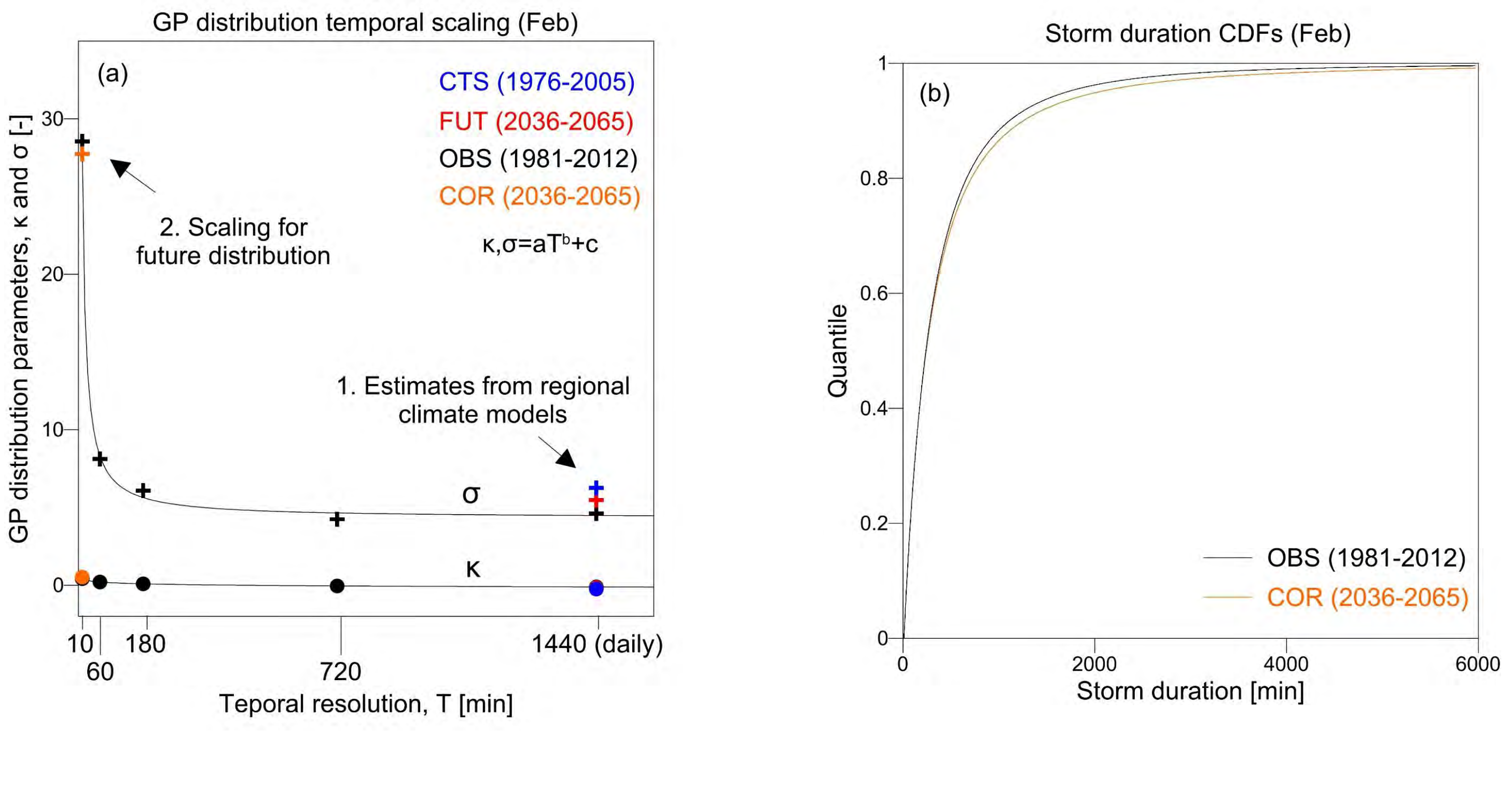
The observed daily rainfall time series (d) will be corrected to represent the future rainfall amounts (e).



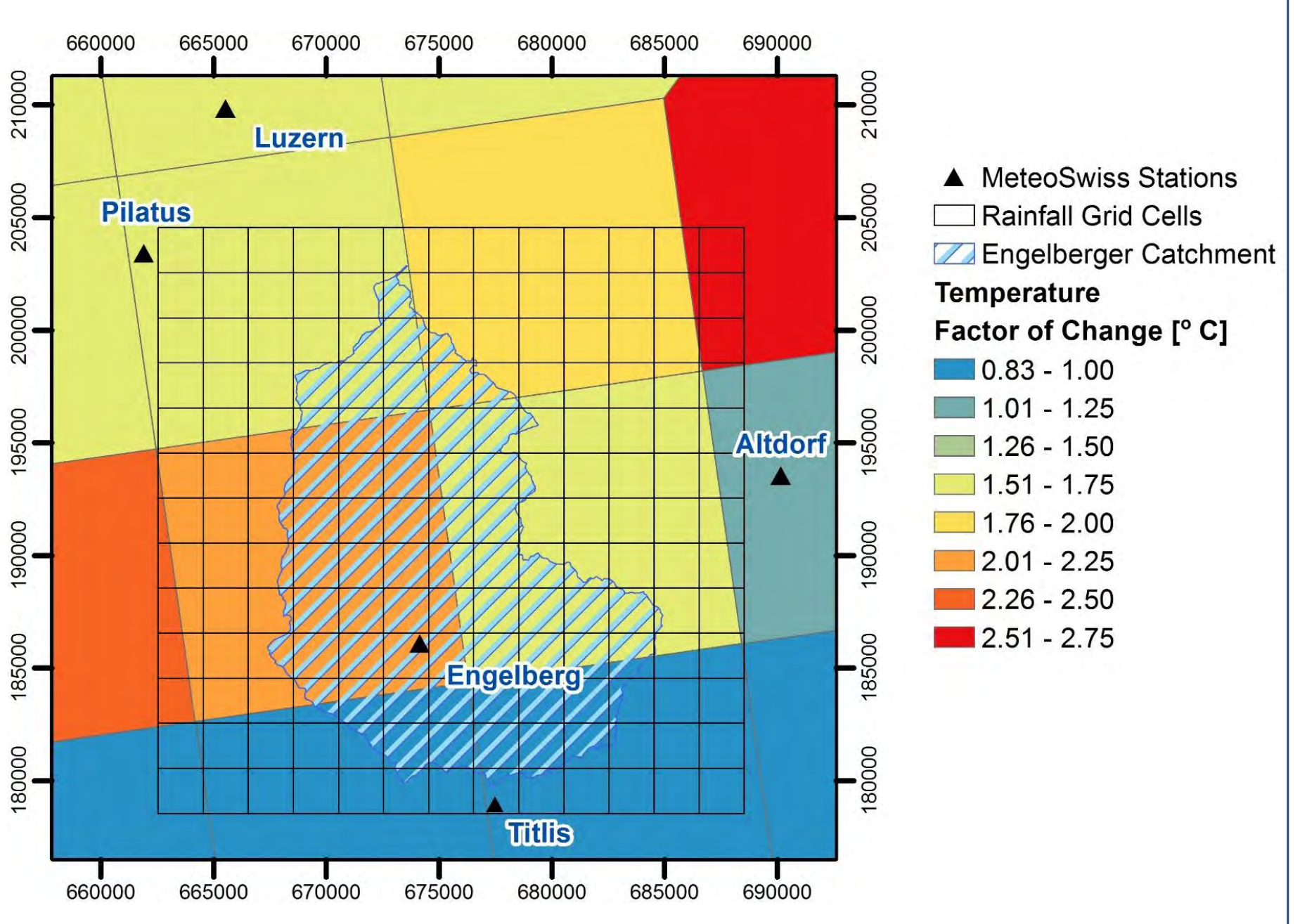
Re-evaluating Storm Arrival Process

A scaling method will also be applied in order to estimate the changes expected in climate statistics from the daily scale of the regional climate models to the 5 minutes resolution of AWE-GEN-2d.

An example is given below for the Generalized Pareto (GP) distribution that represent the statistics for the storm duration for a given month. GP parameters are calculated for CTS and FUT for the daily scale and than estimated for the OBS 10-min scale (a). The corrected distribution (COR) that represent the storm duration for the future is than calculated (b).



Temperature



An example for the estimation of temperature FC on a grid cell basis is given in the right figure (similar configuration as for the precipitation).

Temperature FC is calculated as FUT-CTS. This allows to re-evaluate the observed hourly temperature for the MeteoSwiss ground stations that are used by AWE-GEN-2d for deriving temperature and lapse-rate parameters.

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[1] See poster at Task 2.1: Generation of high resolution climate variables for hydropower studies: model calibration and validation (Nadav Peleg, Simone Fatichi, Paolo Burlando).

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Snow storage for winter tourism

Grünewald T., Wolfsperger F., Lehning M.

WSL-Institut für Schnee- und Lawinenforschung SLF

Introduction

Snow farming is the conservation of snow during the warm half-year, usually with the aim to secure snow for winter sports activities in early season.

More than 30 snow farming sites documented, mainly in the Alps and Scandinavia

Snow is produced in winter more efficiently than in autumn (lower temperatures) > less energy consumption

Large piles of natural and/or technical snow are formed in spring in order to be conserved over the summer season (Fig. 1)

Well-insulating materials such as chipped wood or styrofoam plates are added as surface cover to reduce melting (Fig. 1)

The stored snow is distributed to the ski runs in autumn (Fig. 2, 3, 6)

Snow volumes of up to 800.000 m^3 stored (~500.000 m^3 of water)

Fig. 1: Snow pile covered with saw dust

Fig. 2: Distribution of snow in autumn

Fig. 3: Cross country skier in autumn

Methods & Data

Detailed **volume balances** of two snow piles have been obtained by repeated **terrestrial laser scanning** (TLS) in spring and autumn (Fig. 4)

The physically based 1D model **SNOWPACK**[1] (Fig. 5) is used to simulate the evolution of the snow piles

A layer of soil on top of the snow is used to represent the isolating material (saw dust)

Meteorological forcing is provided from nearby weather stations

Fig. 4: TLS measurements of snow pile

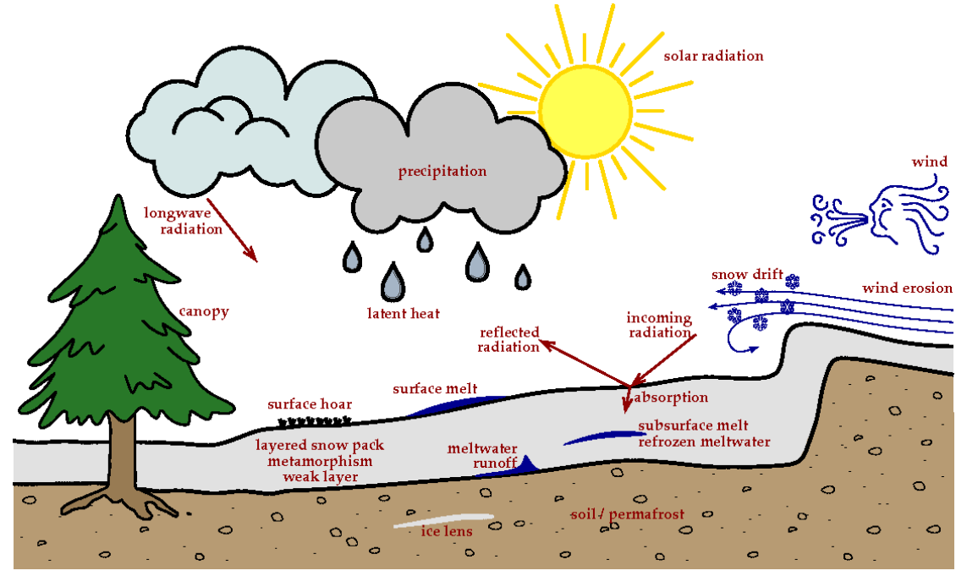

Fig. 5: Principal physical processes included in SNOWPACK

Results

Case study: Snow farming Davos

Purpose: snow farming as basis for early season opening of cross country tracks (Fig. 3)

Location: Large, flat clearing in the Flüela Valley of Davos (Grisons), Elevation: 1730 m a.s.l.

TLS Surveys: 29 April and 8 October 2015

Insolation: ~ 30 cm layer of saw dust

Climate: warmer and drier summer than average (Table 1)

Fig. 6: Snow pile after de-covering

Period	T_{air}°C	P mm
Survey period	11.2	543
Apr-Sept 2000-15	9.3	645

Table 1: Climate conditions at snow farming site

Snow volume and **snow depths** obtained from **TLS**:

Volume	29 Apr	8 Oct
Volume [m^3]	6928	5363
Abs. Volume loss [m^3]	1565	
Rel. Volume loss [%]	**23**	

Table 2: Snow volumes and volume losses obtained from TLS

Snow depth	29 Apr	8 Oct
Maximum [cm]	900	700
Mean loss [cm]	93	
Max loss [cm]	273	

Table 3: Snow depths and depths losses obtained from TLS

Spatial Patterns:

Most snow is lost at the crest of the pile (Fig. 7)

Mass loss decreases with slope that might not be causal (Fig. 8)

No effect for aspect (Fig. 9)

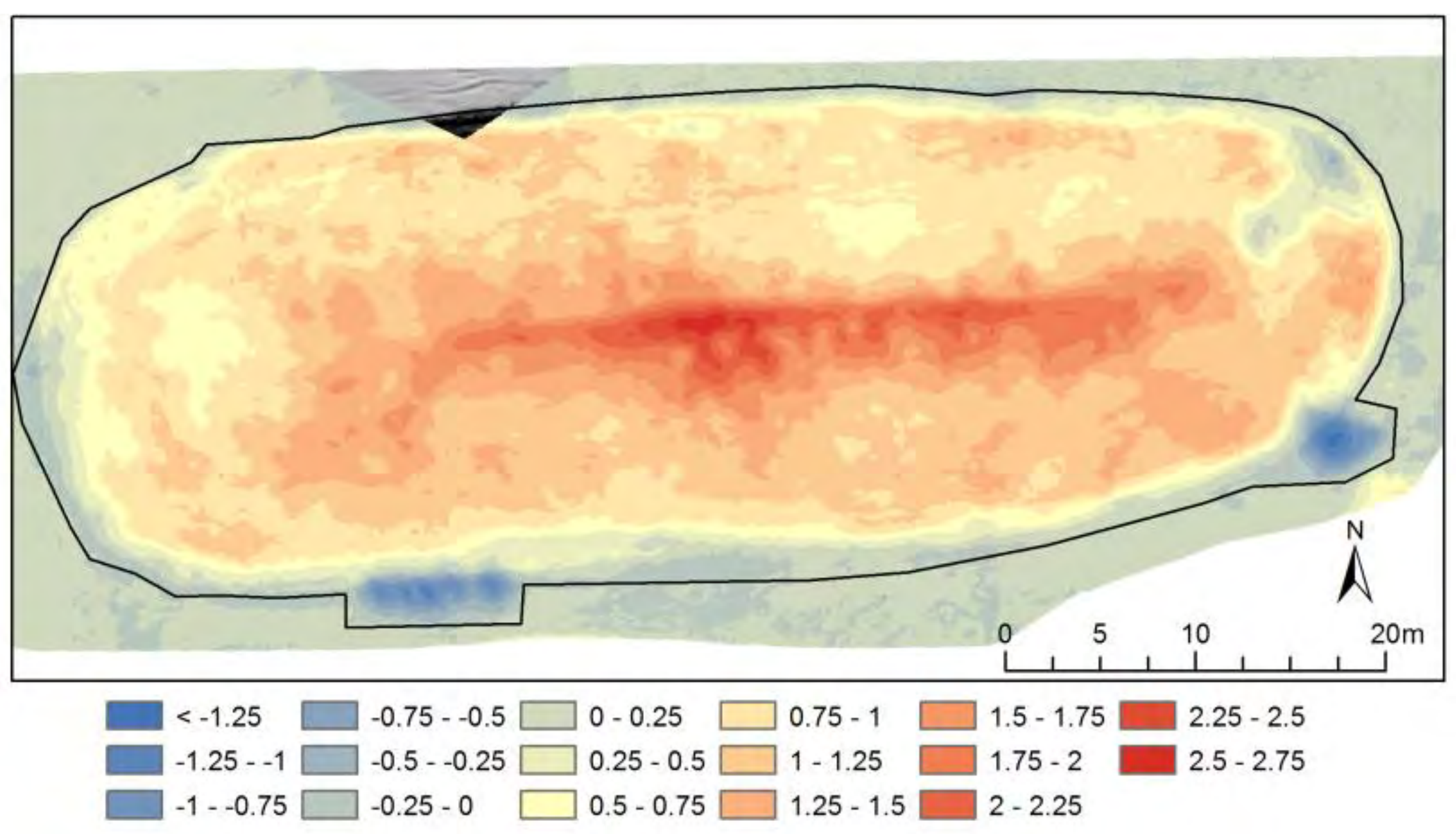

Fig. 7: Snow depth change [m] from 28 April to 8 October

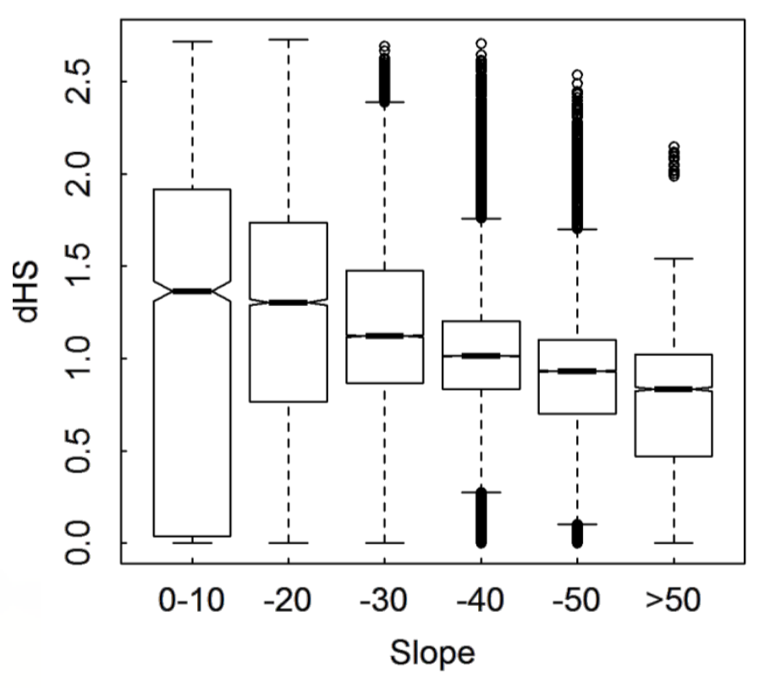

Fig. 8: Boxplot of snow depth vs slope

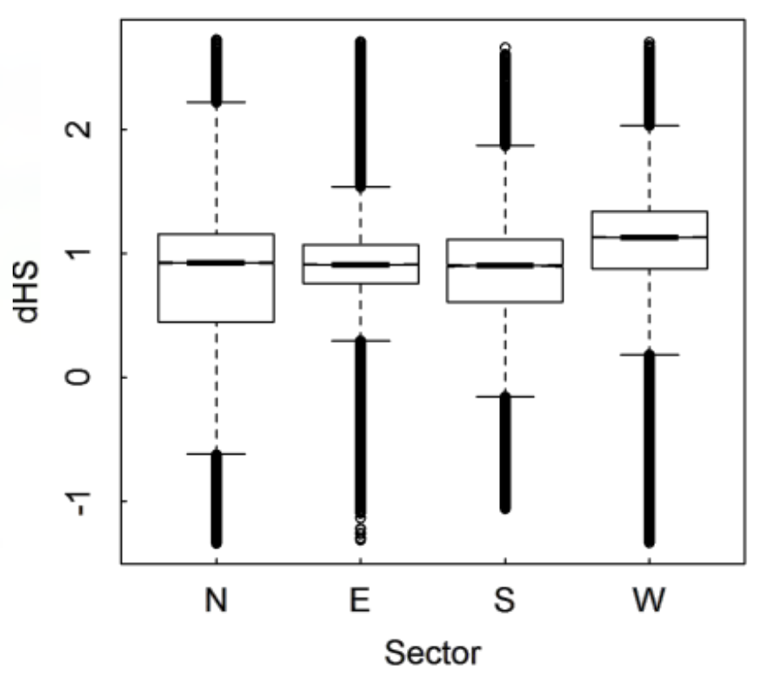

Fig. 9: Boxplot of snow depth vs aspect

Snowpack modelling:

18% of volume loss (Table 4, Figue 10)

> Good correspondence with measurements (Table 2)

Huge effect of saw dust layer on energy balance (long wave, latent heat, sensible heat) > cooling and isolation (Fig. 10, 11)

Short wave radiation most important source of energy (Fig. 11)

Snow depth	29 Apr	8 Oct
Snow depth [cm]	900	741
Abs. loss [cm]	159	
Rel. loss [%]	**18**	

Table 4: Snow depths and depths losses obtained from SNOWPACK

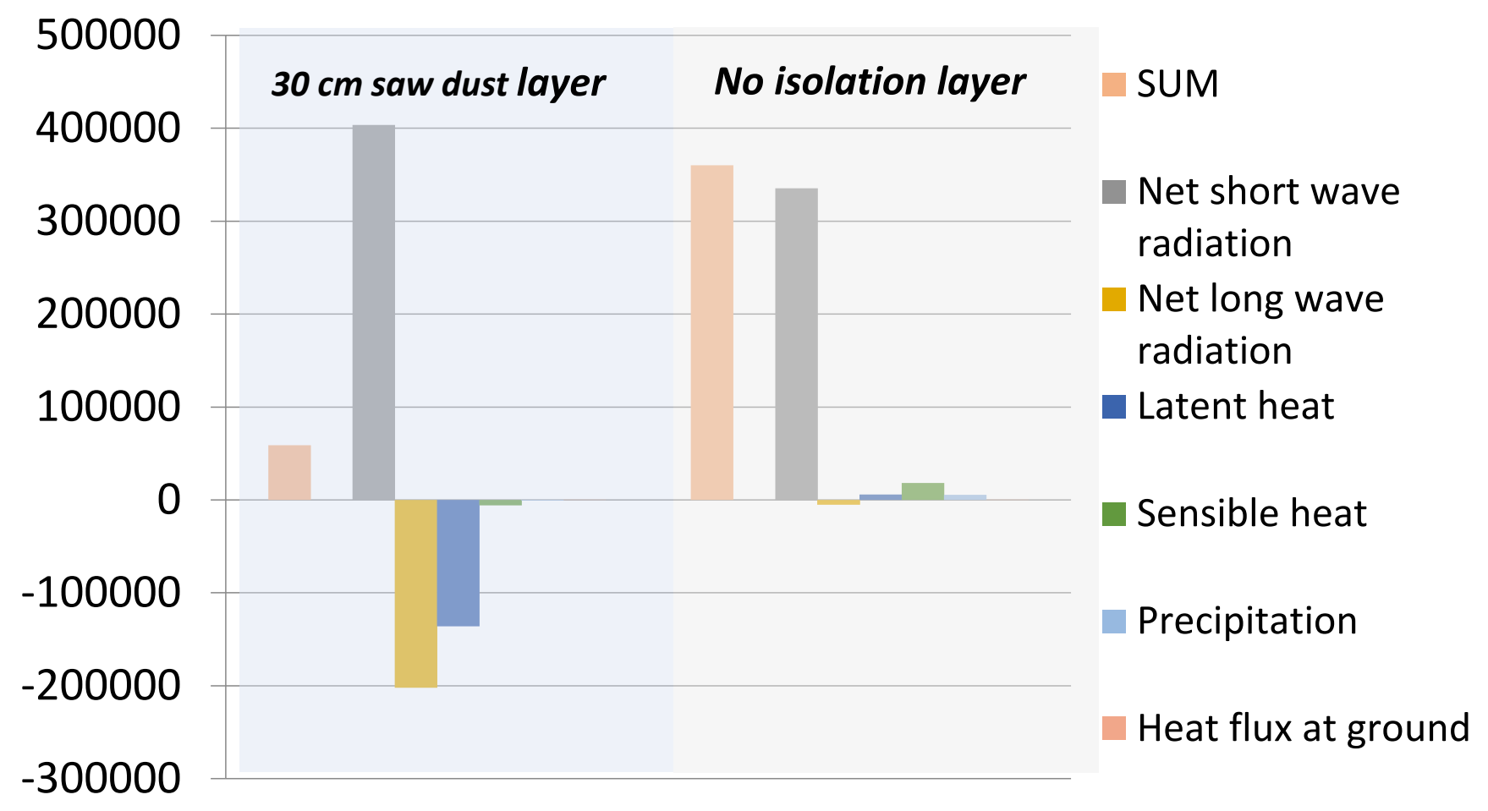

Fig. 11: Net terms of the surface energy balance [W/m^2]

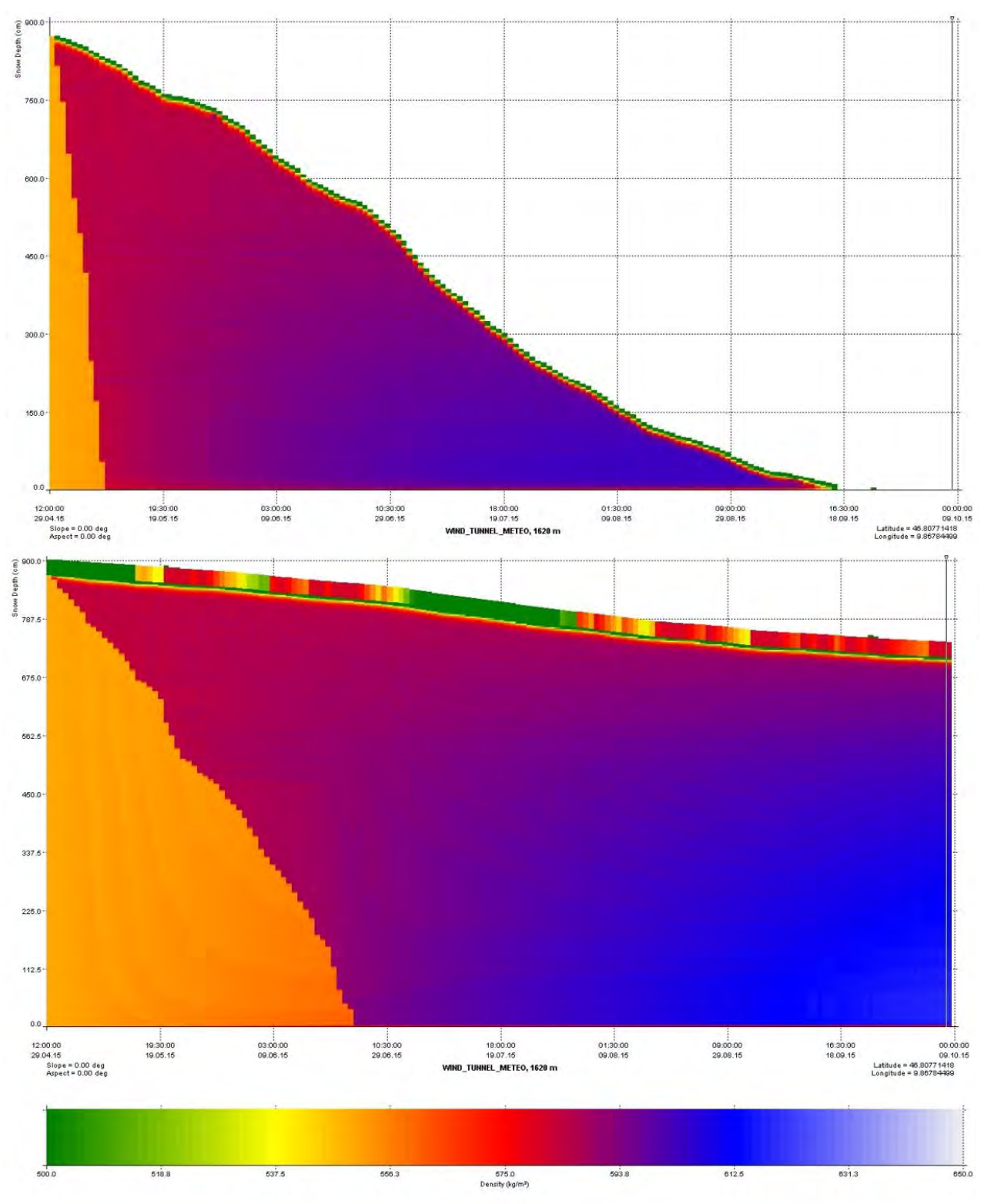

Fig 10: Densification and ablation of the snow simulated in SNOWPACK without (upper) and with saw dust layer

Conclusions

Measurements indicate Volume losses of 23 and 31% in Davos and the Martell (not shown) valley

Losses are in the range of the principal expectations but appear low considering the extremely warm summer

Only weak correlation of ablation with slope and aspect

SNOWPACK was applied successfully to simulate the evolution of the snow pits

Short wave radiation most important energy source for melting

Strong decrease of the energy input by the saw dust layer

Snow farming proofs as an appropriate technique for the conservation of significant amounts of snow but the energy saved during production is compensated for snow distribution

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Short to extended range flow forecasts for small hydropower plants

Michael Schirmer and Konrad Bogner

Motivation

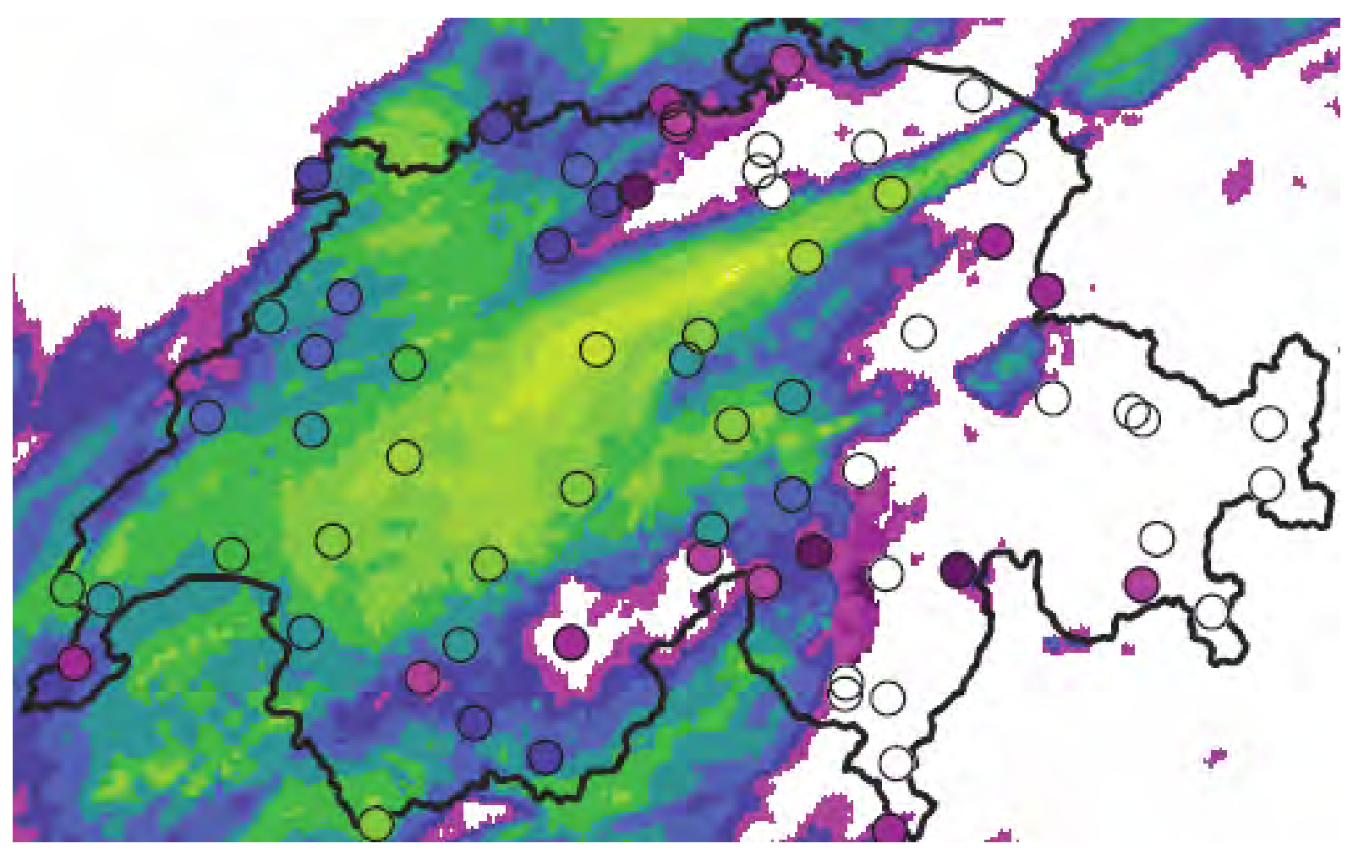
The aim of the project is to demonstrate how small hydropower plants (SHPs) could benefit from short to extended range forecasts through increased flexibility and reliable possibilities of long-term planning. Best estimates of the in-situ hydrological situation in combination with short-range forecasts (now-casts) for the next couple of hours will allow maximum flexibility for the production of energy. Extended range forecasts (days to weeks) will increase flexibility and reliability in long-term maintenance planning like the flushing of the basins and the management of the sediment transport

Methods

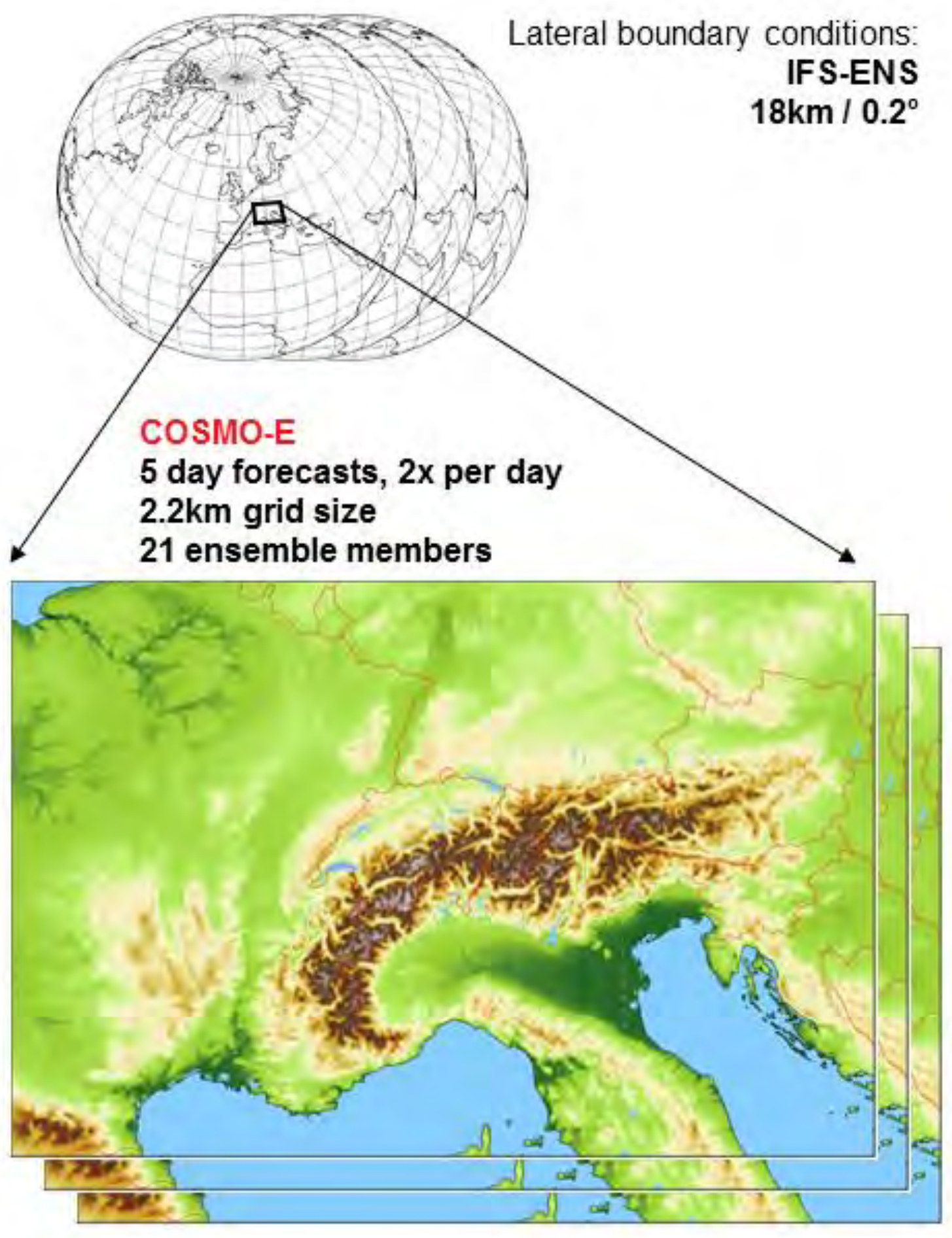
Water intake will be modelled for an SHP in Gletsch, VA, which was recently defined as a demonstrator project within SCCER-Supply of Energy (SoE) collaborators. Meteorological input with benefits at varying lead times from radar-based now-cast to extended-range ensemble weather models will be used to run snow-melt and hydrological models developed at SLF / WSL. Snow observations will be assimilated into the snow-melt model. Finally, forecast quality will be assessed with discharge observations using hind-casts in a quasi-operational work flow.

Meteorological input

Different input due to varying lead times (now-cast to extended-range forecast)



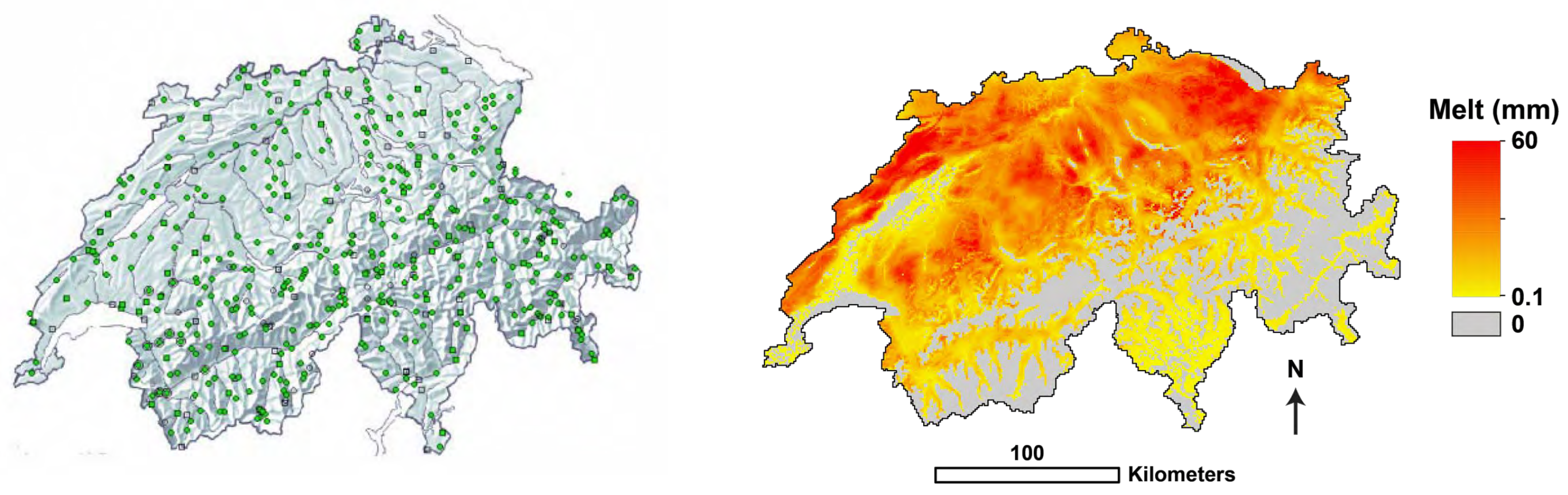
Precipitation radar (Sideris et al., 2014)



COSMO and ECMWF ensemble forecasts to include lead times from hours to days

Snow cover modelling and snow data assimilation

Energy balance and temperature index snow-melt models (1 km resolution)

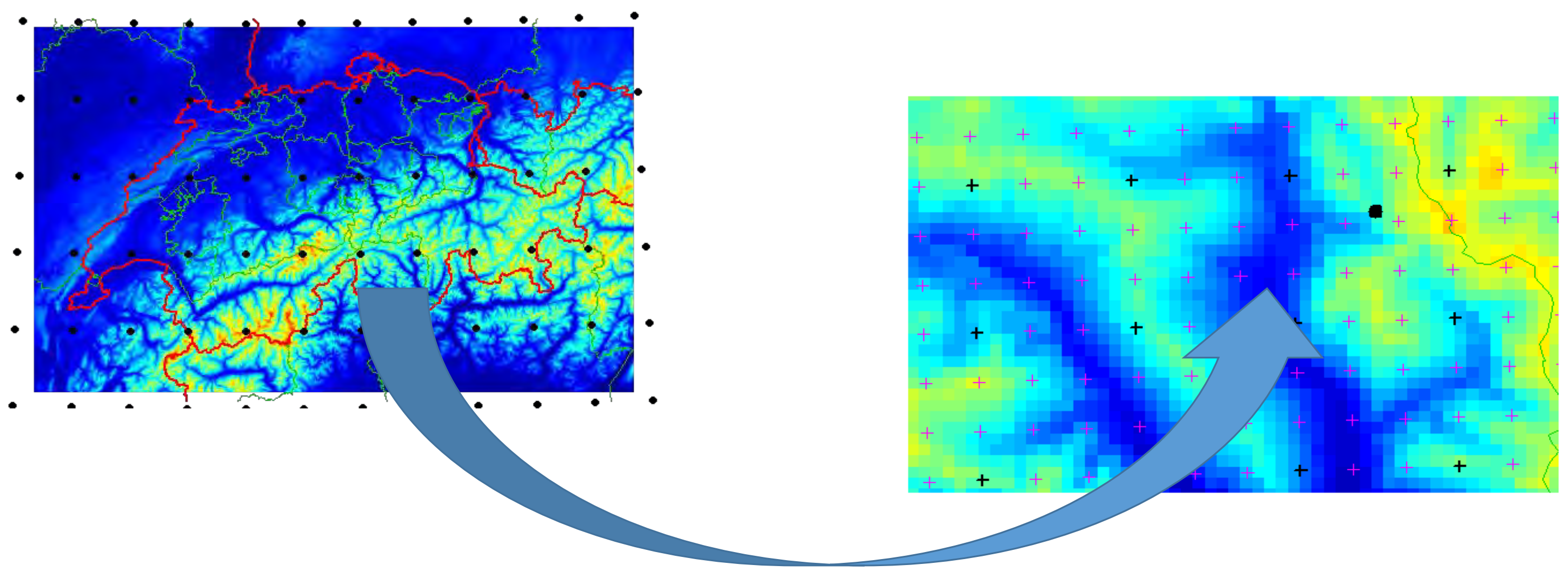


Snow observation locations and snow-melt model output example

- Data assimilation of snow observations with Optimal Interpolation and Ensemble Kalman Filter
- Snow distribution and snow covered area modelling applying sub-grid parameterisations

Downscaling

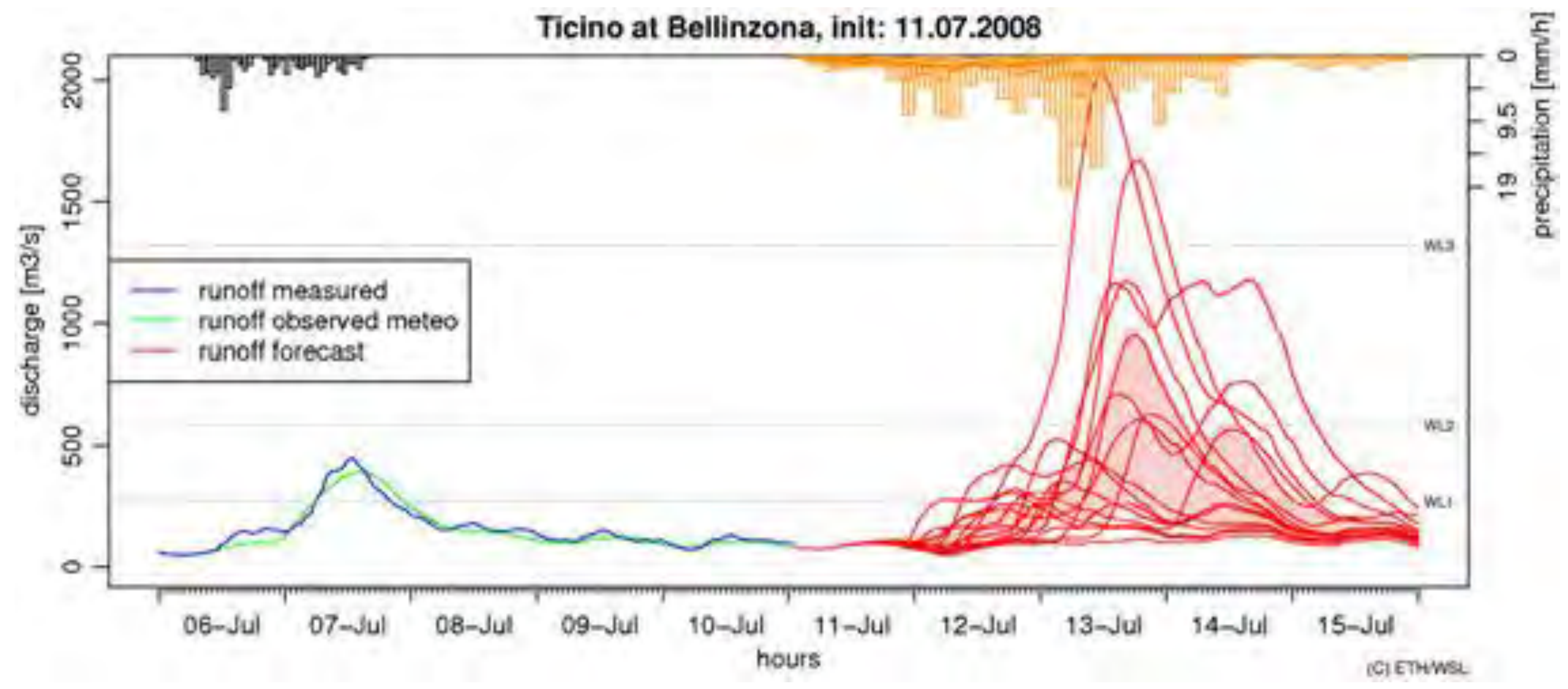
Downscaling precipitation, snow melt and temperature input (1 km to 50 km) to a gridded hydrological model (500 m)



Topography with 500 m resolution compared to 50 km (black dots), 7 km (black crosses) and 2 km (pink crosses).

Hydrological modelling and validation

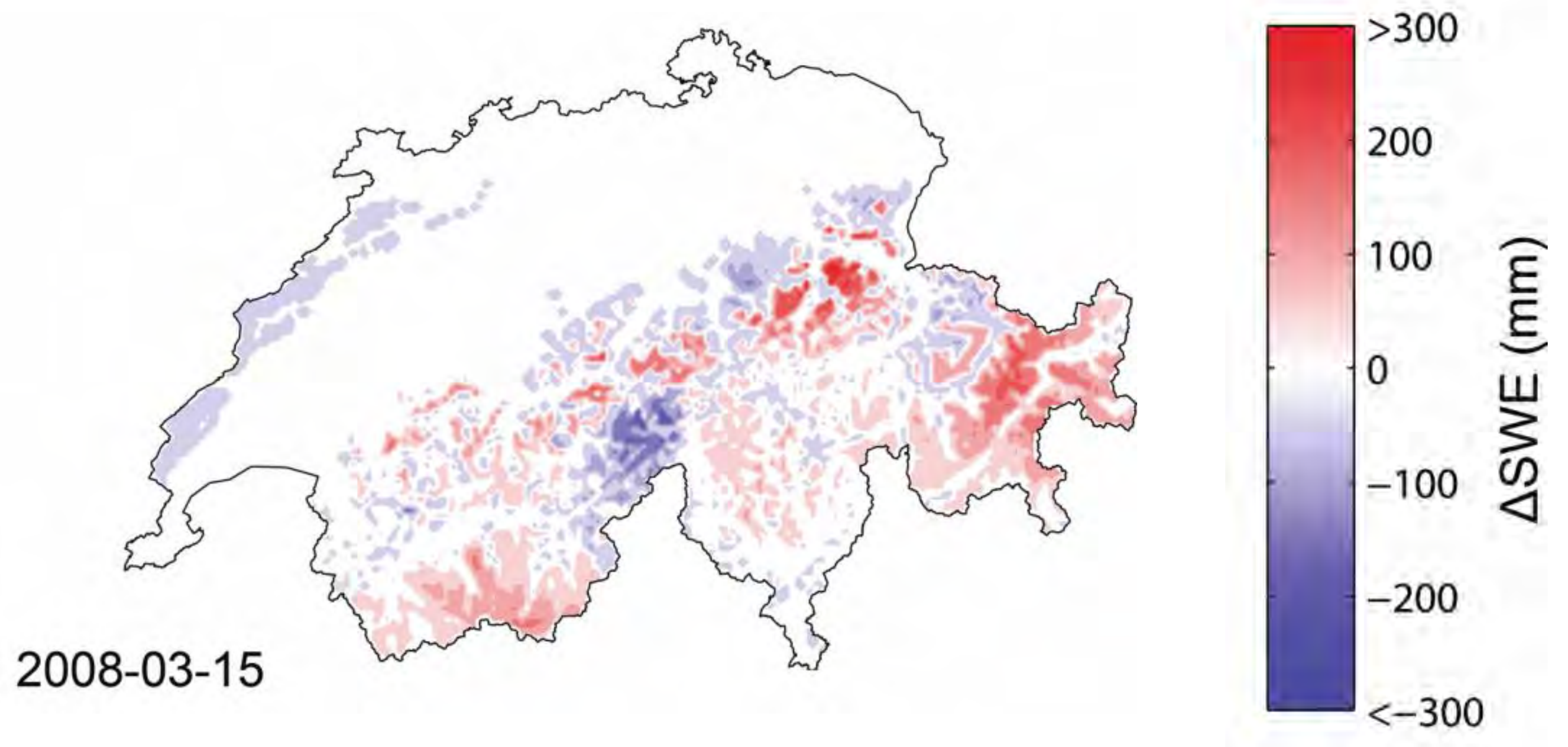
Validating the hydrological model PREVAH in quasi-operational mode with discharge observations in Gletsch, VA, using forecast quality measures which are able to take information from ensemble predictions into account.



PREVAH runoff forced with meteorological ensemble data (Zappa et al., 2013)

Addressing model uncertainty

Ensemble spread and variant model forcing will lead to an assessment of model uncertainty. As an intermediate result, we show the sensitivity of the snow model to applied data assimilation.



Snow model simulations showing a Snow Water Equivalent (SWE) with or without assimilating snow observations.

Outlook

In collaboration with the operator of the SHP in Gletsch, VA, FMV (Force Motrice Valaisanne), and in collaboration with partners within the SCCER-SoE community, we will address the question how such a hydrometeorological forecast in combination with several storage solutions can add value to the existing operation setup (Task 2.1). In collaboration with research partners of Task 2.5 (Integrated simulations of hydropower system operations) we want to assess the additional economic value of such a forecast system when applying flexible operation strategies.

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Replacing glaciers with dams? A provocative thought on the possibility of mitigating future summer-runoff decline

Daniel Farinotti [1,2], *Matthias Huss* [1,3], *Alberto Pistocchi* [4]

1. The issue - Dwindling runoff contributions from glaciers

Due to ongoing climate change and related glacier retreat, concerns about future water availability are often expressed - In particular for the summer, when glacier runoff contributions can be high (Fig. 1).

Runoff share from presently glacierized areas

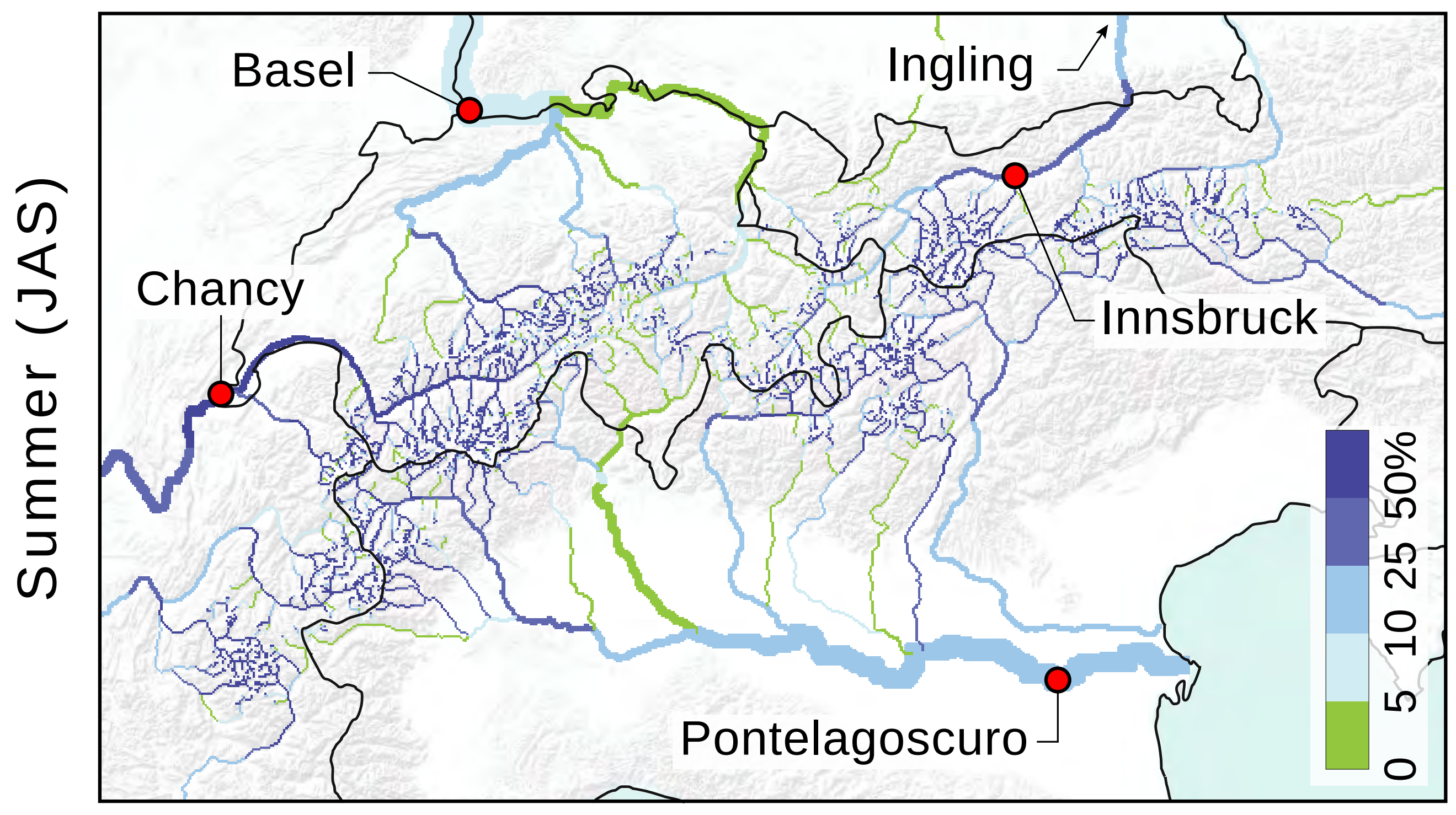


Figure 1 Summer runoff contribution (ice and snow melt + liquid precip.) from presently glacierized areas. Shares are 1980-2009 averages. Glacier contributions are estimates by Huss and Hock (2015), total runoff is from aggregatinon of GRDC composites (Fekete et al., 2002).

2. The idea - Transfer surplus water from spring to summer

Besides a reduction in summer, projections for high alpine catchments anticipate increasing spring contributions. Assuming that maintaining unaltered the current runoff regime is desirable, the surplus water volume could potentially be used to mitigate summer changes (Fig. 2).

Main concept of the analysis

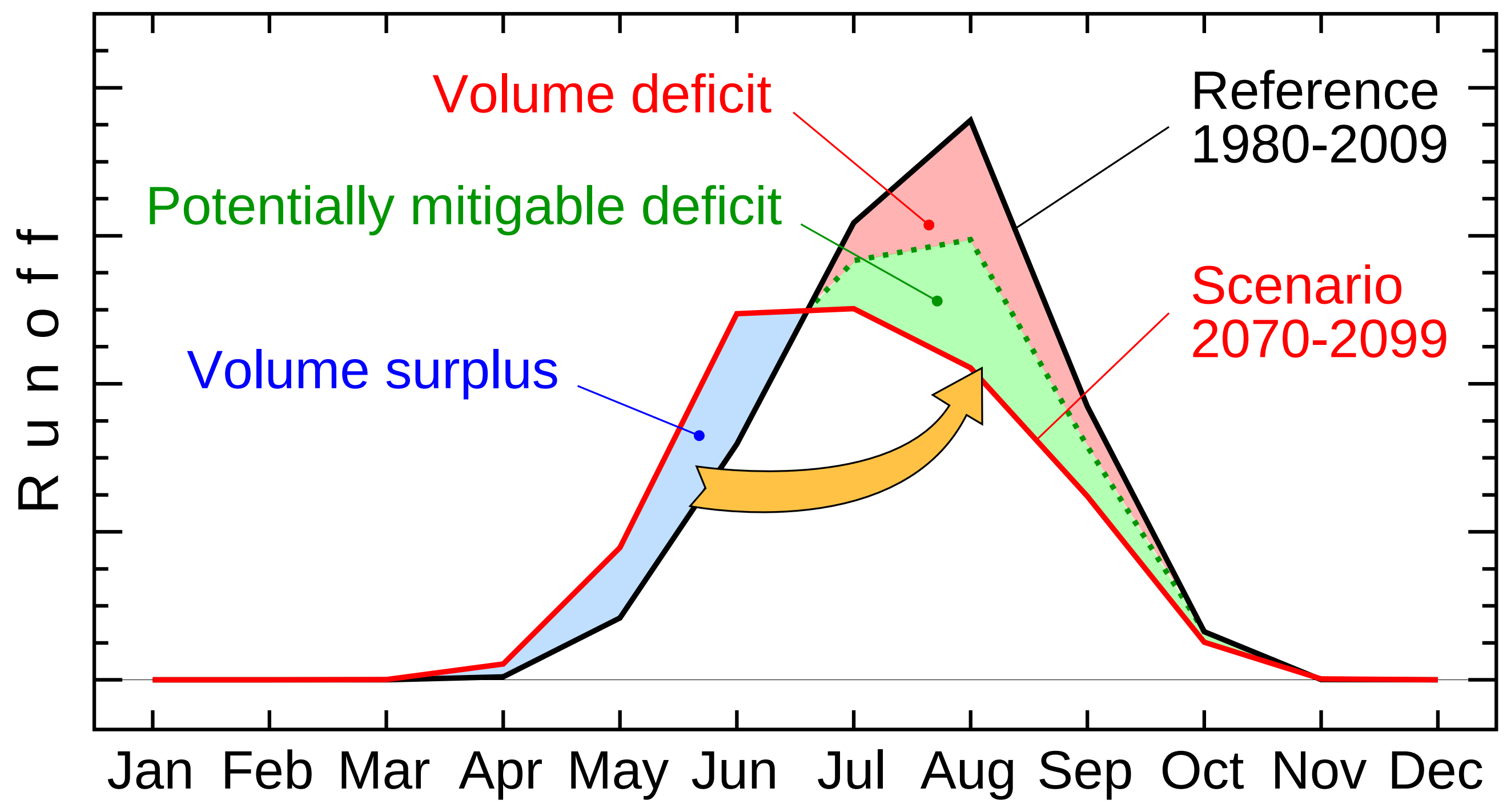


Figure 2 Illustration of the used definition of *mitigation*. *Volume surplus* is the runoff volume that will be in excess to the runoff in the reference period. This volume could potentially be reallocated in order to compensate part of the runoff reduction caused by glacier depletion. *Volume deficit* is the net reduction in annual runoff.

3. The potential - Mitigation of 65% of the expected change

We evaluated the theoretical potential of the above strategy across the European Alps (Fig. 3). The results suggests that by 2100, about two thirds of the expected changes could be mitigated (Table below).

Expected changes in annual and summer runoff

Period	RCP 2.6	RCP 4.5	RCP 8.5
ANNUAL TOTALS			
2010-2039	+1.00 ±0.74 (+18 %)	+1.05 ±0.75 (+19 %)	+1.14 ±0.76 (+21 %)
2040-2069	−0.10 ±0.69 (−1%)	+0.05 ±0.74 (0%)	+0.32 ±0.80 (−6%)
2070-2099	−0.74 ±0.62 (−14%)	−0.73 ±0.67 (−13%)	−0.93 ±0.89 (−17%)
SUMMER – WITHOUT INTERVENTION			
2010-2039	+0.55 ±0.56 (+13 %)	+0.61 ±0.58 (+15 %)	+0.60 ±0.59 (+15 %)
2040-2069	−0.61 ±0.53 (−15%)	−0.64 ±0.58 (−16%)	−0.62 ±0.63 (−15%)
2070-2099	−1.16 ±0.48 (−29%)	−1.48 ±0.53 (−37%)	−2.21 ±0.71 (−55%)
SUMMER – WITH MAXIMAL MITIGATION			
2010-2039	+1.68 ±0.75 (+42 %)	+1.83 ±0.77 (+46 %)	+1.90 ±0.77 (+47 %)
2040-2069	−0.21 ±0.69 (+5%)	+0.44 ±0.74 (+11%)	+0.84 ±0.81 (+21%)
2070-2099	−0.57 ±0.57 (−14%)	−0.52 ±0.65 (−13%)	−0.75 ±0.84 (−18%)
1980-2009	Annual total: 5.28 ± 0.48	Summer total: 3.97 ± 0.36	

−65%

Potentially mitigable change in summer (Jul, Aug, Sep) runoff

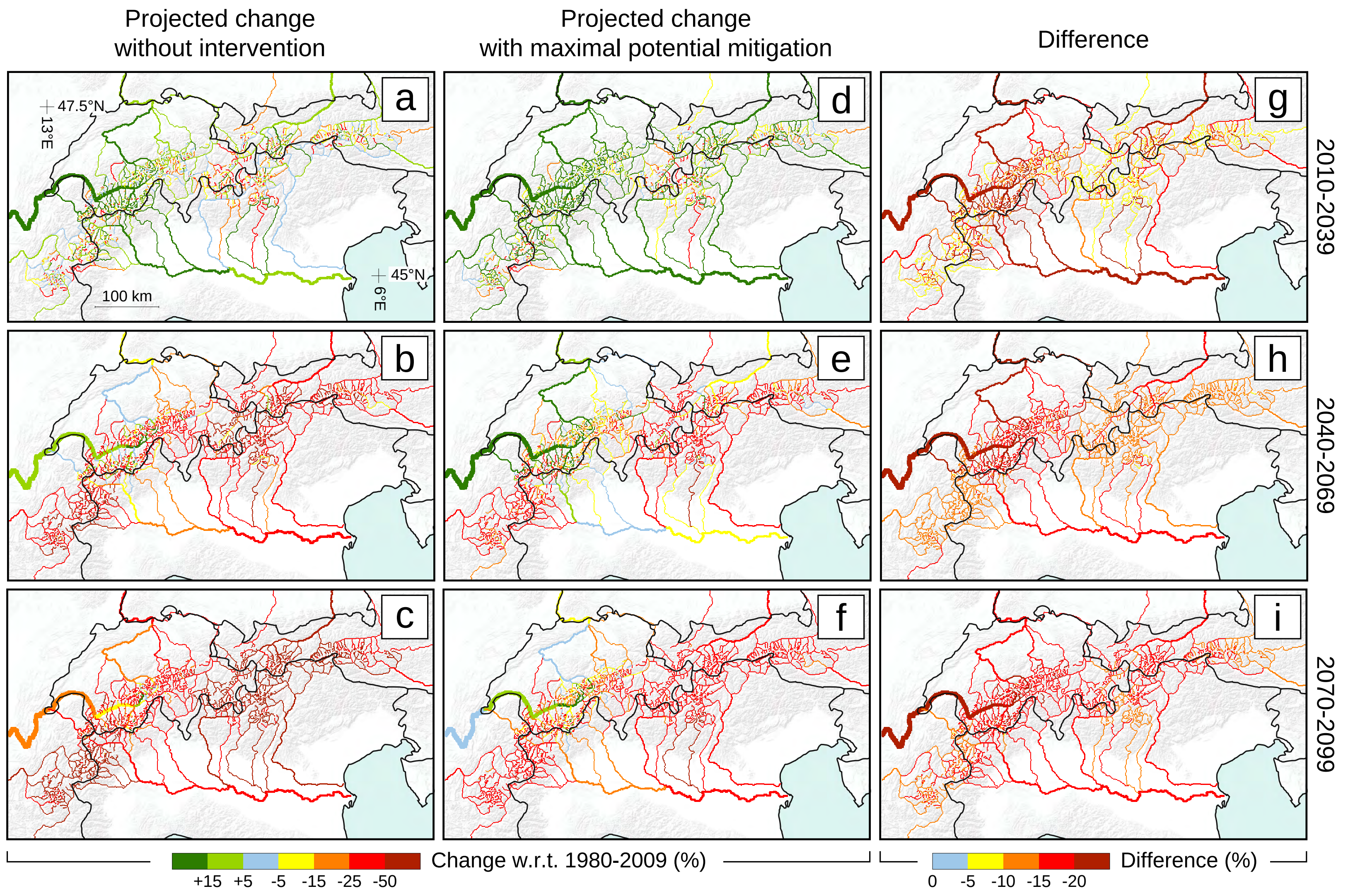
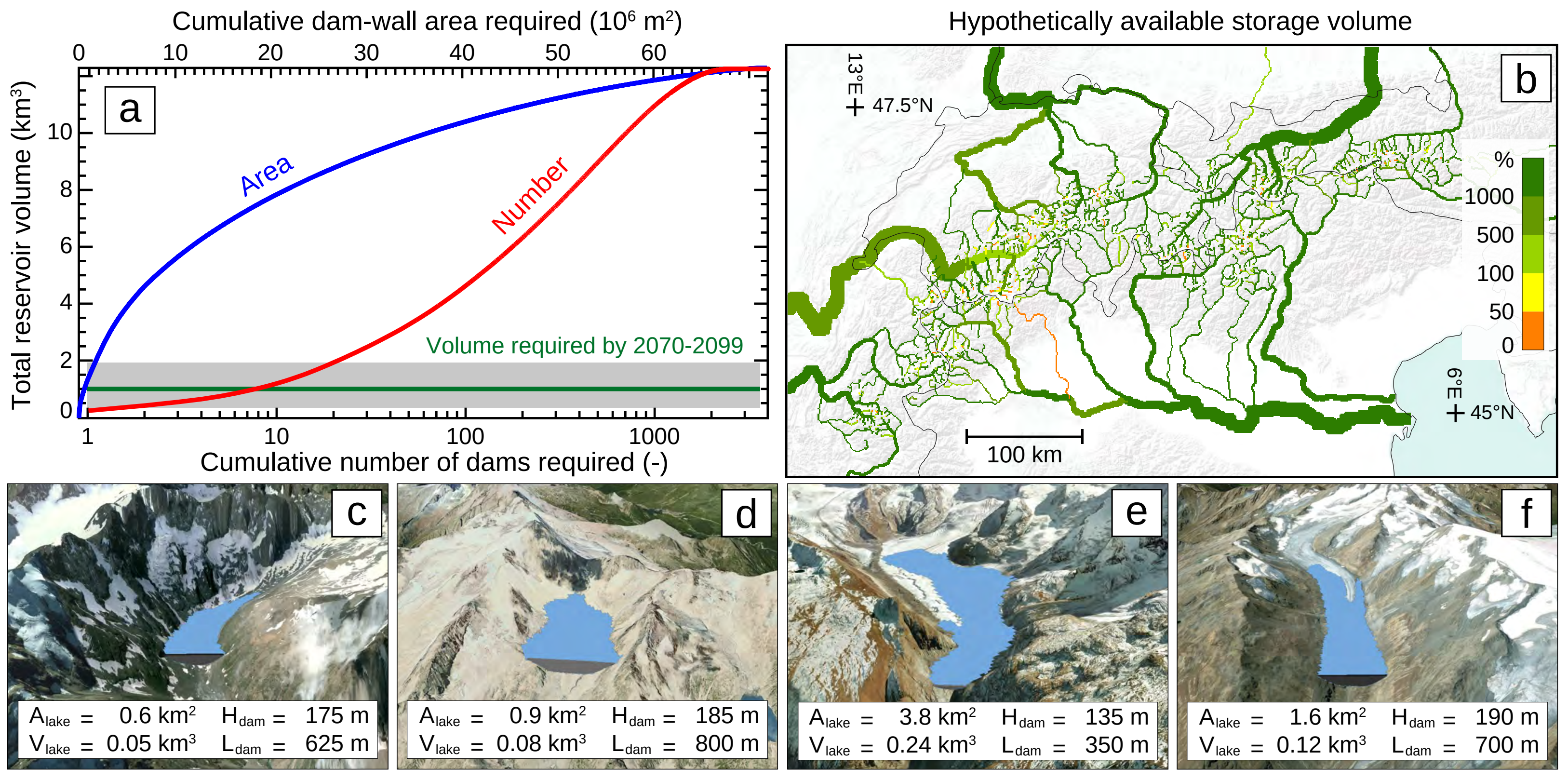


Figure 3 Projected changes in summer (JAS) runoff form presently glacierized surfaces. Changes are relative to 1980-2009 and refer to RCP4.5. Situation (a-c) without intervention, and (d-f) with maximal mitigation (see Fig. 2) realized. The difference is shown separately (g-i).

4. The provocation - Could areas becoming ice-free be used?

In order to put into context the requirement of potentially reallocating ca. 1 km^3 of water (cf. Table), we launch a provocative question: Could the areas becoming ice free because of glacier retreat be used for installing artificial reservoirs?
We show that the potentially installable storage volume is largely in excess of the required one.

Potentially installable artificial storage



c	d	e	f
A_{lake} = 0.6 km^2	A_{lake} = 0.9 km^2	A_{lake} = 3.8 km^2	A_{lake} = 1.6 km^2
H_{dam} = 175 m	H_{dam} = 185 m	H_{dam} = 135 m	H_{dam} = 190 m
V_{lake} = 0.05 km^3	V_{lake} = 0.08 km^3	V_{lake} = 0.24 km^3	V_{lake} = 0.12 km^3
L_{dam} = 625 m	L_{dam} = 800 m	L_{dam} = 350 m	L_{dam} = 700 m

Figure 4 Comparison of required and hypothetically available storage volume. (a) Cumulative number of dams and dam-wall area required for achieving a given storage. (b) Ratio between (1) maximal storage along a given river stretch and (2) volume required for achieving the maximal mitigation. (c-f) Visualization of four virtual reservoirs.

5. The limitations - Implications not yet considered

We understand our work as a first, preliminary and provocative analysis. Limitations and non-considered issues include:

- the actual desirability of an unchanged runoff regime
- technical feasibility and acceptance
- economical and ecological considerations
- exploitation of existing storage infrastructure
- conflicts of interest with other water users

Looking for the related article? →

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The model (Botter XXX modified acc. Schaefli XXXX) behaves adequately for winter, autumn and summer seasons, for the tested case. Assessment of other catchment areas is ongoing.
The model results for the Spring season are not yet satisfying and the model needs further development to estimate snowmelt discharges in this season

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An analytical model to quantify water resources in Alpine environments

LCH LABORATOIRE DE CONSTRUCTIONS HYDRAULIQUES

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Introduction

Hydropower production depends on water availability

Increasing the **reliability** of the discharge estimations will increase the reliability of the design and of the plant operation

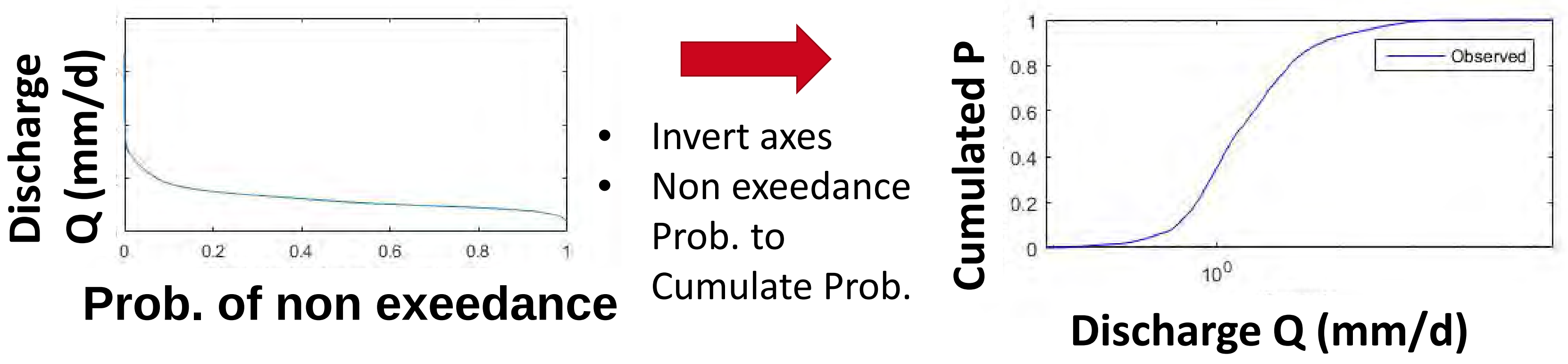
Flow duration curve (FDC): probabilistic distribution of discharges and basic tool to study water availability. It is especially important for run-of river plants.

This research aims to develop semi-analytic models to obtain FDCs for ungauged catchments in Switzerland considering uncertainties. In this phase we are testing existing analytical models to verify if they are suitable for the conditions in Switzerland.

- A model based on the **characteristics of the catchment and the climate** allows the study of discharges in **future scenarios** and may be useful to estimate discharges in **ungagged catchments**.

Methods

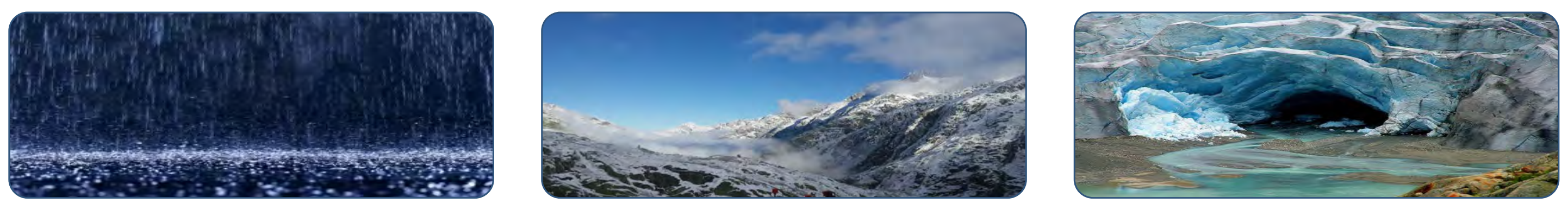
- Probabilities as FDC or cumulative distribution function CDF (Fig. 1):



- Invert axes
- Non exeedance Prob. to Cumulate Prob.

Fig.1: Illustration of the connection between FDCs and CDFs

- Main mechanisms of discharge production:



Pluvial:	**Snow dominated:**	**Glacier:**
Precipitation and evapotranspiration	Precipitation and snow melt	Glacier melt

- The basis of the analytical model (Botter et al., 2007):

Precipitation (marked Poisson process) + Decay (geomorphological characteristics) = Analytical model for daily discharges (Gamma distribution)

$$p(Q,t\rightarrow\infty)=\frac{1}{\Gamma\left(\frac{\lambda}{k}\right)}\frac{1}{Q}\left(\frac{Q}{\alpha kA}\right)^{\frac{\lambda}{k}}exp\left(-\frac{Q}{\alpha kA}\right)$$

Seasonal model

Parameters:
λ: frequency of precipitation events that produce discharge
k: geomorphologic parameter related to the time of response and recession
α: mean daily precipitation depth
A: catchment area

- Adaptation to winter in snow dominated regimes (Schaefli et al, 2013)

$$\boxed{\tau_w=\tau_k+\tau_D}$$

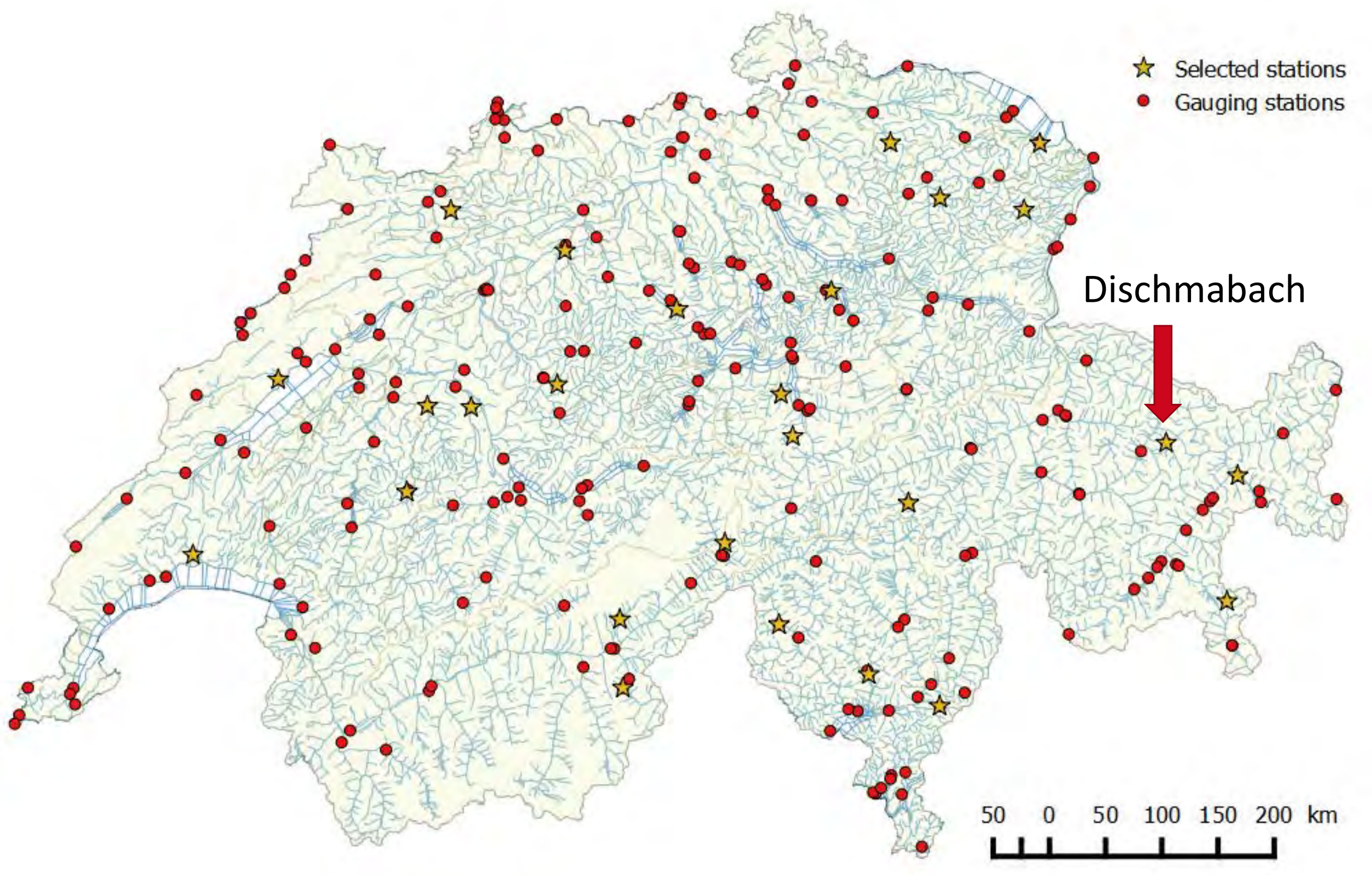
Increase of recession time scale: caused by snow accumulation

$$k_w=\tau_w^{-1}$$

$$p(Q,t\rightarrow\infty)=\frac{1}{\Gamma\left(\frac{\lambda_p}{k_w}\right)}\frac{1}{Q}\left(\frac{Q}{\alpha k_w\boxed{(A-A*)}}\right)^{\left(\frac{\lambda_p}{k_w}\right)}exp\left(-\frac{Q}{\alpha k_w(A-A*)}\right)$$

Reduction of the responsive area: snow-covered areas do not generate discharge immediately

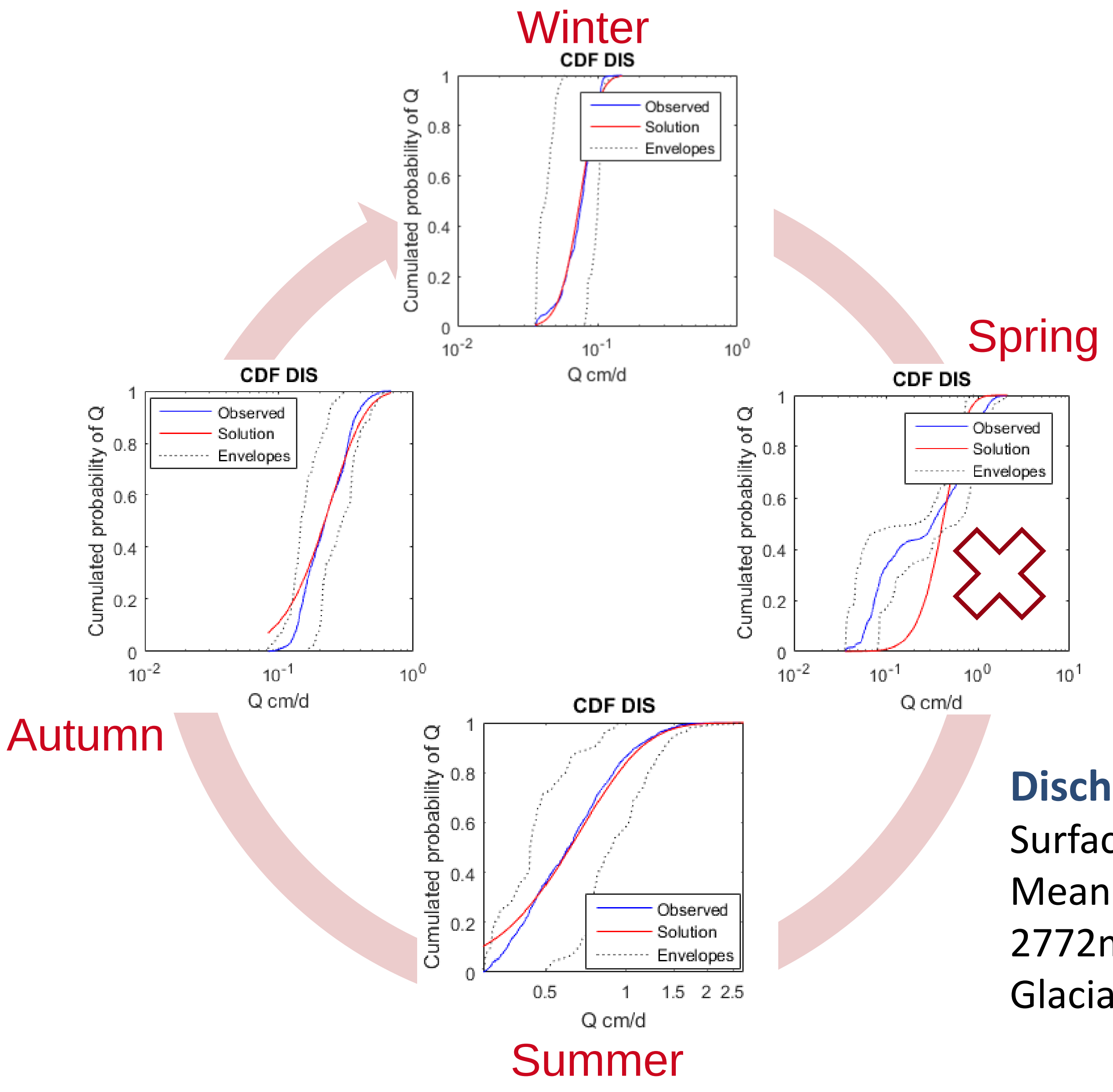
Case studies



- 26 catchments;
- Different discharge regimes;
- Natural discharges;
- Long series of precipitation, air temperature and discharge data available.

Fig. 2: Map of available CH discharge gauging stations

- **Snow-dominated Dischmabach catchment** (Santos et al., 2016)



Dischmabach (see Fig. 2):
Surface area: 43km²
Mean elevation: 2772m.a.s.l.
Glaciation: 2.1%

Fig. 3: Analytic FDC model results for the Dischmabach

The model behaves adequately for summer, winter and autumn, but is not yet adapted to estimate discharge distributions during spring.

Conclusions and perspectives

- The model has a good potential to represent the discharge regimes in Switzerland and to be regionalized
- The results for spring are not yet satisfying and the model needs further development to estimate snowmelt discharges during this season
- Next steps:

Discharge regimes in Switzerland → Test existing models → Models for all seasons and regimes → Uncertainties → Regionalization of models

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Ice Volume Distribution of the Glaciers in Switzerland

Lasse Rabenstein, Lino Schmid, Andreas Bauder, Hansruedi Maurer,
Lisbeth Langhammer, Patrick Lathion, Martin Funk

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Bureau d'ingénieurs et géomètres officiels EPF/SIA

1. Introduction

Accurate measurements of alpine glacier beds and an improved estimation of the ice volume present in the Swiss glaciers is important due to the following facts:

I

- **Retreating glaciers mean a loss of large water resources**
- New reservoirs in eventually ice free glacier valleys are a solution
- Potential but still glaciated dam sites can be identified with **helicopter ground penetrating radar**

II

- **Retreating glaciers change the annual runoff characteristics**
- A quantification of the future runoff is needed for an adequate adaption of hydropower infrastructure
- **The present glacier ice volume** is a highly sensitive parameter for runoff projections (Gabbi et al 2015)
- Future predictions remain uncertain as long as present ice volume estimations have a high uncertainty (>10%)

3. The instrument

The ice penetrating radar consists of a control unit and four 25 MHz antennas (two pairs of transmitters and receivers) which are mounted in a cross orientated fashion on a wooden frame (Fig 4). This allows to simultaneously collect radar data polarized in axial and transverse orientation relative to the glacier flow or flight direction, respectively (Fig 6).

The radar system is town by a helicopter allowing the acquisition of a large amount of measurements in limited time.

Figure 4: *Radar system attached to a helicopter*

5. Polarisation

Figure 6 shows exemplarily two transects (Fig 5) where in one case the glacier bed is better deducible in the axial polarized radar data (Fig 6a) and in the other case in the transverse polarized data (Fig 6d).

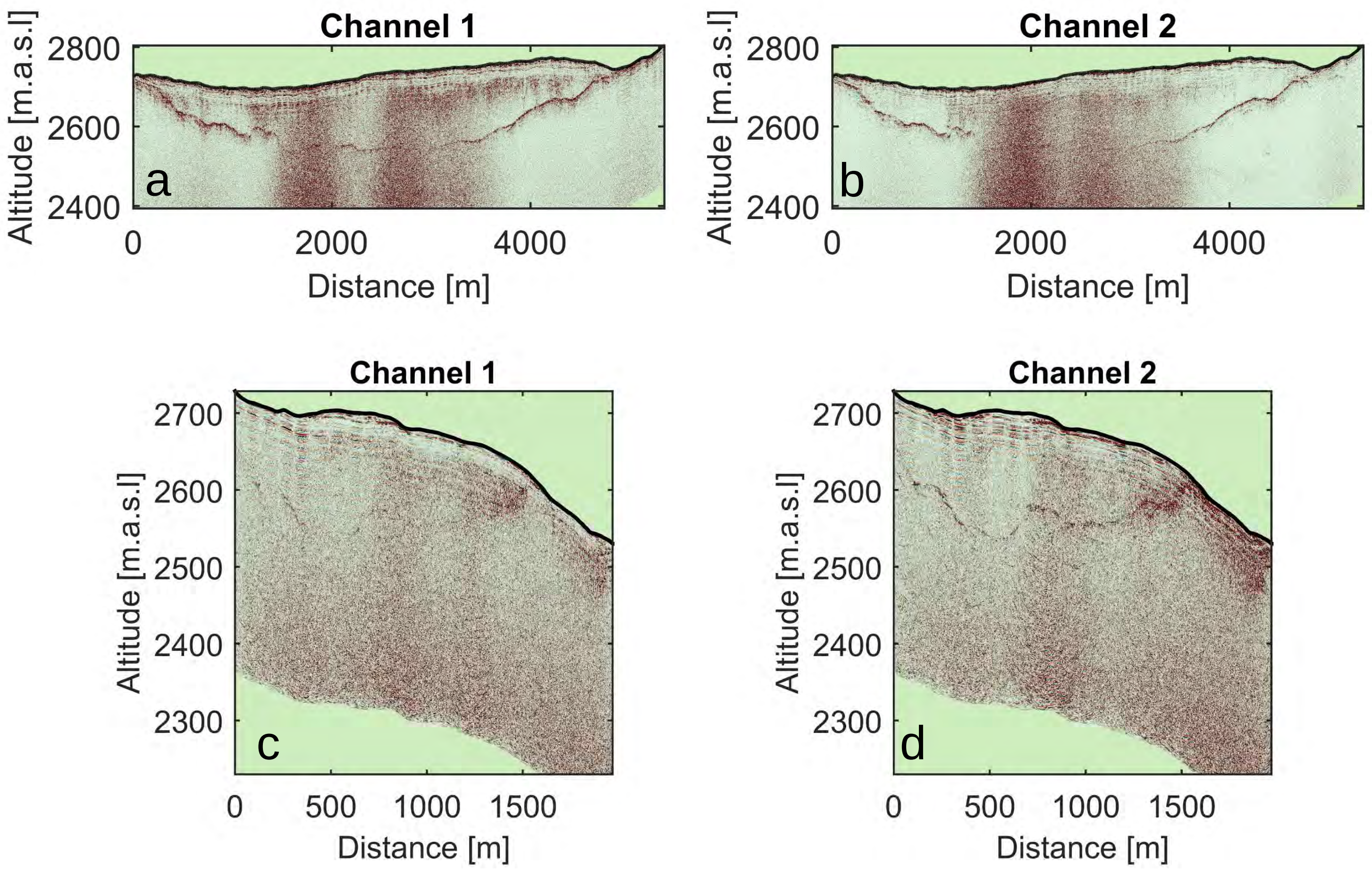


Figure 6: *Radargrams of transects 2 (a & b) and 14 (c & d) polarized across (channel 1, a & c) and along (channel 2, b & d) the flight direction*

2. Project Status

Large efforts were taken to improve Switzerland's capability to measure, processing data and archive glacier bed topography

Measurements: A multi polarization helicopter borne ice penetrating radar instrument was developed (see. Section 3).

Processing: Software libraries were developed in order to derive from raw radar data images of the glacier bed (=2D slices cut through a glacier) and eventually an ice thickness map of an entire glacier.

Database: 2D Images though the glaciers and geocoded ice thickness information are continuously stored in a GIS database, accessible within the VAW at ETH Zurich.

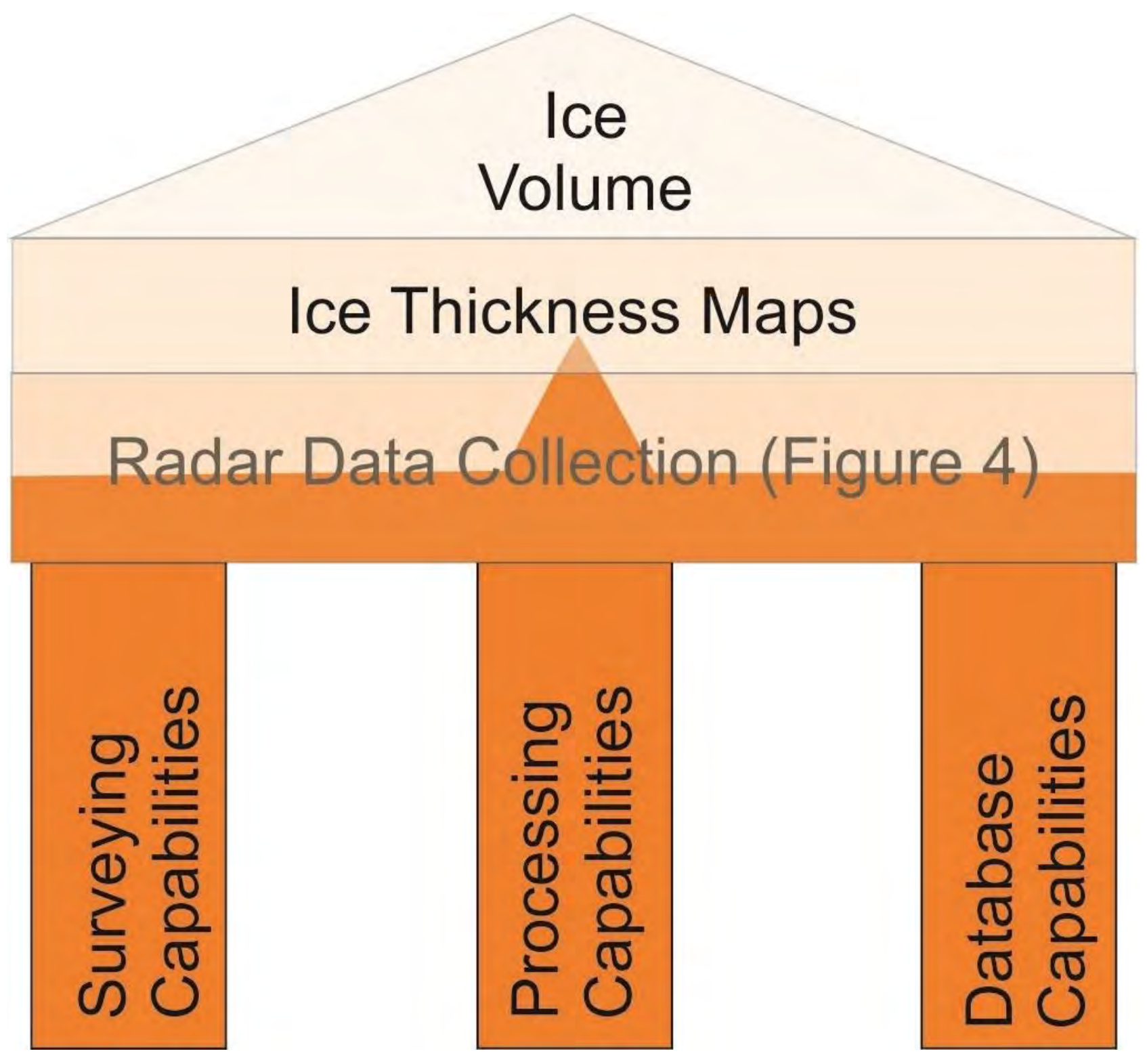


Figure 3: *Project sketch. Three "pillars" of capabilities were needed before the "roof", i.e. the ice thickness data, can be gathered. Dark shaded colours are the completed sections (all three pillars are complete by 9/2016) and light shaded colours are the planned sections. By 9/2016 we are half through radar data collection.*

4. Showcase Glacier de la Plaine Morte

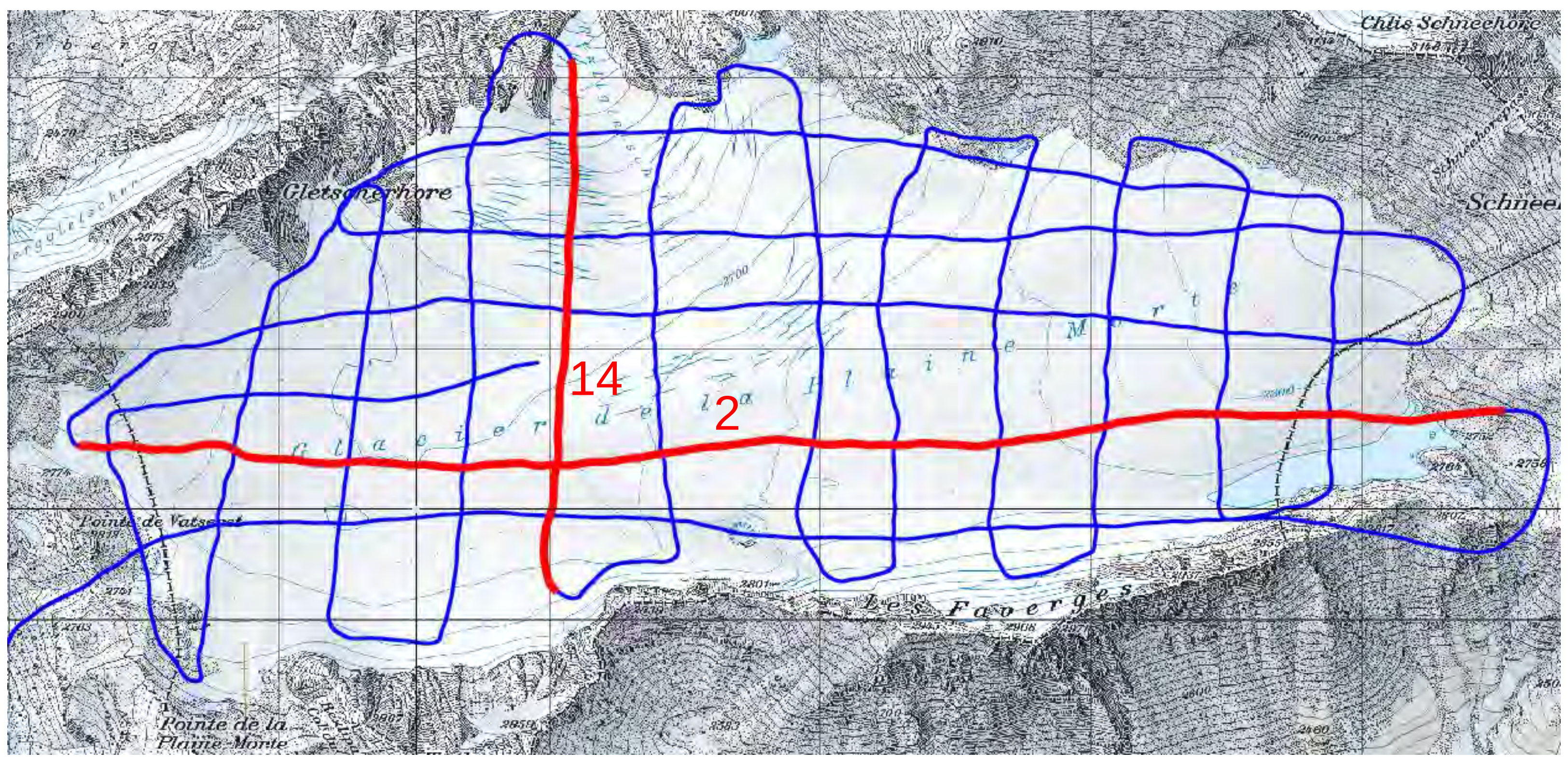
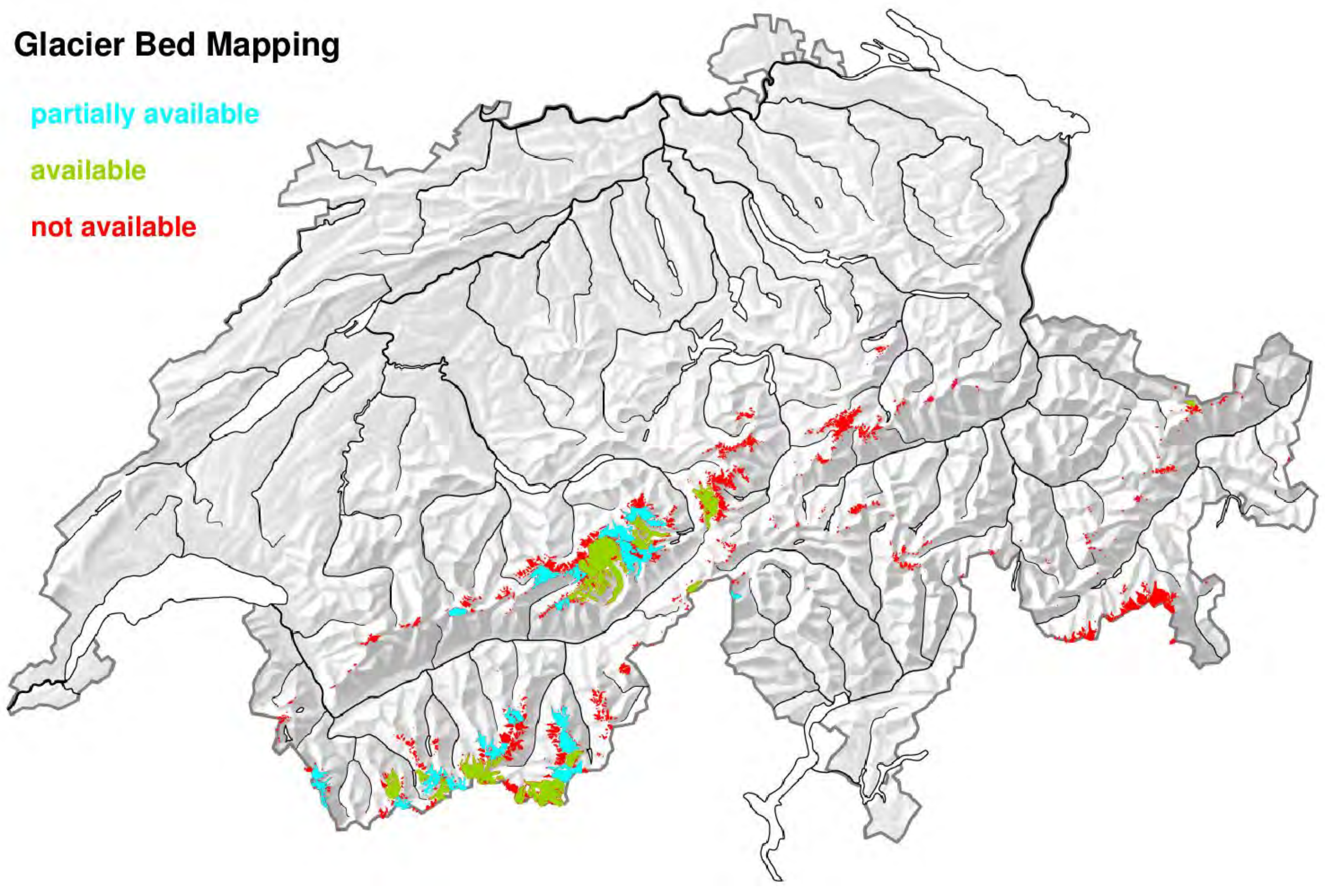


Figure 5: *Radar survey flown on the Glacier de la Plaine Morte. Transects 2 and 14 are highlighted*

6. Current state of evaluation

The map below shows all glacierized regions in Switzerland. Green are areas where ice thickness maps are available and light blue areas where measurements were acquired but not yet completely processed. Red areas are going to be surveyed within the next years.



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Use of UAV photogrammetry on glaciers: Limitation and Challenges

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UAV photogrammetry

Unmanned Aerial Vehicle (UAV) based surveys have become very popular due to the fast evolution of automated close-range photogrammetry and the emergence of consumer-friendly, ready-to-use platforms. Such platforms, together with Structure-from-Motion (SfM) techniques, allow obtaining high-resolution datasets such as orthophotos and Digital Surface Models (DSMs).

This poster discusses the application of UAV photogrammetry on glaciers highlighting its advantages and drawbacks with a focus on Ground Control Points (GCPs). GCPs are recquired for georeferencing the SfM-derived DSMs (SfM-DSM) and their deployement is a time-consuming step. Here we show how the GCPs (their number and location) is influencing the accuracy of SfM-DSMs. This knowlegde is crucial for better field planning and understanding of the output data.

Procedure for field deployment

1. Field planning occurs in the office and consists of optimizing flying time, area covered and resolution. The flight height (H) determines both the ground sampling distance (GSD) and the area covered per flight (A). For our UAV system (Sensefly® eBee; Fig. 1) mounted with a 12MP camera, the relations are:

   a) $GSD = H*3.48e^{-4}$ m   b) $A = H*2600$ m

   70% overlap between adjacent pictures are required. The challenge lies in the flight navigation in rough topography.
2. In the field, GCPs have to be set (in a spatially distributed way) on the surface prior flight and measured with a dGPS (Fig. 2). For the area covered on Findelengletscher, this step needs approximately one day.
3. Once the GCPs are in place, the UAV can be quickly deployed (ready to fly in 10min). In our applications, the survey area was usually several square km. For the eBee, one flight can last up to 40min. Performing the 12 flights from Figure 3, takes around 7 hours.
4. UAV photogrammetry is weather dependent as low wind speed and good light conditions are required. The fieldwork dates are therefore decided a few days in advance only.

Figure 1: Survey material, including UAV, transmitter and computer.

Figure 2: Ground Control Point (GCP) measured with a dGPS.

Data processing

SfM softwares such as MicMac® or Agisoft Photoscan® are available to process the image datasets gathered from the UAV. Data processing is straight forward and automatization through scripts possible.

The processing time depend on the computer, the size of the image dataset and the size of the images themselves. For example, the processing time for the image dataset generated on Findelengletscher (Fig.3, 3040 images) with Agisoft Photoscan® software on an Intel® Xeon® CPU E5-2670 v3 processors with 128GB RAM, is of 12hours. This generates a DSM of 0.2GB and orthophoto of 4.0GB.

Datasets

UAV photogrammetry generates high resolution orthophotos and DSMs. The accuracy of the SfM-DSMs is dependent on the number of GCPs and their location.

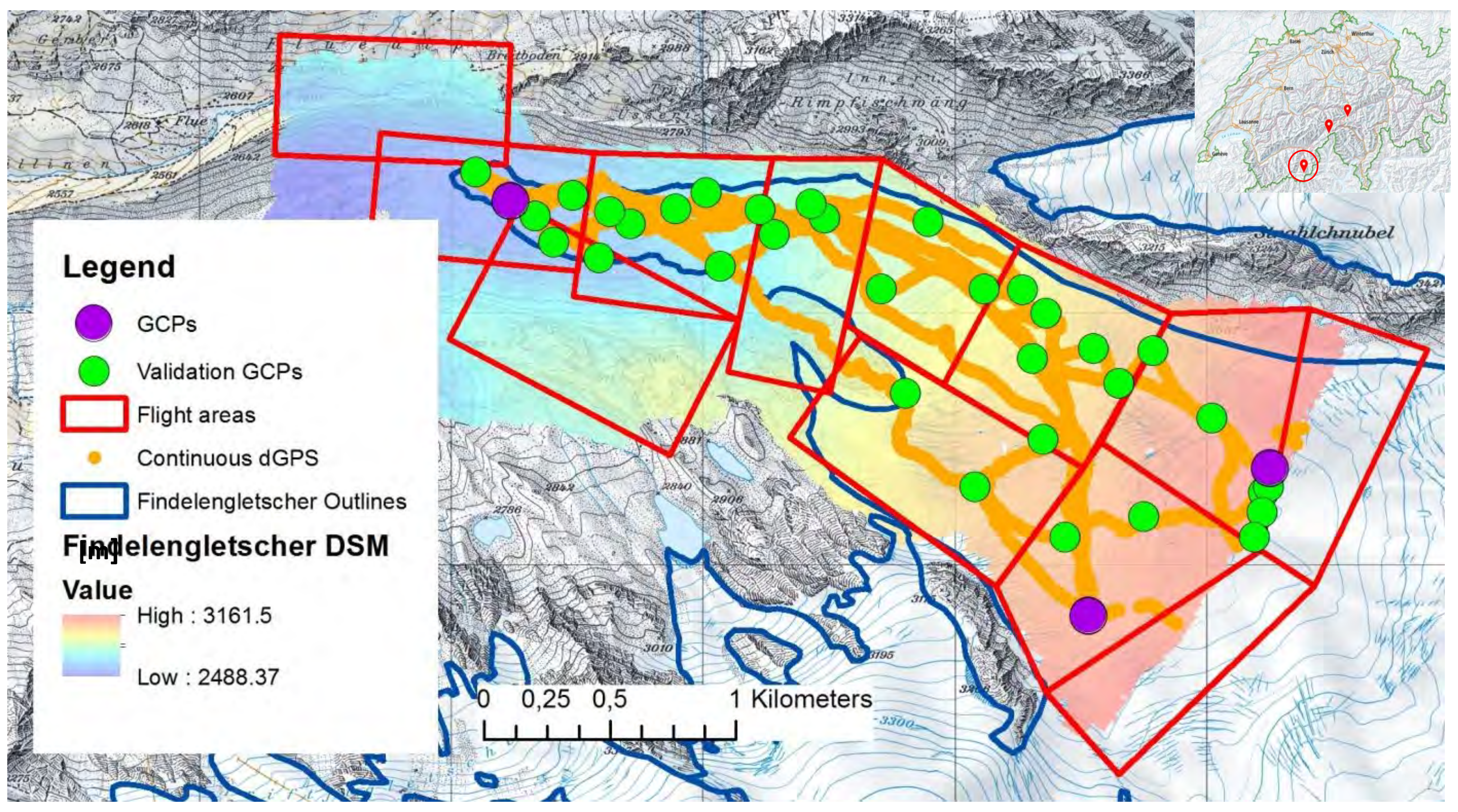

Figure 3: Findelengletscher's tongue: The area covered by the 12 flight areas is of 5km^2. Over 32 GCPs are set on the glaciers surface and part of them are used for validation. For the same purpose, continuous dGPS points have been measured.

Figure 3 gives an example of a field setting on a glacier tongue. Six SfM-DSMs were generated by using three GCPs at a time. The remaining GCPs (validation GCPs) as well as the continuous dGPS points were used to assess the accuracy of the generated SfM-DSMs (Fig. 4). A similar procedure was followed for four GCPs, five GCPs, etc.

Figure 4 shows that the accuracy of the SfM-DSM decreases with increasing number of GCPs up to a certain threshold (here around 12GCPs or 2.5GCPs/km^2). After that, the accuracy is constant. The remaining error might be due to the SfM algorithms or the image quality for instance.

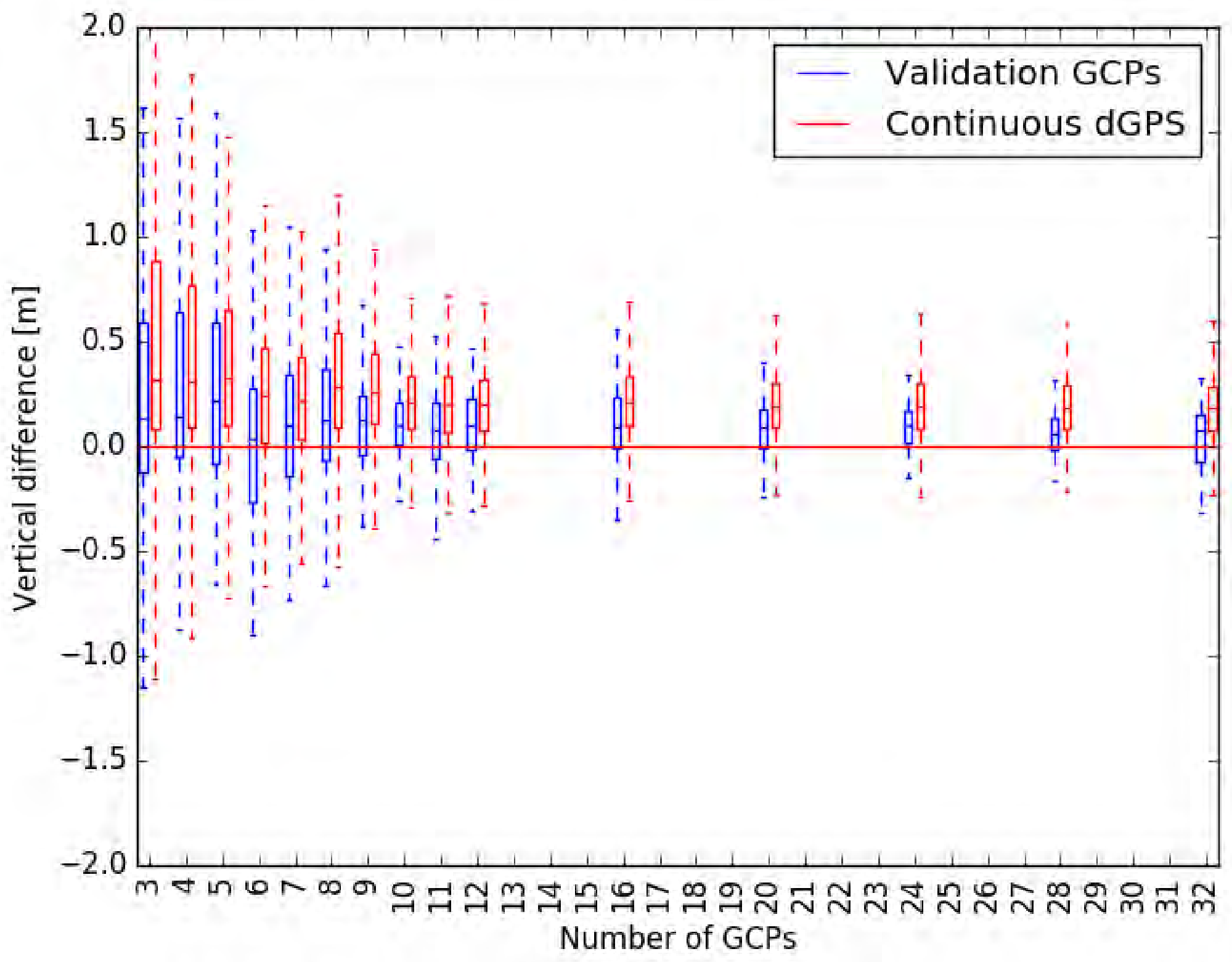

Figure 4: Vertical difference between SfM-DSM and differential GPS points for varying GCP number. The blue (red) boxplots were calculated with the validation GCPs (with the continuous differential GPS points).

Future prospects in glaciology

UAV photogrammetry on glaciers with the use of GCPs is a method applicable for small areas. For larger areas, setting GCPs can be prohibitively time consuming. Costs for logistic and manpower has to be weighed against the cost of a conventional airborne survey.

Recently, UAVs using Real Time Kinematik (RTK) positioning are available, where a base station replaces the need of GCPs, therefore reducing the field campaign time considerably. Comparison studies using both kind of UAVs found that the accuracy of the final products are lower with the UAV-RTK than the UAV requiring GCPs (e.g. Clayput, 2016; Harder 2016).

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Mise en évidence du déficit de stockage des ouvrages de retenue en Suisse

LABORATOIRE DE CONSTRUCTIONS HYDRAULIQUES

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

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1. Contexte

Selon la stratégie énergétique 2050 la production d'électricité des centrales nucléaires (26.3 TWh) devrait être remplacée par une augmentation de la production d'énergies renouvelables (OFEN, 2014). L'hydroélectricité représente 60% de la production totale d'électricité pour une utilisation quasi-totale du réseau hydrographique. L'intégration de plus de production solaire et éolienne demandera le renforcement du stockage hydroélectrique, tant au niveau du stockage saisonnier comme dans son rôle de régulateur du système électrique. Le potentiel d'augmentation du volume des retenues alpines pourrait aussi profiter à la réduction de l'importation d'électricité en hiver.

2. HydroGIS

Base de données spatiales et attributaires des 285 plus importantes usines hydroélectriques avec puissance > 300 kW (Balmer, 2011).

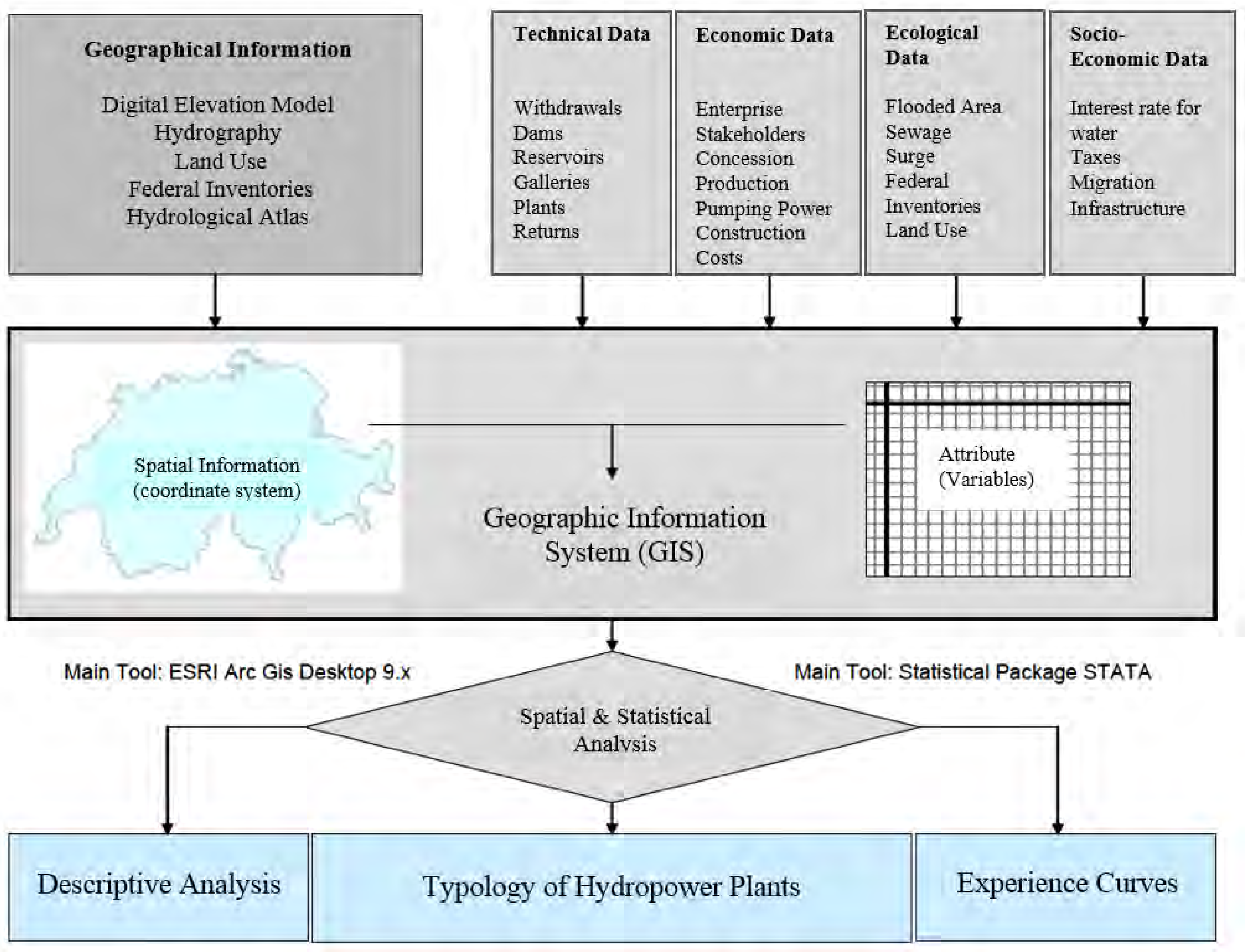

Fig.1: Schéma du contenu de la base de données HydroGIS (Balmer, 2011).

Les informations de cette base de données proviennent de plusieurs sources : WASTA, SWISSDAMS, GEOSTAT, GEWISS, INVENT, HADES, PREVAH, Tunnelstatistik, Swisstopo et sont organisées en couches GIS. Bien que la base de données WASTA contienne aujourd'hui plus de 660 usines hydroélectriques, le contenu d'HydroGIS est plus que suffisant pour permettre une analyse compréhensive sur l'ensemble de la Suisse.

3. Modèle d'estimation des apports mensuels des réservoirs de barrage en Suisse

L'estimation des apports naturels pour chaque ouvrage de retenue est effectuée à l'aide d'un module de calcul intégré sur la plateforme HydroGIS, à partir des données de débits mensuels rastérisés (données OFEV obtenues avec le logiciel PREVAH). Ce module permet d'effectuer les analyses suivantes:

- Identification automatisée des bassins versants naturels (Fig.2) participant aux apports pour chaque ouvrage de retenue inclus sur HydroGIS, par découpage et somme de sous-basins contributeurs;

- Intégration des données de débits mensuels (Fig. 3) sur le bassin versant naturel obtenu précédemment, pour le calcul des apports mensuels pour chaque retenue, puis les apports annuels cumulés.

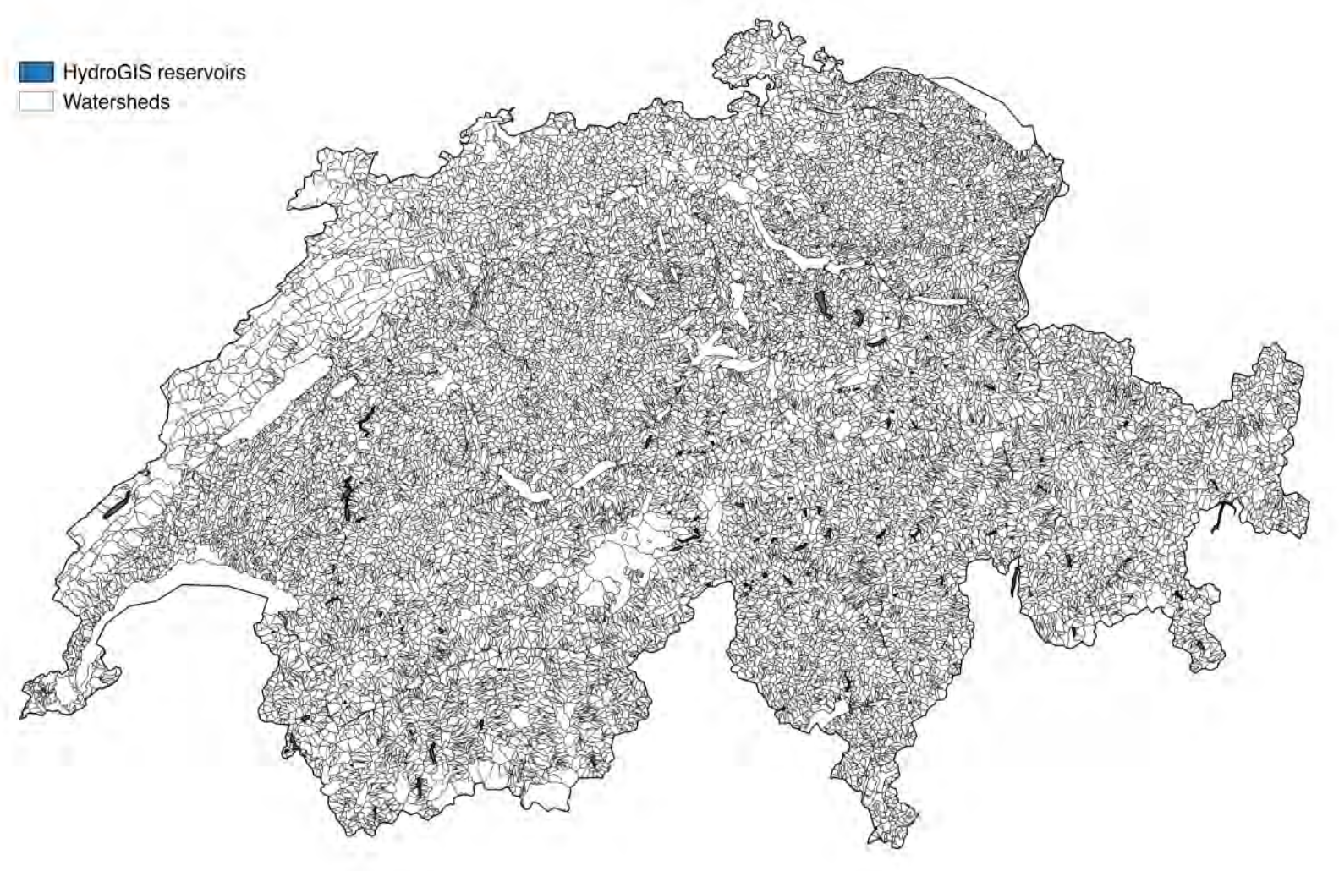

Fig. 2: Découpage du territoire suisse en bassins versants standardisés de 2 km² par l'OFEV

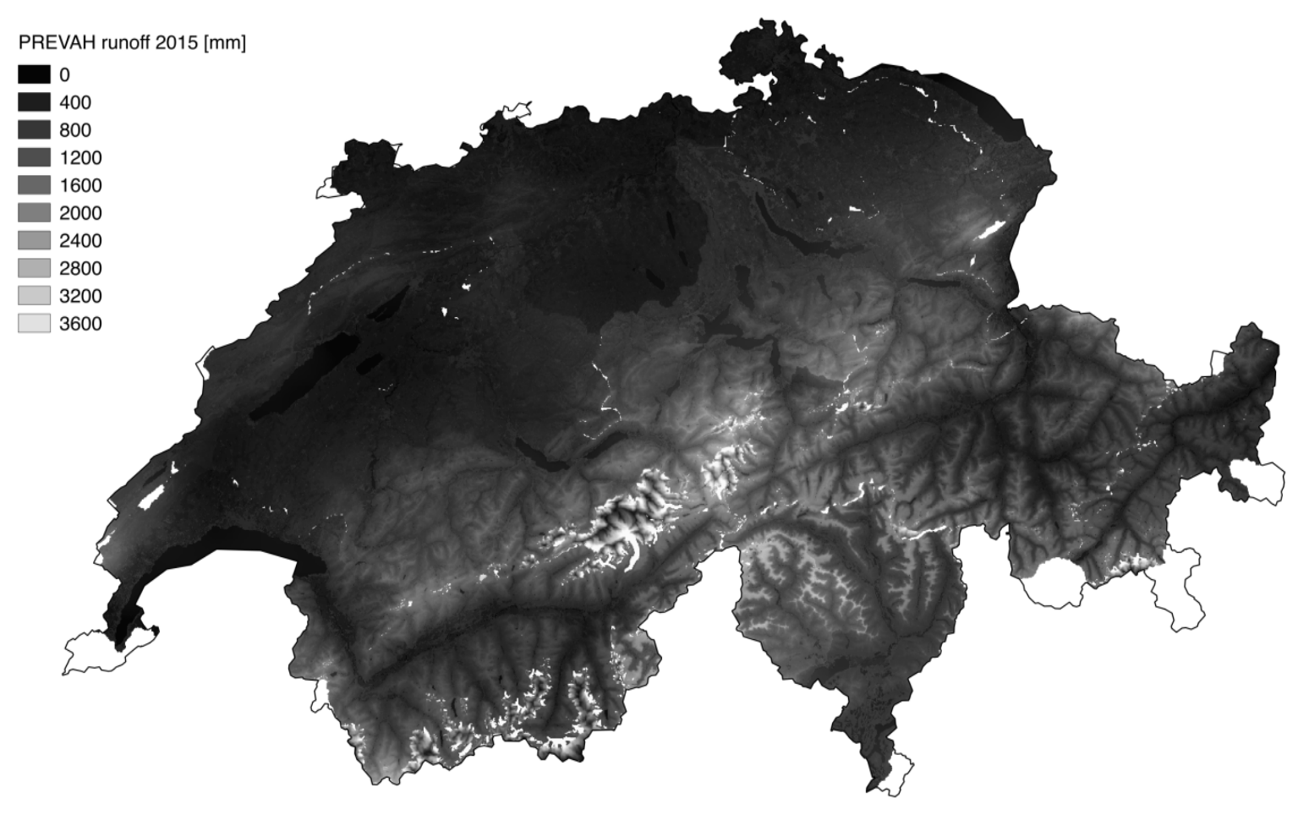

Fig. 3: Débits annuelles en 2015 obtenus à partir de débits mensuels PREVAH

4. Estimation du taux de déficit de stockage

Le calcul du Taux de Déficit de Stockage (TDS) est un moyen efficace d'obtenir une vision globale du potentiel d'optimisation des ouvrages de retenues suisses. Ce ratio est calculé de la manière suivante:

$$\text{TDS} = \frac{\mathit{Apports\ Annuels\ Moyens}}{\mathit{Capacité\ de\ Stockage}}$$

Les Apports Annuels Moyens sont estimés pour chaque ouvrage de retenue grâce au modèle présenté précédemment, pour la période de 1980 à 2015.

- **TDS>1 :** Les apports annuels moyens sont supérieurs à la capacité de stockage de la retenue: il existe un déficit de stockage au vu des apports reçus;

- **TDS<1 :** La capacité actuelle de stockage de la retenue est supérieure aux apports annuels des réservoirs: d'avantage d'eau peut être dérivée vers cette retenue (*i.e.* par gravité ou par pompage).

- Le TDS a été estimé pour la plupart des ouvrages de retenue suisses de la base de données HydroGIS (214 ouvrages);
- Ces 214 ouvrages représentent 8778 GWh de capacité de stockage, soit plus de 99% de la capacité totale de stockage hydroélectrique;
- La figure ci-dessous (Fig. 4) présente les ouvrages de retenues ayant un déficit de stockage inférieur à 5. Pour ces ouvrages les apports sont jusqu'à 5 fois supérieurs aux volumes des retenues, ce qui illustre le manque de choix temporelles sur les utilisations de l'eau et la protection contre les crues.

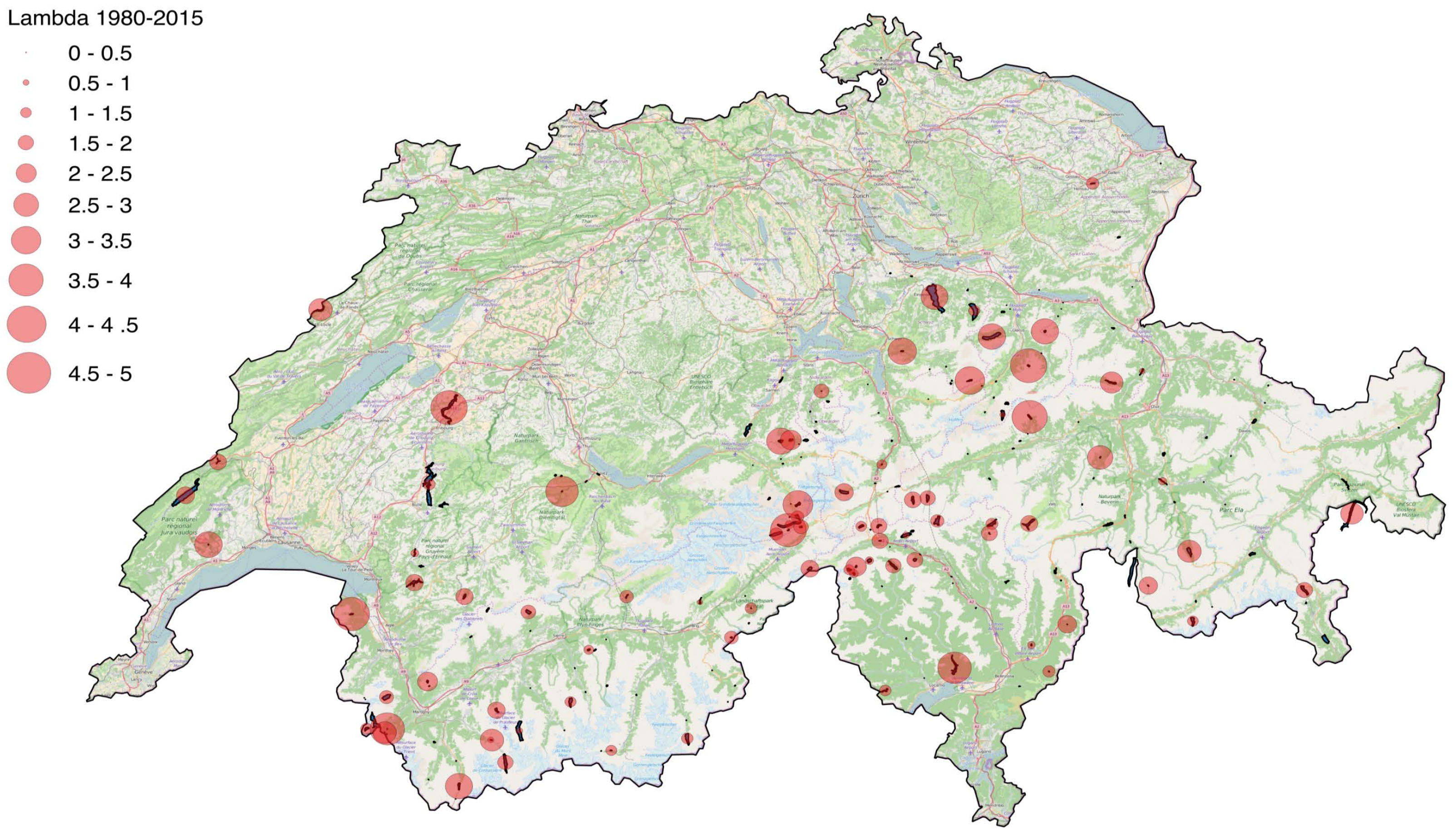

Fig. 4: Taux de Déficit de Stockage (Lambda) pour les 214 retenues contenues dans HydroGIS

5. Conclusions préliminaires et perspectives

- ✓ Le taux de Déficit de Stockage permet une estimation globale et cohérente à l'échelle annuelle de l'optimisation possible d'un ouvrage de retenue.
- ✓ Ces résultats mettent en évidence que pour nombre significatif d'ouvrages il existe un déficit de stockage au vu des apports reçus.
- ✓ Un nombre important d'aménagements hydroélectriques en Suisse fonctionnent sur plusieurs mois à lac plein, au fil de l'eau, par manque de capacité de stockage des apports abondants en été.
- ✓ La surélévation des ouvrages de retenue présentant un déficit de stockage est une possibilité d'optimisation de la production hydroélectrique suisse, permettant une contribution importante à la réduction des importations d'électricité en hiver;
- ✓ L'extension du module d'identification des bassins versants contributeurs aux bassins de dérivation gravitaire et par pompage est en cours de développement.
- ✓ Pour un nombre significatif de retenues le déficit de capacité de stockage peut changer en fonction des effets du changement climatique, en cours d'évaluation pour la période 2015-2100.

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