# Task 2.1

## Title

Morpho-climatic controls

## Projects (presented on the following pages)

Machine learning methods for predicting hourly to monthly energy demand based on hydro-meteorological measurements and forecasts
K. Bogner, M. Zappa

Spatial precipitation interpolation over an alpine catchment
A. Foehn, J. Garcia Hernandez, G. De Cesare, B. Schaefli A. J. Schleiss

Skill transfer from weather to runoff forecasts in high mountain catchments
S. Gindraux, D. Farinotti

Helicopter-borne ice penetrating radar surveys on the glaciers in the Swiss Alps
M. Grab, A. Bauder, L. Schmid, F. Ammann, L. Langhammer, P. Lathion, H. Maurer

Pre- and Post-processing of an Extended-range Hydrometeorological Ensemble Prediction System
S. Monhart, C. Spirig, J. Bhend, K. Bogner, M. A. Liniger, C. Schär, M. Zappa

Generation of high resolution climate variables for hydropower studies: preliminary model simulations
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High spatio-temporal resolution climate scenarios for snowmelt modelling in small alpine catchments
M. Schirmer, N. Peleg, P. Burlando, T. Jonas

Climate change impacts on HP production and required adaptation strategies - a synthesis
M. Stähli + all partners related to task 2.1

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# Machine learning methods for predicting hourly to monthly energy demand based on hydro-meteorological measurements and forecasts

*K. Bogner and M. Zappa*

## Motivation

Prediction of the energy demand could be of interest for the hydro-power production. Especially in periods of water deficits or surplus this information could be beneficial for the planning of optimal strategies for the upcoming weeks and months. Thus different machine learning methodologies have been tested for predicting possible future demands. First tests have been applied based on the information of hydro-meteorological data and the energy consumption of the Canton Tessin given by SWISSGRID (https://www.swissgrid.ch/swissgrid/de/home/reliability/griddata/data_downloads.html)

## Methods

Three different machine learning techniques have been applied:

- **Multivariate Adaptive Regression Splines (MARS)**
  MARS build linear relationships between predictors and a target by segmenting predictor variables. Possible non-linear relationships can be identified by integrating all segments.
- **Support Vector Machines (SVM)**
  Kernel-based learning method uses an implicit mapping of the input data into a high dimensional feature space defined by a kernel function
- **Random Forest**:
  Random forest is a tree-based algorithm which involves building several trees (decision trees), then combining their output to improve generalization ability of the model. The method of combining trees is known as an ensemble method.

Since the demand shows strong periodicity components, intra-day and weekly fluctuation, additionally a **VectorAutoregressiveRegression** model with eXogeneous Input (**VARX**) in the wavelet domain has been applied

## Data

Simplified assumptions: Region of Lugano used as a proxy for the consumption/demand; thus the meteorological data of Lugano are used as main **Predictors**

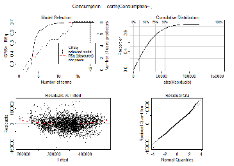
- hourly measurements of Temperature, Precipitation, Global Radiation, Windspeed, Winddirection, Pressure
- Additionally it is assumed that the hydropower plant from Verzasca is the most important producer of energy for the Tessin, thus the inflow to the plant is taken as predictor also
- Further periodicity aspects (intra-daily as Sin and Cos), information of weekday and holidays are included

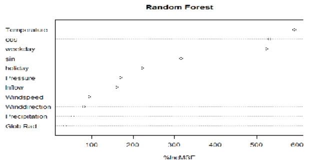
**Target:**
The total consumption/demand of the Canton Tessin

## Results

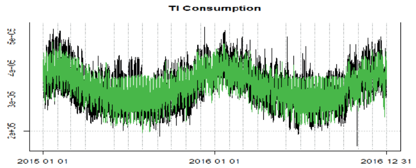
Coefficients of determination ($R^2$, which corresponds to the Nash-Sutcliffe coefficient) of the different models for the training (calibration) period (2015-2016) and the testing (validation) period 2017

| Model | Training | Testing |
|---|---|---|
| **MARS** | 0.70 | **0.64** |
| **SVM** | 0.80 | 0.61 |
| **Regression Forest** | 0.90 | 0.60 |
| **Combination** | 0.84 | **0.66** |





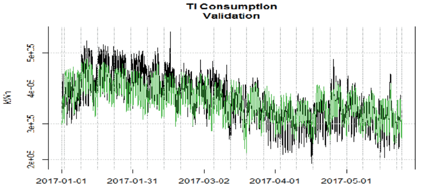
### Results of the MARS model for the training period:



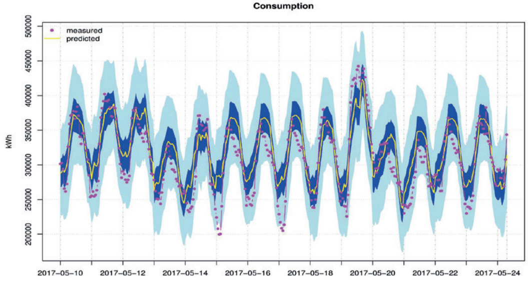
```
                    coefficients
(Intercept)            420357.98
holiday               -39027.83
h(0.5-sin)              7342.88
h(sin-0.5)            -80454.02
h(-0.258819-cos)         9140.52
h(cos- -0.258819)      -69146.05
h(weekday-2)           -35906.66
h(weekday-3)            52533.69
h(weekday-5)           -12798.74
h(6.894-Inflow)          1880.64
h(Inflow-6.894)           246.90
h(6.5-Temperature)       4792.46
h(Temperature-6.5)      -7478.59
h(Temperature-17.3)      7433.11
h(138-Glob.Rad.)          -30.59
h(Glob.Rad.-138)           17.28
h(194-Winddirection)       55.37
h(Winddirection-194)       30.00

Selected 18 of 19 terms, and 8 of 11 predictors
Termination condition: Reached nk 23
Importance: cos, Temperature, sin, weekday,
holiday, Inflow, Glob.Rad., Winddirection,
GCV 1142795537  RSS 1.9959e+13
GRSq 0.699253  RSq 0.7004182
```

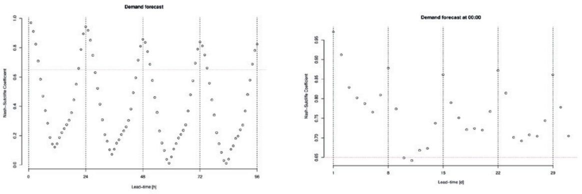
### and for the testing period:



### Prediction of the May of the consumption/demand plus uncertainty bands (50% and 90%)



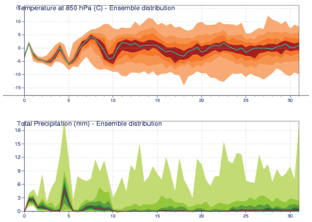
### Results of the VARX model



The Autoregressive model clearly identifies the intra-daily (left) and the weekly fluctuations (right). Around midnight the VARX model gives better results as the MARS ($R^2$ indicated as horizontal line). The Figure on the right side shows the forecasts at midnight only for one month highlighting the weekly periodicity and the good performance of the VARX at the weekend.

## Outlook

Coupling of monthly weather forecasts and the MARS, VARX models and estimation of the predictive uncertainty



Example of a monthly Ensemble forecast, which could be used for demand forecasting

## Open Question:

**How useful is this for the hydropower industry as additional information for optimizing the production? Any comments are very much appreciated: konrad.bogner@wsl.ch**

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# Spatial precipitation interpolation over an alpine catchment

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## Motivation

Estimating with good accuracy the precipitation causing floods is crucial for the security of the population and infrastructures. Optimal exploitation of the available data is therefore desired. Combination of available **rain-gauge networks** and **weather radar** data (Sideris 2014) over the Upper Rhone River basin upstream of Lake Geneva in Switzerland is therefore explored in this study (Fig. 1).

The project aims at evaluating and compare the respective performances of the interpolation methods based on the combination of the available data.

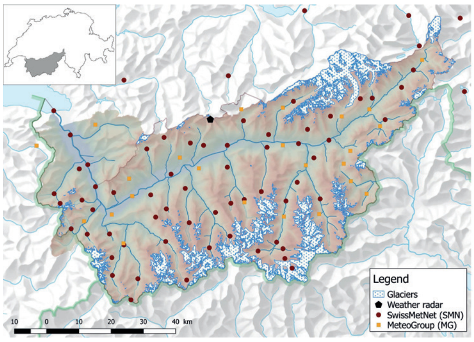

Fig. 1 : Upper Rhone River basin (case study) with location of the meteorological stations and the weather radar of Pointe de la Plaine Morte.

## Case study and methodology

Two independent networks of rain-gauges are used for the study, the SwissMetNet (SMN) network of the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss) and the data of the private company MeteoGroup Schweiz AG (MG).

Three different methods are applied and investigated :

- **Raw radar data**: the hourly raw radar composite precipitation estimate is used as precipitation estimate over the basin.
- **Inverse distance weighting (IDW)**: inverse distance weighting is applied to the SMN stations, with a power coefficient of 2.
- **Regression co-kriging (RCK)**: a linear regression is first applied to the radar precipitation estimates to define a multiplying coefficient for both the primary (SMN) and secondary (MG) variables. Application of these coefficients to the radar raster provides the trend. Residuals are then computed at all stations, given by the difference between the rain-gauge values and the values of the corresponding trend pixels. To obtain interpolated residuals, co-kriging (Myers, 1982) is applied to the residuals. This raster of interpolated residuals is then added as a local correction to the trend to obtain the final estimation.

The performance of the methods is evaluated based on the leave-one-out cross-validation approach using five performance indicators:

$$\mathbf{Bias} = 10\log_{10}\frac{\sum_{i=1}^{N}\hat{g}_i}{\sum_{i=1}^{N}g_i} \qquad \mathbf{MAD} = \operatorname{median}(|\hat{g}_i - g_i|) \qquad \mathbf{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(\hat{g}_i - g_i)^2}{N}}$$

$$\mathbf{MRTE} = \frac{1}{N}\sum_{i=1}^{N}(\sqrt{\hat{g}_i} - \sqrt{g_i})^2 \qquad \mathbf{Scatter} = \frac{1}{2}(\mathrm{CEDF}_{84} - \mathrm{CEDF}_{16})$$

where $g_i$ is the observed value at a station, $\hat{g}_i$ the cross-validation estimation, $N$ the number of rain-gauges and CEDF the cumulative error distribution function of the ratios between estimated and observed values, expressed in decibel. The four analysed events are described in Table 1.

Table. 1 : Events considered for the analysis.

| Event | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Occurrence | Nov. 14 | May 15 | Jan. 16 | Mar. 17 |
| Duration [h] | 44 | 84 | 69 | 46 |
| Median cumulative rain at gauges [mm] | 37.5 | 96.2 | 41.2 | 34.2 |
| Maximum cumulative rain at gauges [mm] | 179.5 | 375.7 | 158 | 68.3 |

## Results

The obtained performance indicators, aggregated per event, and the total precipitated volume over the basin, are presented in Fig 2. Detailed results on an hourly basis are provided for the second event in Fig. 3.

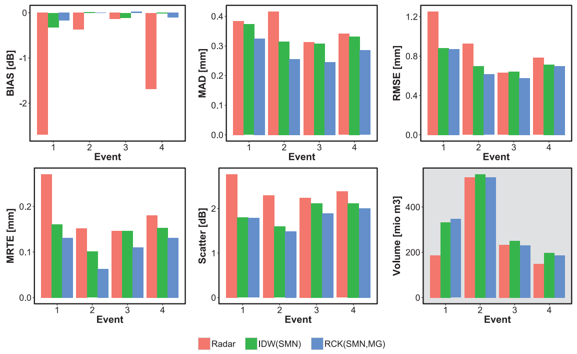

Fig. 2 : Event-average performance indicators and total precipitated volume (gray background) for the four events.

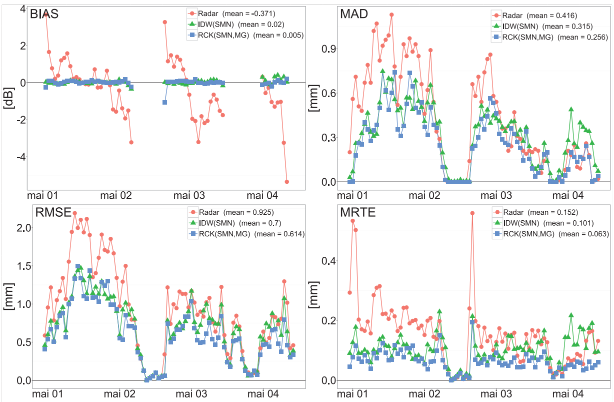

Fig. 3 : Hourly performance indicator values for the event 2 (May 2015). The scatter indicator is not shown as it is computed only over the event.

## Discussion and conclusion

The **RCK method using both SMN and MG provides the best results** (Fig. 2), whereas using raw radar data leads to the lowest performance, in particular in terms of bias. **The difference between IDW and RCK is higher when the precipitation fields are characterized by strong spatial gradients**. This is well visible in Fig. 3 over the last ten hours of event 2 (MAD and MRTE), during which a clear south-west to north-east precipitation limit was visible over the studied basin.

Future improvements of the methodology could include pre-treatment of the radar data, to account for shielding of the radar beam by mountains, and integration of additional covariates in the RCK regression step.

## References

Foehn, A., García Hernández, J., Schaefli, B., De Cesare, G. and Schleiss, A. J. (2016). *Spatialization of precipitation data for flood forecasting applied to the Upper Rhone River basin*, International Conference Hydro 2016, Montreux.

Myers, D. E. (1982). *Matrix formulation of co-kriging*. Journal of the International Association for Mathematical Geology, 14(3). 249–257. ISSN 0020-5958, 1573-8868. doi: 10.1007/BF01032887.

Sideris, I. V., Gabella, M., Erdin, R. and Germann, U. (2014). *Real-time radar-rain-gauge merging using spatio-temporal co-kriging with external drift in the alpine terrain of Switzerland: Real-time radar-rain-gauge merging*. Quarterly Journal of the Royal Meteorological Society, 140(680). 1097–1111. ISSN 00359009. doi: 10.1002/qj.2188.

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# Skill transfer from weather to runoff forecasts in high mountain catchments

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## Context and objectives

**Aim of the study:**

1. Investigate the propagation of forecast skills from weather to runoff predictions in high mountain catchments.
2. Examine if the skill transfer is affected by the morphological characteristics of a given catchment or/and by the hydrological model used.

⇨ The overall objective is to improve runoff forecasts which in turn will help increasing the electricity production in the hydropower sector.

**Research question:** How does a given skill in meteorological input variables translates into the skill of the corresponding hydrological forecasts?

**Main steps followed:**

1. Weather prediction were produced in a modeling framework and their forecast skill was quantified.
2. The weather forecasts were used to a force hydro-glaciological model in order to generate runoff predictions.
3. The transfer of the skill is evaluated (ongoing study).

## Methods

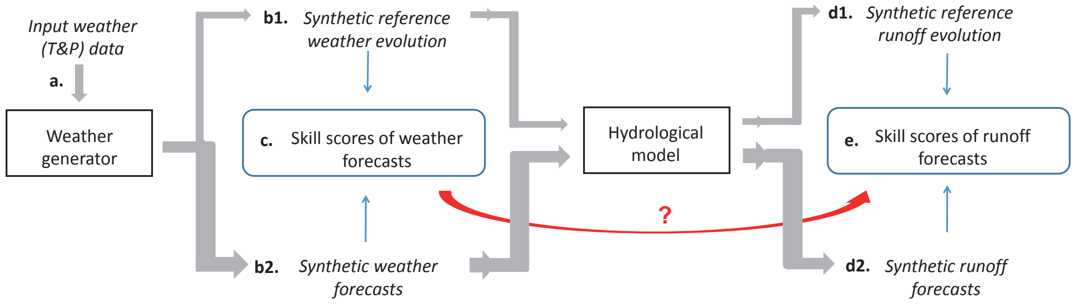
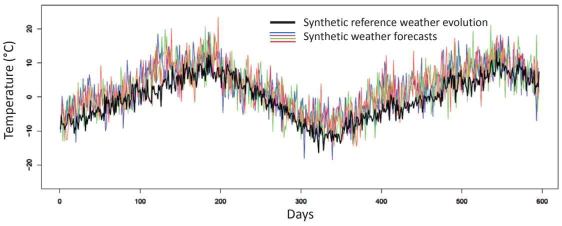


**Figure 1: Methodological workflow of the study**

**a:** An observed temperature and precipitation time was used as input in an in-house weather generator (Farinotti 2013).
**b1:** A time series that is statistically equivalent to the input data was generated and used as synthetic reference weather evolution.
**b2:** The synthetic weather forecasts were generated by modifying the reference weather evolution (i.e. addition of a trend, a bias, noise, etc.).
**c:** Skill scores of the weather forecasts were calculated based on the reference forecast.
**d1:** The reference weather evolution was fed into a hydrological model to generate the reference runoff evolution.
**d2:** Each weather forecast were fed into the same hydrological model to produce its corresponding runoff forecast.
**e:** The skill scores for the runoff forecasts were calculated.

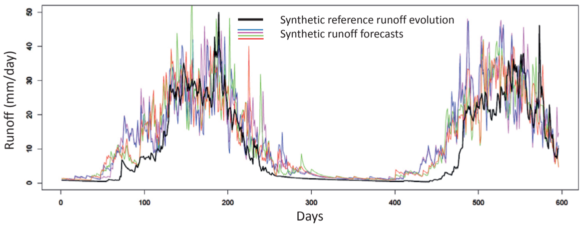
## Preliminary results

### Example of synthetic weather forecasts (from step b1+b2)



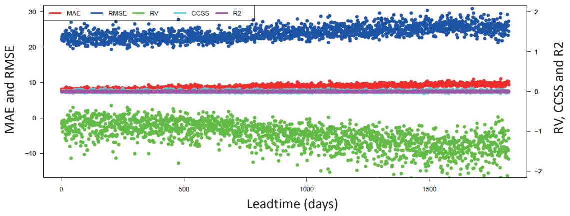
Daily forecasts generated with a trend of 4°C, a bias of 2°C, a long-term oscillation, changes in daily, monthly and yearly variability as well as random noise.

### Example of runoff forecasts (from step d1+d2)

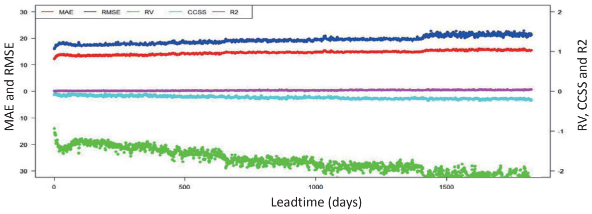


Daily synthetic runoff forecasts generated with the Glacier Evolution Runoff Model. The synthetic weather forecasts were used as input data.

### Skill scores of the synthetic weather forecast (from step  c)



### Skill scores of the runoff forecast (from step e)



Mean Absolute Error (MAE) / Root Mean Square Error (RMSE) / Reduction of Variance (RV) / Correlation Coefficient Skill Score (CCSS) / Correlation coefficient (R2)

## Next steps

The next step is to analyze the transfer of forecast skills. For this, the skill scores calculated from the weather forecasts (temperature and precipitation) will be evaluated against the corresponding scores calculated from the runoff forecasts, over different leadtimes. A similar analysis will be conducted on a glacier-free catchment to observe if the forecast skill transfers differently.

**Reference:** Farinotti, D. (2013). On the effect of short-term climate variability on mountain glaciers: insights from a case study. *Journal of Glaciology*, *59*(217), 992-1006

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# Helicopter-borne ice penetrating radar surveys on the glaciers in the Swiss Alps

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*Melchior Grab, Andreas Bauder, Lino Schmid, Fabian Ammann, Lisbeth Langhammer, Patrick Lathion, Hansruedi Maurer*

## 1. Introduction

Electricity production from hydropower plants in Switzerland is dependent on the water resources existing in the alpine area and on the annual river run-off from these regions. With the ongoing retreat of the glaciers in the Swiss Alps, these factors will change strongly in the near future. Thus, to adapt the strategies for the hydropower production under consideration of these changing environmental conditions, better knowledge is required about the present volume and geometry of alpine glaciers and of the topography of the glacier beds.

## 2. Project – Overview and Current State

The goal of this project is to estimate the total ice volume in the Swiss Alps and to deliver information about the glacier bed topography. During the first phase of SCCER-SoE, the three "pillars", needed to reach this project goal, were obtained. This includes (see Fig. 1) the helicopter-borne ground penetrating radar (GPR) instrument (surveying capabilities), the MATLAB®-based software libraries to derive the glacier bed from the radar data (processing capabilities), and a GIS database through which the 2D Images through the glaciers showing the ice-thickness can be organized (Database capabilities).

Based on these pillars, the focus was set during the past year on the radar data acquisition and the data processing in order to obtain the ice thickness maps ("roof" of the project, Fig. 1)

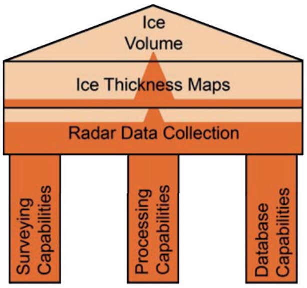

***Figure 1:** Project sketch. Three "pillars" of capabilities were needed before the "roof", i.e. the ice thickness data, can be gathered. Dark shaded colors are the completed sections and light shaded colors are the planned sections.*

## 3. GPR Instrument and Data Acquisition

The data is acquired with two pairs (Tx & Rx) of 25 MHz GPR antennas, mounted orthogonal to each other on a wooden frame, which is carried by a helicopter (Fig. 2). After the GPR-system was lost during a campaign in October 2016, a new system has been built with the newest available hardware and with an optimized assemblage and cabling. The new system was successfully tested in February 2017 and then used for acquiring data until early Summer 2017. A data example is shown in Fig. 3.

## 4. GPR Data-Processing

The GPR data is processed using the processing capabilities, built during the first phase of the SCCER-SoE project. Parts of it were recently optimized in the frame work of a Master thesis. This includes an optimized removal of signal ringing due to the interference with reflections from the helicopter (see Fig. 3, top), and a more powerful migration algorithm, which enables to image reflections effectively at their presumably true position also in presence of steep reflectors and strong lateral inhomogeneities, e.g. due to a rough glacier surface. The updated processing flow looks as follows:

- `Set time zero`
- `Time window cut`
- `Optimized SVD-filter for ringing removal`
- `Bandpass filtering`
- `Determination of surface reflections`
- `Deconvolution`
- `Reverse time migration (RTM)`
- `Glacier bed picking`

A data example, processed using the newest processing features, is shown in Fig. 3. Bed rock reflections are easily identifiable and are also visible in shallow parts which are more affected by signal ringing.

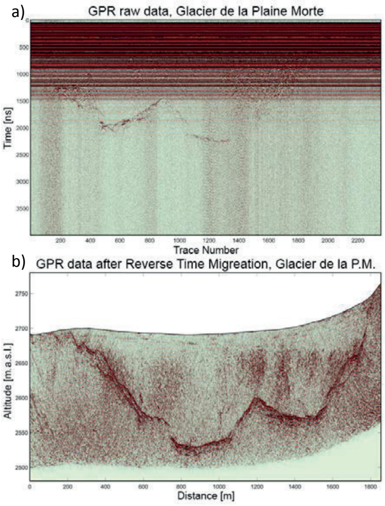

***Figure 3:** a): Raw data. Ringing (interference with helicopter) superimposes bed rock reflections. b): Final reflection profile, processed using the updated processing flow.*

## 5. Glacier Beds and Ice Thickness Maps

From the processed GPR-reflection profiles, the glacier bed is identified, whereas reflections from other rock faces and off-plane objects are excluded from the interpretation (example shown in Fig. 4 b). Continuous ice thickness maps are then obtained from glaciological ice thickness estimation modelling, which uses the discrete GPR profiles as input parameters. Exemplarily, such an Ice thickness map, obtained for the Glacier de Zinal, is shown in Fig. 4 c.

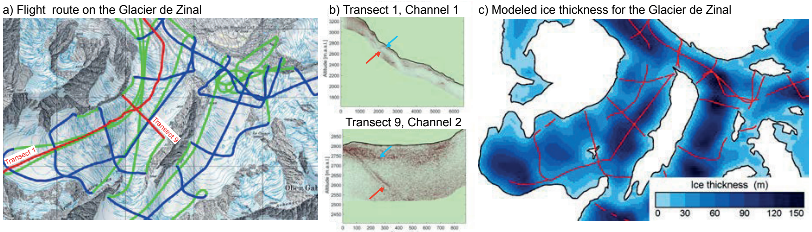

***Figure 4:** a) GPR survey flown on the Glacier de Zinal, transects are marked blue, number 1 and 9 are highlighted red. b) GPR profiles of transect 1 and 9, with glacier bed indicated with the blue arrow. Red arrows show reflections from a rock face. c) Ice thickness based on GPR data, red lines show the transects where the glacier bed was identified in the GPR data*

## 6. Outlook

Currently, our focus is on the processing of the data, recorded during the winter season 2016/2017 in Graubünden and in the Bernese and Valais alps (blue areas in Fig. 5). For the upcoming winter season, data acquisition in central Switzerland and in the Lauterbrunnen/Grindelwald region is planned (encircled areas in Fig. 5).

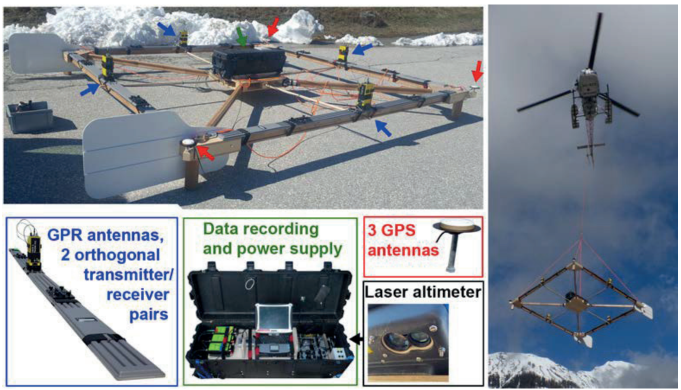

***Figure 2:** Left: Components of the GPR system, mounted on the wooden frame. Right: GPR system attached to a helicopter.*

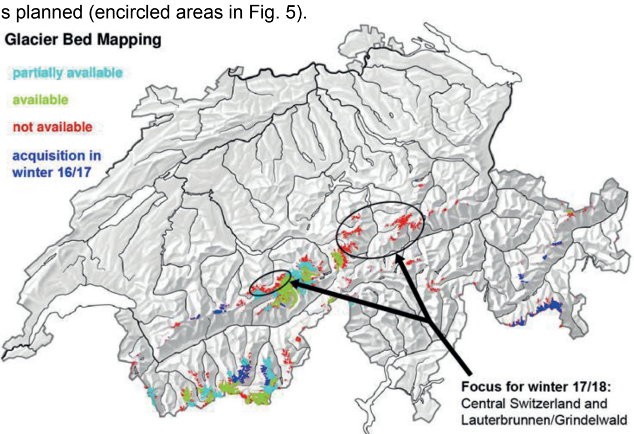

***Figure 5:** Current (September 2017) status of the glacier bed mapping*

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# Pre- and Post-processing of an Extended-range Hydrometeorological Ensemble Prediction System

*Samuel Monhart[1,2,3], Christoph Spirig[2], Jonas Bhend[2], Mark A. Liniger[2], Konrad Bogner[1], Christoph Schär[3] and Massimiliano Zappa[1]*

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[2] Federal Office of Meteorology and Climatology, MeteoSwiss
[3] ETH Zurich, Institute for Atmospheric and Climate Science

## Motivation

We aim at highlighting potential benefits from probabilistic hydro-meteorological forecasts based on Ensemble Prediction Systems in order to provide planning basis for Alpine catchments with installed hydropower capabilities.

Test case: In quasi-operational model the hydrological model PREVAH is driven by extended-range weather forecasts provided by ECMWF (from April 2014 to April 2015). These forecasts consist of 51 members and cover lead times up to 32 days. First results and the verifications of the statistical correction of meteorological input data (pre-processing) and hydrological outputs (post-processing) will be presented here.

## Pre-processing

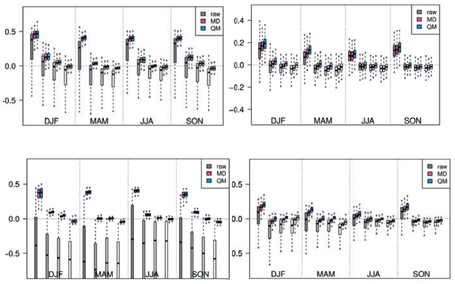
**Problem:** Gap between meteorological (50 km) and hydrological (500 m) model resolutions and inherent biases of the meteorological forecasts

**Method:** A mean debiasing and a Quantile Mapping (QM) technique have been applied to correct the forecasts. We use temperature and precipitation for 1637 stations across Europe to evaluate the meteorological forecasts used as input to the hydrological model.

**Verification:** Continuous Ranked Probability Skill Score (CRPSS), a measure considering both the sharpness and the reliability of the forecast. Reference: Climatology.

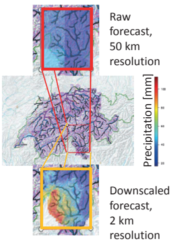
## Pre-processing: Results

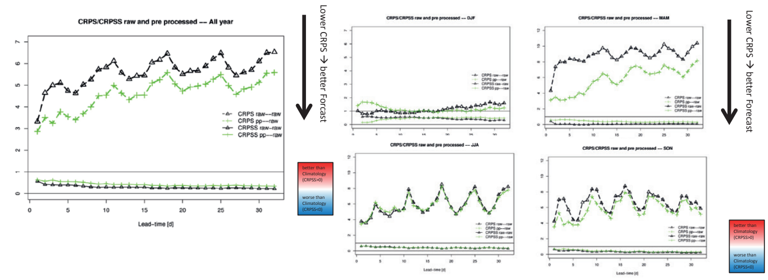
The skill of the forecasts depends on the lead time, the season and the location. In terms of reliability and resolution (CRPSS) the forecast show skill for about two weeks. The QM approach outperforms the simple mean debiasing. Forecasts for stations in complex terrain show less skill but the relative effect of the bias correction is larger.



## Results: Quality of the hydrological Forecasts

For the hydrological processing, the meteorological forecasts are corrected following the procedure described above but using a 2km grid for a small catchment in the southern part of the Alps (Verzasca). Results indicate that pre-processing enhances the CRPSS for all lead times. In spring and autumn, the benefit is largest, whereas during summer and winter there is no clear benefit.





## Post-processing

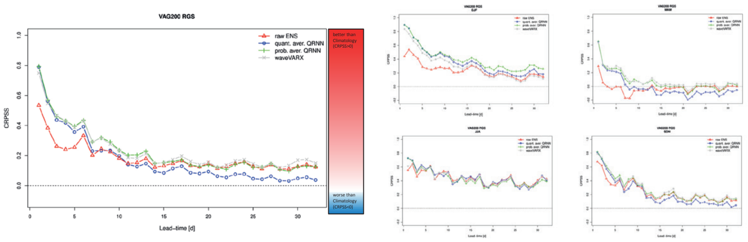
**Problem:** hydrological predictions exhibit biases.

**Method:** 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)

**Verification:** Continuous Ranked Probability Skill Score (CRPSS). Reference: Climatology

## Post-processing: Preliminary results

For the verification of the quality of the hydrological forecasts the CRPSS for the uncorrected and the corrected ensemble is shown for streamflow predictions in the Verzasca catchment (VAG). Depending on the correction method the forecasts from this particular year are improved up to day 7 and 14 respectively. Seasonal differences are even more pronounced.



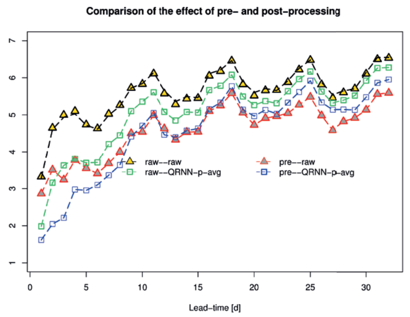
## References and Partners:

- *MeteoSwiss* for the verification and processing of the meteorological forecasts
- Scientific collaboration with the *Institute of Environmental Engineering, ETHZ*, hydropower optimization, (see poster by Anghileri et al.)
- Private partner *Hydrique Ingenieurs* for the operational setup of the prediction system including hydropower optimization

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.

## Combination of Pre- and Post-processing: Preliminary results

For the verification of the quality of the hydrological forecasts the CRPSS for the uncorrected and the corrected ensemble is shown for streamflow predictions in the Verzasca catchment (VAG). Depending on the correction method the forecasts from this particular year are improved up to day 7 and 14 respectively. Seasonal differences are not yet analysed.



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# Generation of high resolution climate variables for hydropower studies: preliminary model simulations

*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 regional climate models (RCMs) from the Euro-CORDEX initiative.

The climate variables are simulated using a new stochastic weather generator, **A**dvanced **WE**ather **GEN**erator for **2-d**imension grid (AWE-GEN-2d), that was recently developed. A re-parameterization scheme has been suggested in order to simulate climate variables for future climate, but has yet to be peer-reviewed.

Here, we demonstrate the ability of AWE-GEN-2d to simulate high-resolution climate variables for a future climate by simulating a single realization driven by a single RCM for the years 2020-2100. The Engelberger catchment, representing a complex orography terrain in the Alps, was chosen as a case study.

**AWE-GEN-2d products will be available for the SCCER members upon demand.** An example for an ongoing collaboration (Gletsch Glacier) is presented in the poster by Schirmer et al.

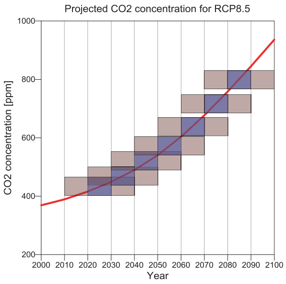
## AWE-GEN-2d re-parameterization

The method for generating future climate projections consists in re-evaluating some of the parameters of AWE-GEN-2d, as compared to the parameter values obtained from observations, using inferences from climate model outputs. Factors of change (FC) are used to quantify the projected change for several statistics of climatic variables by comparing a specific control scenario (a period of time when both observations and climate model simulations are available) with a specific future scenario (only model simulations are available).

FC is estimated only for precipitation (considering the future changes in spatial occurrence and precipitation intensity), cloud cover (during intra-storm period) and near-surface air temperature (delta change approach is applied). 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. The FC is determined from a set of 14 daily regional climate models (from Euro-CORDEX project).

AWE-GEN-2d is used to simulate the climate variables for the 21st century period (2020—2100). This is done by applying a decadal moving window for which the statistics from the climate models are estimated on a 30-year period basis.

AWE-GEN-2d will be used to generate 280 simulations (14 climate models x 2 emission scenarios x 10 realizations) of 80-year period for each location of interest, to account for the uncertainties emerges from the emission scenario, climate models and the internal (stochastic) climate variability.



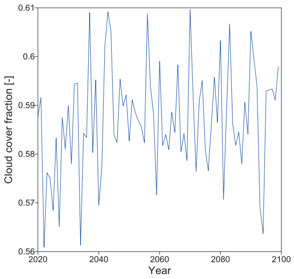
## Case study

AWE-GEN-2d was calibrated and validated for the Engelberger catchment (see Peleg et al., 2017). Precipitation is simulated for 5-min and 2-km resolution, while the other climate variables (e.g. temperature, radiation, relative humidity, near-surface wind speed) are simulated for hourly and 100-m resolution.

FC were calculated for one climate model chain for this demonstration: the SMHI-RCA4 regional climate model that is driven by the CNRM-CERFACS-CNRM-CM5 global circulation model. FC are calculated for the extreme GHG emission scenario (RCP85). Results from a single realization simulating the period 2020—2100 are presented.

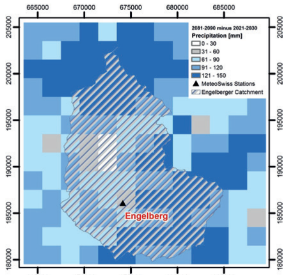
## Cloud cover

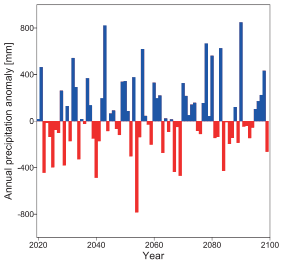
The projected annual mean cloud cover over Engelberger catchments for the period lasting to the end of the century is presented. The future projected cloud cover is very similar to the present cloud cover, as the FC for this region is relatively small (~5%), and fall within the expected range of the natural annual variability (~8%), i.e. the signal of the climate change is not pronounced.



## Precipitation

The projected annual mean precipitation over Engelberg station for the 21th century is presented (right figure). As for the cloud cover, the climate change signal is weak and is in the same order as of the natural annual variability of precipitation (~10%). Large variability is expected in space due to the precipitation stochastic nature, and is indeed captured by AWE-GEN-2d. The mean precipitation difference between two decades representing the end of the century (2081—2090) and near-future climate (2021—2030) is presented in the left figure.

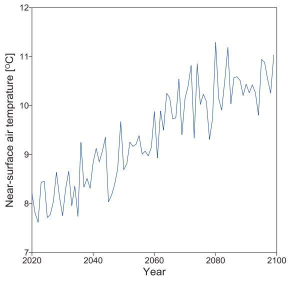


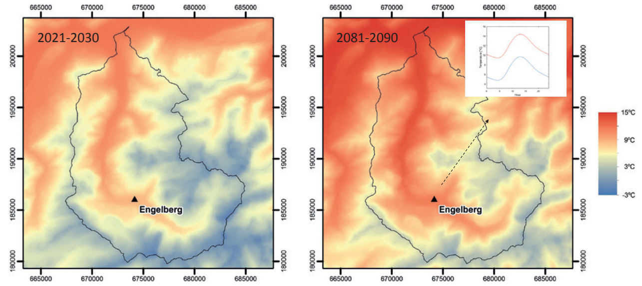


## Temperature

A significant climate change signal in temperature is projected (>3◦C), as demonstrated for the Engelberg station (right figure).

AWE-GEN-2d ability to simulate the projected temperatures on a fine grid scale is shown in the figures below, comparing mean decadal temperatures between near-future (left) and end of the century (right).





Peleg, N., S. Fatichi, A. Paschalis, P. Molnar, and P. Burlando (2017), An advanced stochastic weather generator for simulating 2-D highresolution climate variables, J. Adv. Model. Earth Syst., 9, 1595–1627.

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# High spatio-temporal resolution climate scenarios for snowmelt modelling in small alpine catchments

*Michael Schirmer, Nadav Peleg, Paolo Burlando, Tobias Jonas*

## Motivation

The aim of this project is to support economic risk assessments of long-term investments by small hydropower plant (SHP) operations due to a changing climate. We will estimate the impact of climate change on distribution and frequency of the inflow in a snowmelt dominated tributary of a SHP using an innovative combination of novel components: a stochastic 2-dimensional weather generator, and a high-resolution energy balance snow cover model. Preliminary results for the present climate are presented.

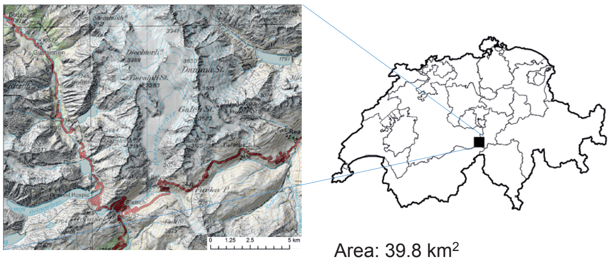
## Methods

The weather generator (AWE-GEN-2d, see poster by Peleg et al.) produces a physically-consistent set of climate variables in a high temporal and spatial resolution, satisfying the fine-resolution that is required for energy balance modelling of snowcover accumulation and melt.

The energy balance snow model (JIM/FSM) allows applications at very high spatial resolution by specifically accounting for small-scale processes relevant in mountainous environments. This model upgrade integrates developments such as a subgrid-paramerization of snow covered area based (SCA) on terrain variables to implicitly account for snow redistribution.

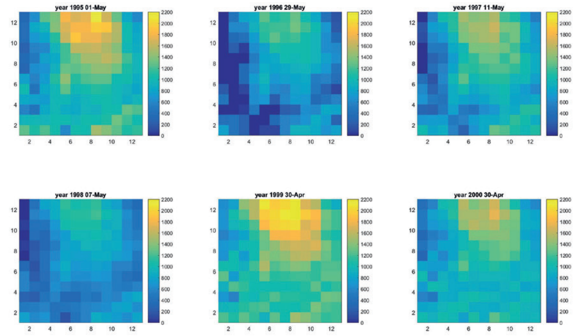
40-year of monitoring data for snow water equivalent (SWE) was used to verify snow distribution patterns at coarser spatial scale.

## Location – Demonstrator project for SHPs



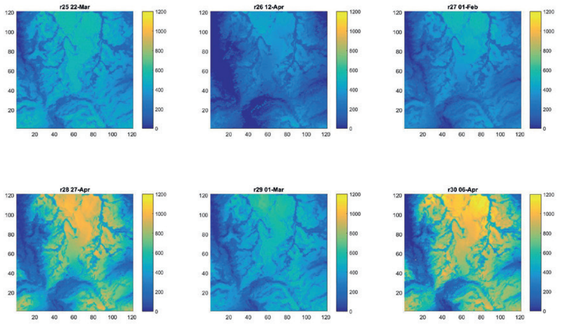
Area: 39.8 km$^2$
Glaciation: 52%
Mean elevation: 2719 m a.s.l.

## Comparison with SWE climatology



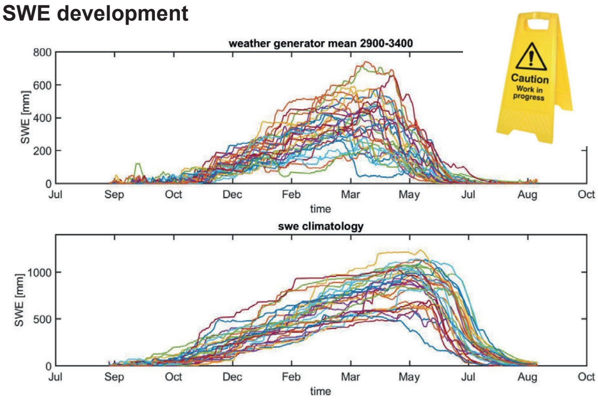
- SWE in mm at peak of the season (date)
- 40 years available
- 1 km resolution based on observations, temperature index modelling and data assimilation techniques.

## Preliminary results



- SWE in mm at peak of the season (date) of six realizations
- Weather generator (WG) delivers 30 realisations representing the natural climate variability
- WG provides hourly data in a spatial resolution of 100 m by 100 m
- Energy balance (EB) model integrates terrain based precipitation and SCA parameterisations (e.g. less snow in steep locations)

## SWE development



- Average SWE of 30 years/realizations in an elevation band of 2900 to 3400 m
- Preliminary results of WG/EB model has certain differences to a current climatology, e.g. related to SWE amounts, mid winter melt conditions, earlier melt out

## Outlook

- Account for differences between SWE climatology and the results of the weather generator/energy balance model combination
- Couple results with a gridded hydrological model and compare results with 30 years of runoff observations
- Generate time series climate scenarios based on the output of regional climate models
- Estimate the impact of climate change on distribution and frequency of the inflow at the intake of the SHP in Gletsch and other small mountain catchments (e.g. Adont, Grisons)
- **This is the first time that such an innovative combination of methods is applied enabling a realistic representation of small-scale processes in alpine terrain. Accounting for spatial variability is key to accurately assess changes in the distribution and frequency of runoff in small mountain catchments.**

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# Climate change impacts on HP production and required adaptation strategies – a synthesis

*All partners related to Task 2.1 (Lead: Manfred Stähli, WSL)*

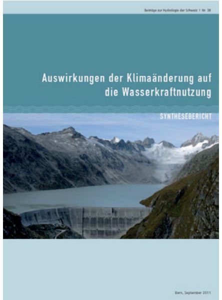
## Background

Climate change will considerably alter the timing and the amount of water available for HP production, and it will change the supply and transport of sediments to HP dams and infrastructure. In addition to these natural controls, climate change will also have indirect impacts on future HP production: for example, the demand for electricity – and thus the market price – will change with a warming climate, and climate change will also control the production of alternative renewables.

HP industry needs to know what that finally means for the hydropower production in the future and how they can adapt in an optimal way.

Recognizing that is one of the most pressing issues for HP industry, SCCER SoE decided to compile a specific synthesis on this issue by the end of phase II.

## Previous syntheses of climate change impacts on HP production in Switzerland



This will not be the first comprehensive study of climate change impacts on HP production in Switzerland. One of the first such assessments was published by Westaway (2000) for the Grande Dixence hydro-electricity scheme. A first synthesis for the Swiss alpine HP production was compiled by Schaefli et al. (2007). The most recent comprehensive synthesis was issued by SwisselectricResearch, BfE, Canton Valais and FMV and published in 2011.

## Why yet another synthesis on climate-change impact on HP production?

- Climate change scenarios for Switzerland will be updated in 2018 (based on most recent emission scenarios)
- A lot of new research results have been gained since 2011, and numerical models have been improved and applied in a more integrated way.
- Adaptation measures were not considered in previous studies.

## Preliminary concept of the upcoming synthesis

The synthesis report will consist of two parts:

- one summarizing **the (quantitative) changes** in water availability, sediment yield and HP production accounting for climate-change induced effects on electricity demand and other renewables.
- one proposing **adaptation measures** for the HP industry.

The synthesis report shall be guided by specific questions of operators, decision makers and administrators of HP production in Switzerland (see below).

*Timeline*:
Nov 2017: Synthesis concept is approved (Site visit KTI) and list of guiding research questions is consolidated.
Dec 2017: New climate-change scenarios CH2018 available
Dec 2018: First preliminary draft of the synthesis available

## Specific questions to be answered in this synthesis

Operators, decision makers and administrators of HP production in Switzerland have very clear specific questions when it comes to the future impact of climate change. Our synthesis shall be guided by such questions and answer them explicitly.

Here is a selection of potential questions that could be addressed:

- How will HP production change in winter (in relation to the expected overall winter-time demand)?
- Where (in Switzerland) will sediment delivery to HP intakes increase/ decrease in future?
- What consequences would changes in general weather patterns (e.g. jet stream) have for HP production?
- Worste-case scenario – what are the perspectives for HP if the international climate politics fails?