# High resolution climate change projections and design of hydropower reservoir operations to balance productivity and profitability

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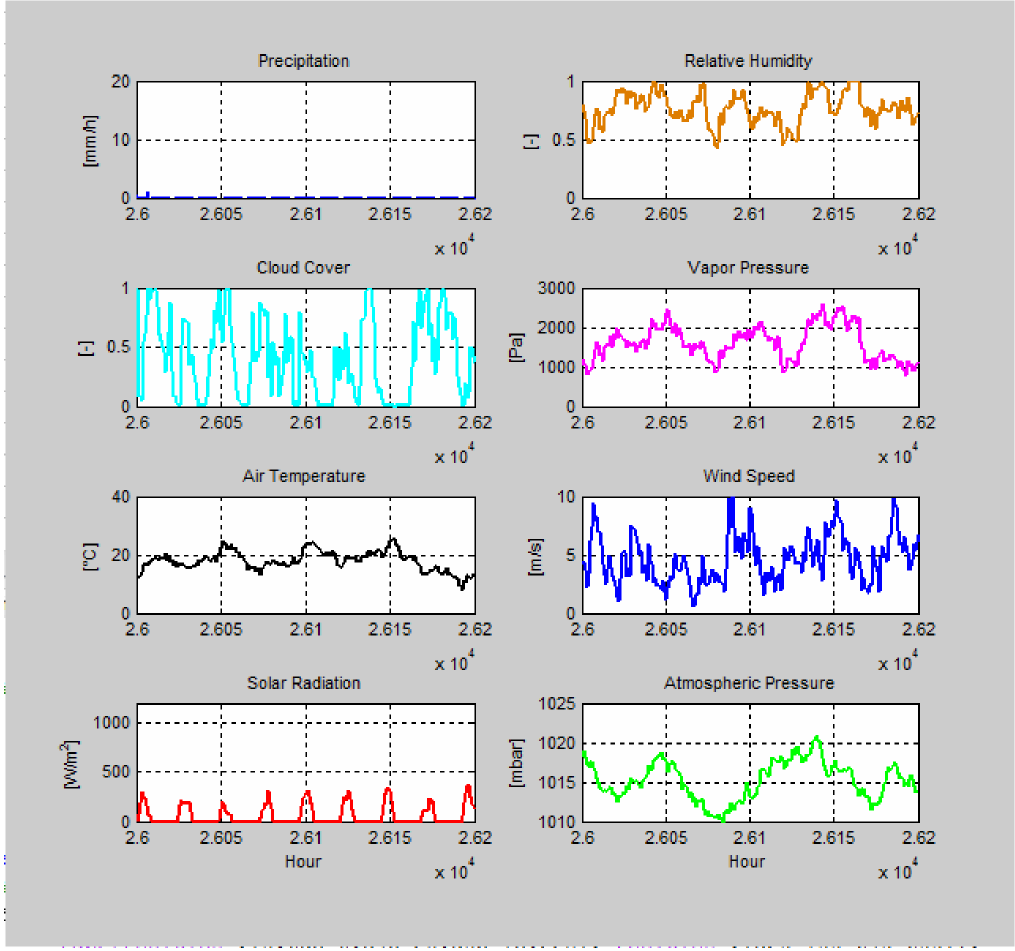
# General framework

This work represents a joint effort of task T2.1 (Morpho-climatic drivers) and T2.5 (Hydrology hydropower simulation)

We combine high resolution stochastic weather generator model with spatially distributed hydrological model and advanced water resources management techniques to analyze current and future hydropower production under climate and price scenarios.

# Stochastic weather generator

- Downscaling of climatic variables based on climate model data and observations
- Many stochastic realizations of current and projected climates can be generated
- Quantifying the variability related to climate
- Estimating the uncertainty related to hydropower

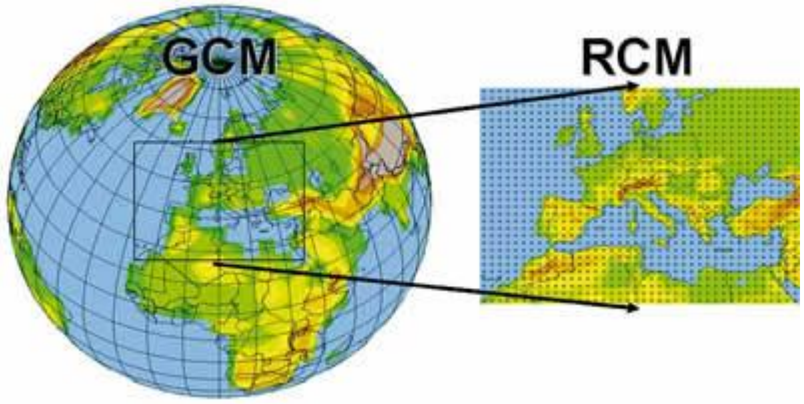


AWE-GEN (*Fatichi et al., 2011*)

# What is the required spatial and temporal resolution?

250 km , daily

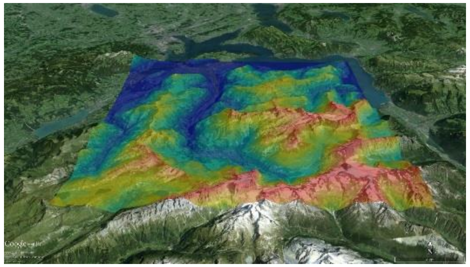
Euro-CORDEX
12-50 km , 6-h



Climate4impact.eu

stochastic
weather
generator

downscaling



100 m , minutes

# AWE-GEN-2d

## A **stochastic** weather generator

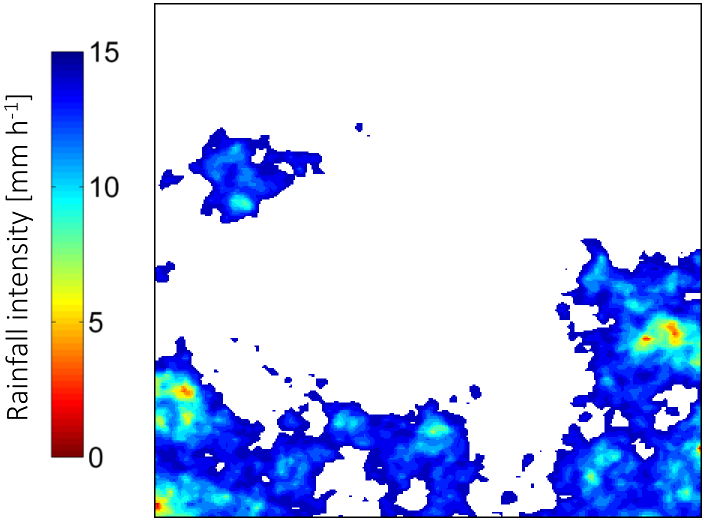
- The AWE-GEN-2d (**A**dvanced **WE**ather **GEN**erator for **2-D**imension grid) follows the philosophy of combining physical and stochastic approaches to generate gridded climate variables at a high spatial and temporal resolutions.
- It is relatively parsimonious in terms of computational demand and allows generating many space-time stochastic realizations of current and projected climates in a fast and efficient way.

# AWE-GEN-2d

## Rainfall fields

Spatial resolution of 2 x 2 km$^2$

Temporal resolution of 5 min



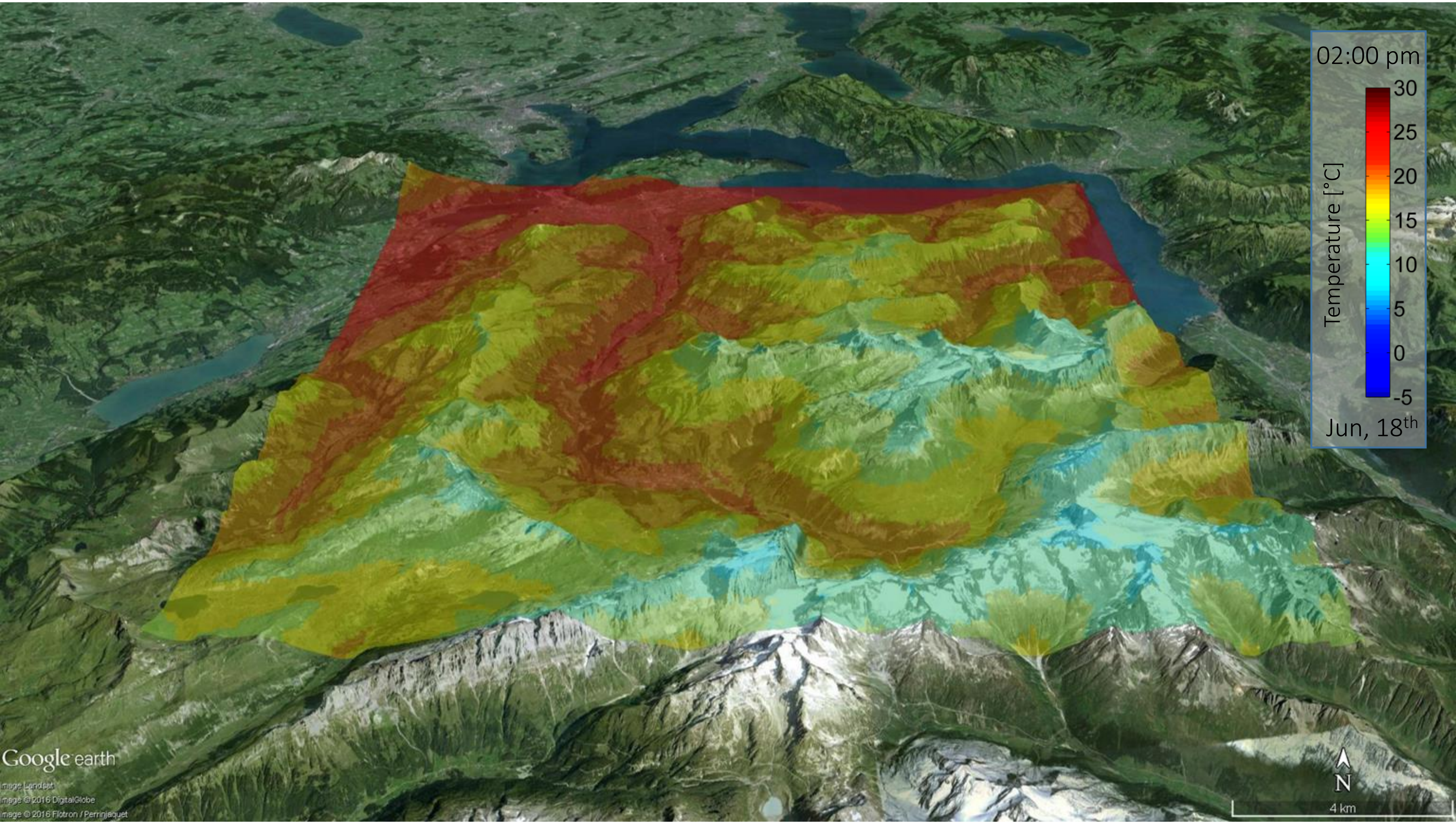
STREAP (*Paschalis et al., 2013*)

## All other climate variables

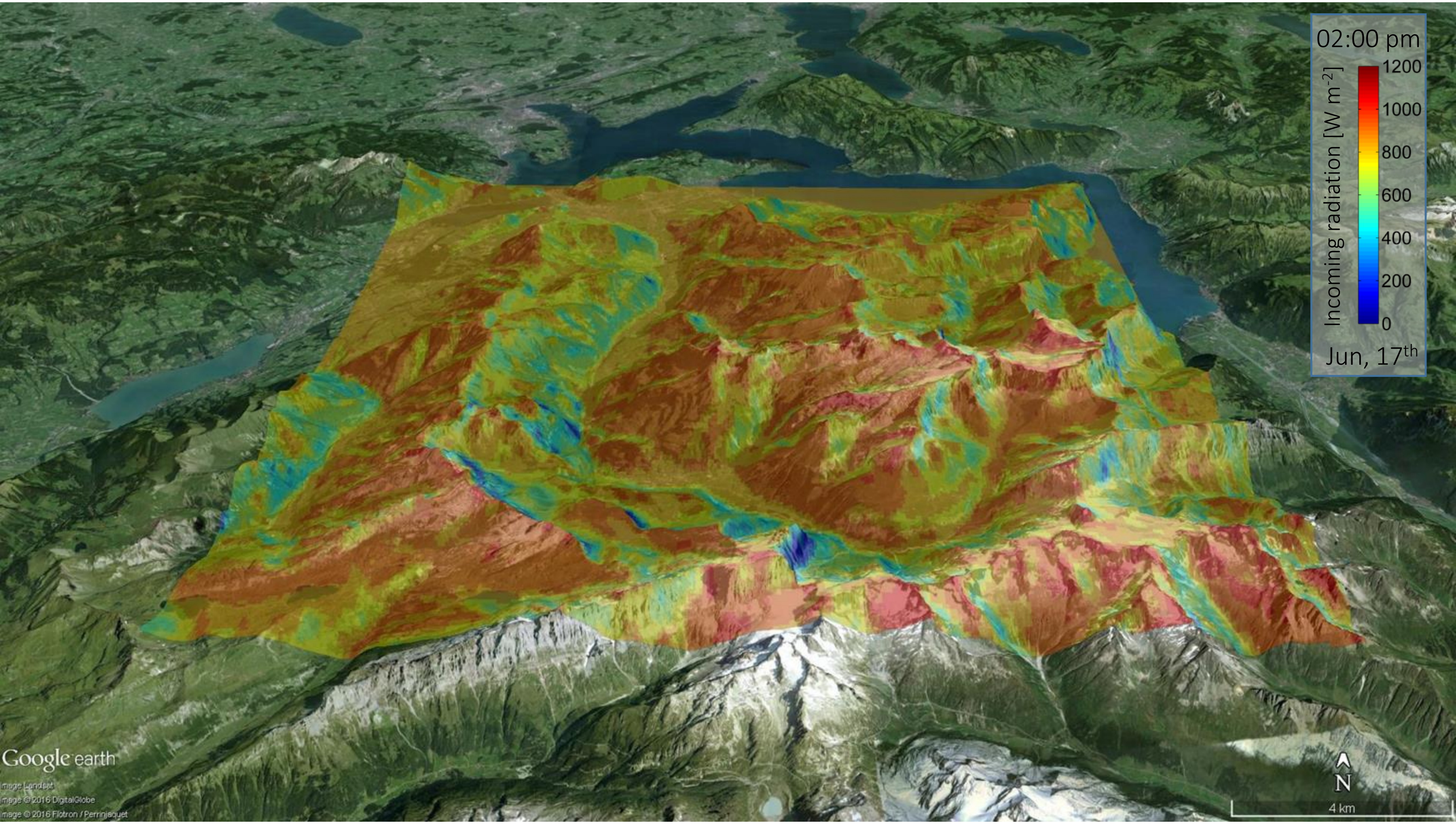
Spatial resolution of 100 x 100 m$^2$

Temporal resolution of 1 hour

# Temperature

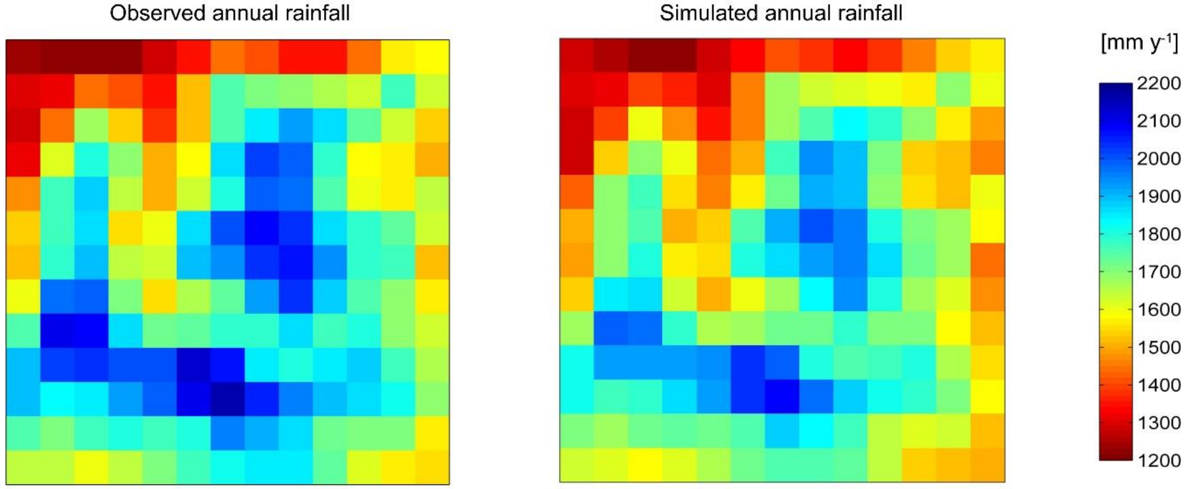


# Radiation

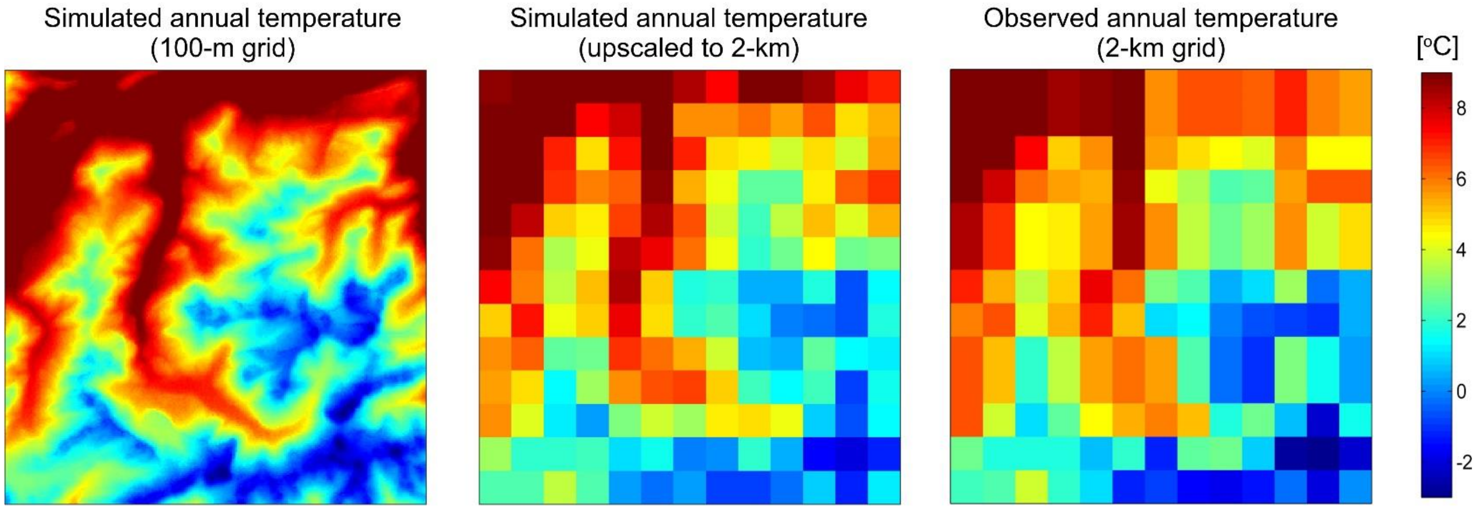

02:00 pm
Incoming radiation [W m⁻²]
1200
1000
800
600
400
200
0
Jun, 17th
Google earth
Image Landsat
Image © 2016 DigitalGlobe
Image © 2016 Flotron / Perrinjaquet
N
4 km

# Validation

Precipitation

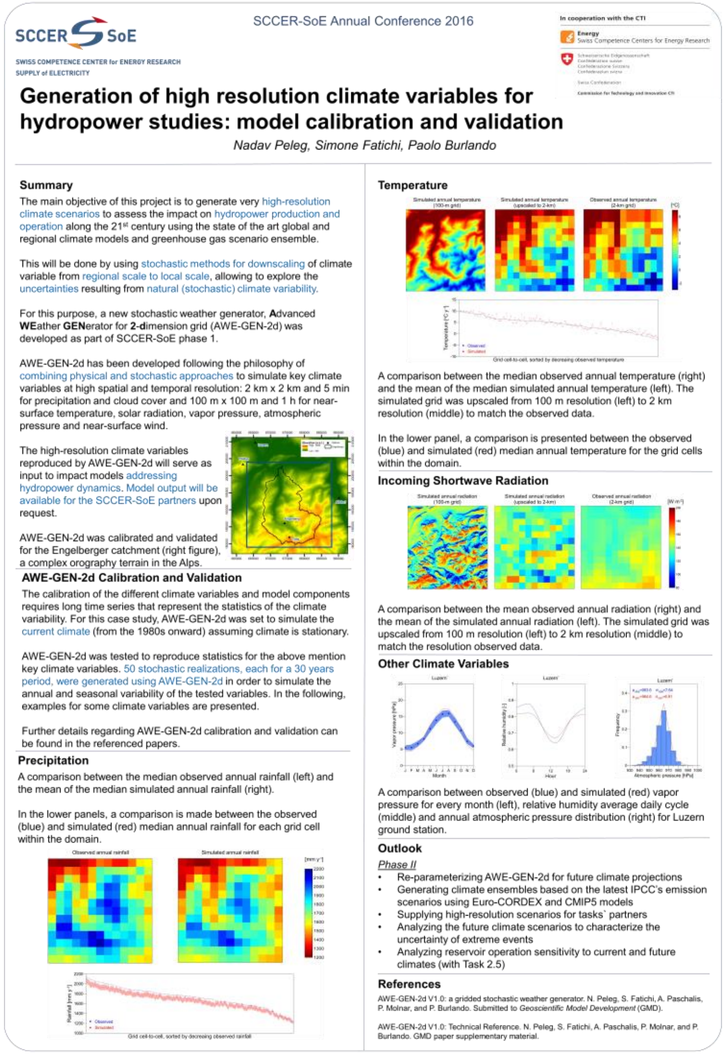


Temperature



# AWE-GEN-2d

## posters



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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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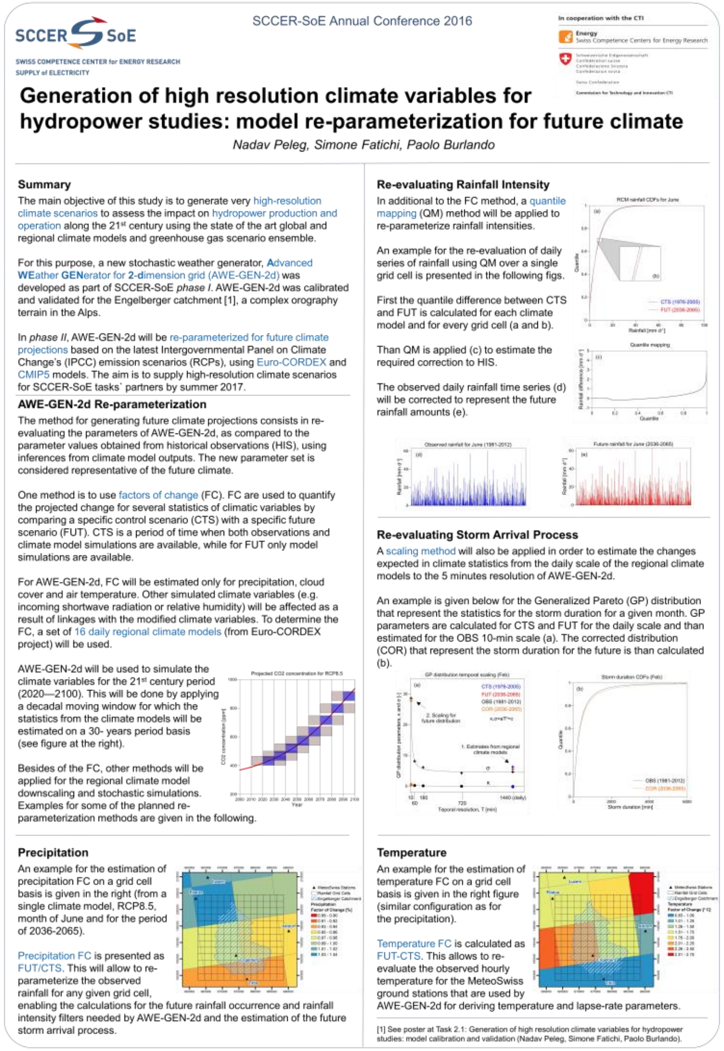

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### Generation of high resolution climate variables for hydropower studies: model re-parameterization for future climate

*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.

[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).

# Hydropower Simulation Objective

Focus:

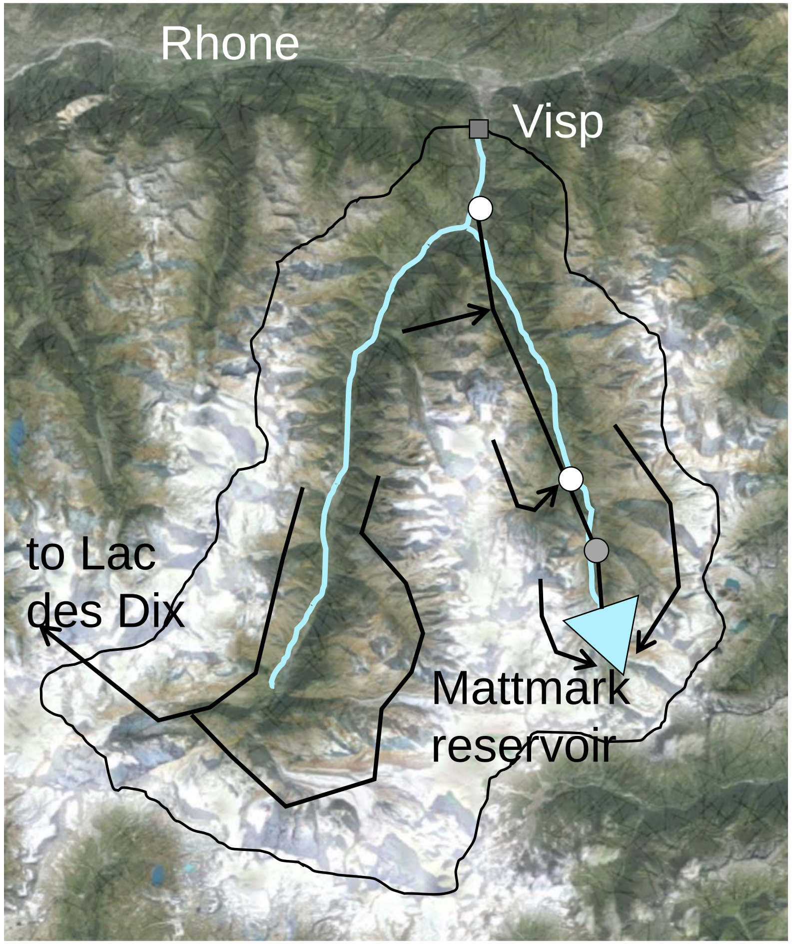
- Modeling hydropower (HP) systems and their operation
- Analyzing the impacts on HP systems of changes in the hydrological and socio-economic drivers

Research questions:

- How much can we increase hydropower production (without infrastructural investment)?
- What is the effect of climate change on water availability and reservoir operation?
- What is the effect of energy demand and price changes on reservoir operation?
- What is the combined effect of climate and price changes

# Pilot application

## Mattmark reservoir – Visp valley (CH)



**Active storage**: about 100 million m$^3$

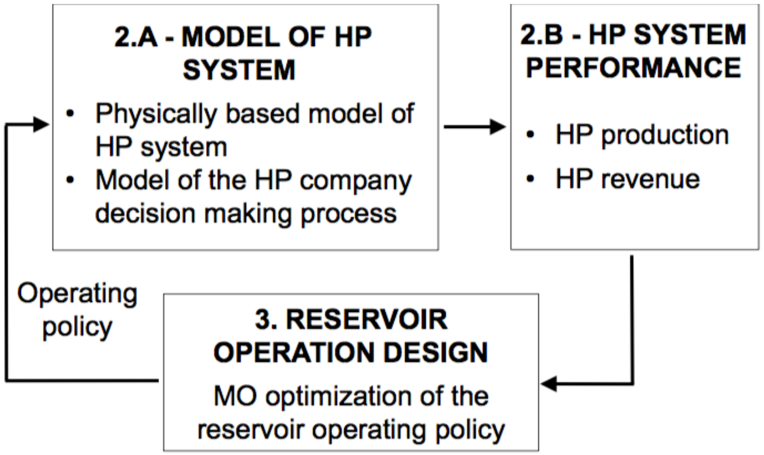
**Catchment**: 37.1km$^2$ + 55.1 km$^2$ (connected through diversion channels)

**Hydrology**: ice- and snow-melt dominated

**Glacier**: 29% of the catchment area

# Methods: decision analytic framework

- Model of HP systems (reservoirs and plants) and their interaction with the natural environment
- Design of the HP operating policy using multi-objective (MO) optimization techniques



**2.A - MODEL OF HP SYSTEM**

- Physically based model of HP system
- Model of the HP company decision making process

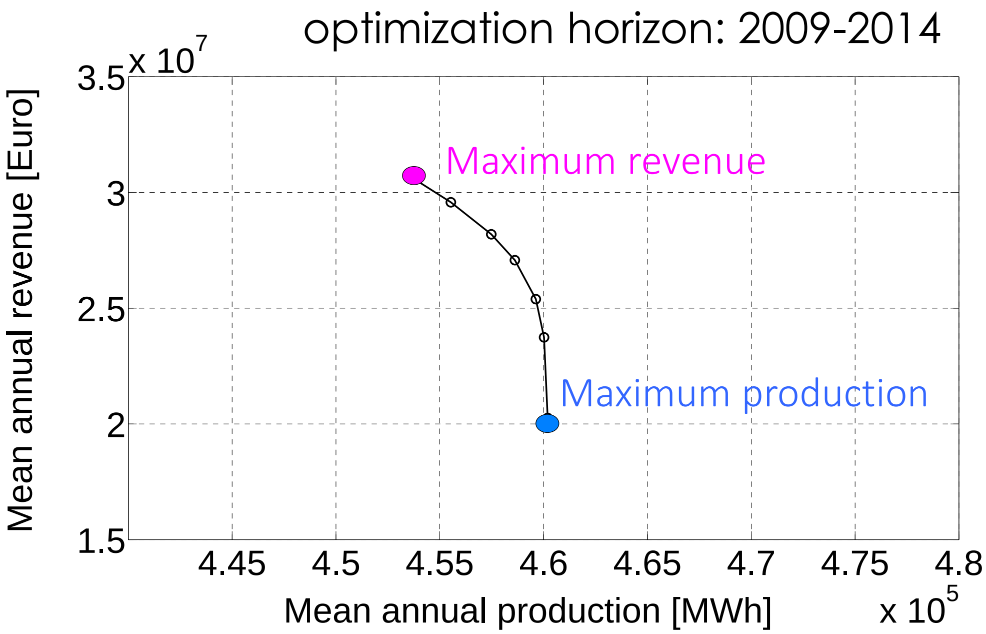
**2.B - HP SYSTEM PERFORMANCE**

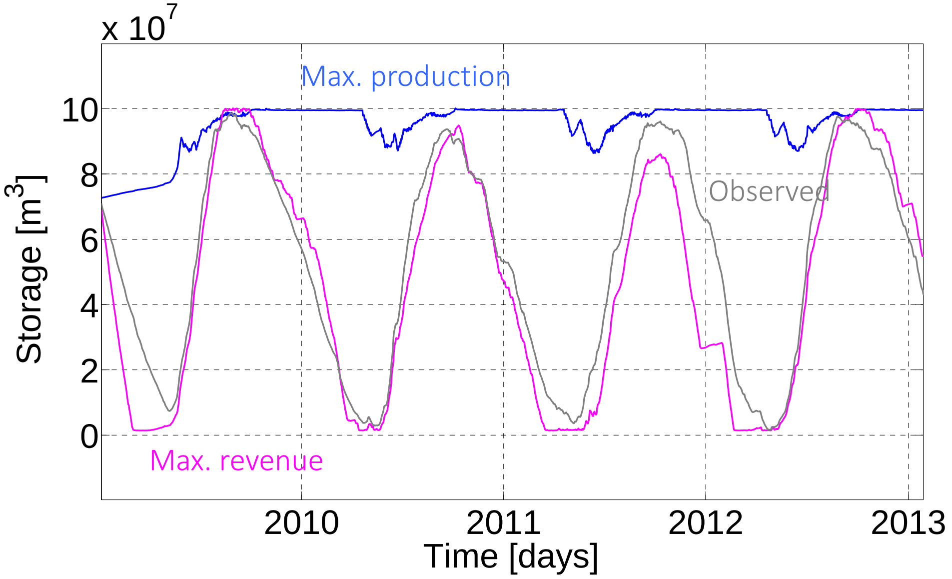
- HP production
- HP revenue

**3. RESERVOIR OPERATION DESIGN**

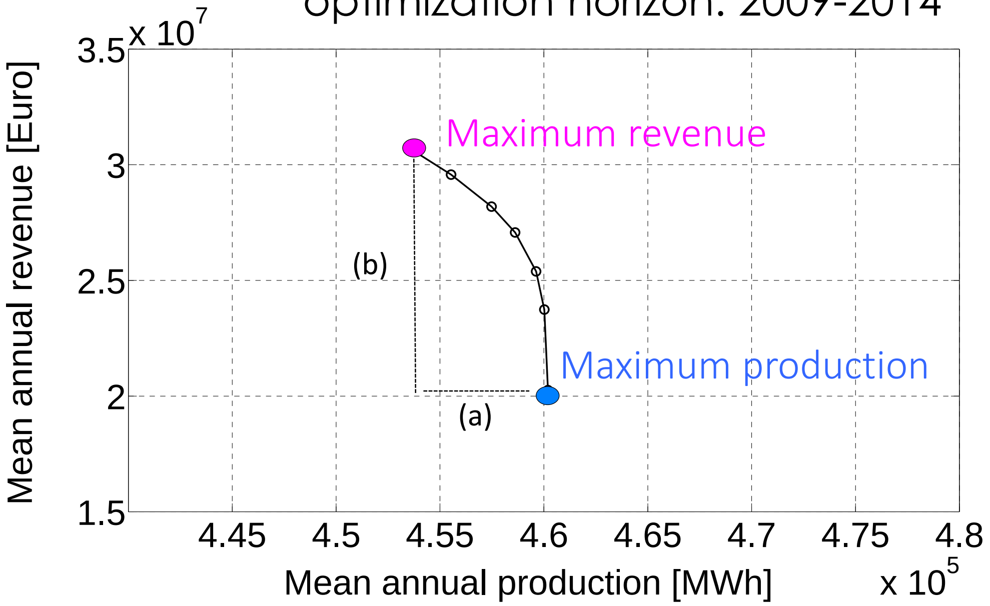
MO optimization of the reservoir operating policy

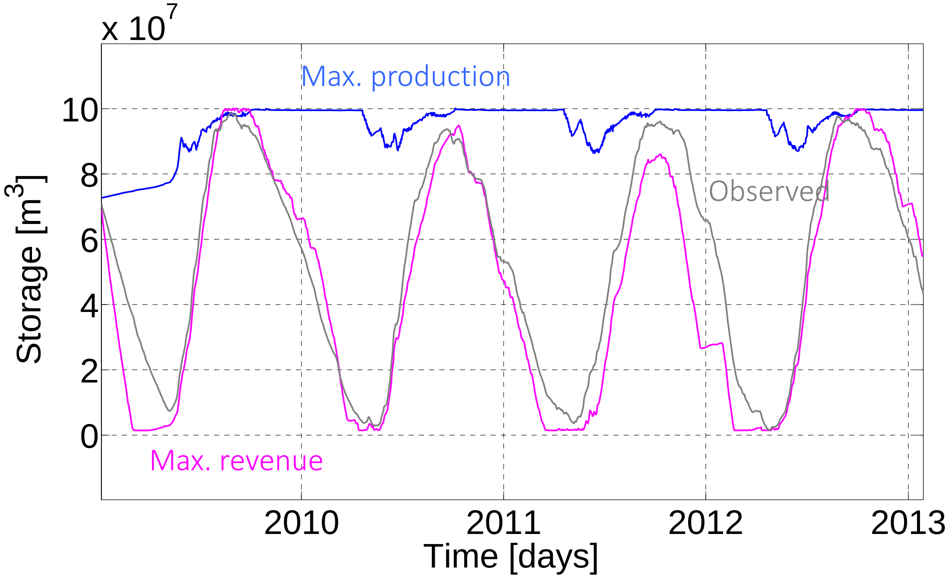
# Max production vs max revenue?





# Max production vs max revenue?


optimization horizon: 2009-2014



(a) **Low flexibility in production:**

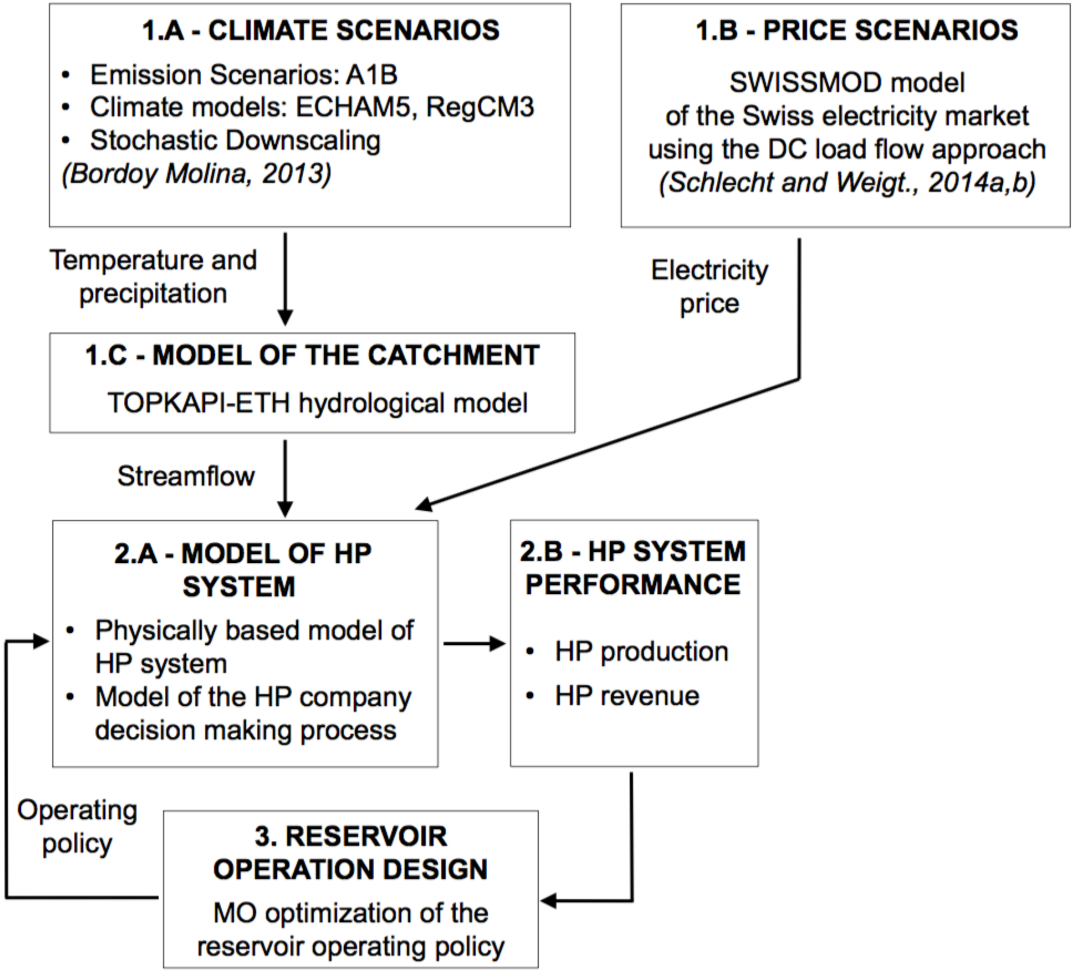
$$\frac{\text{Max Prod} - \text{Min Prod}}{\text{Max Prod}} = 1.4\%$$

(b) **High potential revenue loss:**

$$\frac{\text{Max Rev} - \text{Min Rev}}{\text{Max Rev}} = 33.8\%$$

# Methods: decision analytic framework

- Analysis of the HP system performances evolution under different climate and price scenarios



**1.A - CLIMATE SCENARIOS**

- Emission Scenarios: A1B
- Climate models: ECHAM5, RegCM3
- Stochastic Downscaling

*(Bordoy Molina, 2013)*

**1.B - PRICE SCENARIOS**

SWISSMOD model of the Swiss electricity market using the DC load flow approach *(Schlecht and Weigt., 2014a,b)*

**1.C - MODEL OF THE CATCHMENT**

TOPKAPI-ETH hydrological model

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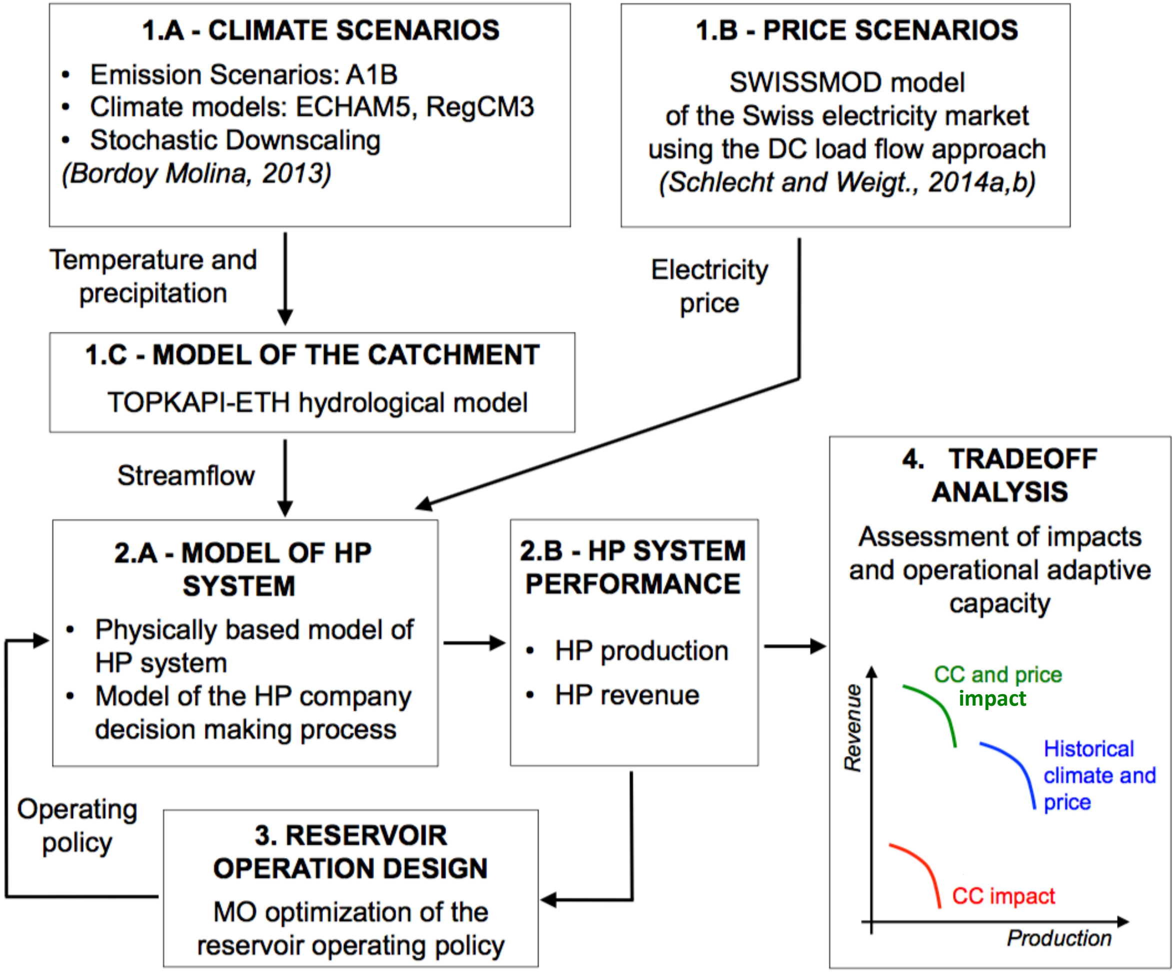

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Temperature and precipitation

Electricity price

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Streamflow

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- HP production
- HP revenue

**4. TRADEOFF ANALYSIS**

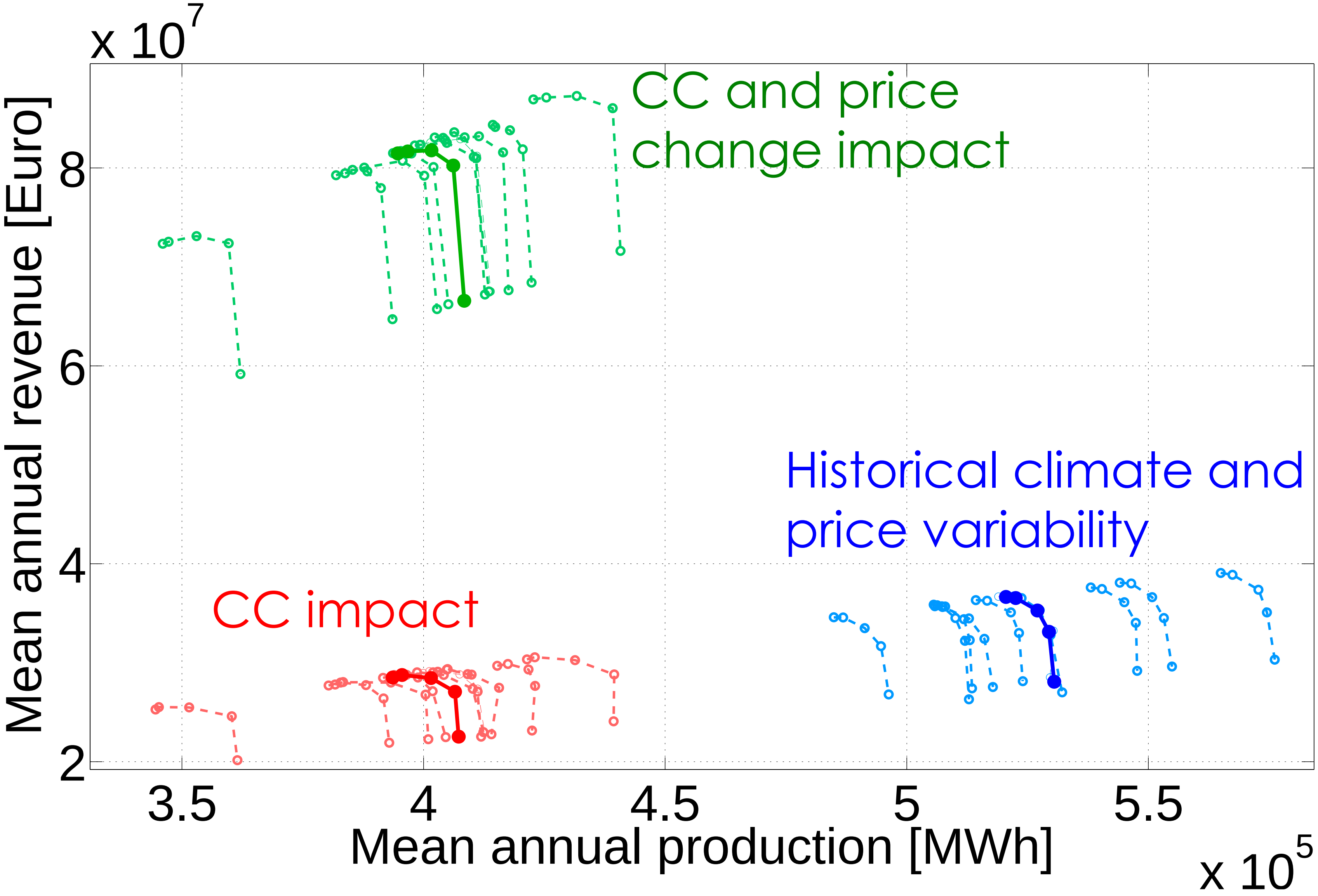
Assessment of impacts and operational adaptive capacity

Operating policy

**3. RESERVOIR OPERATION DESIGN**

MO optimization of the reservoir operating policy

# Tradeoff evolution analysis



# Next steps

- Apply the decision analytic framework to other pilot studies
- Consider and/or add other (> 2) objectives (e.g., environment)
- Explore different HP operating strategies

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# Exploring productivity and profitability of Alpine hydropower plants under climate change and price variability

*Daniela Anghileri, Andrea Castelletti, and Paolo Burlando*

## Motivation

Fast dynamical and uncertain processes will probably characterize the Swiss hydropower (HP) sector in the future because of:

- climate change (CC), which is affecting the timing and amount of water availability,
- energy market liberalization and increasing share of new renewable energy sources, which are resulting in lower energy prices and increased price volatility,
- nuclear phase out by 2035, whose energy production would be partially replaced by HP and other new renewable energy sources.

As a consequence, HP systems' operators will likely change the current operating strategies to be more flexible and robust with respect to the current situation.

## Objectives and relevance of the work

We develop a decision analytic framework to:

- design several HP reservoir operating strategies to explore different tradeoffs between productivity and profitability of HP systems,
- investigate how these tradeoffs may evolve in time under current and future climate change and energy price projections.

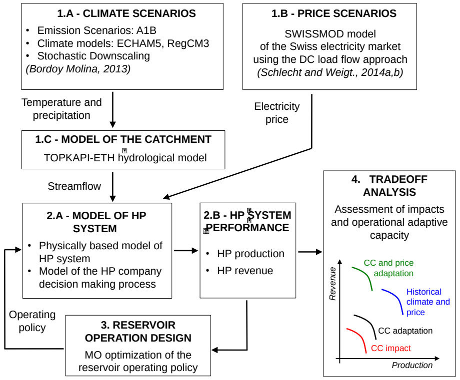
Results inform about:

- the impacts of changes in water availability and energy price on Alpine HP systems,
- the adaptive capacity of HP reservoir operation to water availability and price changes,
- to which extent HP companies could cope in the future with both secure energy supply and profitable operation.

## Methods

The decision analytic framework consists of 4 phases:

1. Generating water availability and price scenarios,
2. Modelling HP systems (reservoirs and plants) and their interaction with the natural environment,
3. Designing the HP operating policy using multi-objective (MO) optimization techniques,
4. Simulating and analysing the HP system performances.



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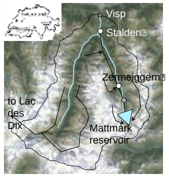
MO optimization of the reservoir operating policy

- Bordoy Molina (2013). Spatiotemporal downscaling of climate scenarios in regions of complex geography. PhD. Thesis – ETH Zurich.
- Schlecht and Weigt (2014a). Linking Europe. The role of the Swiss  electricity tarnsmission grid until 2050. *Social  Science Research Network*.
- Schlecht and Weigt (2014b). Swissmod. A model of the Swiss electricity market. *Social Science Research Network*.

## Study site



Mattmark HP system

Hydropower company: Kraftwerke Mattmark AG c/o Axpo Power AG

Mattmark storage: 100,101,000 m$^3$

Zermeiggern power plant: 38.8 MW

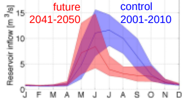
Stalden power plant: 187 MW

Catchment area: 778 km$^2$

Glacier extention: 29% of the catchment

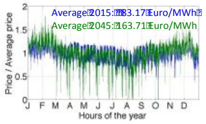
## Results

### Reservoir inflow and energy price scenarios



Future reservoir inflow shows a reduction of the annual volume due to changed snow-melt dynamics and glacier retreat.

Future energy price shows increasing mean and variance due to higher share of renewables (Schlecht and Weigt, 2014b).



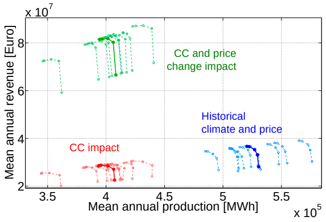
### Impacts of changes in water availability and energy price

Each Pareto Frontier (PF) represents different reservoir operating strategies, balancing maximization of energy production and revenue.

The blue PFs represent the current climate (dashed PFs are 10 different stochastic realizations; solid PF is their average) and current energy price: natural climate variability can produce a variation in production and revenue of ±6%.

The red PFs represent the impact of CC: the reduction of water availability causes a reduction of about -20% in production and revenue.

The green PFs represent the impact of CC and energy price change: the increased price average induces a big increase in the revenue and the increased price variability induces a slightly more pronounced conflict between production and profitability.



### Adaptive capacity of HP system operation to climate change

The operation of the HP system can be optimized to account for the future changed water availability (black PFs).

The performances w.r.t. both production and revenue are only slightly improved, meaning that a change in the HP system operation alone could not cope with the decrease in the annual water volume flowing into the reservoir.