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SWISS COMPETENCE CENTER for ENERGY RESEARCH
SUPPLY of ELECTRICITY

Climate Change and Hydropower

Paolo Burlando (paolo.burlando@ethz.ch)

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In cooperation with the CTI

Energy
Swiss Competence Centers for Energy Research

Schweizerische Eidgenossenschaft
Confédération suisse
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Swiss Confederation

Commission for Technology and Innovation CTI

Introductory remarks (1/3)

On Climate Change

- Climate change is expected to induce significant changes in the hydrologic regimes (e.g. precipitation, streamflow), especially in the Alps, and in all hydrology driven processes (e.g. erosion)
- Prediction of climate change scenarios are
  - *typically available at large scales from General Circulation Models and Regional Climate Models*
  - *Affected by a high uncertainty (not only due to emission scenarios/pathways), particularly in orographically complex regions*
- Climate change is expected to increase the retreat of glaciers

Introductory remarks (2/3)

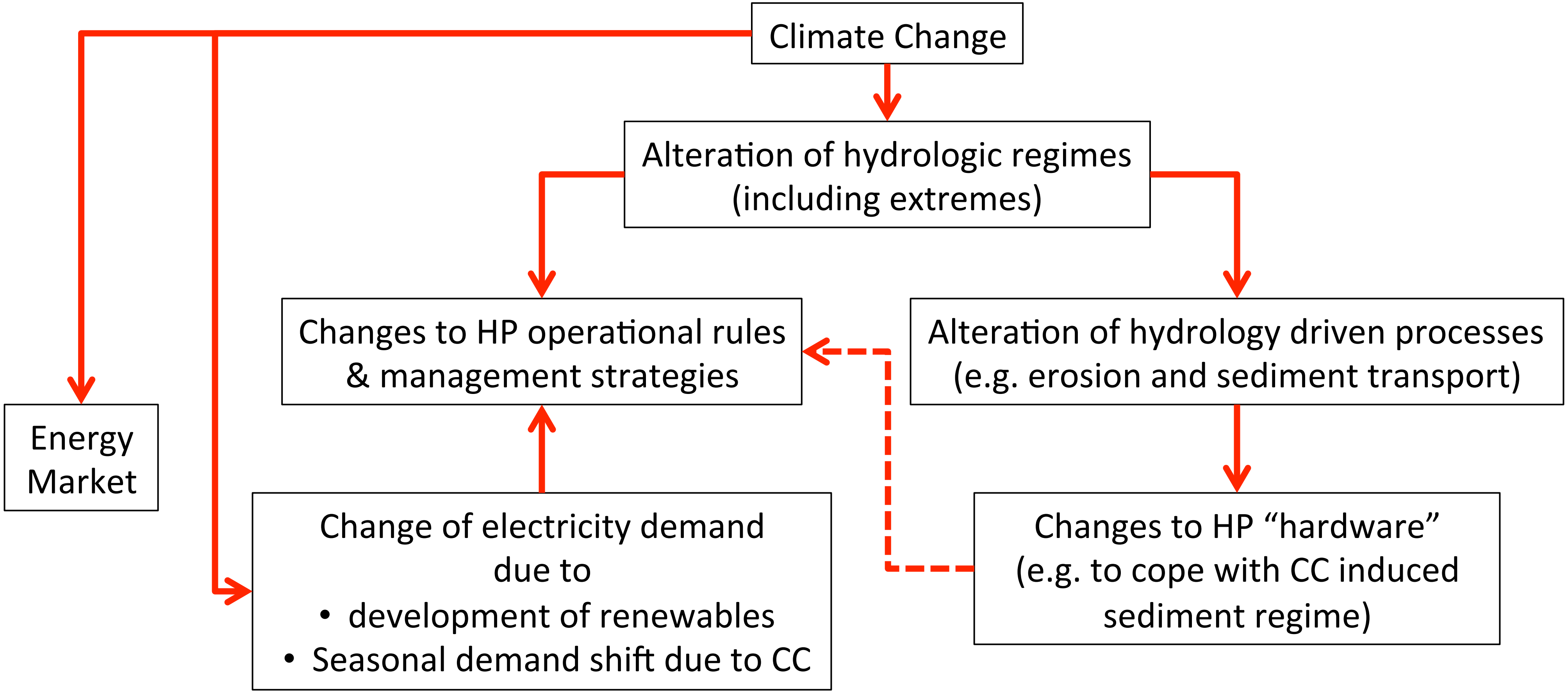
On hydropower

- Hydropower is among the most important renewable energy sources and is central to the energy strategy of many countries.
- It is a key resources for electricity production in the European Alps
- In Switzerland, it is central to the future energy strategy and its production is expected to increase from ≈37 TWh/yr (2010) to ≈40 TWh/yr within 2050 (upgrade of pump-storage by ≈10TWh).
- It can be operated (technically) in a quite flexible way.
- In the next decades a large number of concessions must be renewed and conflicts can increase between environmental needs and new management rules to cope with the demand for higher and more flexible electricity production.

Introductory remarks (3/3)

On interactions and causal relationships

↳ **climate change as primary driver**



Climate Change

Alteration of hydrologic regimes (including extremes)

Changes to HP operational rules & management strategies

Alteration of hydrology driven processes (e.g. erosion and sediment transport)

Energy Market

Change of electricity demand due to
- development of renewables
- Seasonal demand shift due to CC

Changes to HP "hardware" (e.g. to cope with CC induced sediment regime)

Design of climate change forcing (1/3)

Requirements

- *as reliable as possible (little to no bias, thoroughly validated on historical climate)*
- *accounting for variability (not only mean changes)*
- *explicitly accounting for uncertainty*
- *able to predict changes at the basin (meso)scale, i.e. at spatial and temporal scales consistent with those of basin response*

  ↳ *< 1 km^2, <1 day*

Past studies rarely complied with these requirements

↳ *e.g. studies in CH used delta-change-like approaches (e.g. Swisselectric / BfE study)*

Design of climate change forcing (2/3)

- **Hypothetical scenarios**

  arbitrary, no physical basis

- **Direct forcing from one/more deterministic GCM/RCM**

  basin scale inconsistent, limited temporal scale, limited accuracy for key variables (adds the uncertainty due to GCM/RCM diversity in case of multiple GCMs)

- **Deterministically downscaled forcing from one or more GCM/RCM (Δ change)**

  no basin scale inconsistency, historical variability (no change in VAR), limited to daily scale

- **Statistically downscaled forcing from one or more GCM/RCM**

  no basin scale inconsistency, partly overcomes limitations of deterministic downscaling

- **Stochastically S-T downscaled forcings from one or more GCM/RCM**

  no basin scale inconsistency, no temporal scale limit, accounts for changes in process variability and intrinsic climate variability, allows uncertainty analysis through stochastic simulation

- **High resolution dynamical downscaling**

  improved RCM models in space-time resolution, physically consistent, still computationally demanding, deterministic simulations

Design of climate change forcing (3/3)

Why stochastic downscaling

- *links the large scale trends with their effects at local/regional scales*
- *minimum GCM/RCM bias propagation*
- *model parameterisation under CC different from that under historical (stationary) climate*
- *suitability for long-term (Monte Carlo) simulations → uncertainty accounting*
- *low computational demand*
- *ability to consider changes in variability and precipitation internal structure and not only in the mean*
- *simulation across scales (lower scale: sub-hourly)*
- *not limited to precipitation and/or temperature (→ weather generator)*

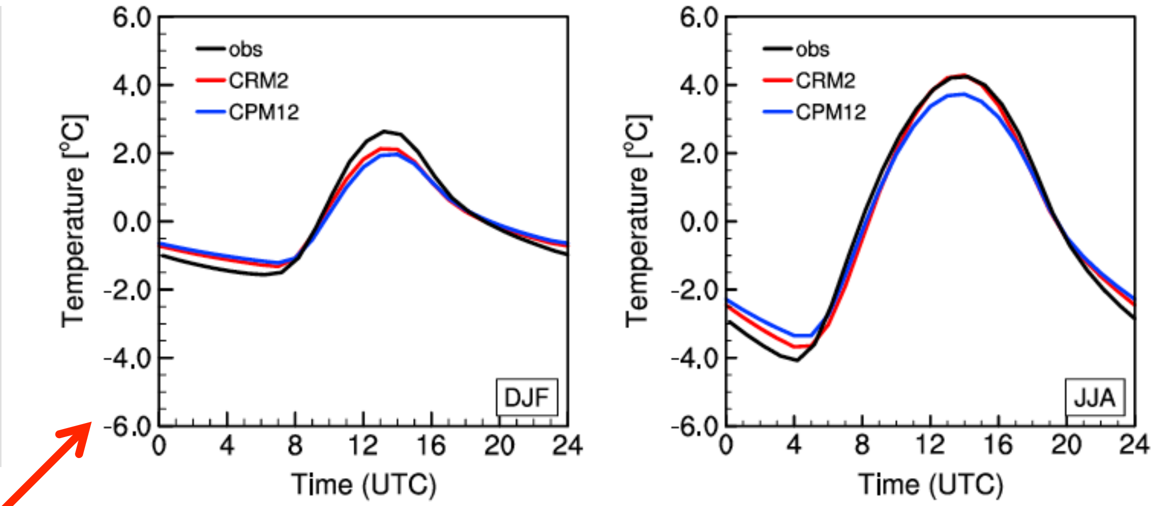
Example of high resolution RCM

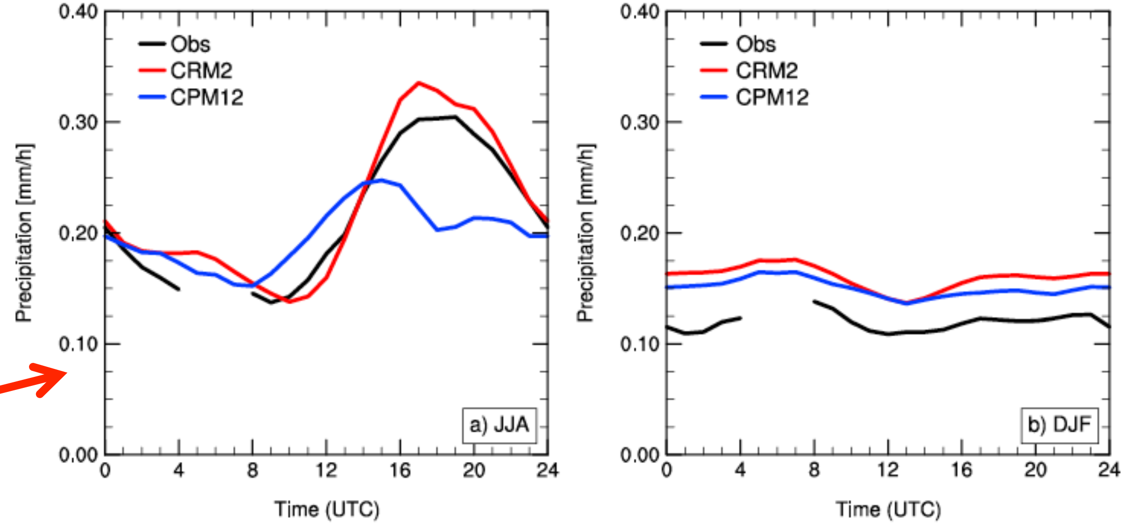
[Ban, Schmidli & Schär, JGR-A, 2014, 10.1002/2014JD021478]

- **Convection resolving (CRM2) and convection parameterising model (CPM12)**
- **High spatial resolution, 2km (CRM2) and 12 km (CPM12)**
- **Comparison with spatially interpolated P and T fields at sub-daily temporal resolution**

- **Comparison of diurnal cycle of T anomaly**

- **Mean diurnal cycle of precipitation**



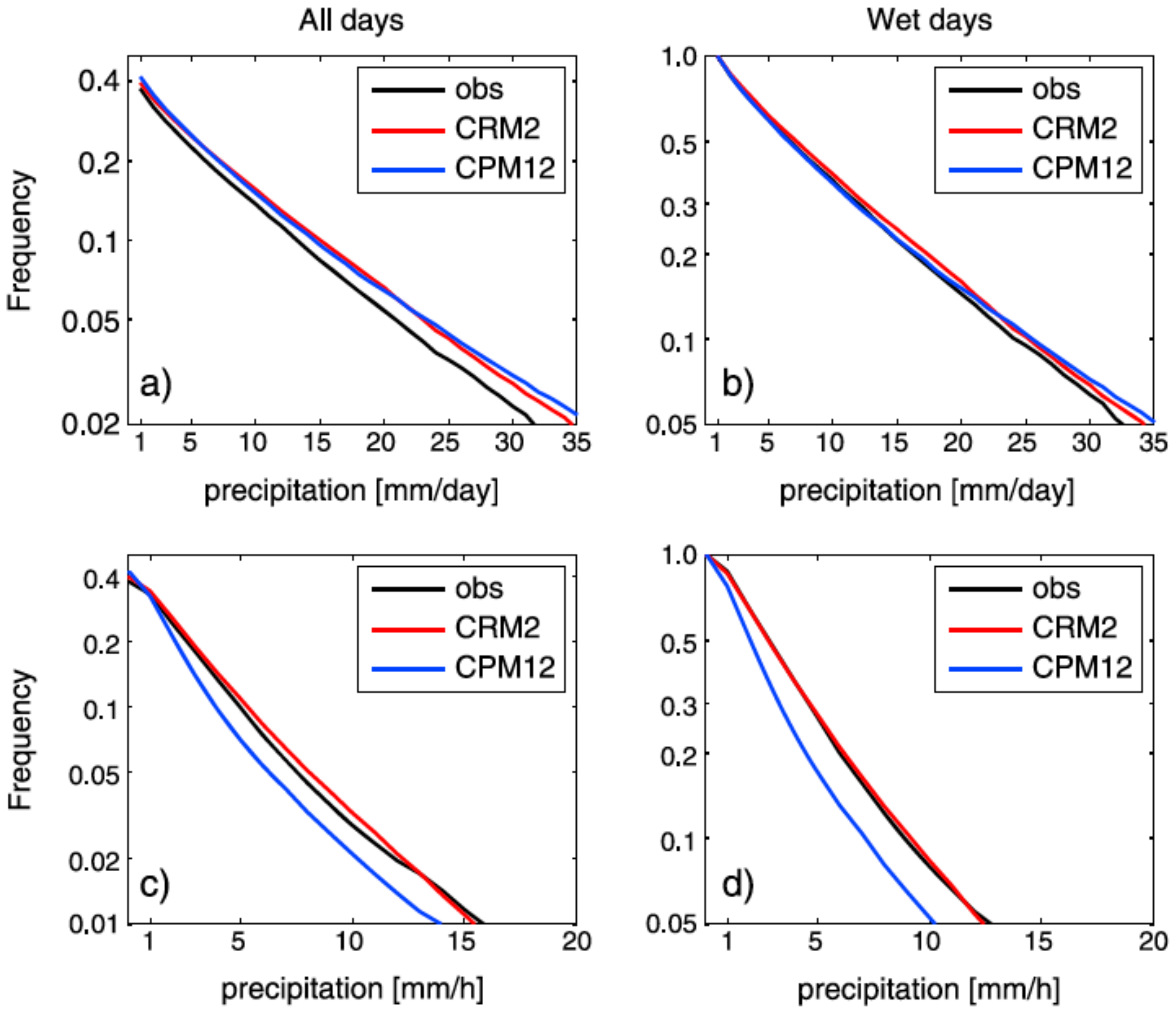


Example of high resolution RCM (extremes)

[Ban, Schmidli & Schär, JGR-A, 2014, 10.1002/2014JD021478]

CDF of daily precipitation

CDF of daily max 1h precipitation



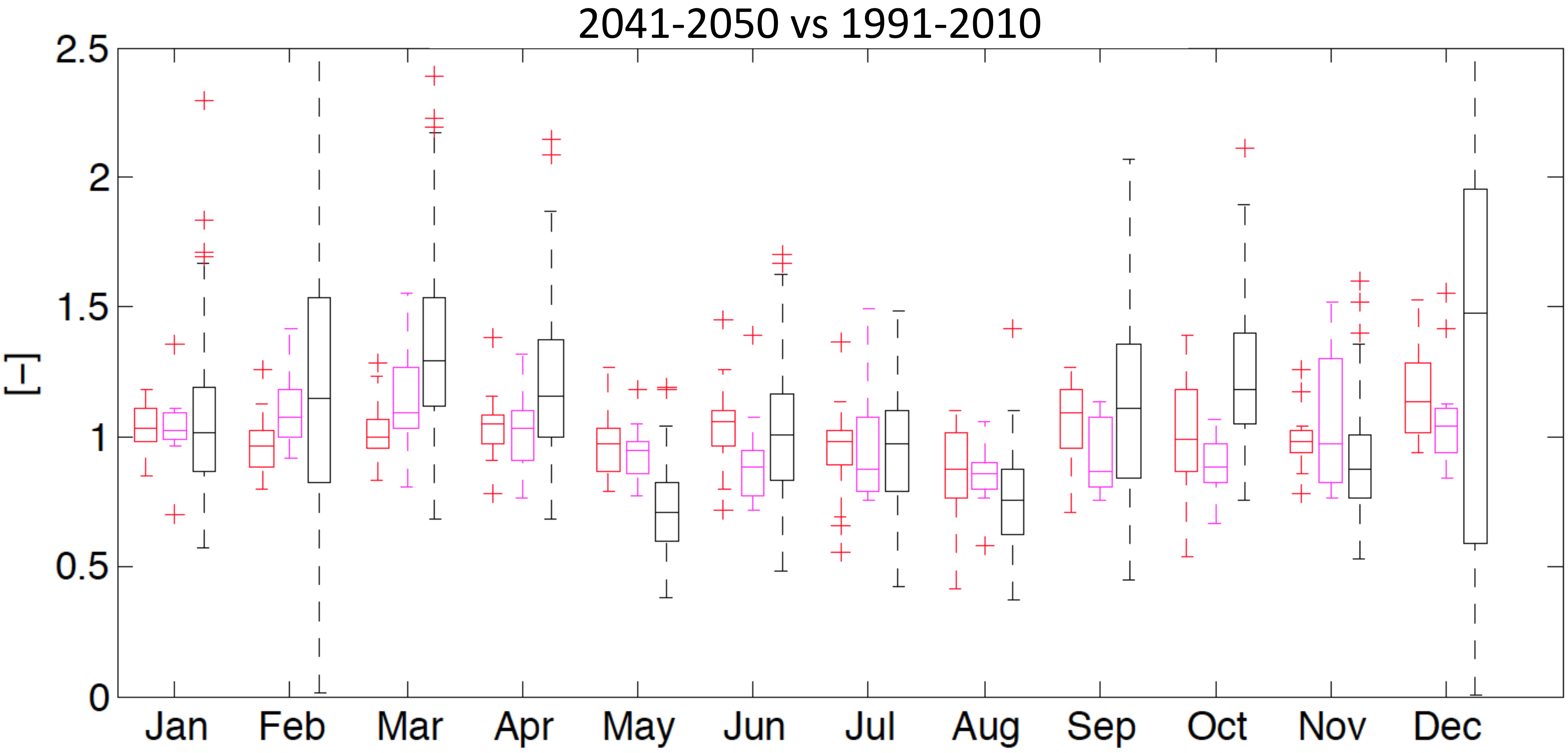
New potential for dynamical downscaling

Stochastic downscaling - uncertainty

[Bordoy, PhD thesis #21201, ETH Zurich, 2013; Bordoy & Burlando, WRR, 2014]

Anomaly of mean precipitation

☐ RCM Ensembles
☐ GCMs CMIP3 (4th AR)
☐ downscaled stochastic simulations



Hydrology of river basins and CC

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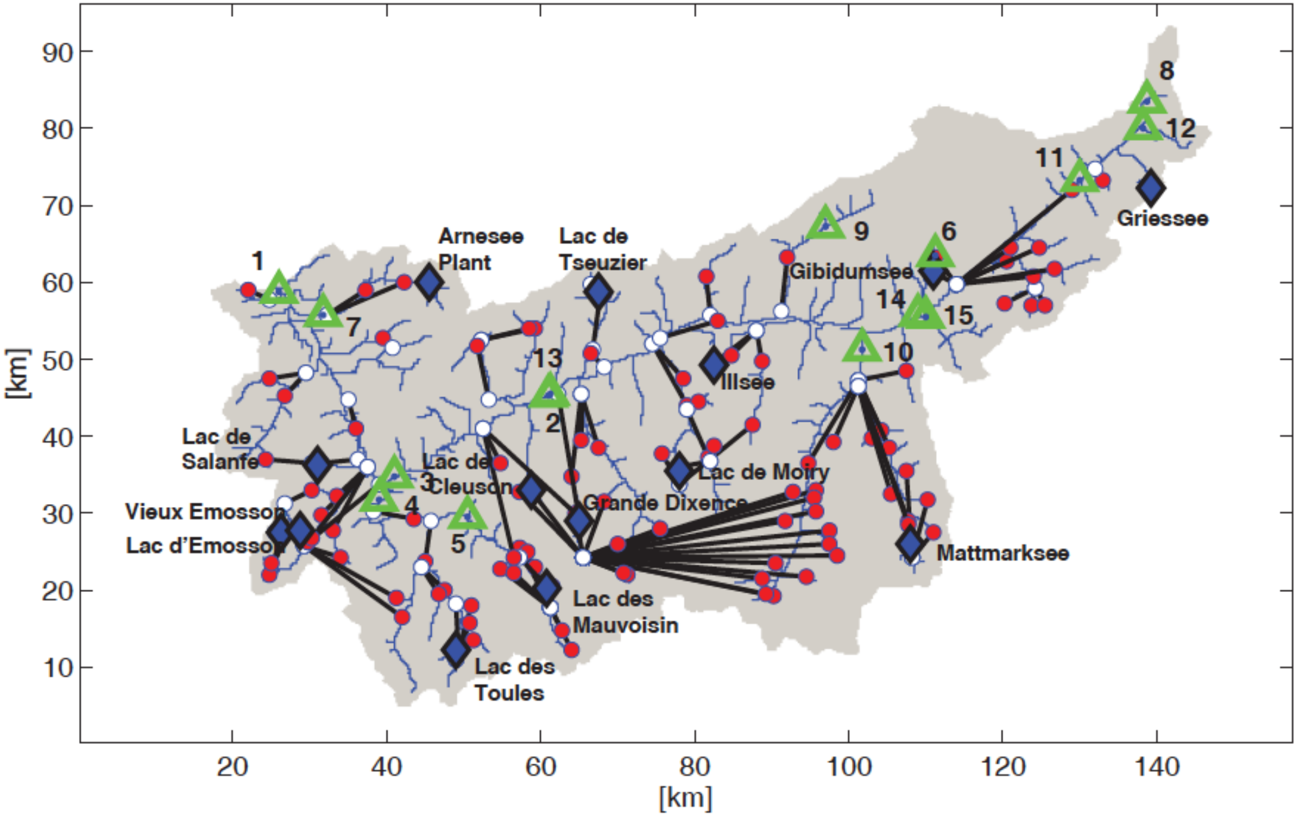
- **Effects of glacier retreat**
  - *uncertain prediction due to unknown ice volume and ground topography*
  - *risk of increased siltation due to the retreat of glaciers and larger exposure debris-covered areas and increased erosion due to higher flood runoff*
- **Impact of climate change on streamflow regimes**
  - *at reservoir locations (existing storage systems, downstream of glaciers)*
  - *in downstream reaches (existing run-of-river systems)*
  - *at locations where the hydropower potential must be assessed*
- **Hydrological safety of dams (risk)**
  - *hydrological safety of main structure, safety organs and floodplain downstream against potentially higher flood risk*
  - *slope stability hazards → risk of slope failures and subsequent impulse waves (Vajont effect)*
- **Impact on reservoir storage dynamics**

EXPLORATIVE STUDY, RHONE BASIN

whole basin, selected glaciers

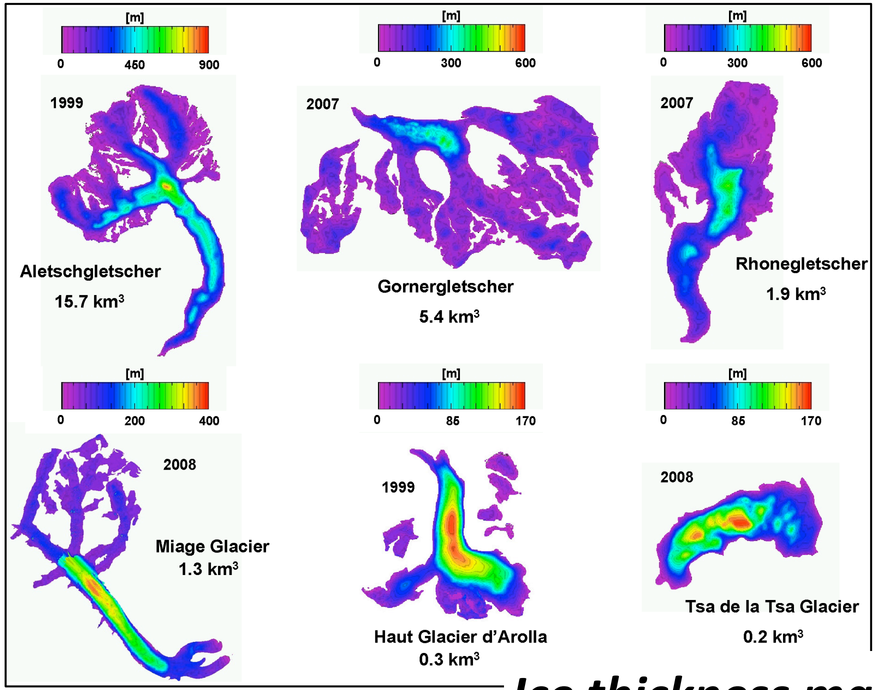
Explorative study, Rhone basin (CH)

- Stochastic transient climate scenarios
- Physically based / explicit, fully distributed model
- 183 glaciers
- 14 reservoirs, 115 diversions
- 297 tracked control river cross sections
- Explicitly accounting for anthropogenic disturbances
- Hydropower production following target level policy
- 5338 km^2
- 250 x 250 m horizontal resolution
- 85409 COMPUTATIONAL ELEMENTS

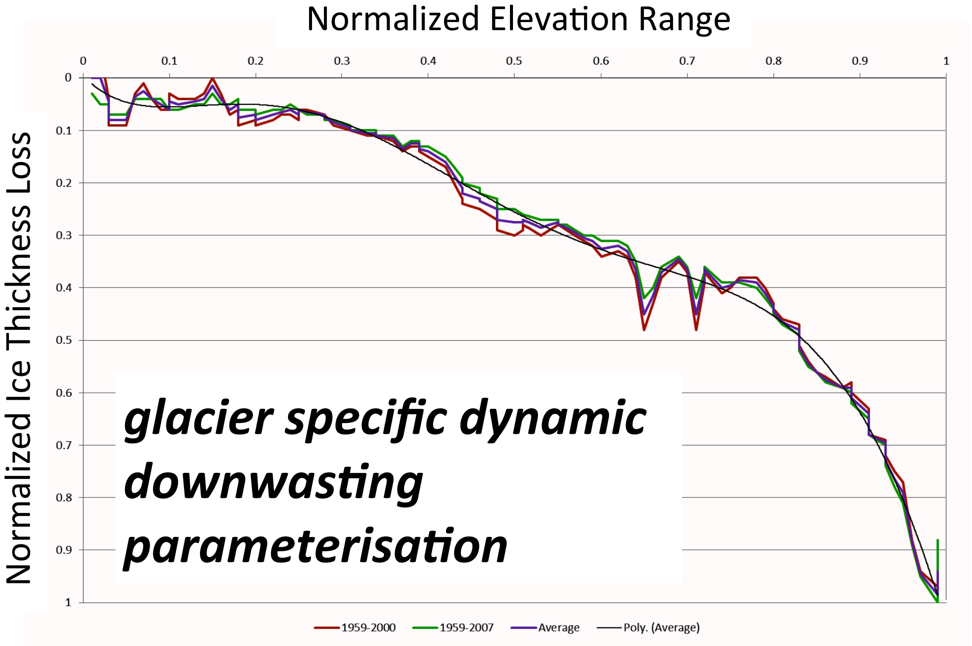


[Fatichi et al., HESSD, 2013]

Explorative study, glaciers

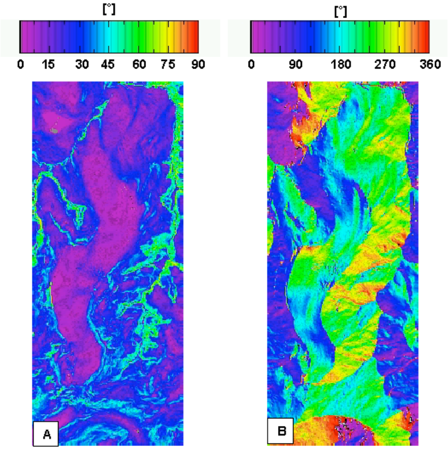


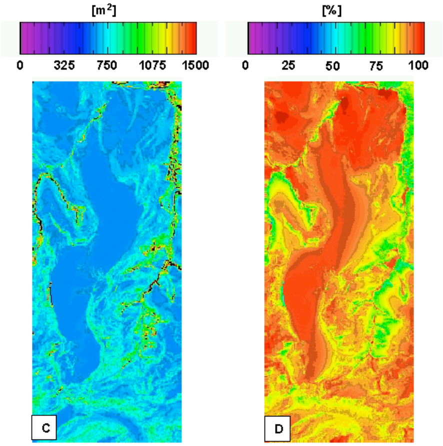
Ice thickness map



glacier specific dynamic downwasting parameterisation

Slope and Aspect

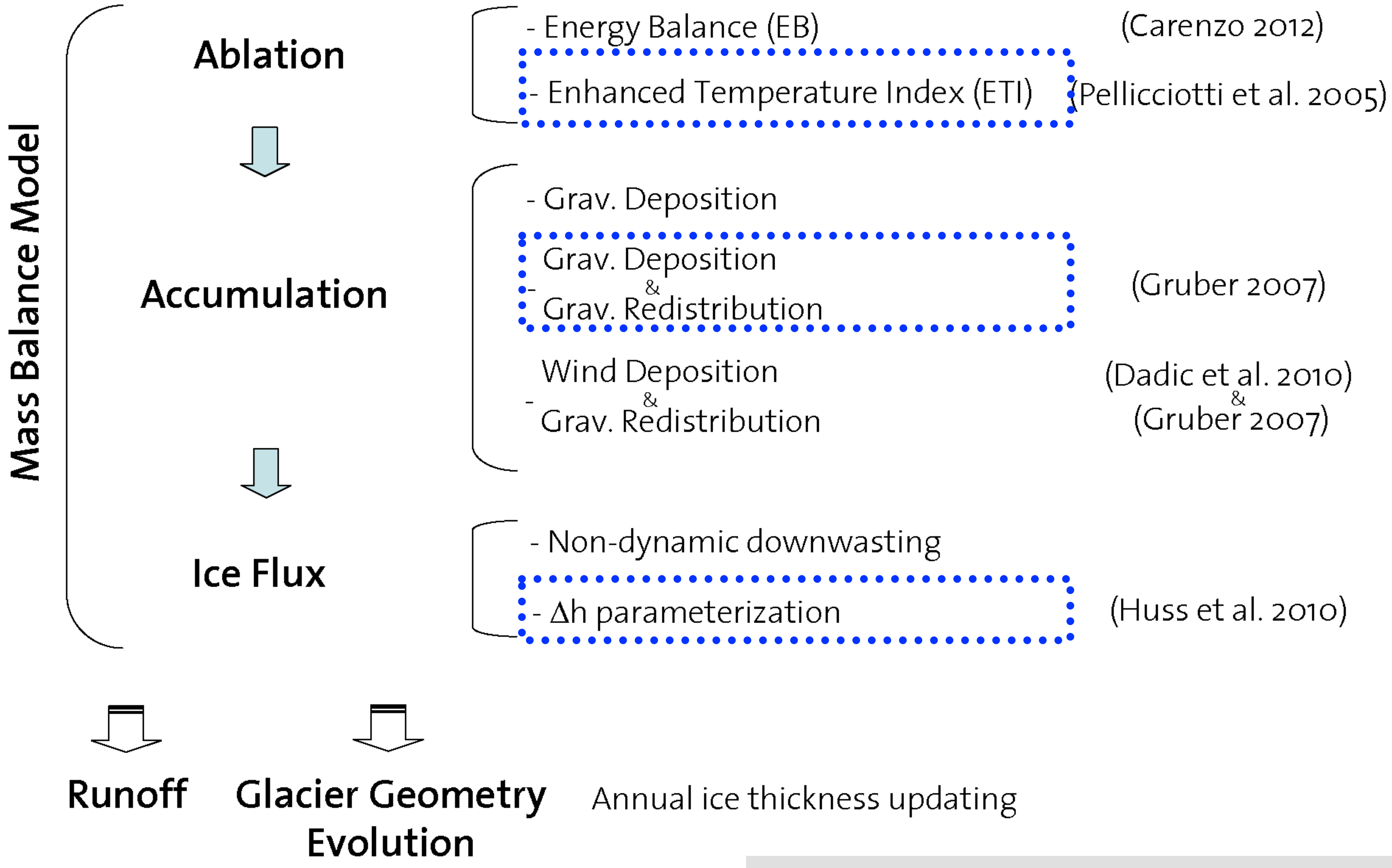




Area and Sky View Factor

[Carenzo, PhD thesis #20616, ETH Zurich, 2012
DOI: 10.3929/ethz-a-007636154]

Explorative study, glacier model



Mass Balance Model

Ablation
- Energy Balance (EB) (Carenzo 2012)
- Enhanced Temperature Index (ETI) (Pellicciotti et al. 2005)

Accumulation
- Grav. Deposition
- Grav. Deposition & Grav. Redistribution (Gruber 2007)
- Wind Deposition & Grav. Redistribution (Dadic et al. 2010) & (Gruber 2007)

Ice Flux
- Non-dynamic downwasting
- Δh parameterization (Huss et al. 2010)

Runoff

Glacier Geometry Evolution

Annual ice thickness updating

- **State of the art for long-term (stochastic) simulations**
- **Physically based / explicit**
- **Fully distributed, high resolution (raster 10 x 10 m^2)**

[Carenzo, PhD thesis #20616, ETH Zurich, 2012
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Hydrology of river basins and CC

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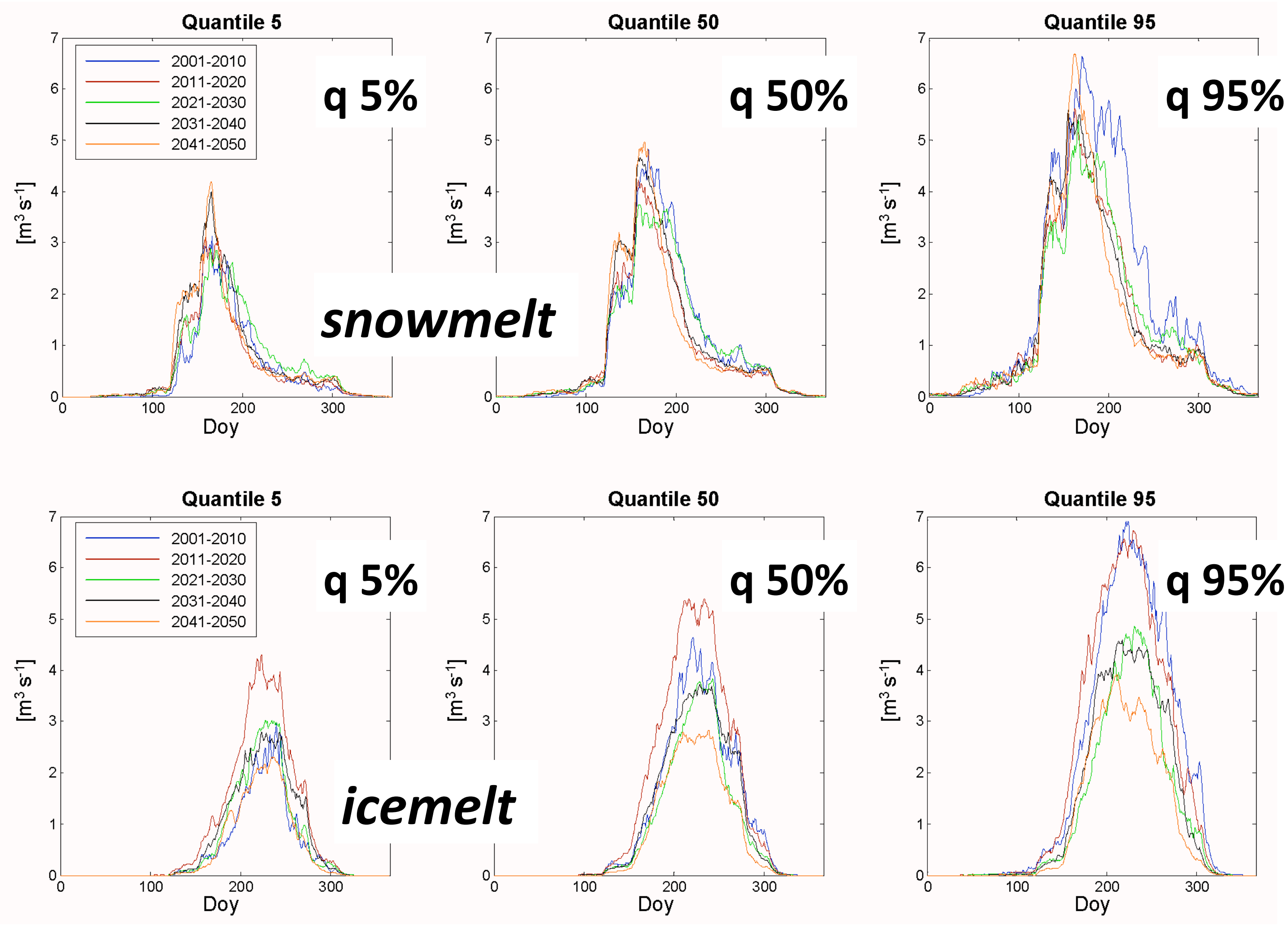
- **Impact on reservoir storage dynamics**

Glacier response, Rhonegletscher

up to 2050

- *no major changes of snowmelt in the early part of the season*
- *noticeable change of icemelt (the larger and thicker the glacier, the lower is the reduction)*
- *dependence on glacier morphology*

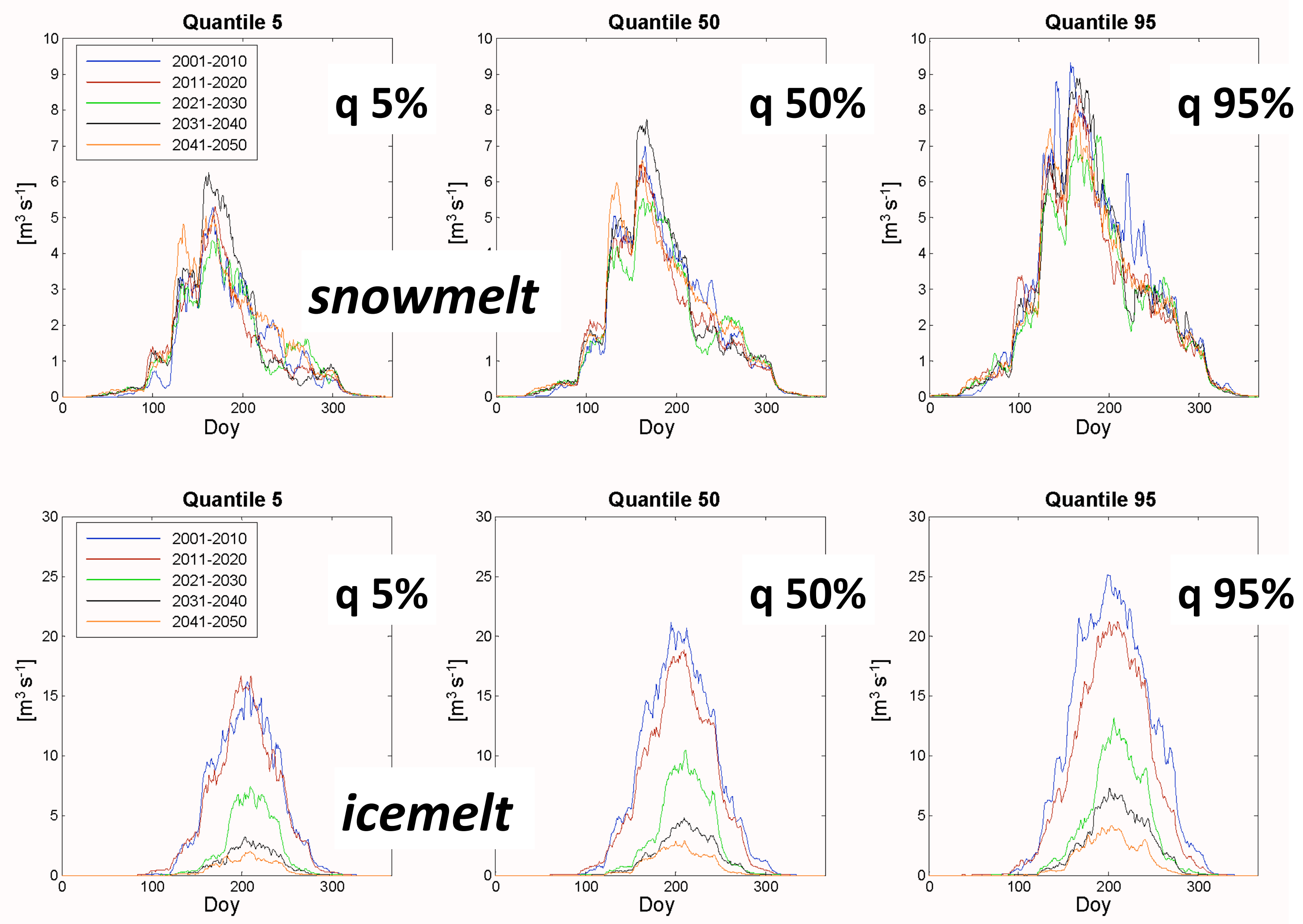


[Carenzo, PhD thesis #20616, ETH Zurich, 2012
DOI: 10.3929/ethz-a-007636154]

Glacier response, Gornergletscher

up to 2050

- *no major changes of snowmelt throughout the season*
- *significant changes of icemelt throughout the season*
- *dependence on glacier morphology*



q 5%

q 50%

q 95%

snowmelt

icemelt

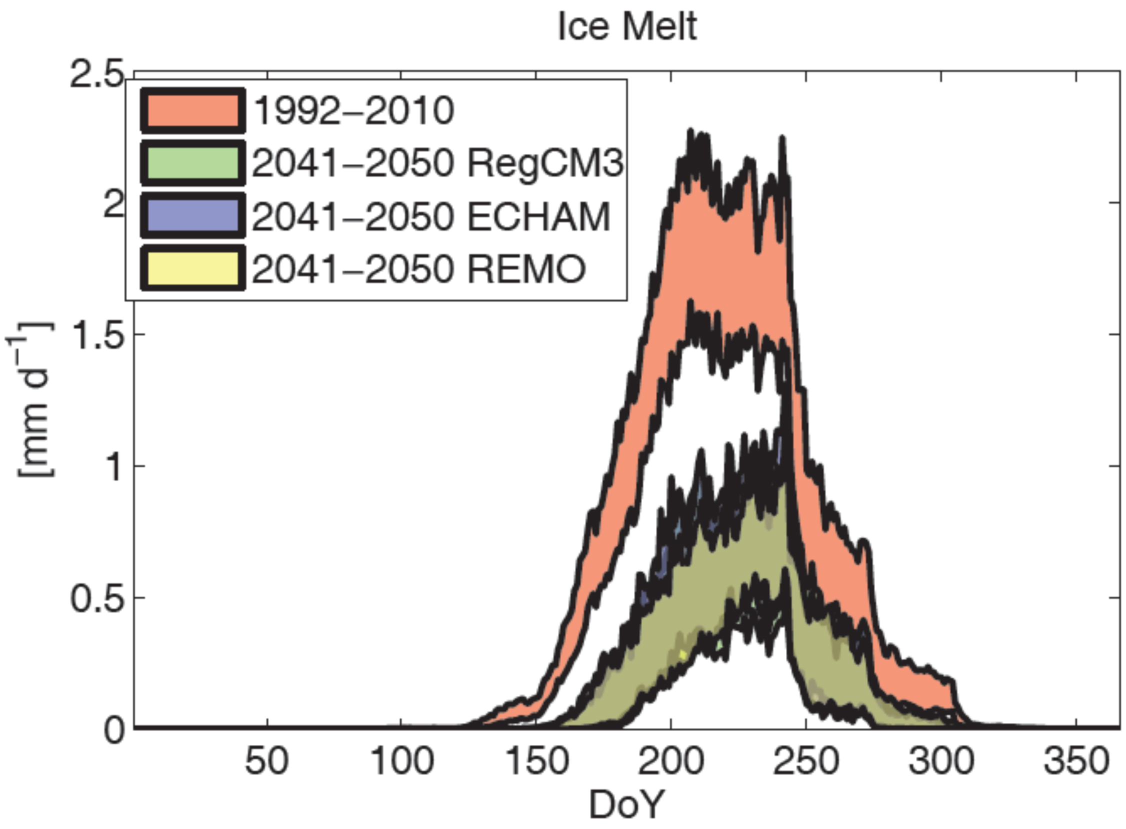
[Carenzo, PhD thesis #20616, ETH Zurich, 2012
DOI: 10.3929/ethz-a-007636154]

Rhone basin response, average icemelt

2041-2050 vs 1992-2010 (control sc.)

coloured band: values within the 10th and 90th percentile of the stochastic simulation

- *changes consistent for all climate downscaling chains*
- *changes are larger than the stochastic variability in a decade*
- *glacierised area and ice-melt reduced by ~ 50% by 2050*
- *glacier disappear below 2500 m a.s.l. by 2050*
- *icemelt contribution to streamflow reduces from ~13% to ~4%*



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- **Impact on reservoir storage dynamics**

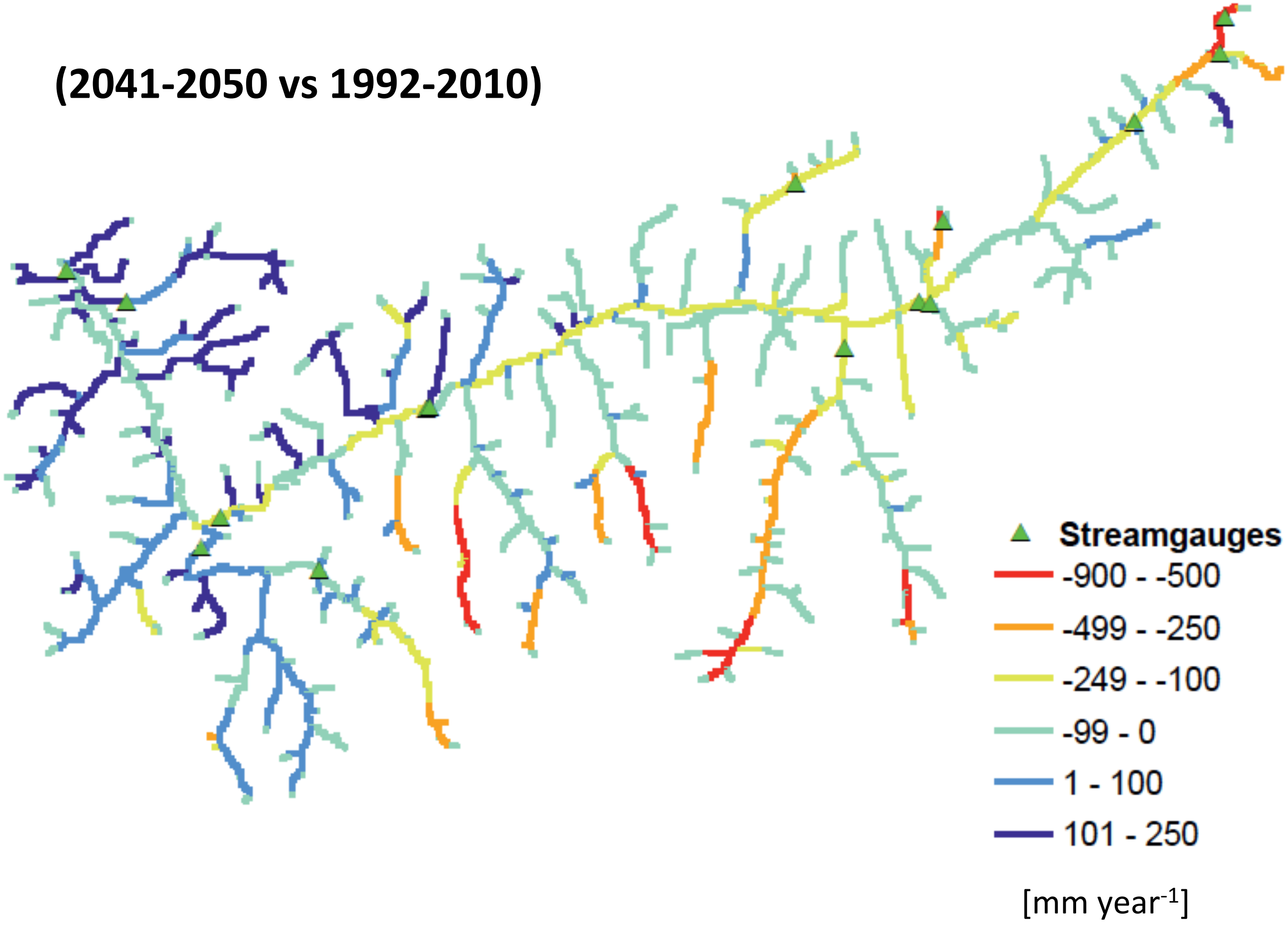
CC impact on mean runoff

- *Robust signal of the* **elevation dependence**

- *Negative changes downstream of glaciers and positive changes in areas with increased P lead to small changes in the main stream →* **dampening effect of river network**

[Fatichi et al., HESSD, 2013]

(2041-2050 vs 1992-2010)

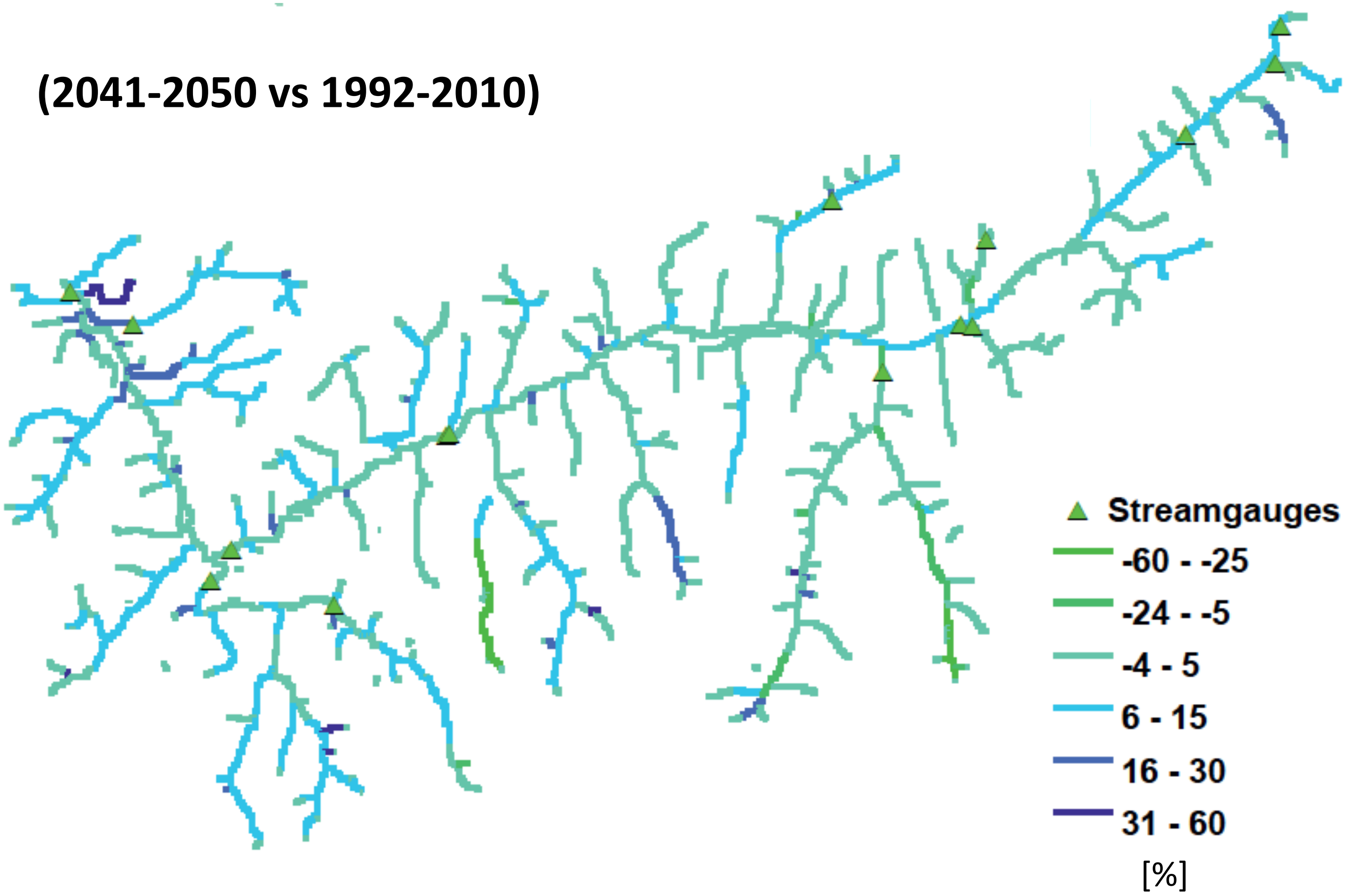


CC impact on min daily streamflow

[Fatichi et al., HESSD, 2013]

(2041-2050 vs 1992-2010)

- *Noticeable role of*
  - **hydropower systems**
  - **precip distribution**
- *Changes are typically small and in the uncertainty range*
  - **-5 to +15% → unclear**
- *Local conditions may play a role*



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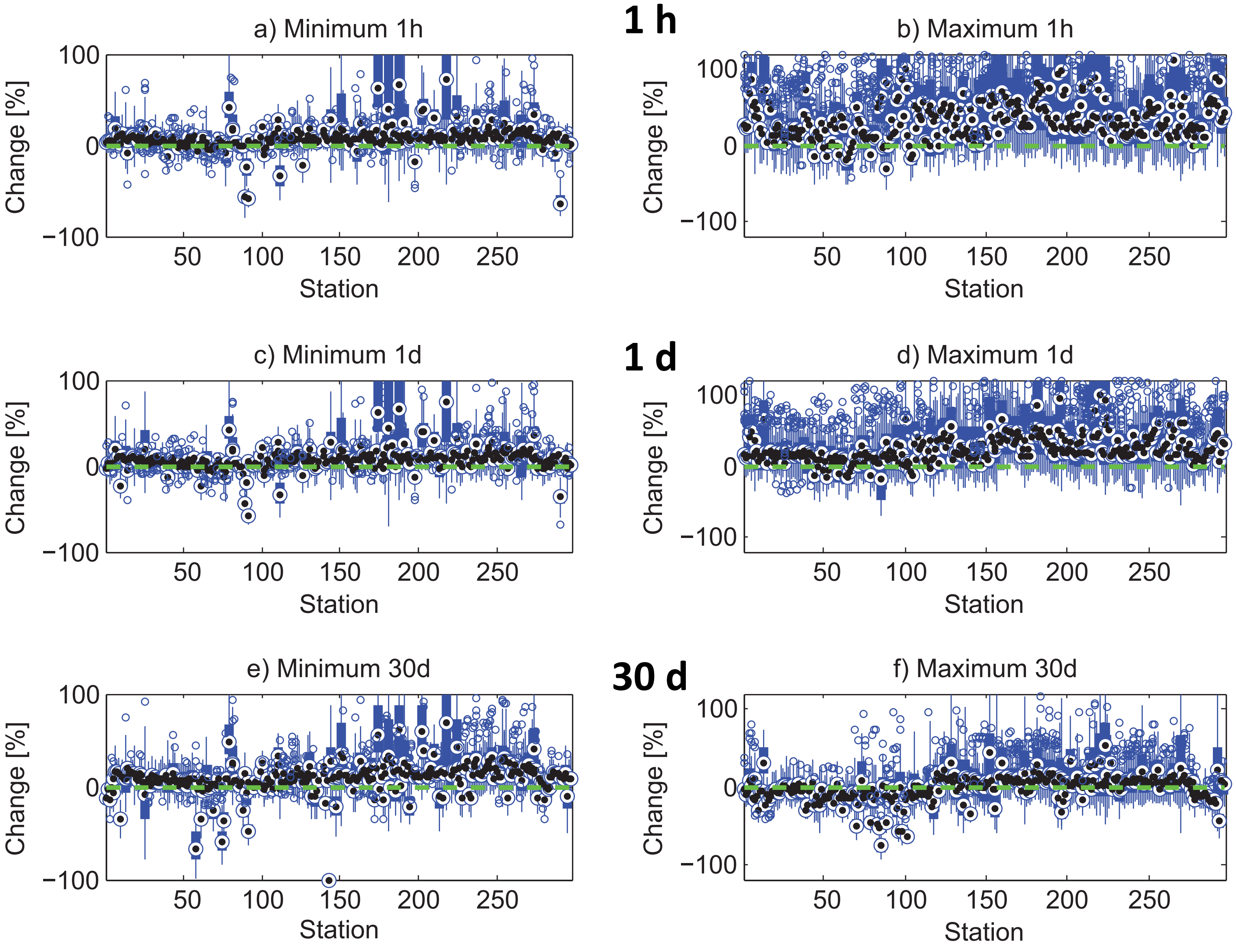
- Impact on reservoir storage dynamics

CC impact on maxima/minima

[Fatichi et al., HESSD, 2013]

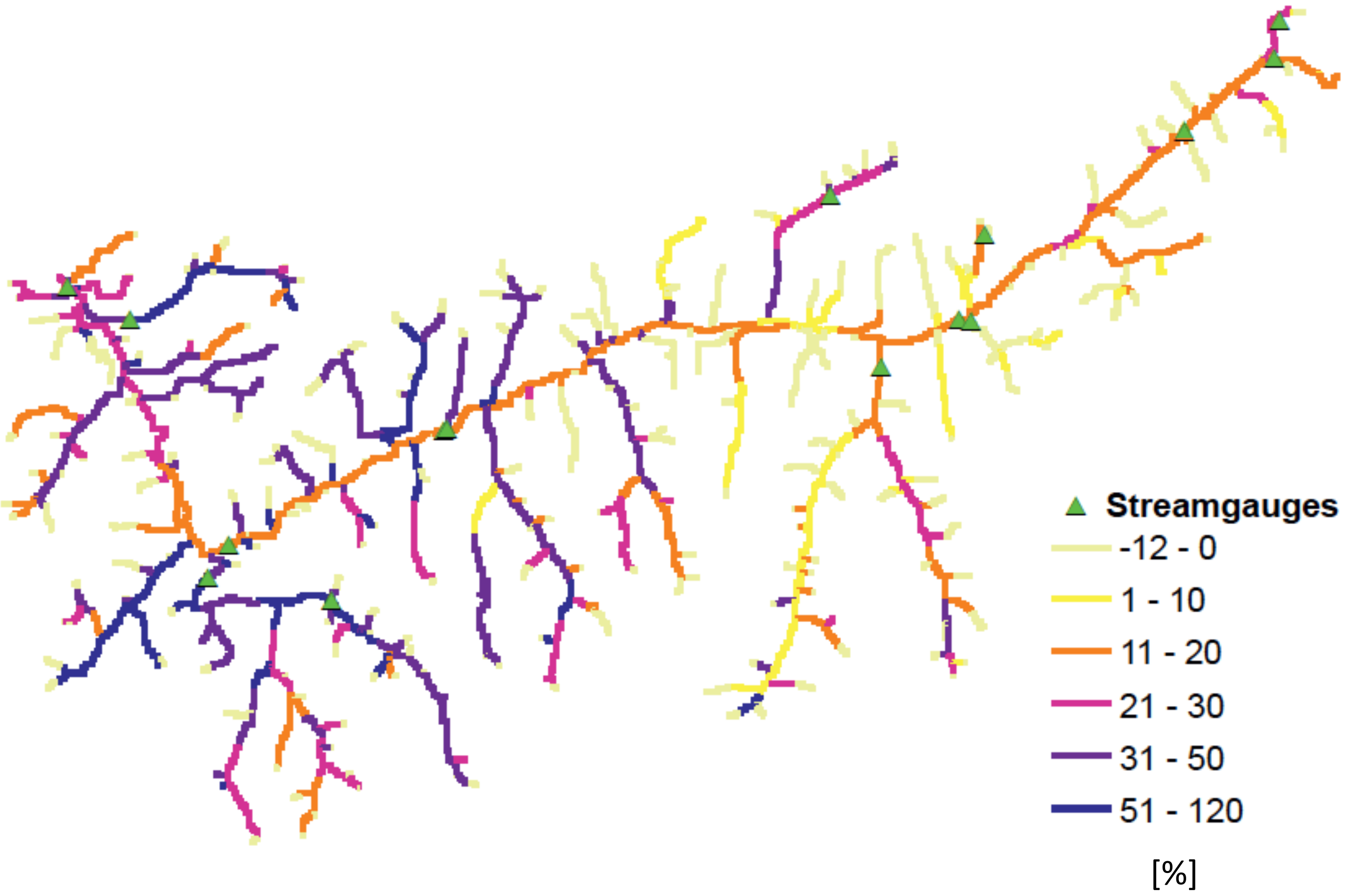
- **large uncertainty**
- *15 to 25% increase of max for 1h and 1d (larger for 1h)*
- **increase of max** *independent of driving scenario*
- *changes for* Q_{min} *at all temporal aggregations and* Q_{max} *for 30d are* **comparable with the stochastic variability → uncertain**



CC impacts on max daily runoff

[Fatichi et al., HESSD, 2013]

- *Important role of*
  hydropower systems
  precip distribution
- *Areas affected by larger precipitation show*
  peak flow increase up to 20-50%
- *Dampening of peak increase in the main valley*



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- **Impact on reservoir storage dynamics**

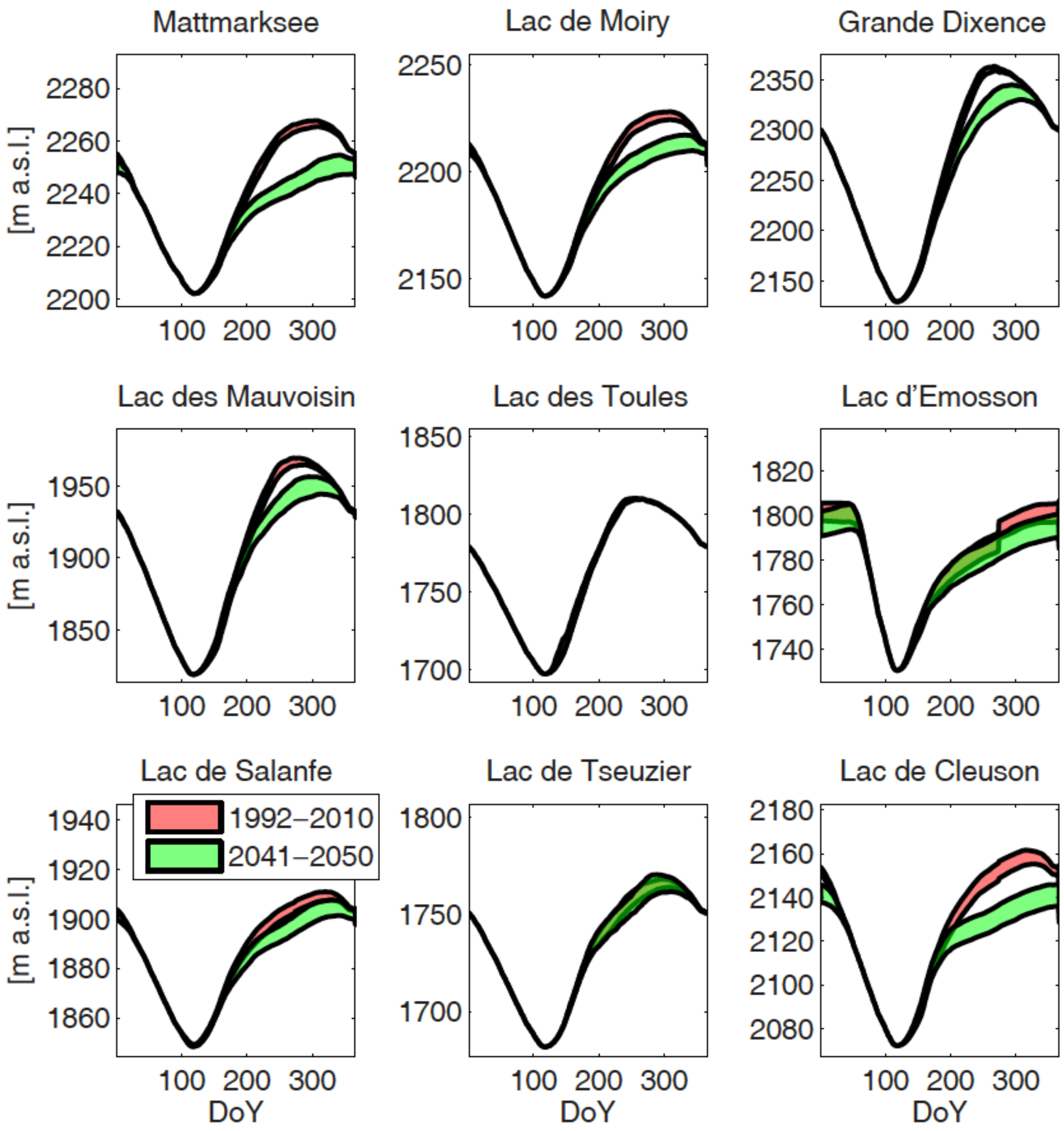
CC impact on annual cycle of reservoir levels

[Fatichi et al., HESSD, 2013]

2041-2050 vs 1992-2010 (control sc.)

coloured band: values within the 10th and 90th percentile of the stochastic simulation

- *in general significantly lower levels in summer and autumn (effect of reduced ice melt)*
- *changes larger than stochastic variability*
- *larger variability in future climates (higher dependence on precipitation variability)*



Concluding remarks (1) – glacier scale

- **The gradual disappearing induced by climate change may confine a glacier to higher elevations causing a possible slow down of the retreat rate**
  - *strong dependence on the glacier morphology*
  - *strong influence of winter accumulation of precipitation*
- **Importance of accounting for debris cover**
  - *insulation effects may lead to anomalous retreat trajectories*
- **Large glaciers present a slower response up to 2050**
  - *relative changes in glacier geometry are significantly lower than those obtained for small and medium-scale glaciers*
- **The glacier evolution and the related changes in the runoff regime are a highly complex and non-unique-trajectory process**
  - *considering explicitly the variability in the meteorological forcing is important*

Concluding remarks (2) – basin scale

- **Robust modelling framework (→ plausible response modelling)**
  - *model validation/confirmation good across spatial and temporal scales despite unprecedented complexity of the simulation for this typology of catchment*
  - *model technology hydrologically consistent and suitable for high resolution (space-time) impact analysis*
- **Importance of accounting for anthropogenic disturbances in CC impact analyses**
  - *changes in space show the alteration of CC impact throughout the network due to streamflow regulations and viceversa the impact of CC on the operation of hydropower systems*
  - *CC impacts are comparable or smaller than regulations due to hydropower*
- **Importance of distributed high resolution analysis**
  - *it reveals high variability, elevation dependence and potential for impacts on river corridors and aquatic ecosystems, in addition and due to streamflow regulation by hydropower*
- **Importance of analysing intrinsic (future) climate variability by stochastic scenarios**
  - *it reveals that uncertainty is often of the same order of magnitude of the change*
  - *highlights the limits of direct use of climate models (besides resolution) and simple approaches such as delta change*

Concluding remarks (3) – basin scale

- **Robust climate change signals (i.e. exceeding climate intrinsic variability) found in basins at high elevations, where icemelt represents a significant fraction of total runoff**
  - *Rhone: large extent of the glacierised area*
  - *Po: dry summer enhance the importance of even small glacier contributions*
- **CC induced precipitation increase dominates future local response**
  - *Rhone: west upper sub-basins*
  - *Po: Toce and Ticino sub-basins*
  - *robustness dependent on climate model and downscaling chain*
- **Stochastic variability of precipitation maintains the signal to noise ratio low for most of Rhone and Po basins**
  - *intrinsic climate variability can overwhelm change*
  - *designing (or checking) infrastructures for stochastic variability can implicitly address adaptation issues*
- **Considerable impacts on hydropower production**
  - *in icemelt fed reservoirs summer and autumn levels cannot be mantained without changing operations*
  - *under present operation policies CC induces a larger variability of water levels in reservoirs*

Concluding remarks – way forward

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- **Adaptation of existing hydropower plants**
  - *new operation and optimization of hydropower plants under constraints of future streamflow regimes*
  - *long-term sustainability, upgrade and safety*
  - *increased sediment production and siltation risk*
  - *more flexible operation to compensate irregular electricity supply by renewables*
  - *increased risk of device failure (e.g. turbines) due to flexible operation (short circuiting → aeration)*
- **Development of hydropower**
  - *development of new systems*
  - *centralized vs decentralized solutions*
  - *network regulation through pump-storage systems*
  - *hydraulic and electromechanical devices to cope with new operation regimes (e.g. network regulation)*
  - *environmental impact/compatibility of new systems/new operating rules*
- **Institutional/economical aspects**
  - *review of concession criteria in the context of CC*
  - *compatibility of concessions with environmental protection regulations in the context of CC*
  - *prediction of CC induced demand change and new supply configuration and their effect on electricity markets*

Need for interdisciplinary research and pilot projects to simulate future climate, operation conditions, changes of demand and market