Improving physically based snow simulations by assimilating snow depths using the particle filter

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Snow melt can contribute or cause floods

Accurate forecasts sometimes help people to save something irreplaceable

Better reservoir management with good snow data

Possible to produce more energy with accurate forecasts of reservoir inflows

Snowpack stability determines avalanche danger

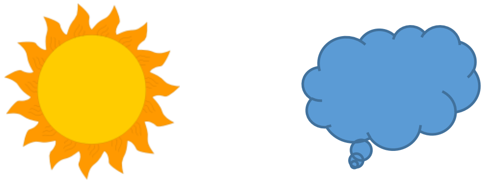
Information about week layers help avalanche forecasters to give accurate warnings

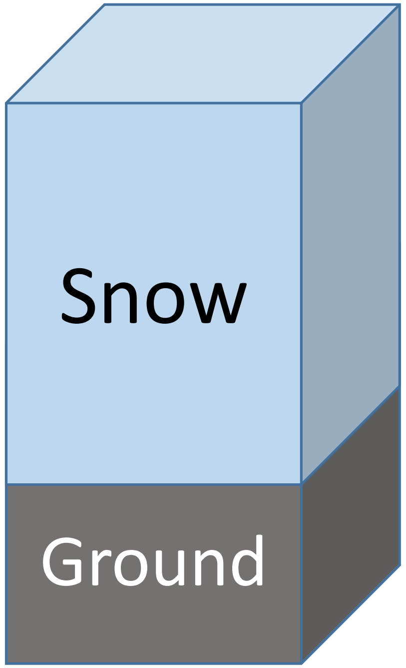
Studying the impact of raising temperatures

PHOTO: AXEL LINDAHL, NORSK FOLKEMUSEUM OG OSKAR PUSCHMANN, NIBIO

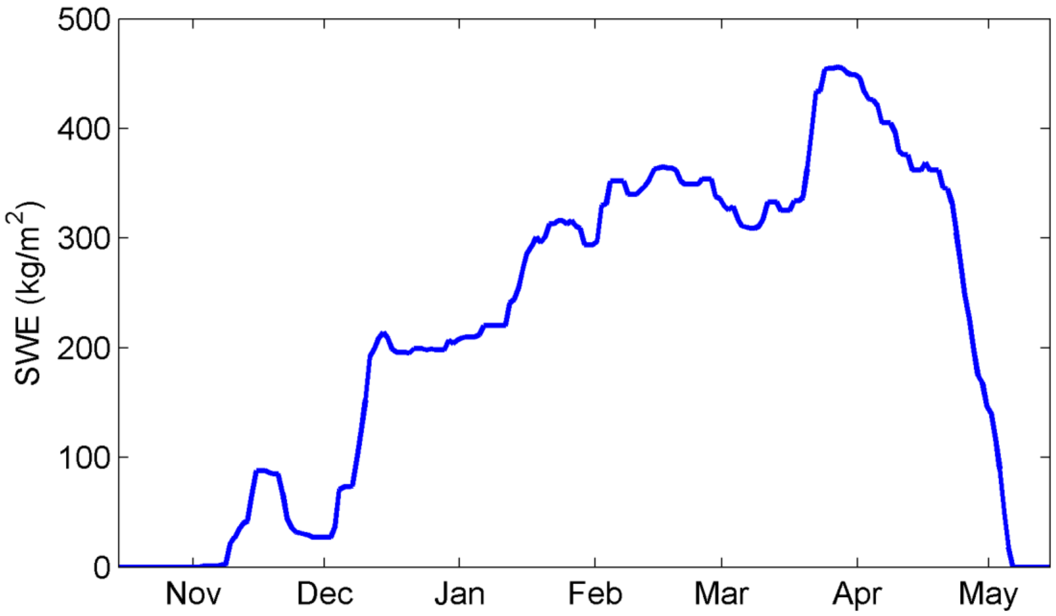
Modelling snow accumulation and melt helps predicting changes in the mass balance of glaciers

Simple snow models – hydrology, glacier mass balance…

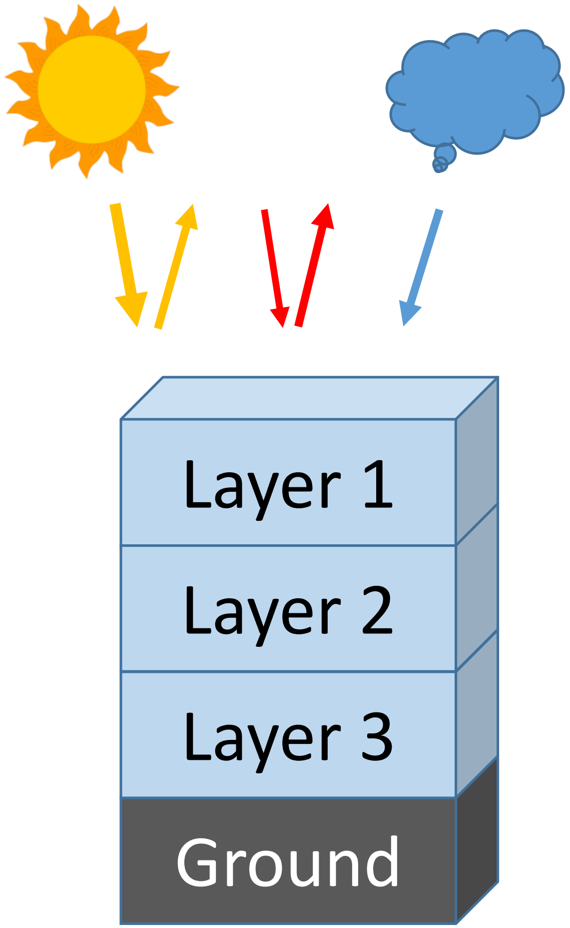


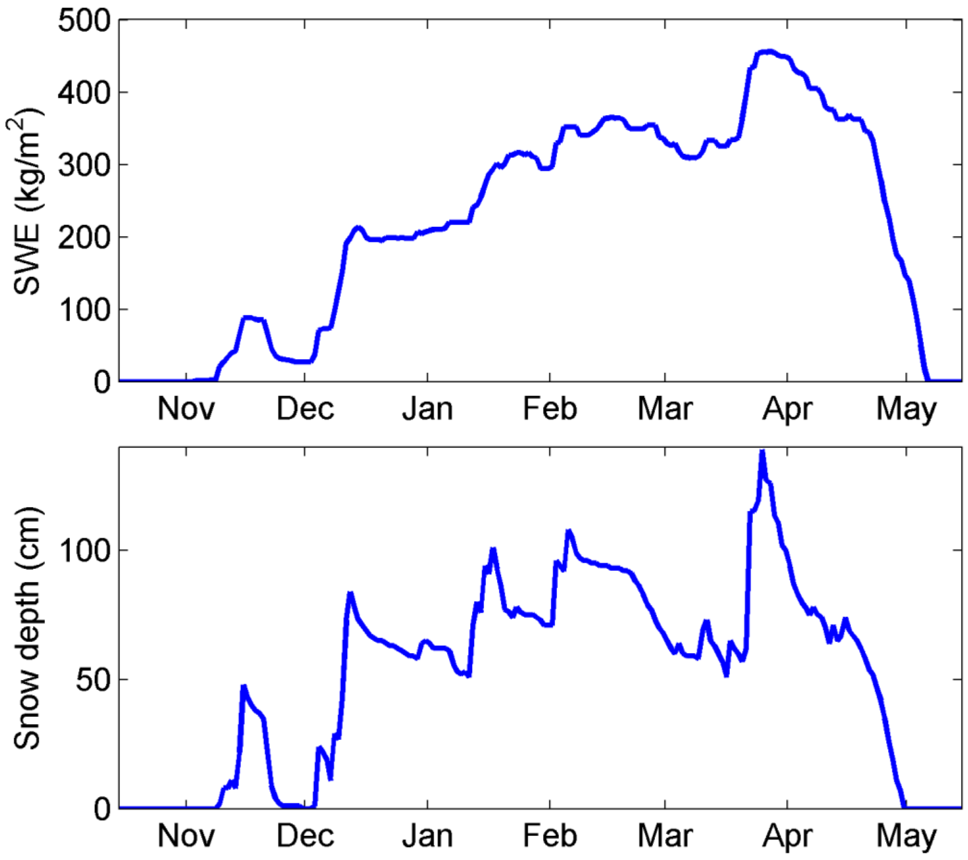


- Snow water equivalent – Mass of snow per unit area (kg/m^2)
- SWE(t) = SWE(t-1) + Snowfall(t-1) – Melt(t-1)
- Snowfall = f(Air temperature, Precipitation)
- Melt = f(Air temperature)



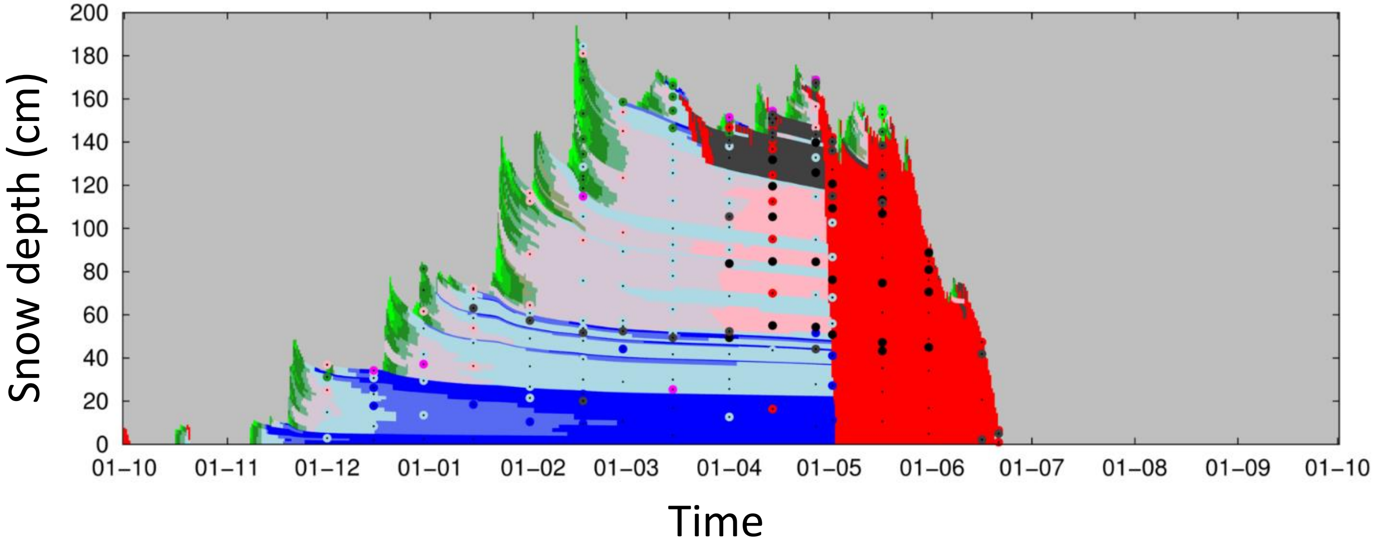
Energy-balance snow models – climate models, hydrology





- Simulates mass conservation and energy balance
- Requires many inputs (air temperature, humidity, wind speed, radiation)
- Layers with different properties (temperature, density…)
- Layering changes with time (adding or removing layers)

Detailed models for avalanche forecasting



- Computes the mass and energy balance
- Often hundreds of layers (grain type, layer bounds…)
- Used for analyzing snow stability (weak layers)
- Used for snow research (benchmark for simper models)

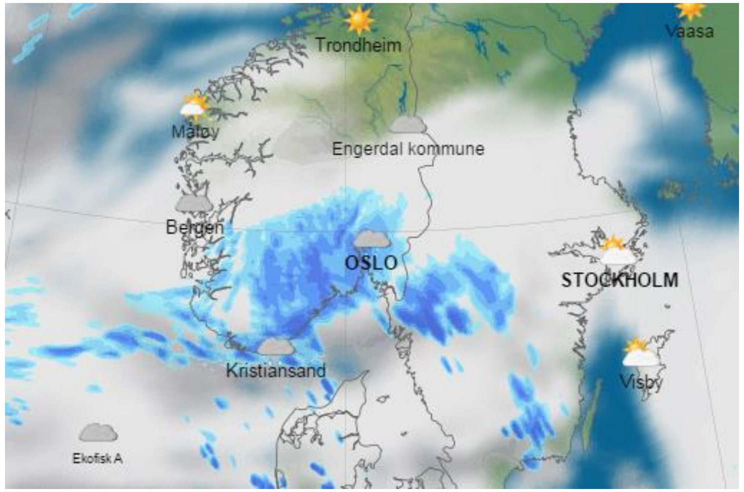
Why do we need these models?

Much work to measure the water equivalent of the snowpack

Dangerous to find weak layers of the snowpack in steep terrain

Hard to monitor energy exchanges over large landscape units (weather forecasting, climate modelling)

Use easily available data to improve snow simulations

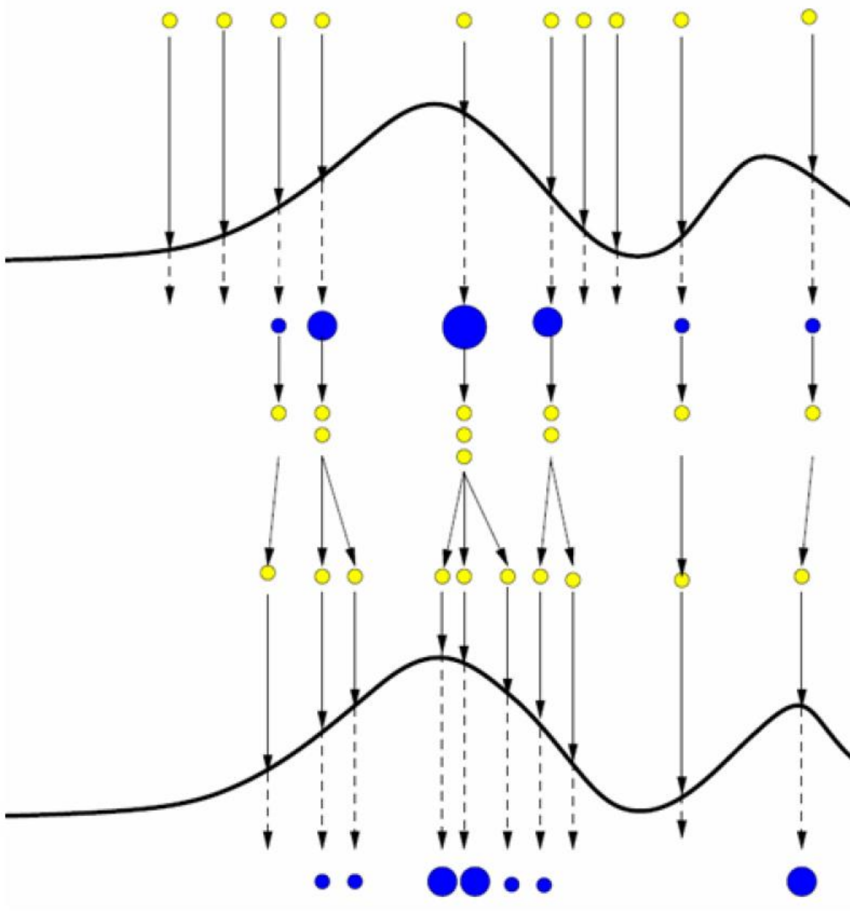


- **Assimilation data:** Snow depth is easy to measure, automatically as well as manually, and quite reliable
- **Input data:** Weather forecasting data, available more or less everywhere, but error prone
- **Model:** Multi-layer energy-balance snow model, varying layer structure over time (one to three layers)
- **Assimilation method:** Able to handle multi-layer energy-balance models, and even more detailed ones

Particle filter setup

- **Particle filter algorithm:** A basic version of the algorithm, or *'the most simple data assimilation setup anyone could ever imagine'*
- **Particle/ensemble generation:** Forcing the model with inputs perturbed using time-correlated noise
  - Additive normally distributed noise for air temperature, relative humidity, longwave and shortwave radiation
  - Multiplicative log-normally distributed noise for precipitation and wind speed
- **Resampling:** If efficient sample size is lower than 80% of total number of particles (residual resampling)
- **Likelihood function:** Normal probability distribution where the variance of the observation error increases proportionally with snow depth

Illustration of the particle filter algorithm



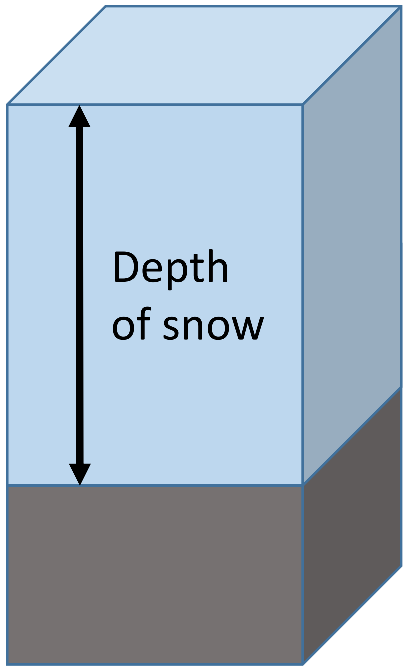
1) Initial set of particles with equal weight
2) Scale the weights using the likelihood function
3) Resample particles with probability proportionally to their weights
4) Propagate the particles using the model

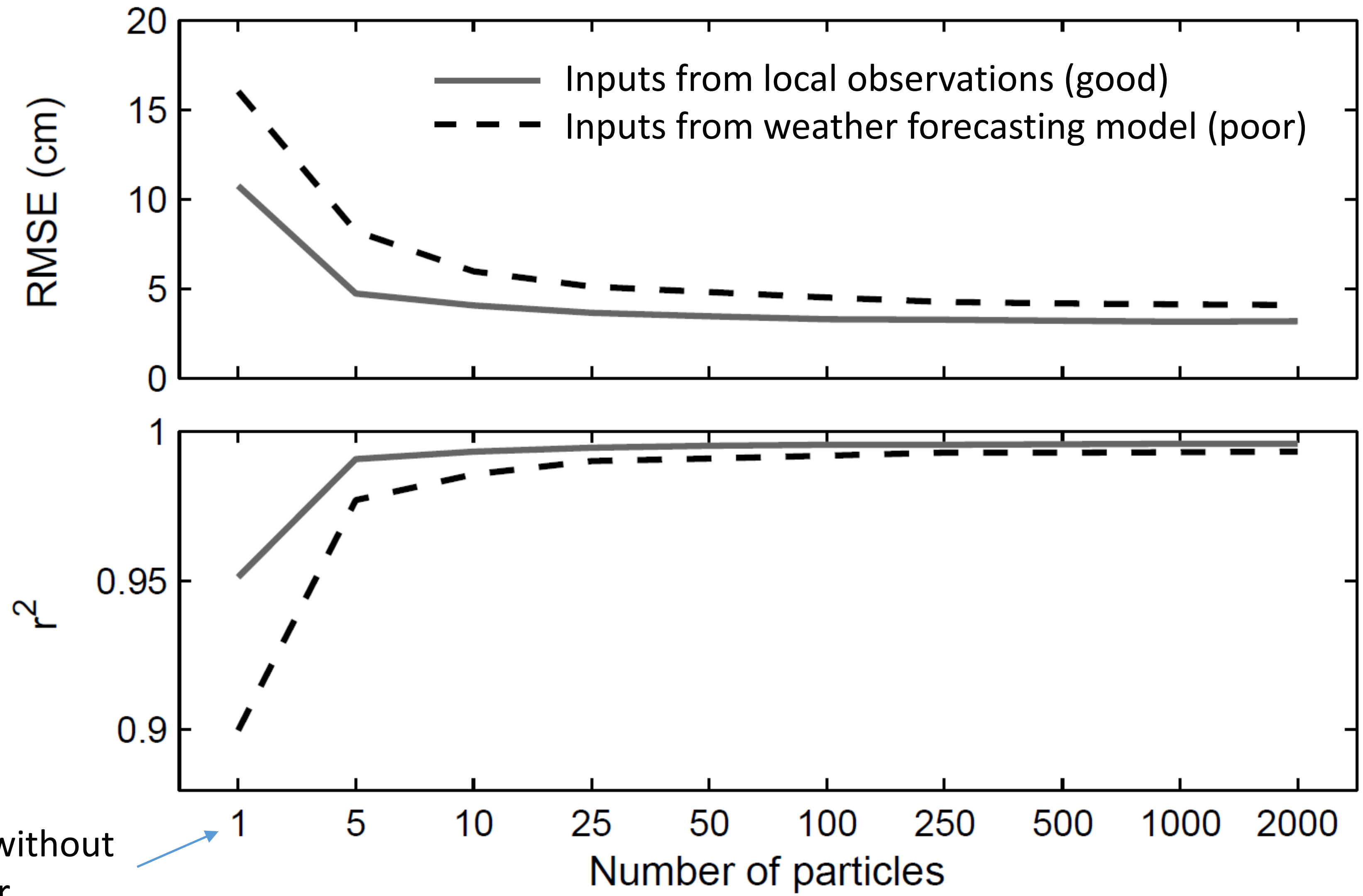
Test at a research field site with high-quality data

Col de Porte, 15km north of Grenoble, France
At 1300 m and 16 years of data

- Good knowledge about the measurements, often several instruments measuring the same variable
- Often easy to simulate snowpack variables at this sites due to good data quality (possible to remove biases in inputs prior to simulations)
- Two experiments: Using input data measured locally and provided by a weather forecasting model
- Similar sites rare since the maintenance requires large maintenance efforts

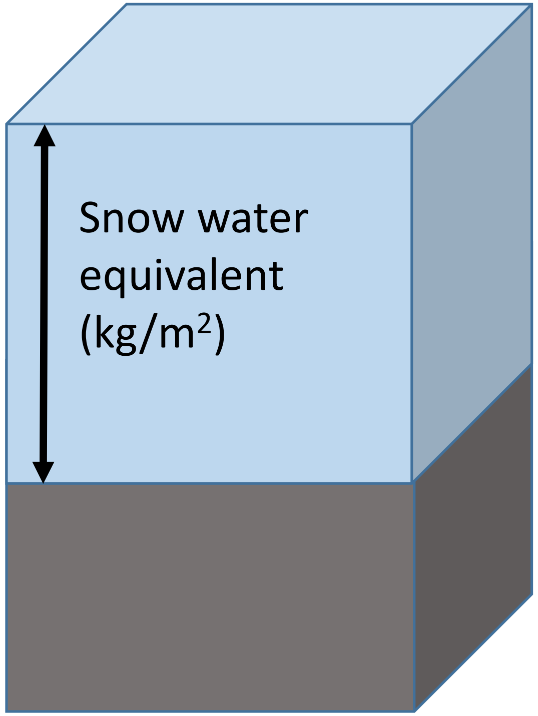
Results for Col de Porte – Snow depth

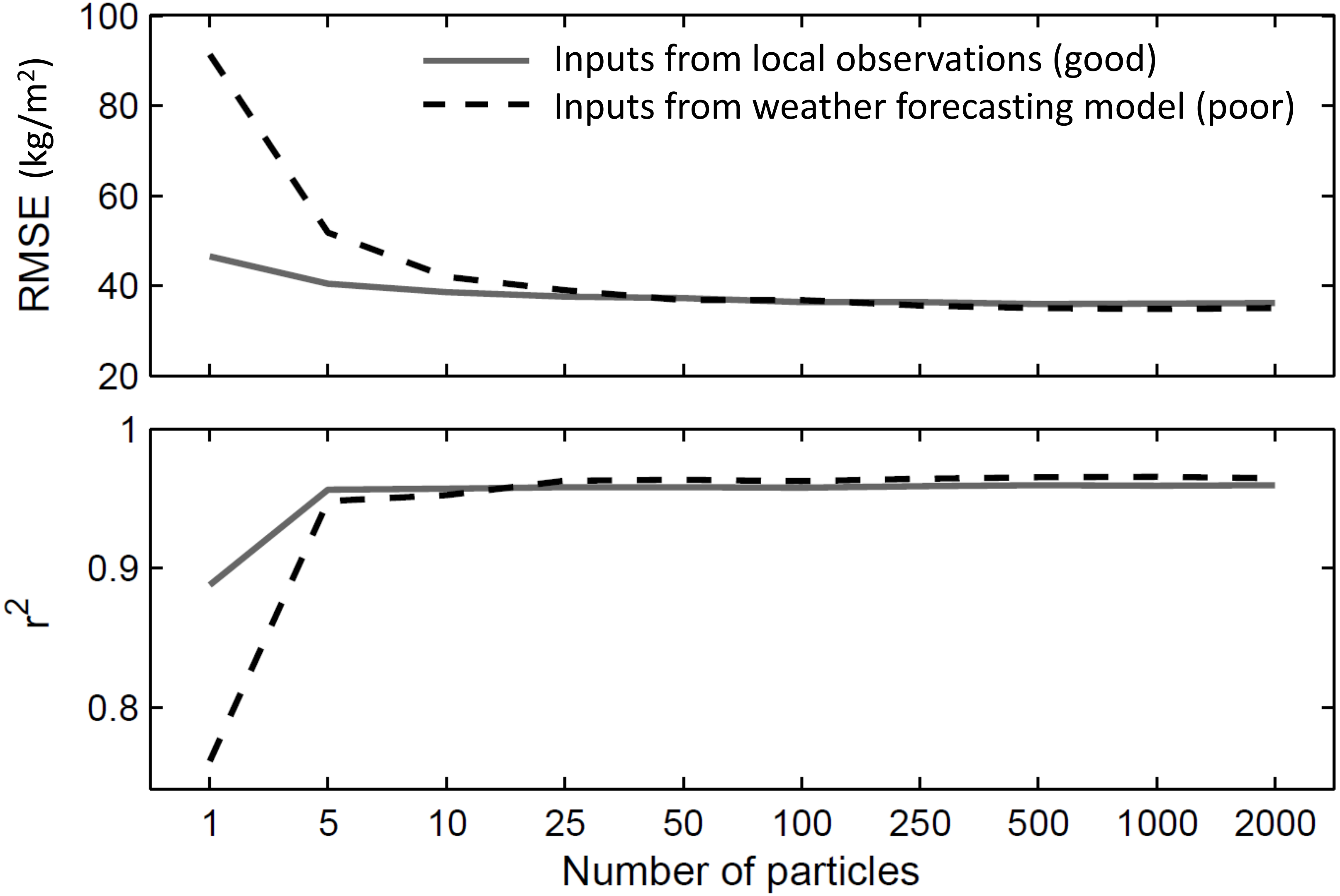




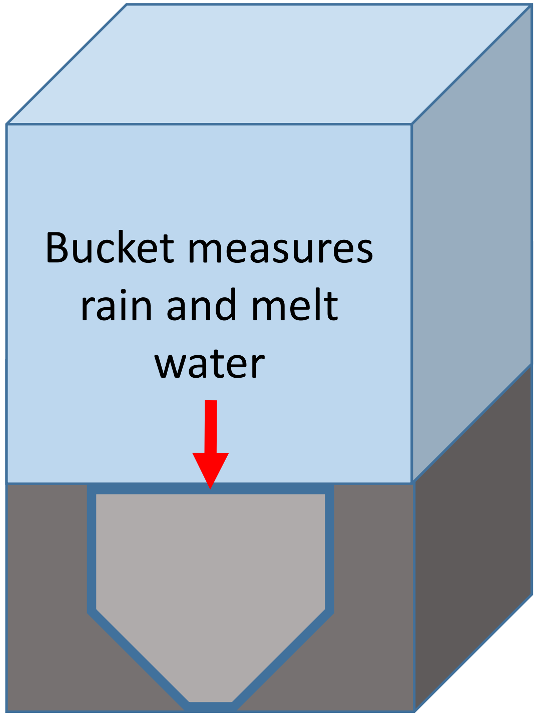
Deterministic run without
Perturbations/filter

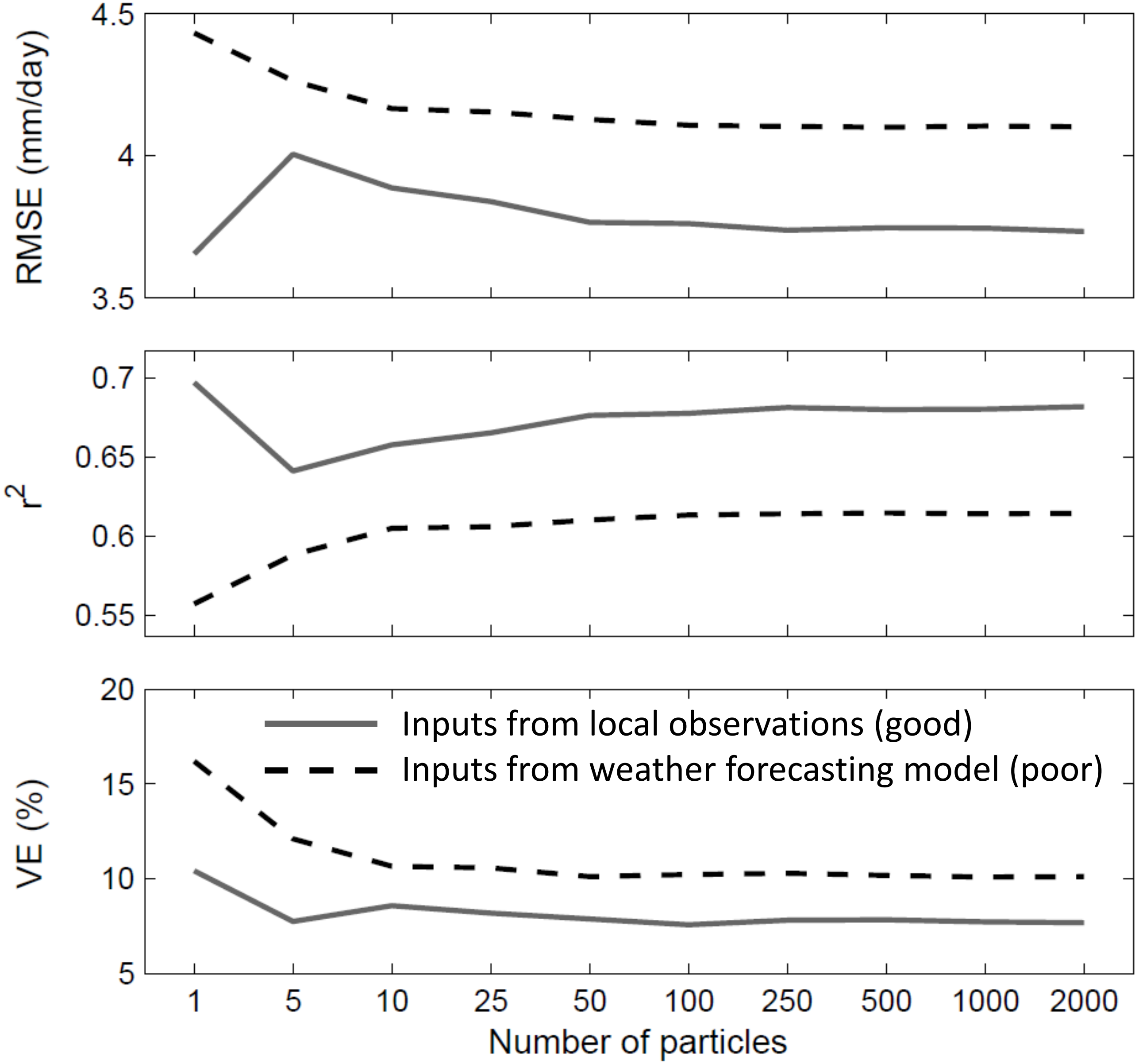
Results for Col de Porte – SWE



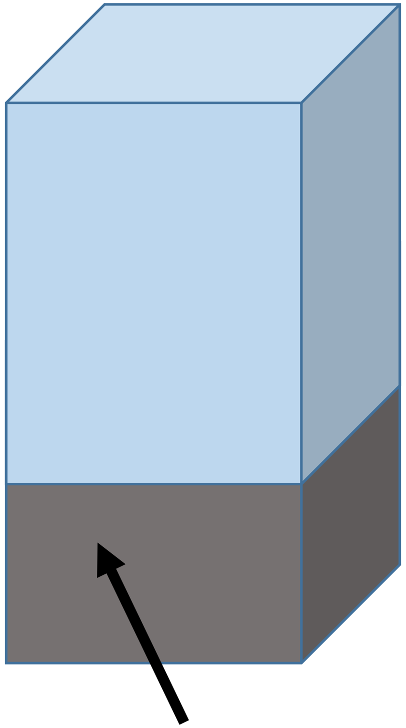


Results for Col de Porte – Runoff

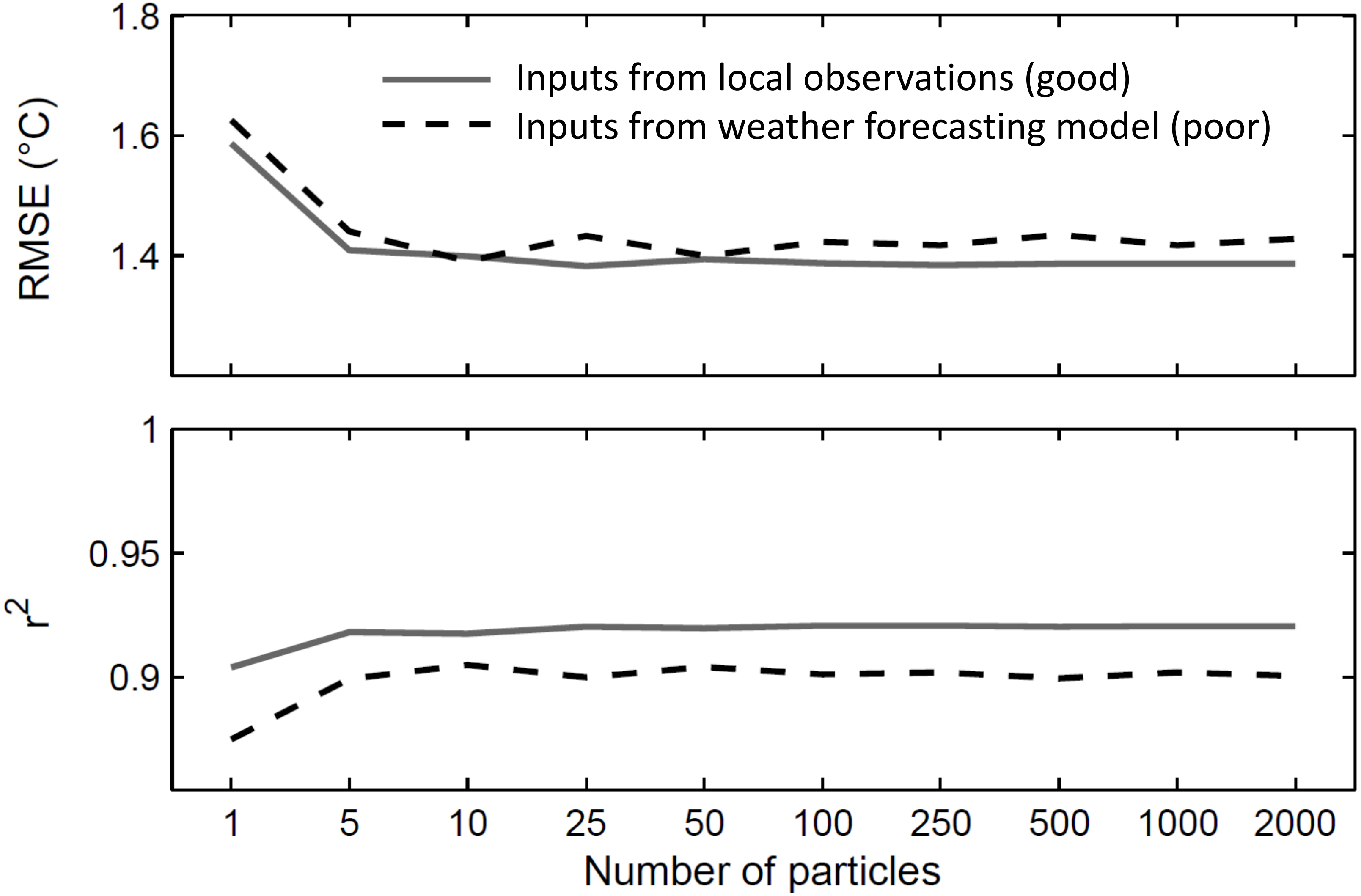




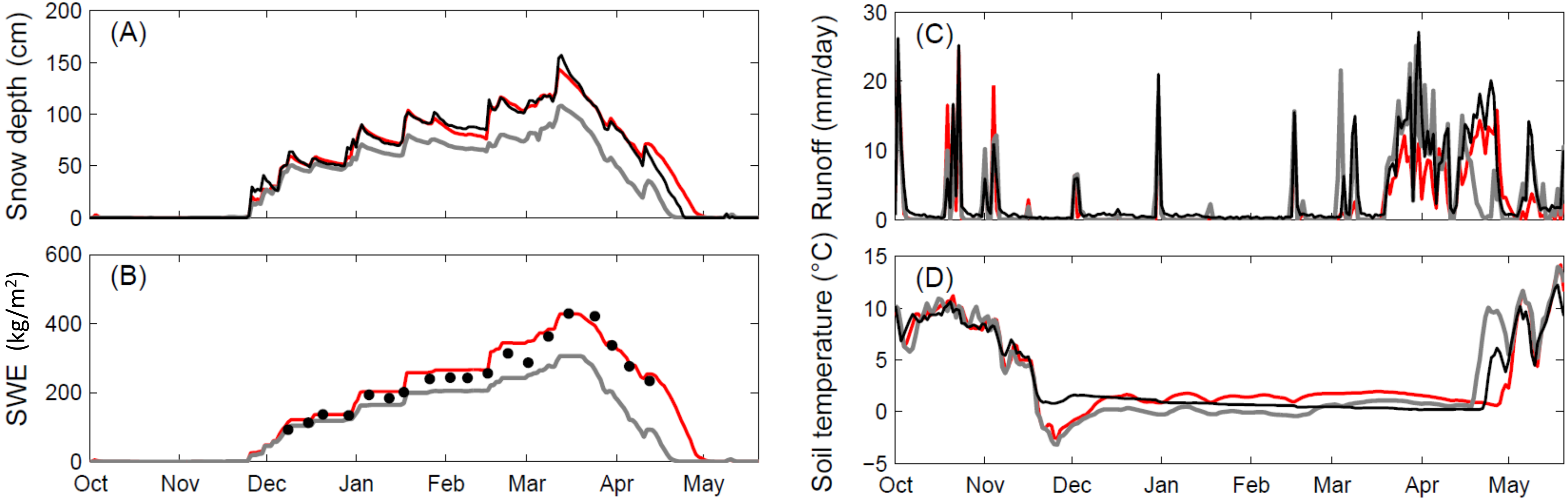
Results for Col de Porte – Soil temperature



Thermistor measuring the temperature of the soil 20cm below ground

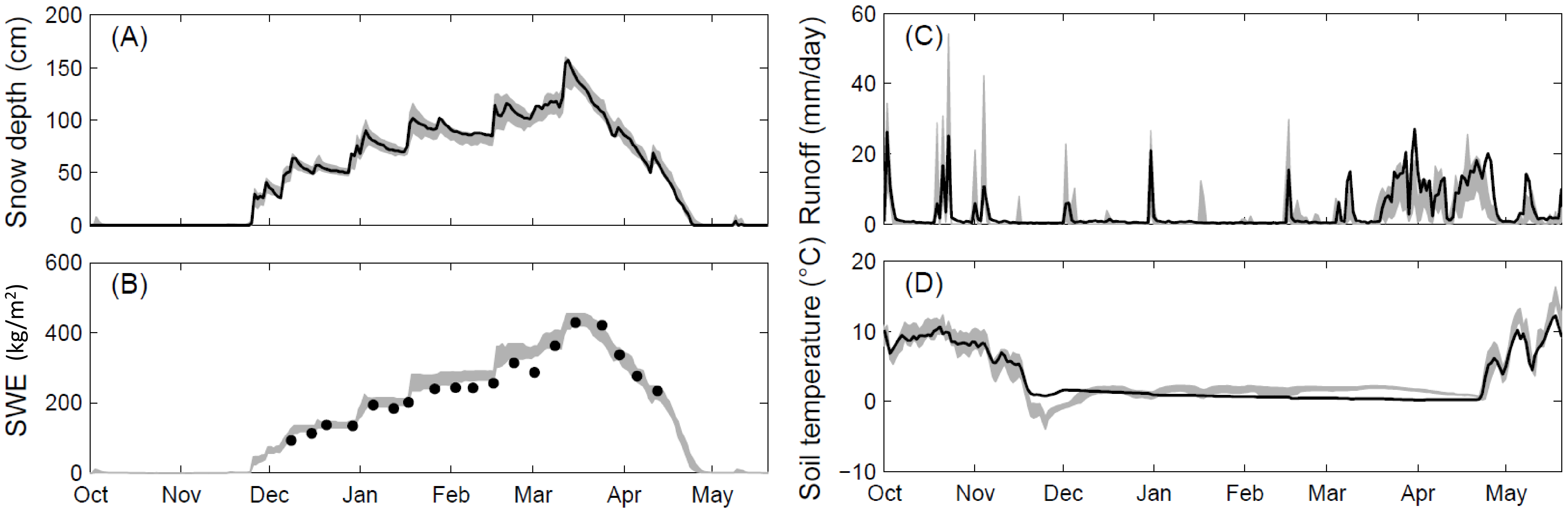


Results for Col de Porte – Deterministic runs



Black – Measured
Red – Inputs from local observations (good)
Gray – Inputs from weather forecasting model (poor)

Results for Col de Porte – Particle filter results



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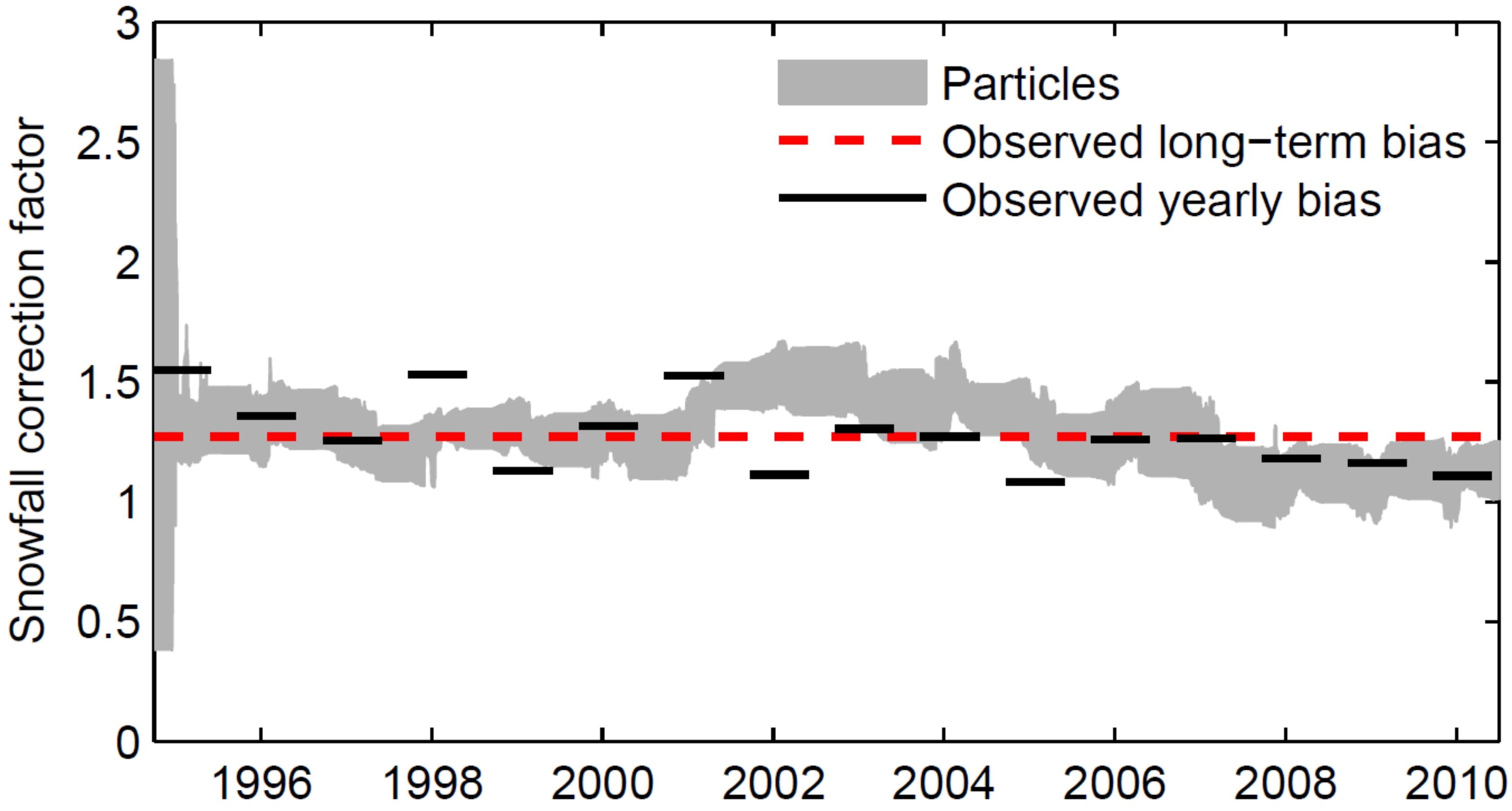
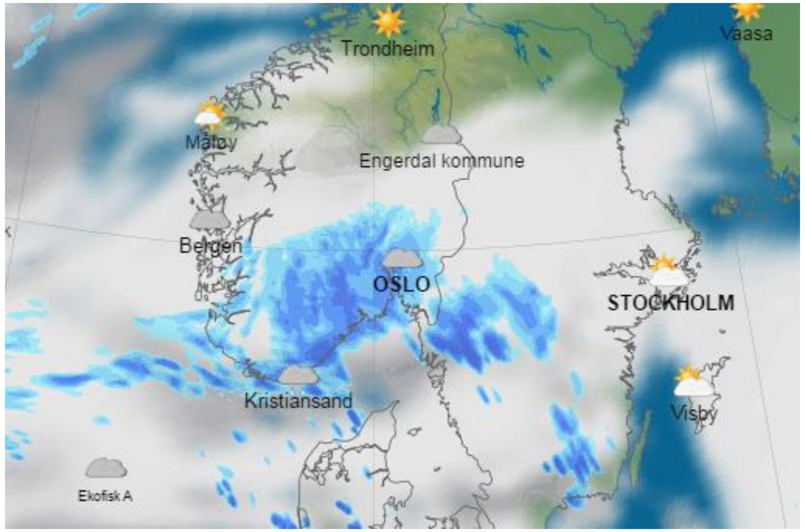
Results from Col de Porte – Parameter estimation



$$Sf_{corr} = P_{corr} * Sf$$

Typically field sites have insufficient data



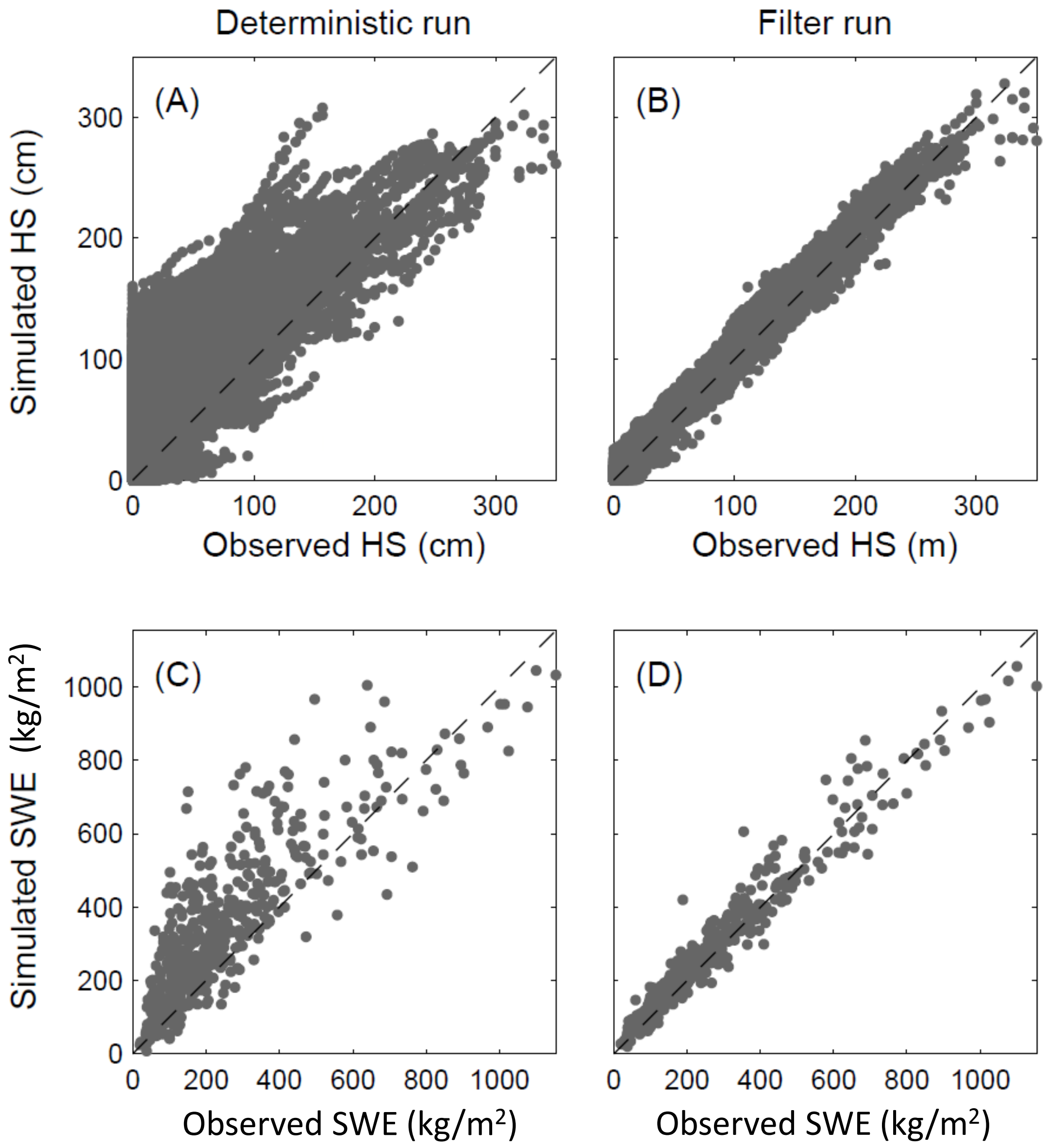
- Often only measuring a subset of input variables, if any at all
- Measurements usually compromised by errors (snow on radiation sensors, precipitation gauges not collecting all snowfall…)
- Model validation impossible since we lack data (e.g. snow water equivalent)

Next experiment: Only manual snow observations and weather forecasting data available for many sites

Results for Switzerland

Experiment setup

- 40 sites in Switzerland
- Covering altitudes from 1200 to 2700 m
- 2 winters of data
- Used operationally for avalanche and flood forecasting
- Daily measured snow depth
- SWE measured every second week
- Model inputs from weather forecasting model
- Same filter setup as for Col de Porte



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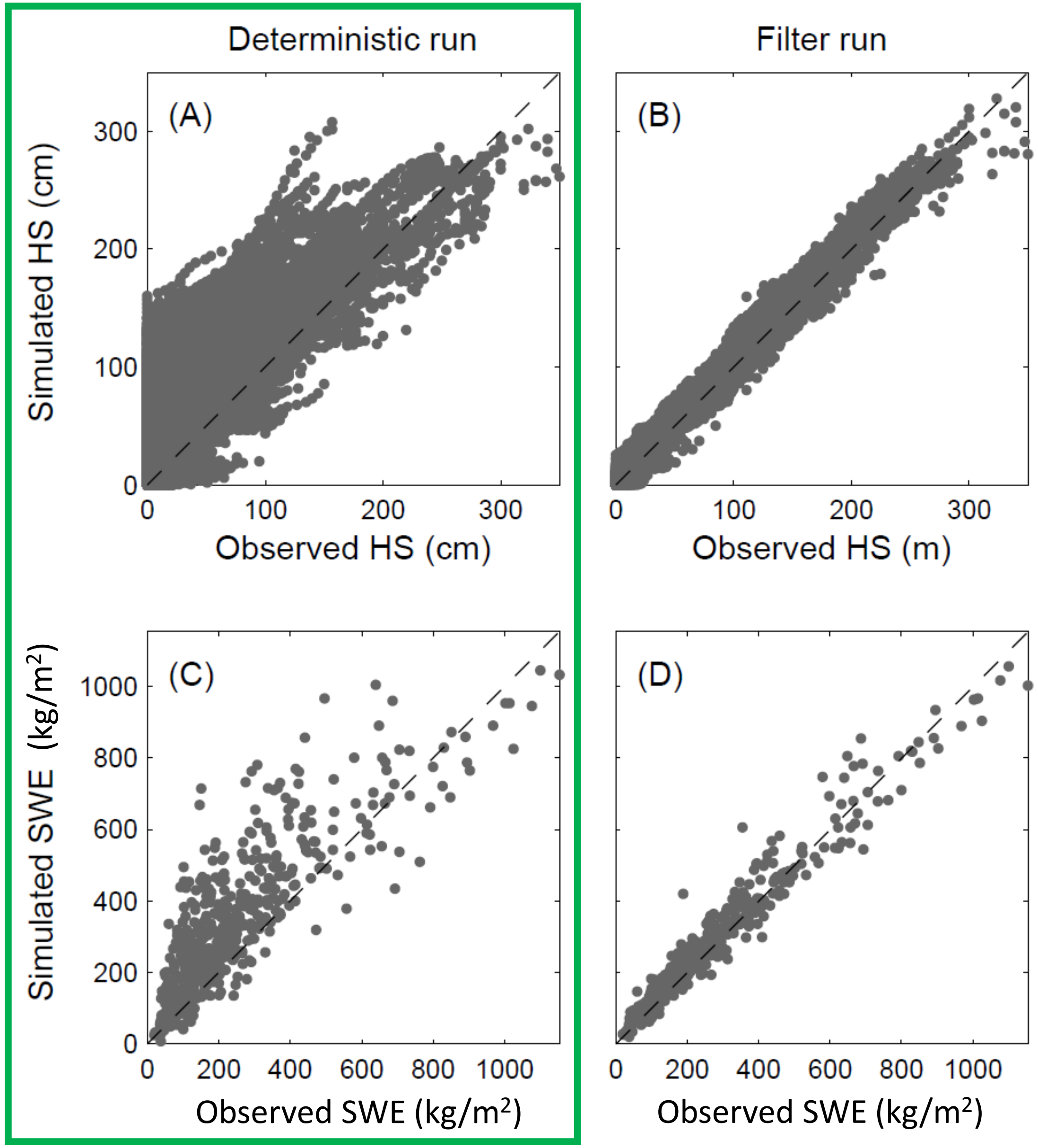

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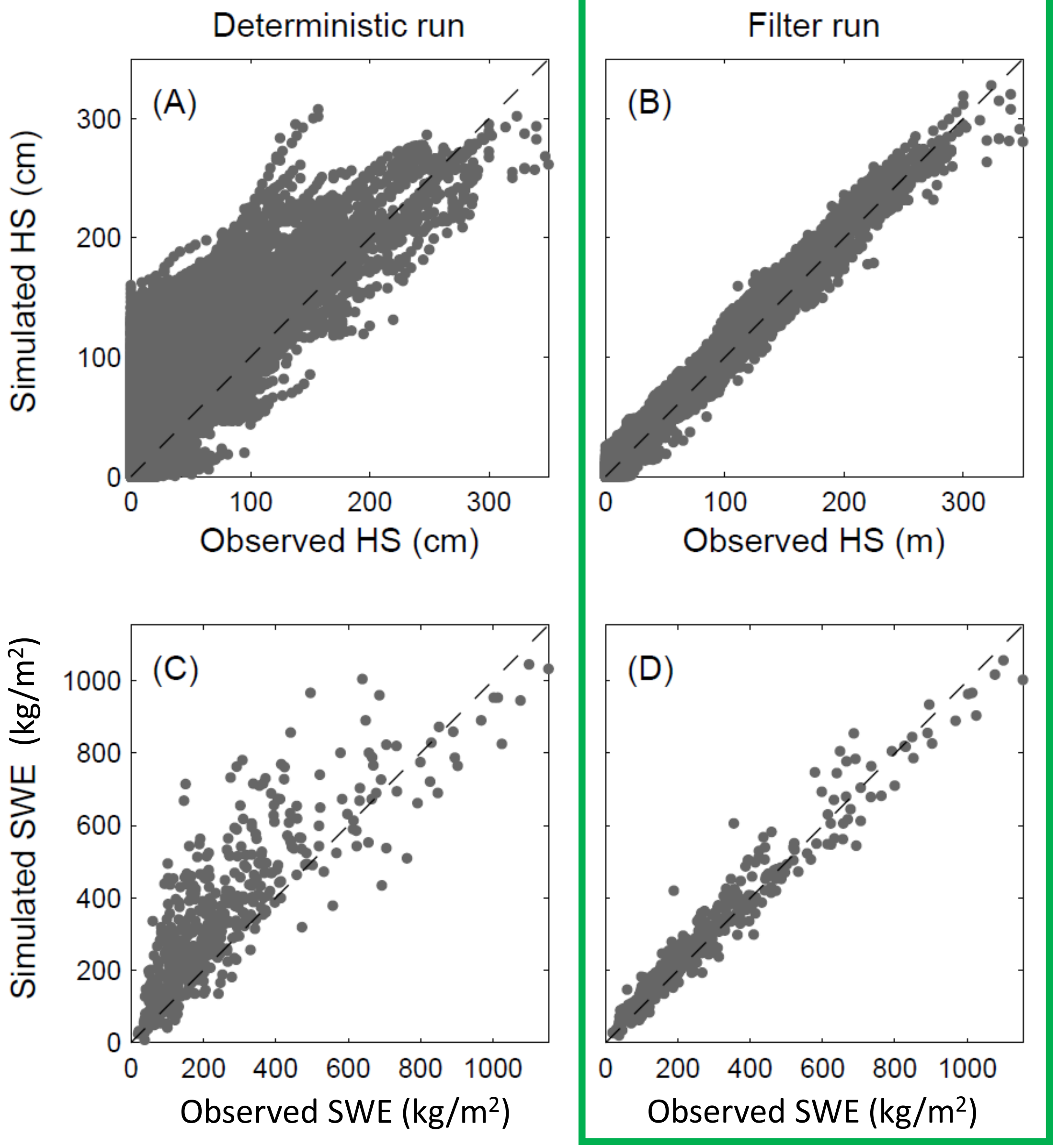
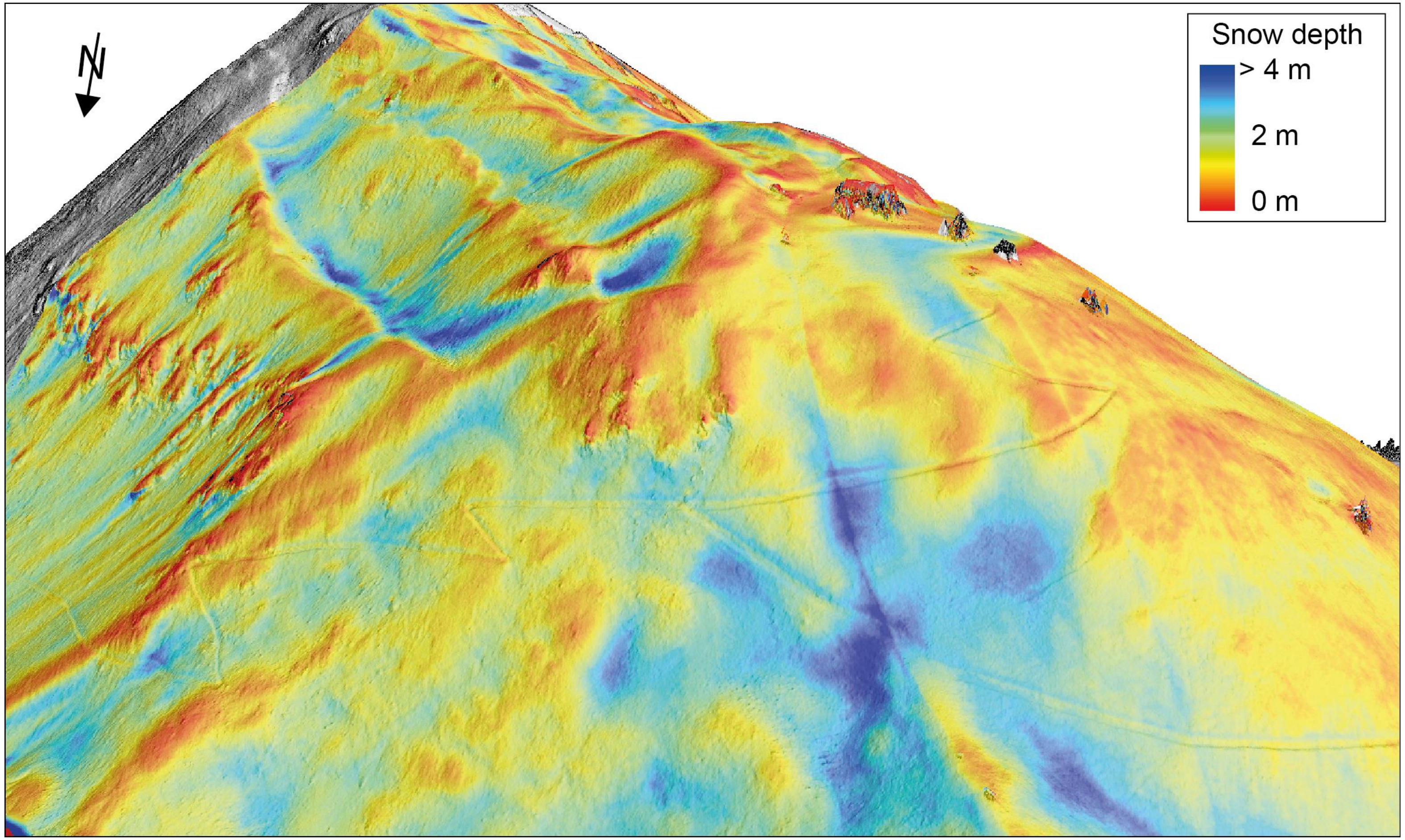


Going from single sites to a distributed model

Remote sensing of snow depth

- Unmanned aerial vehicle
- The Ice, Cloud, and land Elevation Satellite-2 (ICESat-2)



Mapping snow depth in alpine terrain with unmanned aerial systems (UASs): potential and limitations, Y Bühler, MS Adams, R Bösch, A Stoffel - The Cryosphere, 2016

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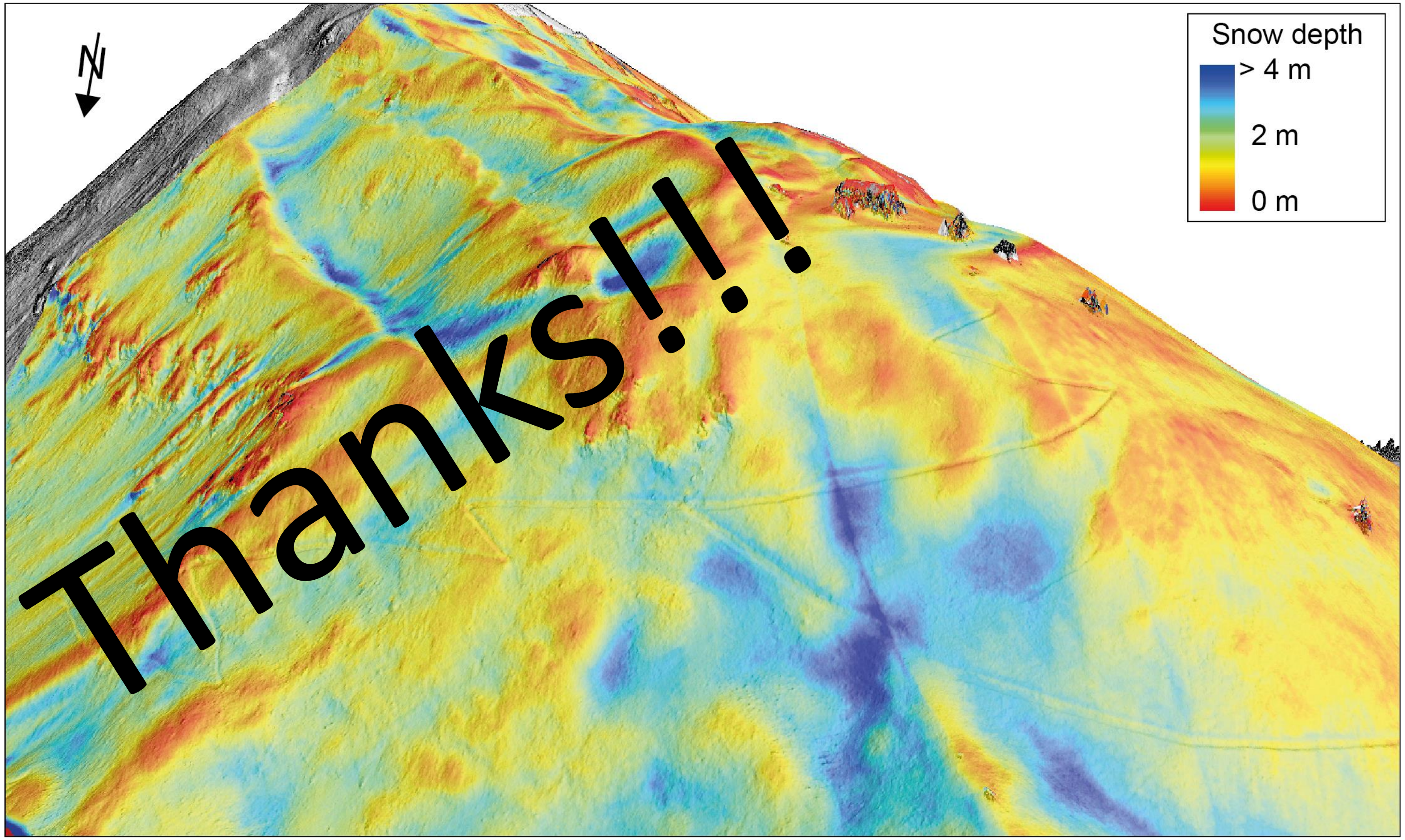

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