11th Workshop of International Precipitation Working Group – Tokyo Insitute of Technology

Correcting Snowfall Elevation Gradients by using Sentinel-1 Based Snow Depth Observations

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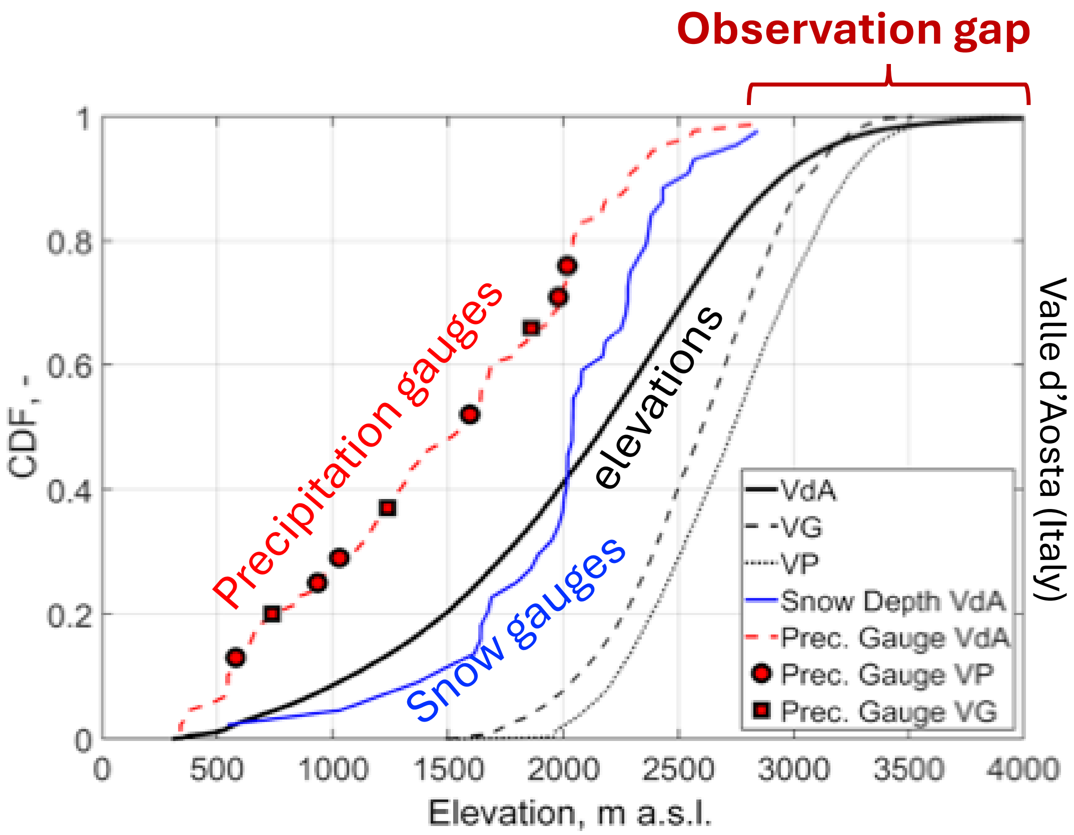
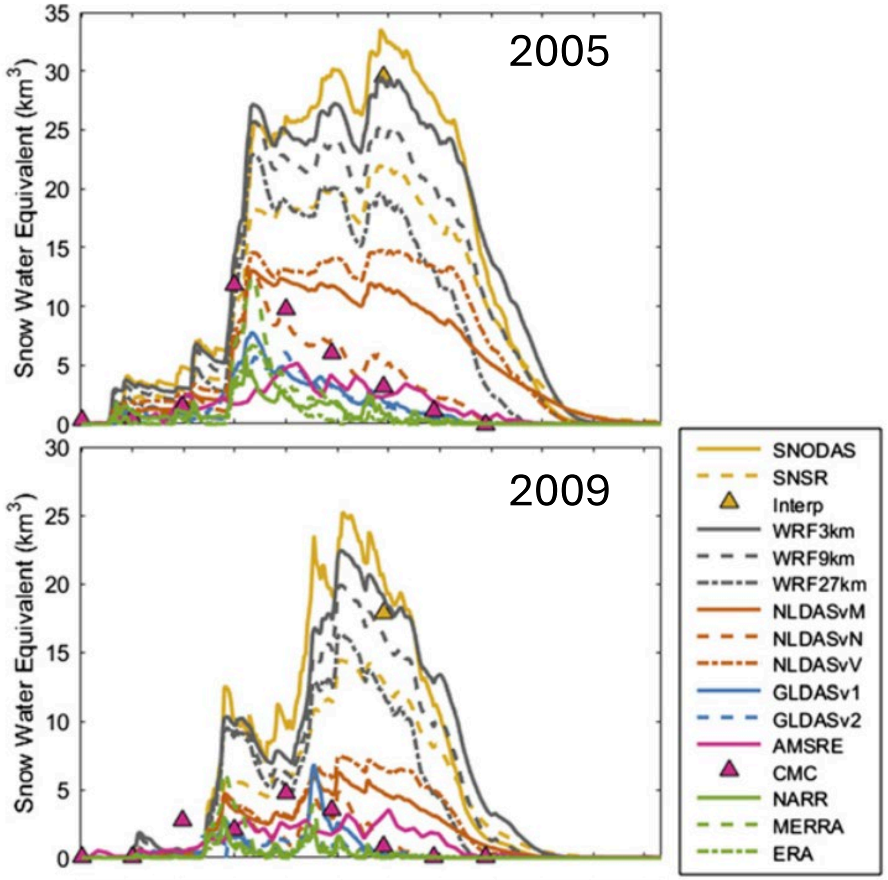
Snow estimates are uncertain



Avanzi et al., (2021), HESS
Valle d'Aosta (Italy)



Wrzesien et a., (2017), JHM
Sierra Nevada (California)

Errors in SWE modeling estimations are caused by uncertainties in:

- **Orographic Precipitation Amounts**;
- Rain/Snow Partitioning;
- Ablation (melt) Parameterization

$$\alpha * P \pm V - M = \frac{dSWE}{dt}$$

α = Snow Correction Factor

Sentinel-1 snow depth observations

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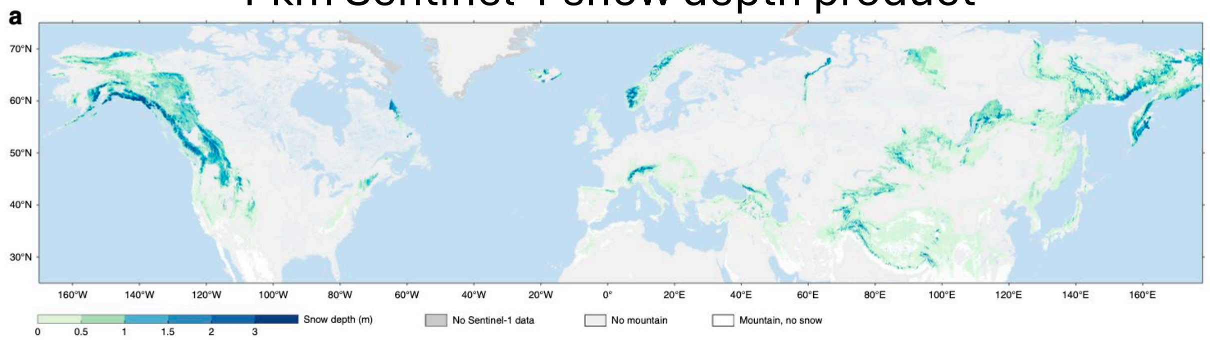
Snow depth variability in the Northern Hemisphere mountains observed from space

Lievens et al. (2019)

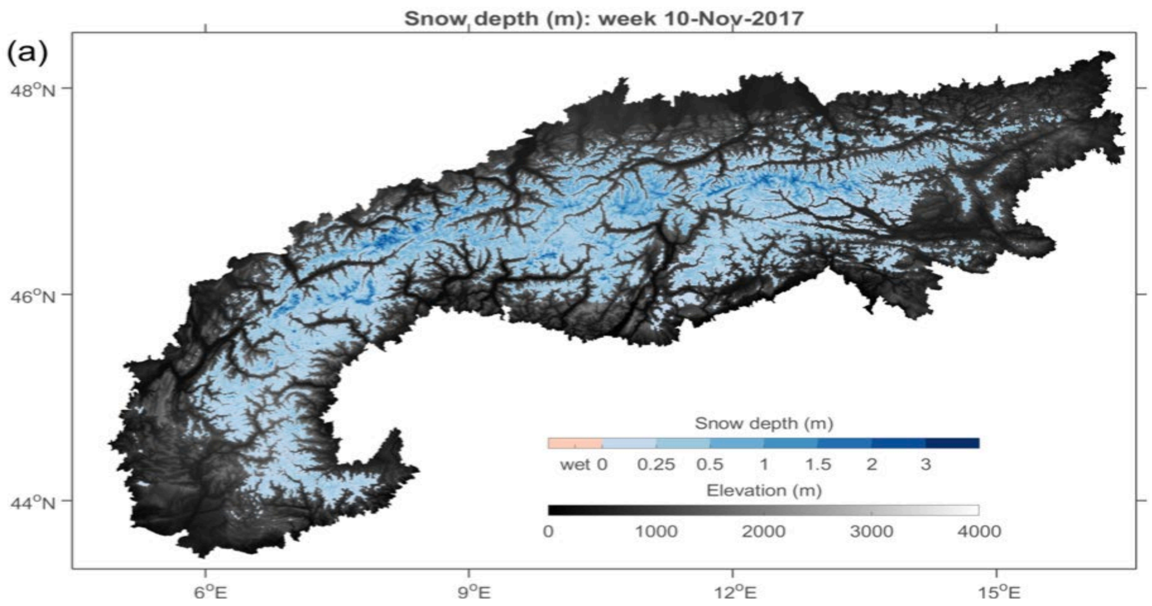
<u>Sentinel-1 Snow depth data</u>:

- Derived from C-band radar backscatter
- Increase spatial sample vs. in-situ observations
- 100 m - 1 km; every ~6-12 days
- 2017-present
- Good only for dry snow
- Not good for shallow snow

1 km Sentinel-1 snow depth product



Lievens et al., (2019), *Nature Communications*



Lievens et al., (2022), The Cryosphere

100 m Sentinel-1 snow depth product

Can we correct snowfall using Sentinel-1 SD?

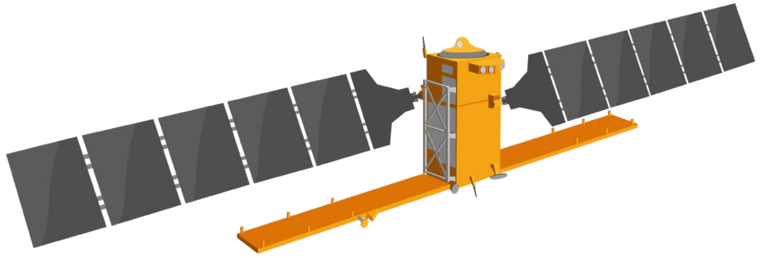
$$SWE = SWE(\rho, SD)$$

$$\alpha * \boldsymbol{P} \pm V - M = \frac{dSWE\ (\rho,SD)}{dt}$$

$$SD = f(\rho, \boldsymbol{P}, T, \vartheta[\alpha, \dots], \varepsilon)$$

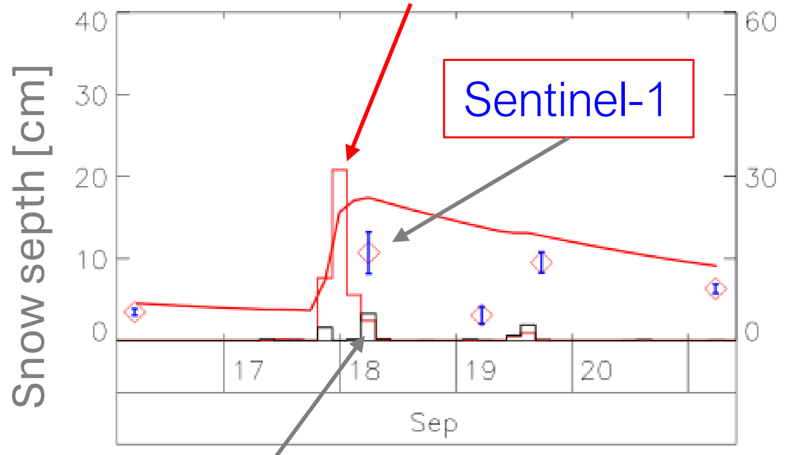
Modelled SD

Observed SD from S-1



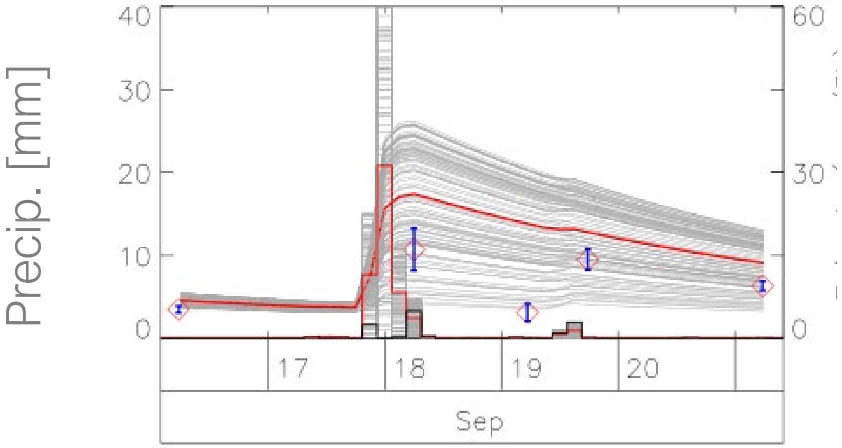
Particle Batch Smoother (PBS) concept

Satellite precipitation



True snowfall

Precipitation perturbation

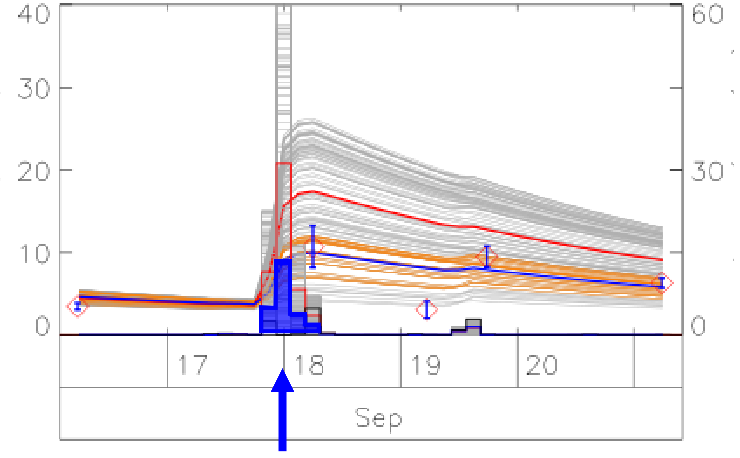


Pi = P * **α**

$\alpha \sim \log(\mu, CV)$

$\mu = 1$(unbias), CV = 100%

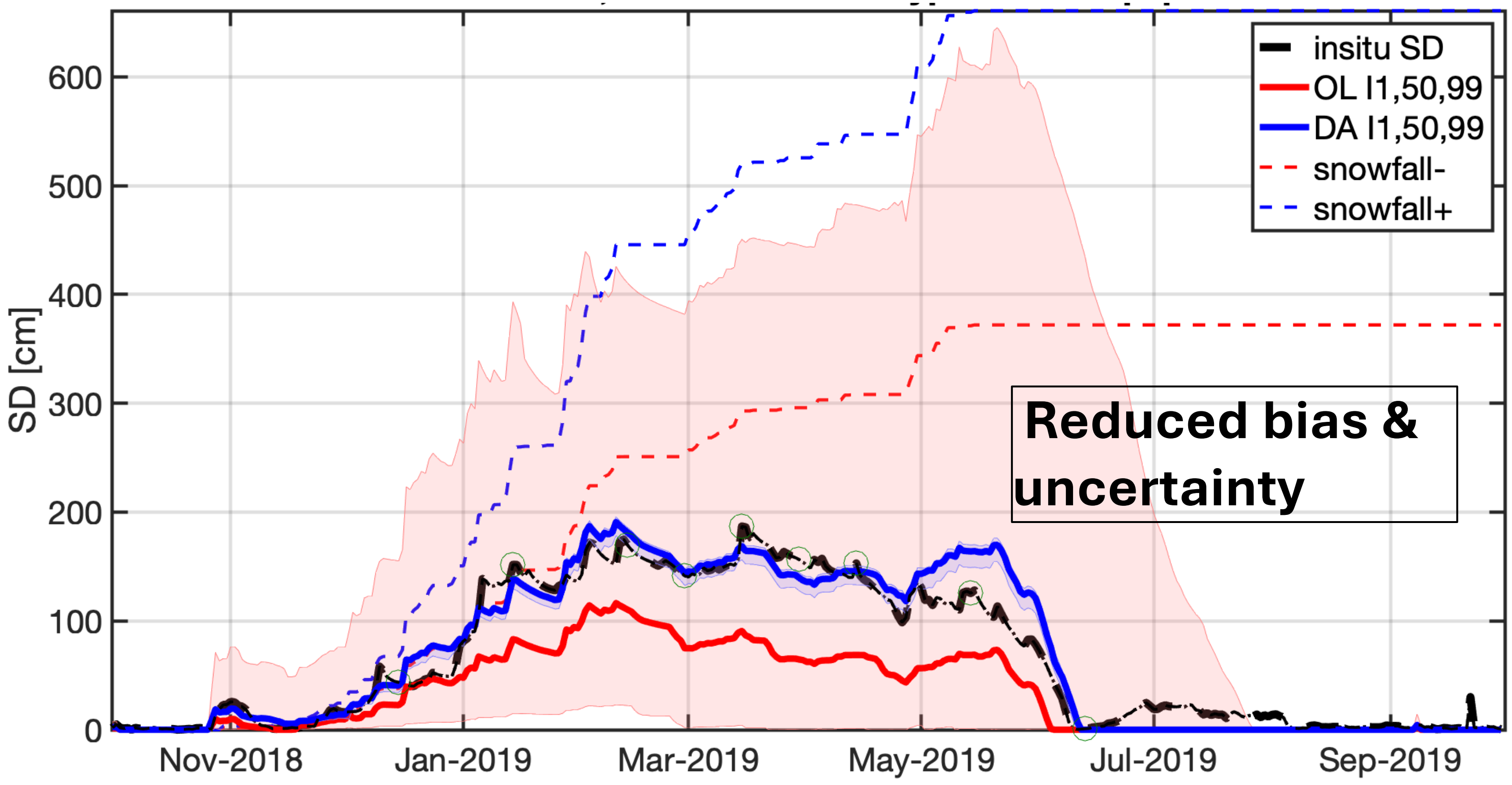
Most probable SD trajectories



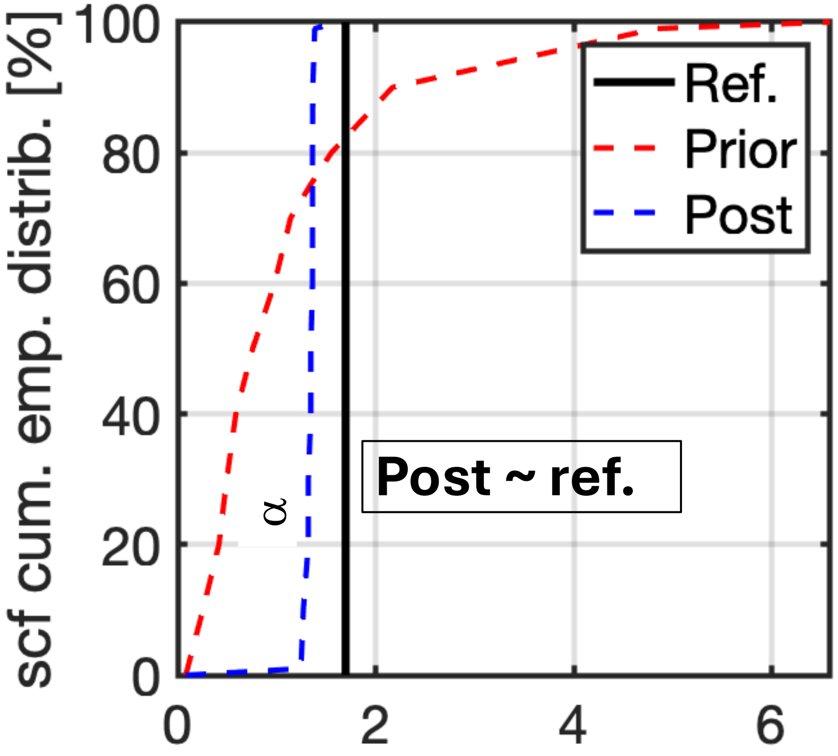
Corrected snowfall product

Results – point scale observation

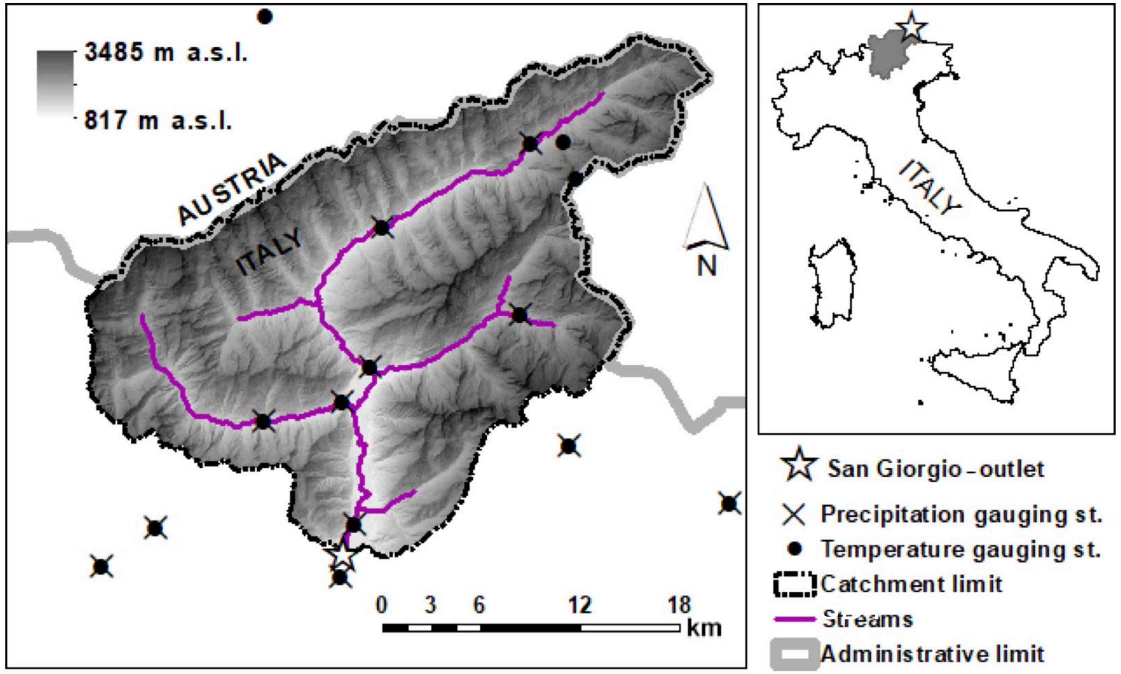
Snow depth and cumulative snowfall



Distributions of the snow correction factor (α)

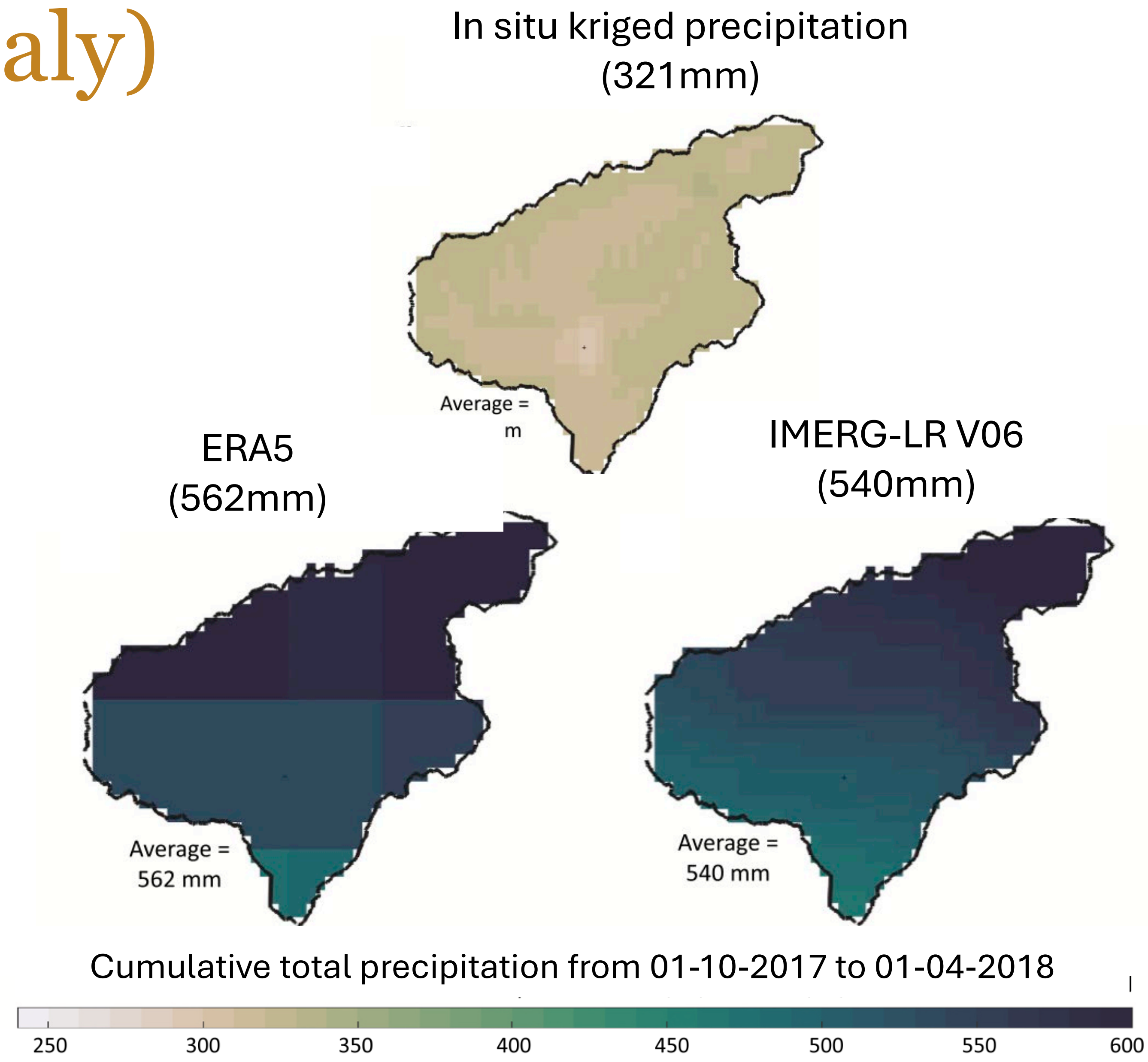


Test-Case Alto Adige (Italy)



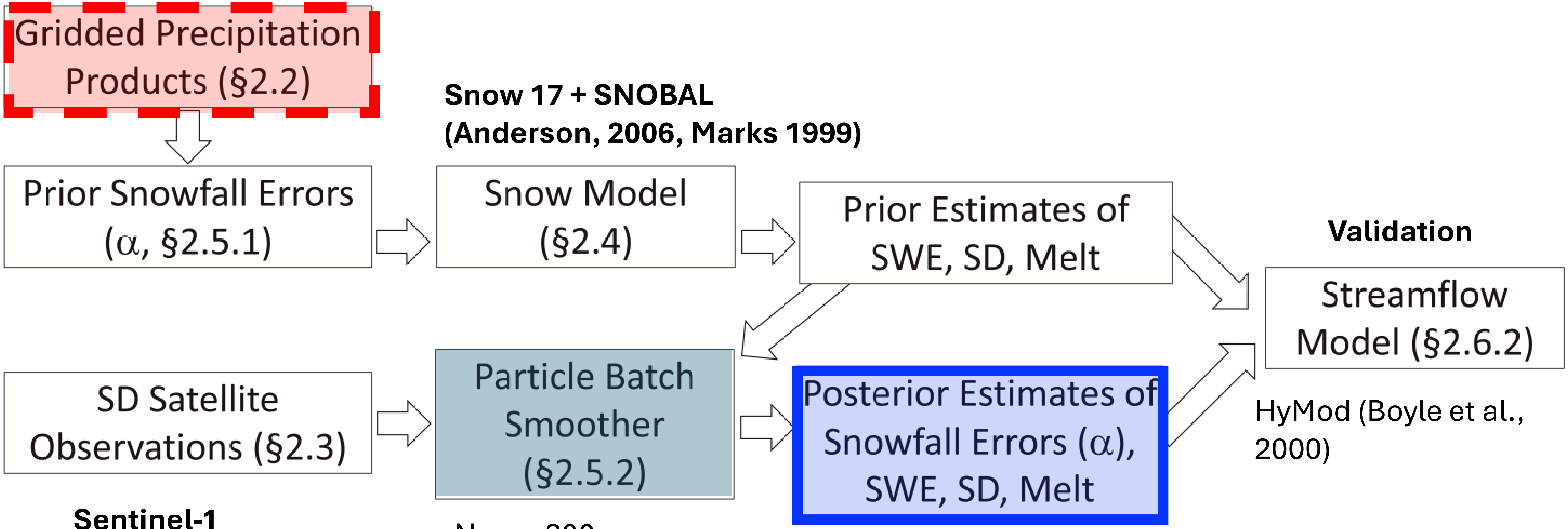
Aurino Basin, northern Italy (614 km^2)

Additional Data:
Streamflow gauge “San Giorgio” (2016-2019)
2 ground-based snow depth sensors



Experimental setup

IMERG-LR V06, ERA5, In situ P



Sentinel-1

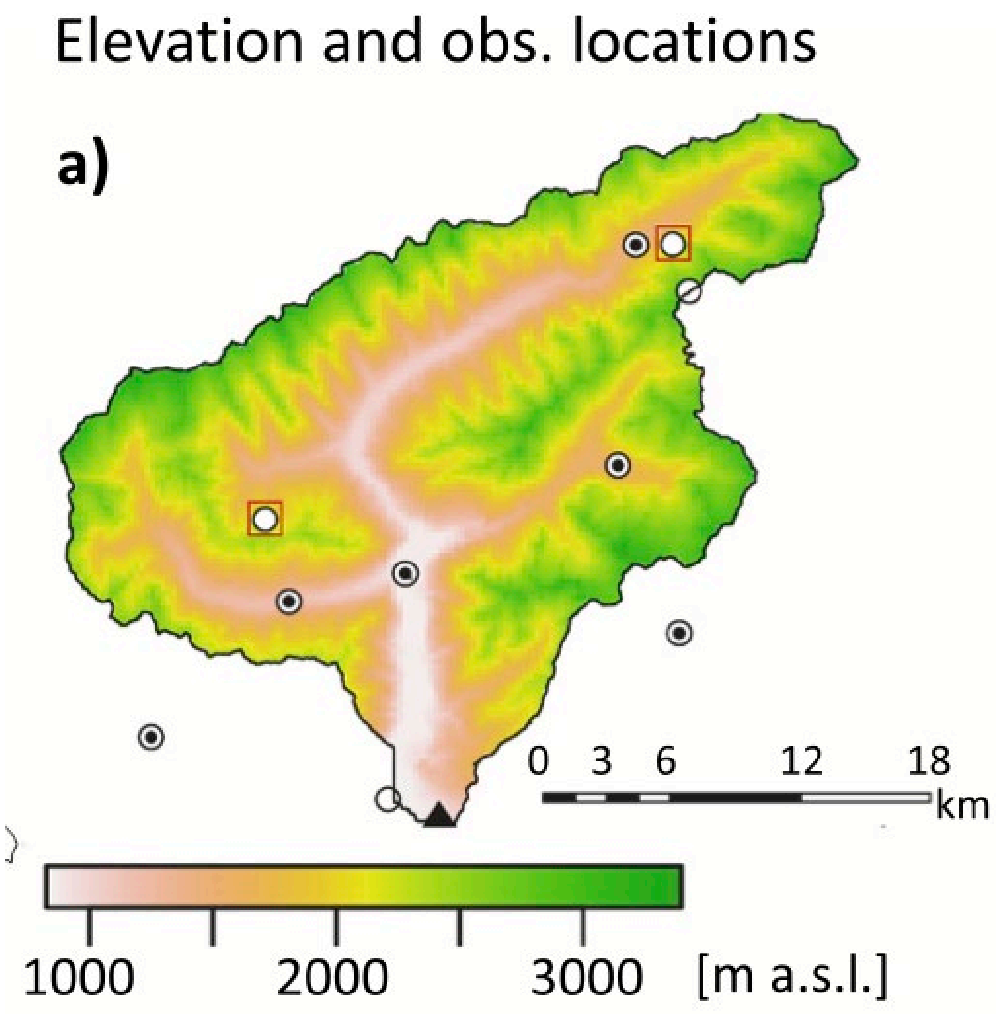
$N_{ENS} = 200$

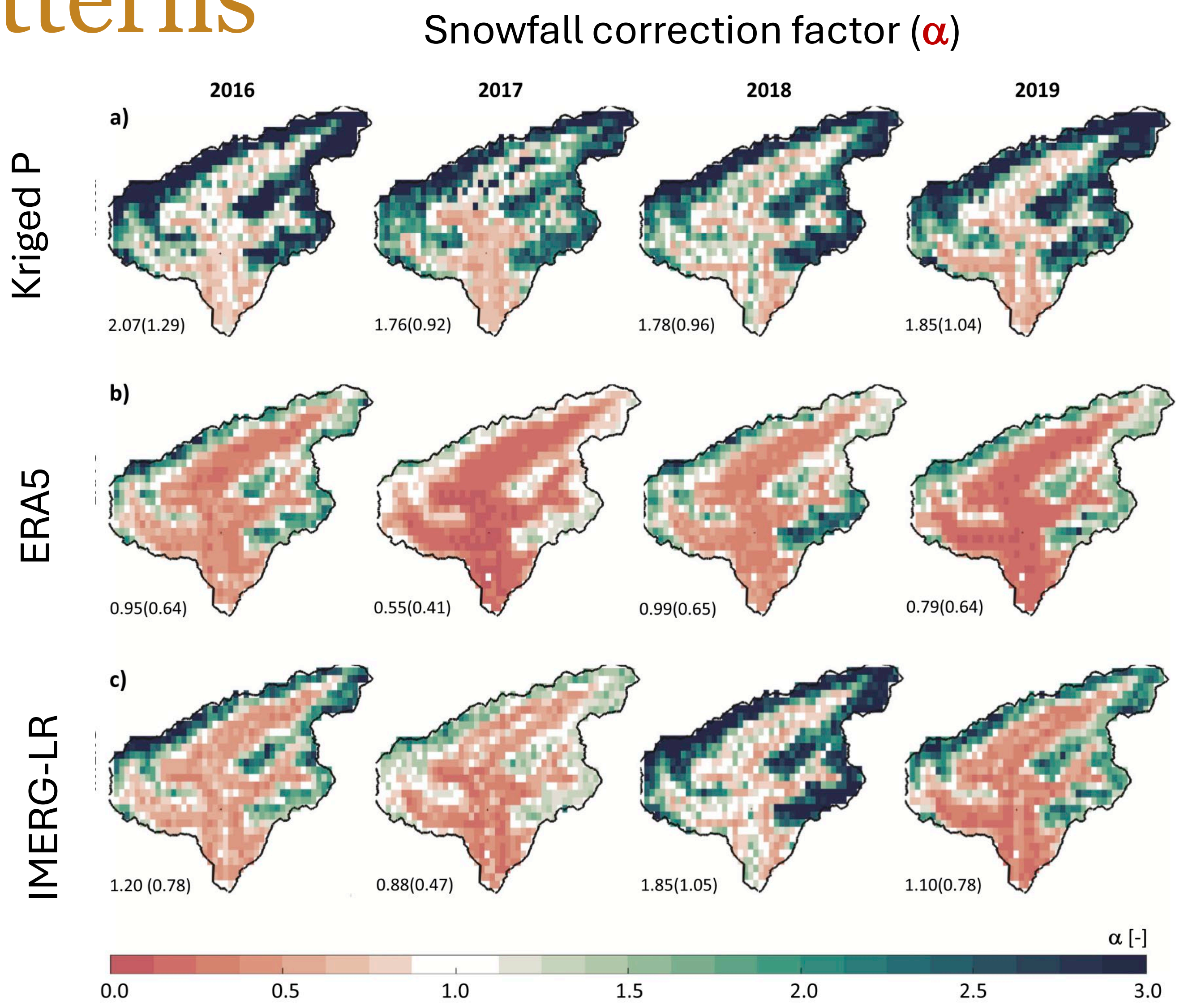
$\alpha \sim \log(\mu, CV)$ $\mu = 1(\text{unbias}), CV = 100\%$

DA of 1 snow depth obs per month

Girotto et al., 2024, *STOTEN*

Snowfall Orographic Patterns



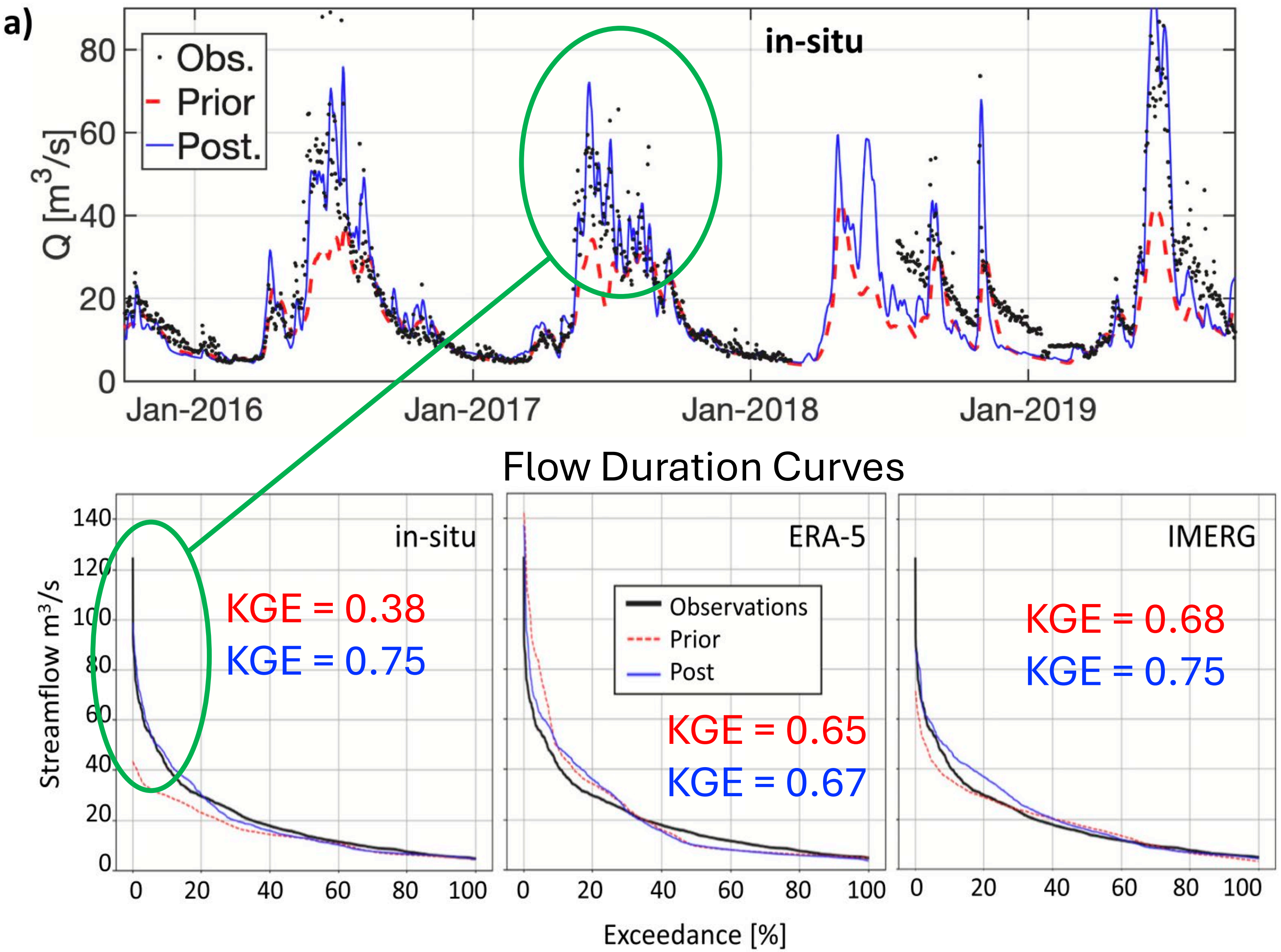


Girotto et al., (2024), *STOTEN*

Streamflow

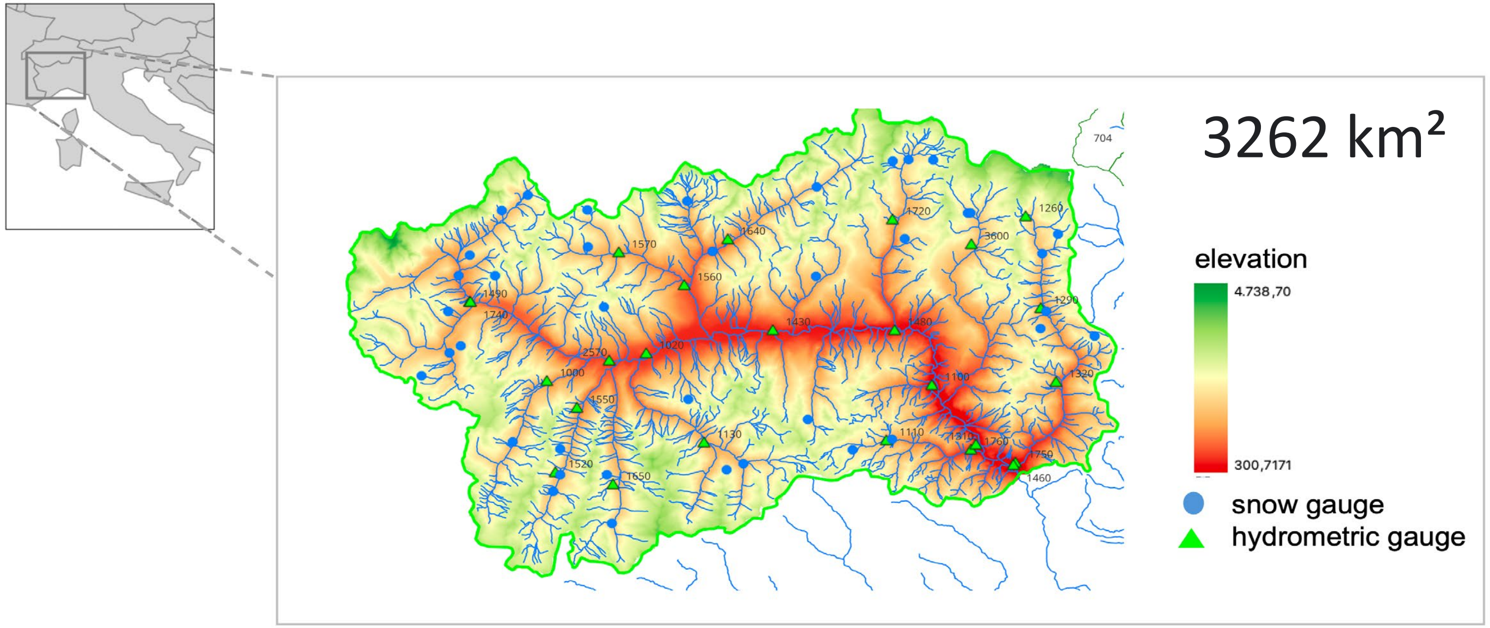
- Improvements in streamflow estimates especially during summer high flows

The higher elevation (increased snow) releases water via snowmelt more slowly than the prior case (colder temperature, and longer travel times)



Girotto et al., (2024), *STOTEN*

Second Test Case: Aosta Valley



310-4810 m - mean elevation=2000 m

Models
- Snow Model: GEOframe - Hock model (Formetta et al., 2014) + SNOBAL
- Streamflow Model: GEOframe (Bancheri et al., 2019)

Validation data:
- Streamflow gauge: 13 gauges (2015-2018)
- More than 30 ground-based snow depth sensors

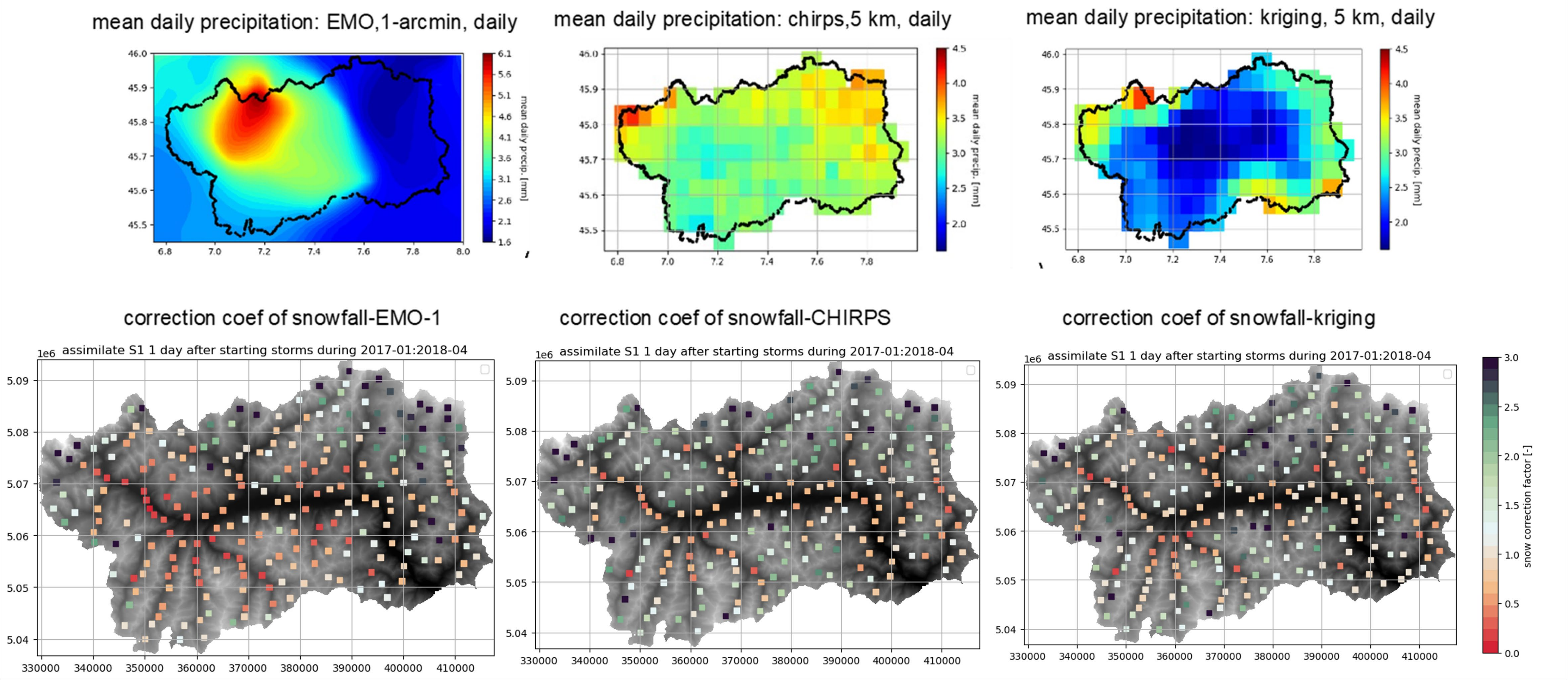
Particle Batch Smoother:

$N_{ENS} = 100$
- DA over the storms during Jan 2017 to Apr 2017 and Jan 2018 to Apr 2018

Precipitation data:
1) interpolated over 83 rain gauges
2) EMO-1arc minute (Gongalo et al. 2020)
3) CHIRPS (5 km) (Harrison et al. 2022)

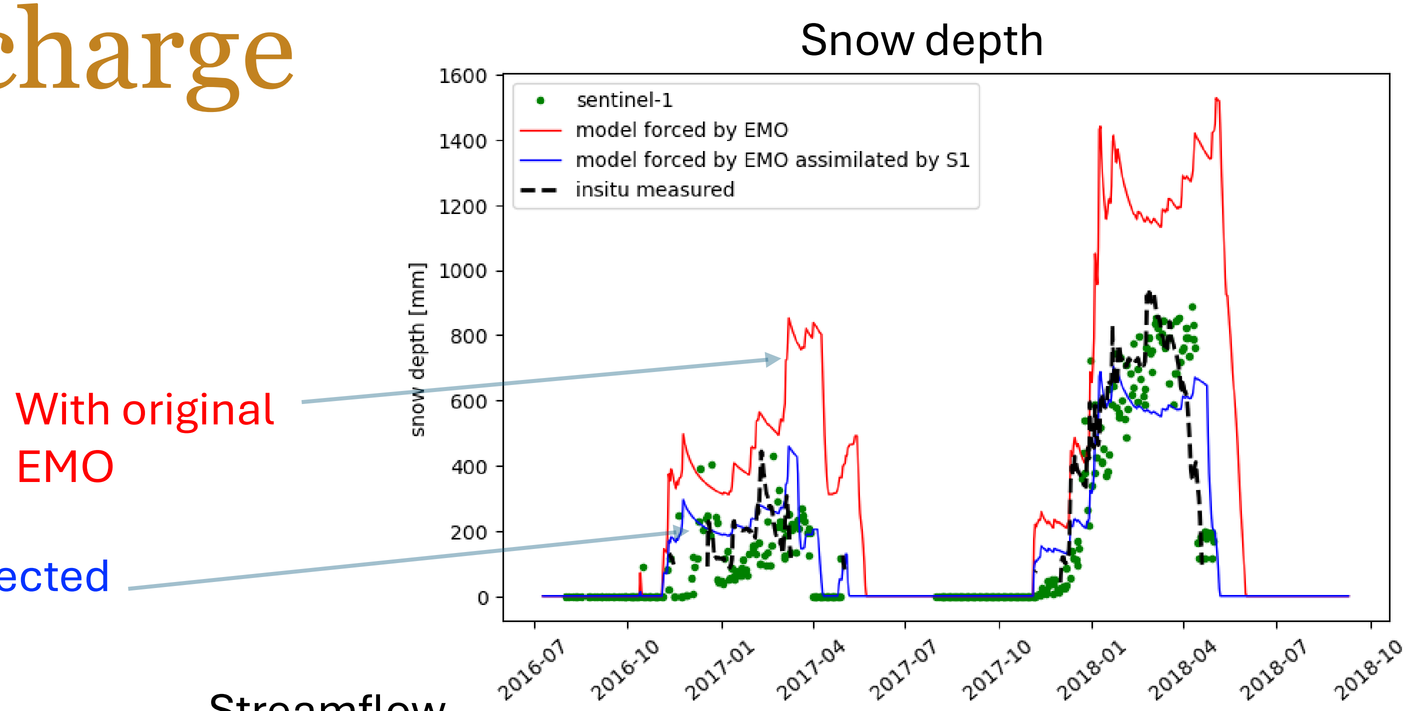
Azimi et al. (2024), *In preparation*

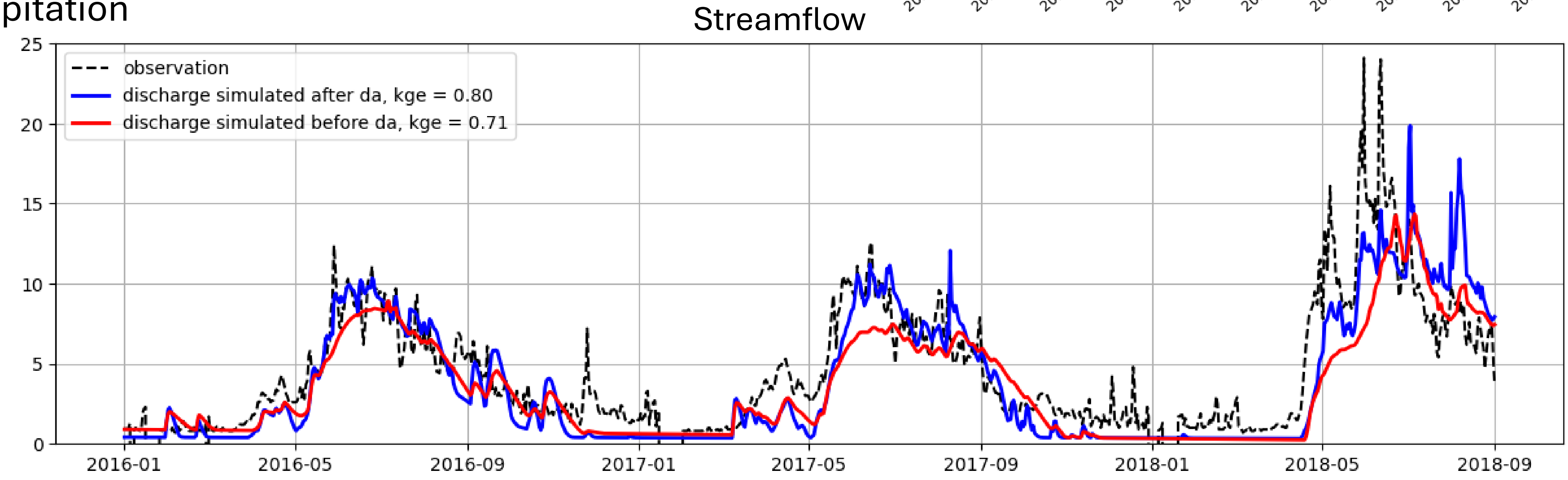
Second Test Case: Aosta Valley



Effect on river discharge

- Snow model: GEOframe - Hock model (Formetta et al., 2014) + SNOBAL (Anderson, 2006, Marks 1999)
- Streamflow Model: GEOframe (Bancheri et al., 2019)
- Model forced with EMO-1 precipitation





Conclusions

- **Accurate SWE and streamflow predictions** depend on **accurate snowfall** estimates
- We developed a **Particle Batch Smoother** Data Assimilation technique to correct solid precipitation with **Sentinel-1 snow depth** data
- Our results suggest that:
  - SWE (SD) **orographic patterns** are more visible after DA
  - Evidence of **improve streamflow** estimates, especially in summer flow

Future developments:

- Developing **correction factors** for satellite precipitation (e.g., IMERG products over the Alps and European Mountains ranges)
- Implementing **near real time correction of snowfall** using classical Particle filter.

References

1. Girotto, M., Formetta, G., Azimi, S., Bachand, C., Cowherd, M., De Lannoy, G., Lievens, H., Modanesi, S., Raleigh, M.S., Rigon, R. and Massari, C., 2024. Identifying snowfall elevation patterns by assimilating satellite-based snow depth retrievals. Science of The Total Environment, 906, p.167312.
2. Avanzi, F., Ercolani, G., Gabellani, S., Cremonese, E., Pogliotti, P., Filippa, G., Morra di Cella, U., Ratto, S., Stevenin, H., Cauduro, M. and Juglair, S., 2021. Learning about precipitation lapse rates from snow course data improves water balance modeling. *Hydrology and Earth System Sciences*, *25*(4), pp.2109-2131.
3. Harrison, L., Landsfeld, M., Husak, G. et al. Advancing early warning capabilities with CHIRPS-compatible NCEP GEFS precipitation forecasts. Sci Data 9, 375 (2022). https://doi.org/10.1038/s41597-022-01468-2
4. Anderson, E. A. (2006). Snow accumulation and ablation model–SNOW-17. US National Weather Service, Silver Spring, MD, 61.
5. Gomes, Goncalo; Thiemig, Vera; Skøien, Jon Olav; Ziese, Markus; Rauthe-Schöch, Armin; Rustemeier, Elke; Rehfeldt, Kira; Walawender, Jakub; Kolbe, Christine; Pichon, Damien; Schweim, Christoph; Salamon, Peter (2020): EMO: A high-resolution multi-variable gridded meteorological data set for Europe. European Commission, Joint Research Centre (JRC) [Dataset] doi: 10.2905/0BD84BE4-CEC8-4180-97A6-8B3ADAAC4D26 PID: http://data.europa.eu/89h/0bd84be4-cec8-4180-97a6-8b3adaac4d26
   Harrison, L., Landsfeld, M., Husak, G. et al. Advancing early warning capabilities with CHIRPS-compatible NCEP GEFS precipitation forecasts. Sci Data 9, 375 (2022). https://doi.org/10.1038/s41597-022-01468-2.
6. Lievens, H., Brangers, I., Marshall, H. P., Jonas, T., Olefs, M., & De Lannoy, G. (2022). Sentinel-1 snow depth retrieval at sub-kilometer resolution over the European Alps. The Cryosphere, 16(1), 159-177.