On the Use of High-Resolution Remote Sensing Products to Generate SWE Maps

Valentina Premier[1], Carlo Marin[1], Giacomo Bertoldi[2], Riccardo Barella[1], Claudia Notarnicola[1]

[1]Eurac Research, Institute for Earth Observation
[2]Eurac Research, Institute for Alpine Environment

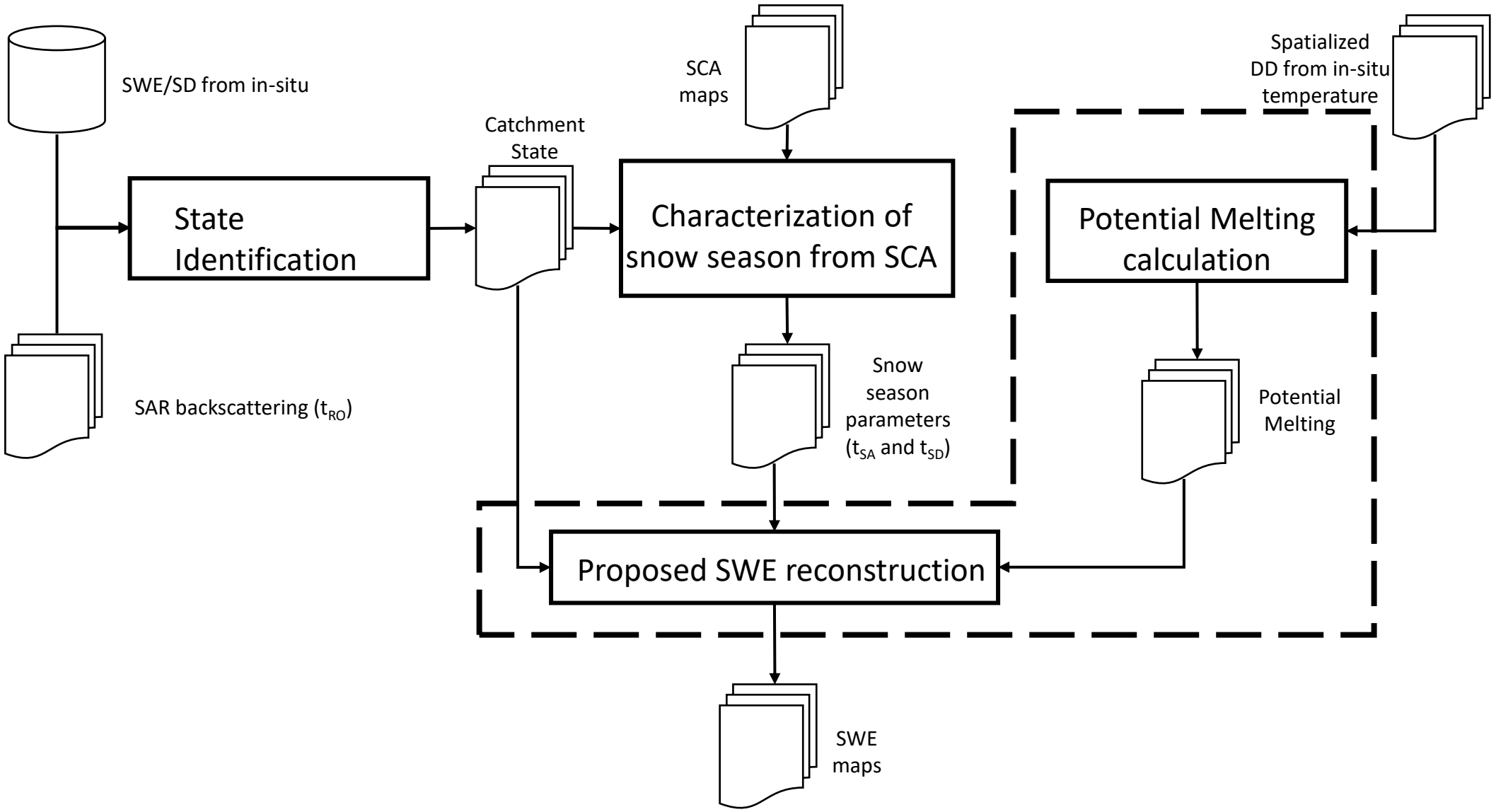
The work has been supported by the project
Snowtinel: Sentinel-1 SAR assisted catchment hydrology:
toward an improved snow-melt dynamic for alpine regions.

Motivation of the work

- Accurate and distributed **snow water equivalent** (SWE) measurements are missing
- Snow hydrological models require accurate **precipitation** measurements
- Recent **remote sensing** products are very promising for SWE monitoring

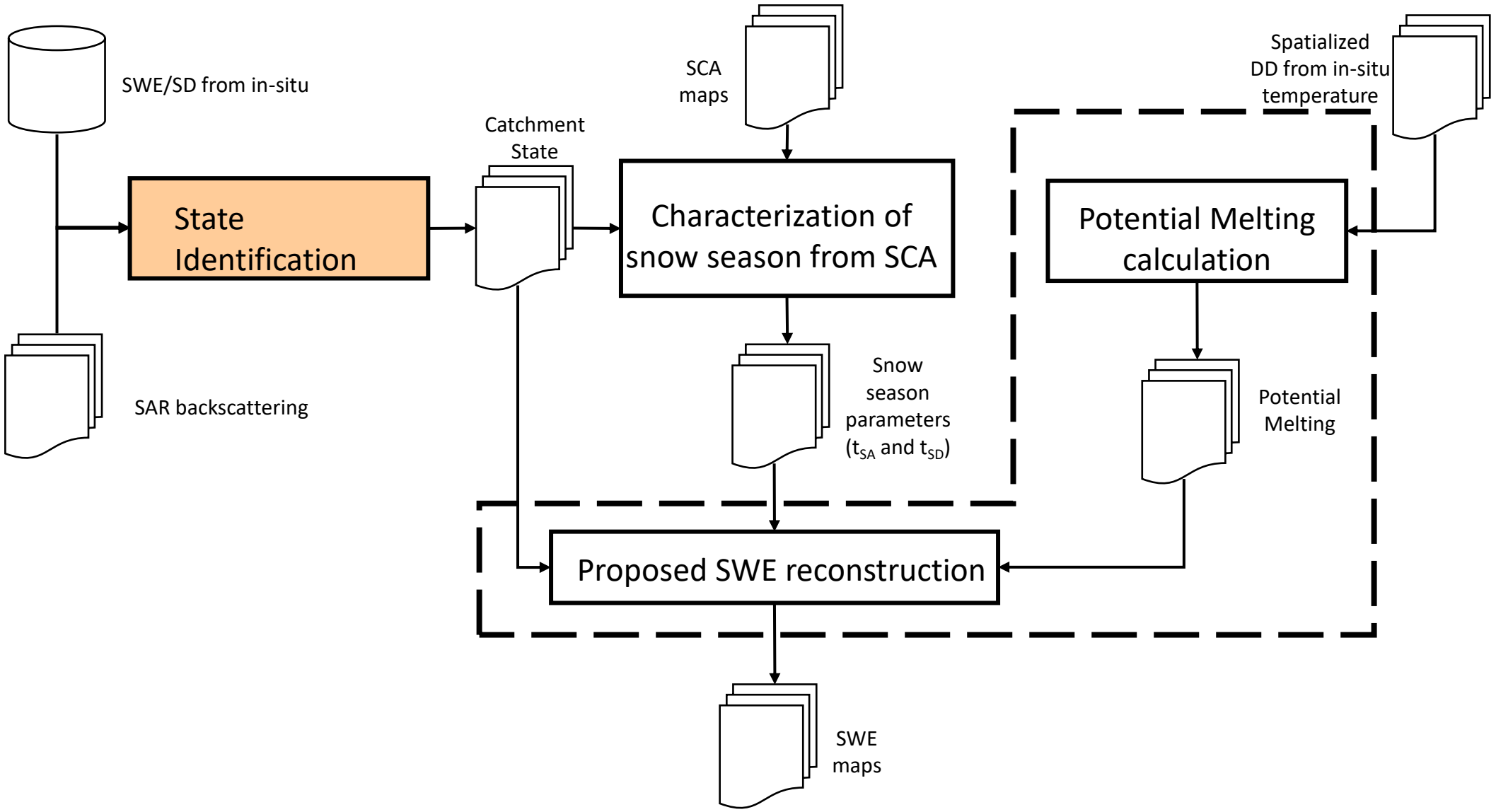
- A novel approach to retrieve **distributed** SWE at **high spatial** and **temporal resolution**
- **Complete time-series** during accumulation and melting phase
- **Multi-source** (optical, SAR) and **multi-temporal** approach
- Parsimonious use of **in-situ** data

Method



Premier, V., Marin, C., Bertoldi, G., Barella, R., Notarnicola, C., & Bruzzone, L. (2022). Exploring the Use of Multi-source High-Resolution Satellite Data for Snow Water Equivalent Reconstruction over Mountainous Catchments. *The Cryosphere Discussions*, 1-42. In review.

Methods

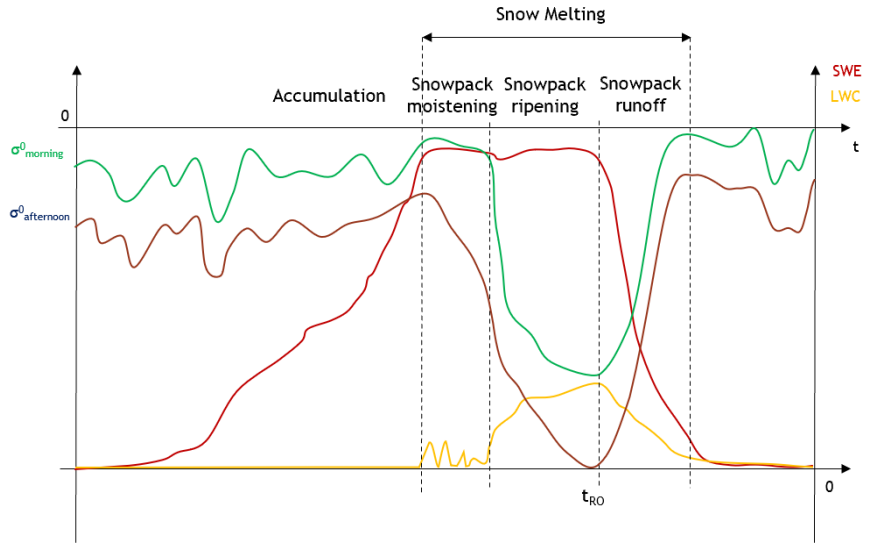


Premier, V., Marin, C., Bertoldi, G., Barella, R., Notarnicola, C., & Bruzzone, L. (2022). Exploring the Use of Multi-source High-Resolution Satellite Data for Snow Water Equivalent Reconstruction over Mountainous Catchments. *The Cryosphere Discussions*, 1-42. In review.

State identification

State	ΔSWE	Class transition t-1	Class transition t	Description
Accumulation	>0	■	□	Snow on bare ground
		□	□	Snow on snow
Ablation	<0	□	■	Snowpack disappearance
		□	□	Snowpack reduction

Legend: □ = snow ■ = snow-free

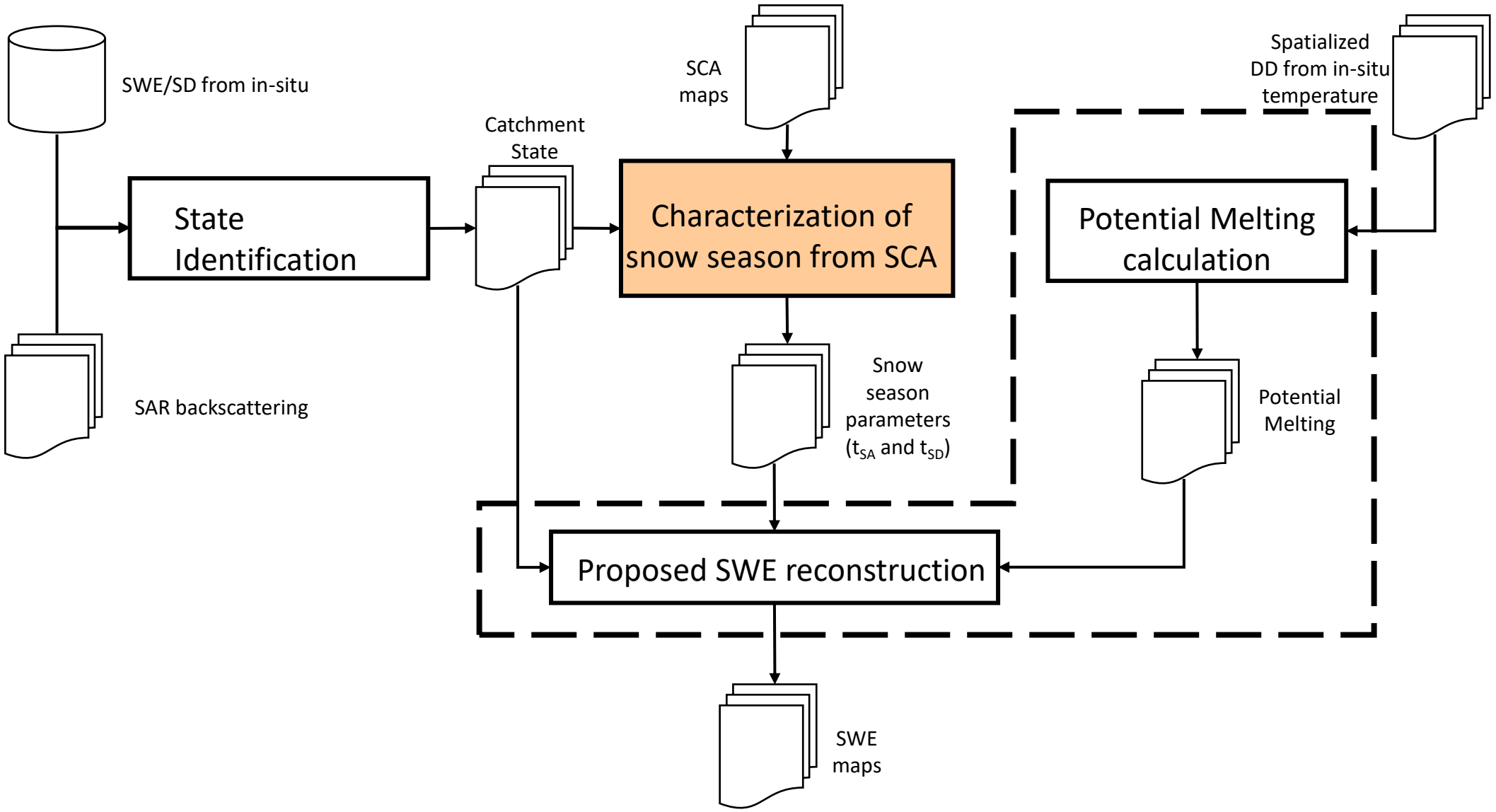


Rules:

- *Accumulation*: if the snow precipitation measurements (SD/SWE) show an increment greater than a defined threshold. The state is the same for all the snow-covered area of the catchment;
- *Ablation*: if i) the date does not experience an accumulation, ii) t_{RO} has been reached (looking at the multitemporal SAR backscattering), and iii) the degree-day is greater than 0.

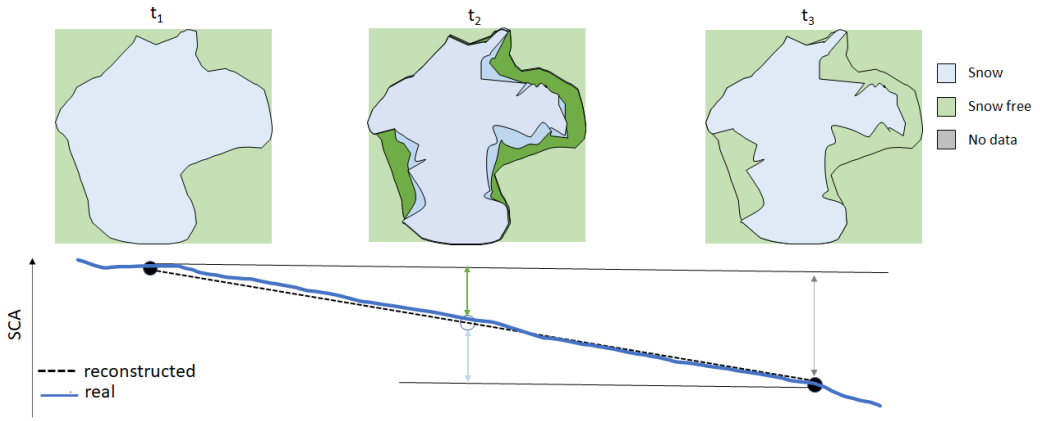
Marin, C., Bertoldi, G., Premier, V., Callegari, M., Brida, C., Hürkamp, K., Tschiersch, J., Zebisch, M., & Notarnicola, C. (2020). Use of Sentinel-1 radar observations to evaluate snowmelt dynamics in alpine regions. *The Cryosphere*, *14*(3), 935-956.

Methods



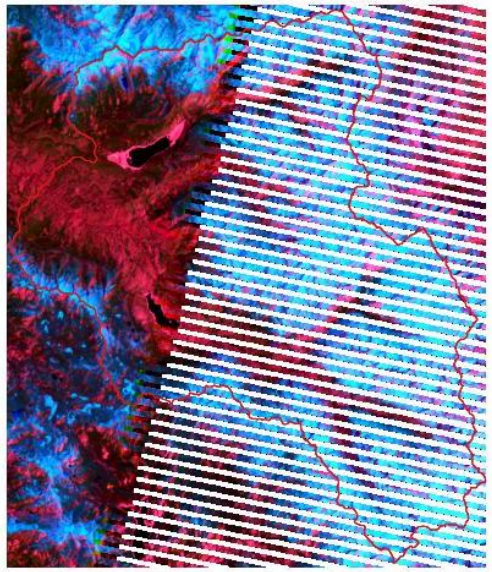
Premier, V., Marin, C., Bertoldi, G., Barella, R., Notarnicola, C., & Bruzzone, L. (2022). Exploring the Use of Multi-source High-Resolution Satellite Data for Snow Water Equivalent Reconstruction over Mountainous Catchments. *The Cryosphere Discussions*, 1-42. In review.

Characterization of snow season from SCA

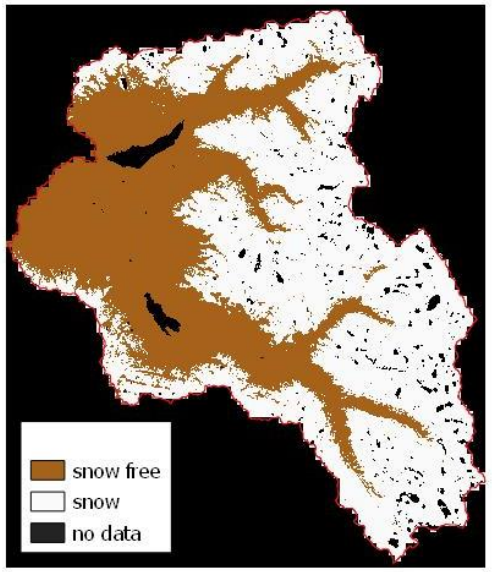


Example: Landsat 7

RGB (SWIR,NIR,RED)



Reconstructed map

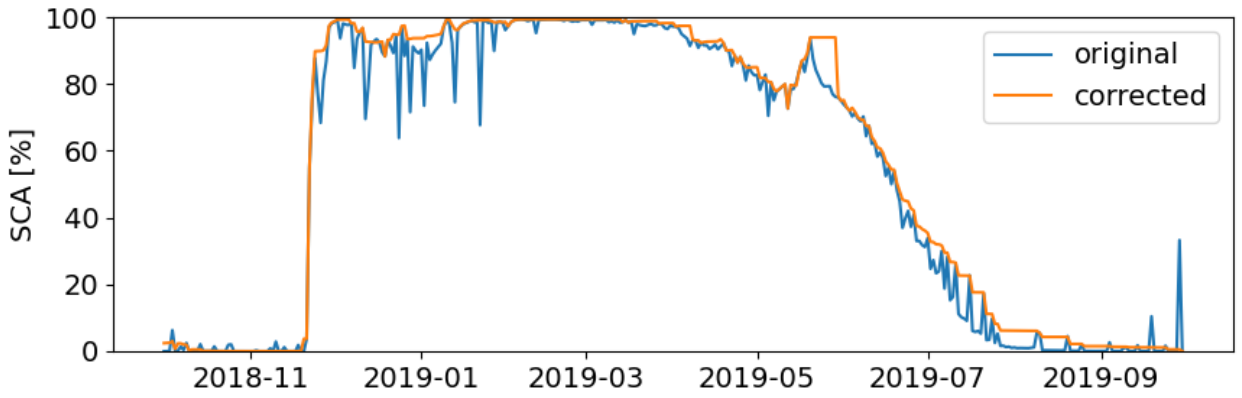


- Inter-annual spatial snowmelt and accumulation follow specific **patterns** influenced by the catchment **topography** and **meteorology**
- **Historical statistical analyses** of long time-series
- Reconstruct the SCA from other sources (**downscaling** from **low-resolution** images when **missing acquisition** or **gap-filling** exploiting known pixels when **cloud obstruction**)

021). A Novel Approach Based on a Hierarchical Multiresolution Analysis of Optical Time Series to Reconstruct the Daily High-Resolution Snow Cover Area. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *14*, 9223-9240.

Characterization of snow season from SCA

- The **daily SCA maps** are affected by errors that may arise from the **classification** or the **reconstruction**
- We observed **two main errors:**
  - **Underestimation of snow under canopy** by **HR** sensors
  - **Snow patches** are **not visible** by **LR** sensors
- We set up a **SCA regularization** that must be **coherent** with the **state**



Algorithm 1 Regularization of the snow cover maps according with the catchment state.

if *Accumulation* **then**

Transition snow-snow free is not allowed! 

The pixel is snow from $t_{SA} \leq t-1$. Between t_{SA} and $t-1$ all states are possible.

We indicate with t_{lastAB} a day $t_{SA} \leq t_{lastAB} \leq t-1$ representing the date of the last ablation after t_{SA}

if $t - t_{SA} < 10$ *days* **then**

Recent t_{SA}**:** check $t \pm 5$ days and compute the most frequent label

else

Old t_{SA}**:** check last up to 5 HR from t_{SA} to t and compute the most frequent label

end

if *most frequent label is snow* **then**

t is a FN (e.g., missed snow under canopy): set t as snow 

else

$t-1$ is a FP (e.g., cloud detected as snow): set $[t_{lastAB}; t-1]$ as snow free 

end

else

Transition snow free-snow is not allowed! 

The pixel is snow free from $t_{SD} \leq t-1$. Between t_{SD} and $t-1$ all states are possible.

We indicate with t_{lastAC} a day $t_{SD} \leq t_{lastAC} \leq t-1$ representing the date of the last accumulation after t_{SD}

if $t - t_{SA} < 10$ *days* **then**

Recent t_{SA}**:** check $t \pm 5$ days and compute the most frequent label

else

Old t_{SA}**:** check last up to 5 HR from t_{SA} to t and compute the most frequent label

end

if *most frequent label is snow* **then**

$t-1$ is a FN (e.g., missed snow patches): set $[t_{lastAC}; t-1]$ as snow 

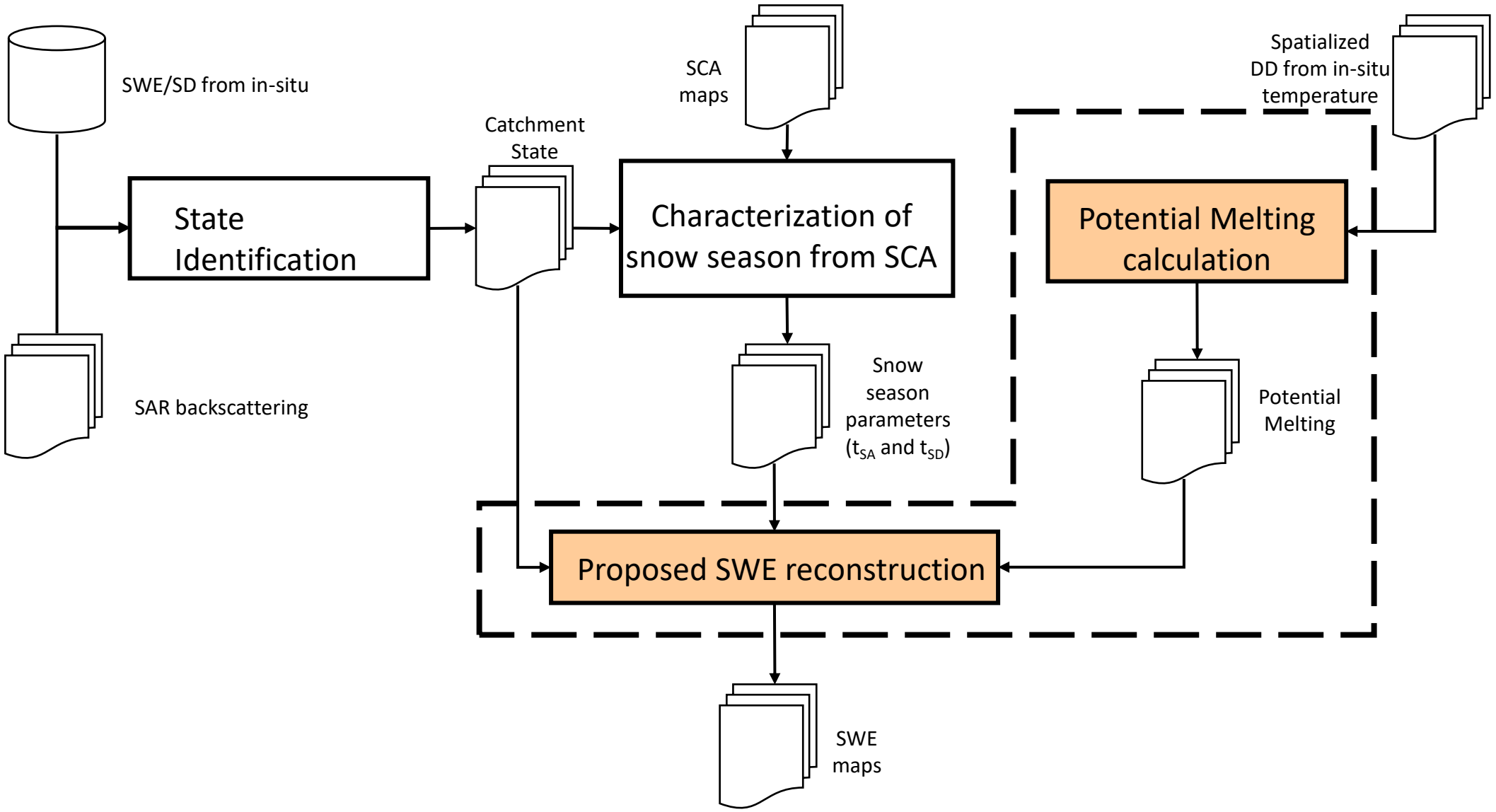
else

t is a FP (e.g., cloud detected as snow): set t as snow free 

end

end

Methods



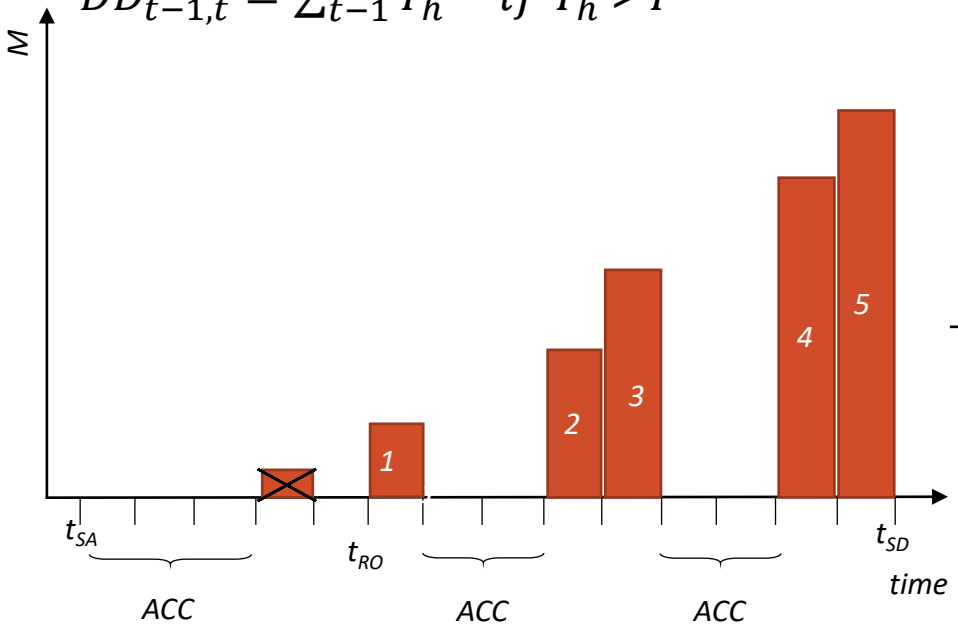
Premier, V., Marin, C., Bertoldi, G., Barella, R., Notarnicola, C., & Bruzzone, L. (2022). Exploring the Use of Multi-source High-Resolution Satellite Data for Snow Water Equivalent Reconstruction over Mountainous Catchments. *The Cryosphere Discussions*, 1-42. In review.

Proposed SWE reconstruction

Potential melting estimation

$$M_{t-1,t}[mm] = a[mm°C^{-1}d^{-1}]DD_{t-1,t}[°Cd]$$

$$DD_{t-1,t} = \sum_{t-1}^{t} T_h \quad if\ T_h > \hat{T}$$



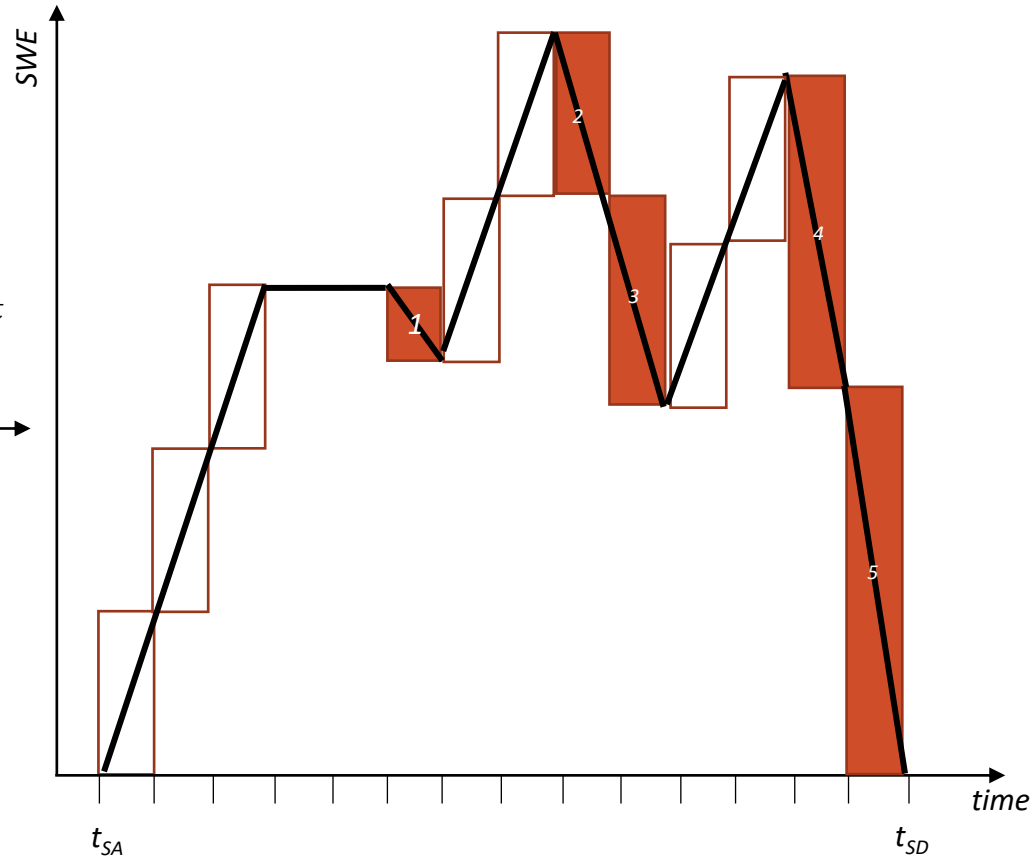
Computation of the total mass

$$A_{tot} = M_{tot}$$

Accumulation estimation

$$A_{t-1,t} = k_{t-1,t}\, A_{tot}$$

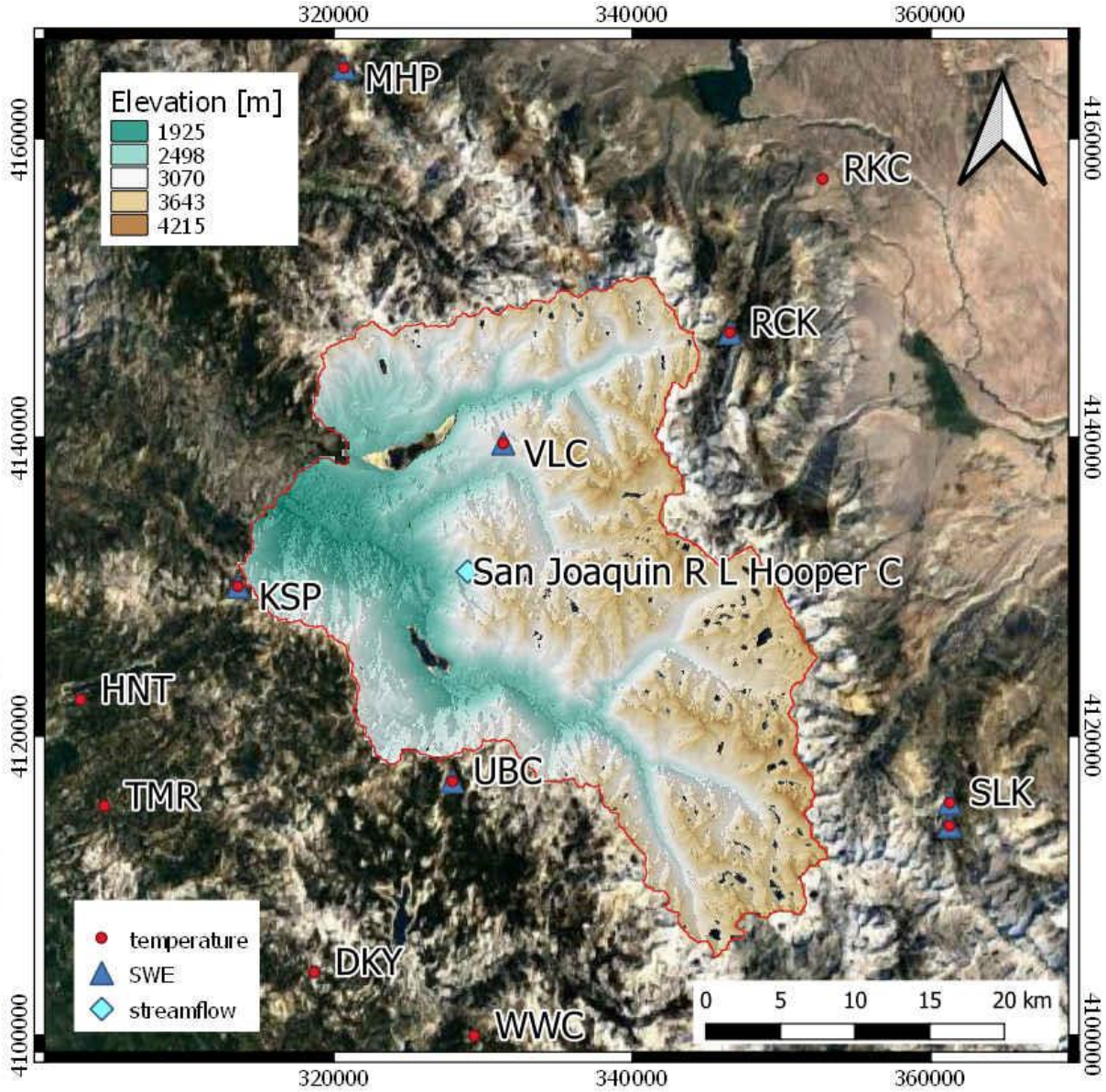
SWE temporal reallocation



Results

South Fork of the San Joaquin River, Sierra Nevada, California

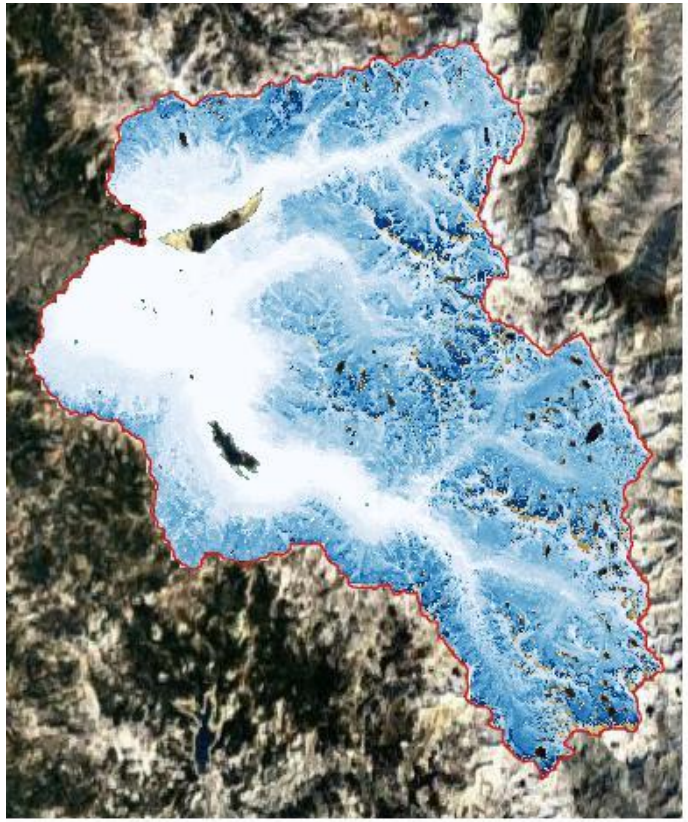
970 km^2



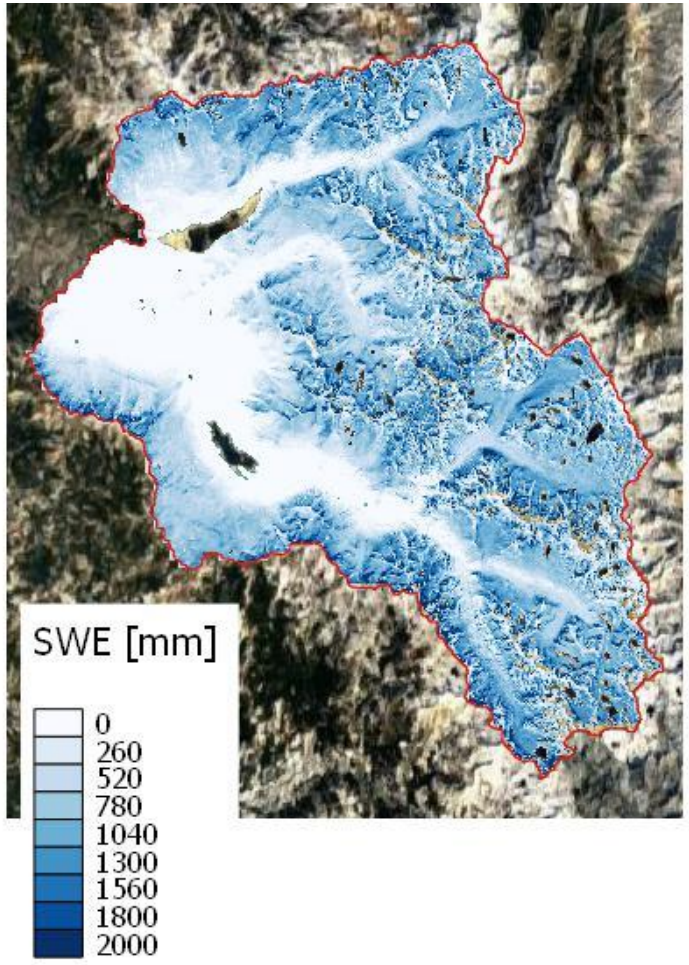
Results

South Fork of the San Joaquin River, Sierra Nevada, California (2nd May 2019)

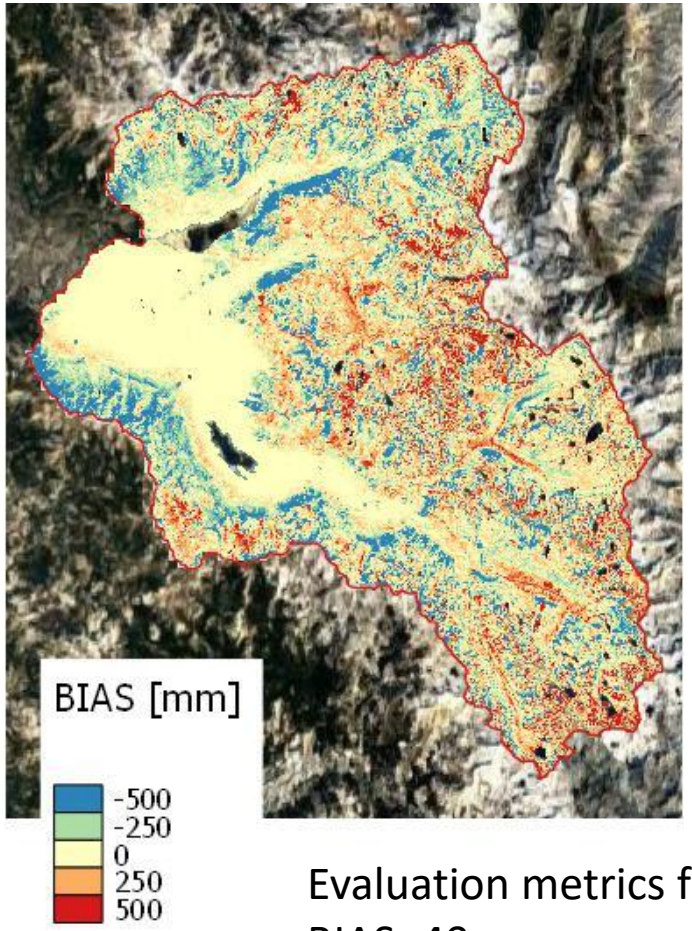
Proposed



ASO



BIAS



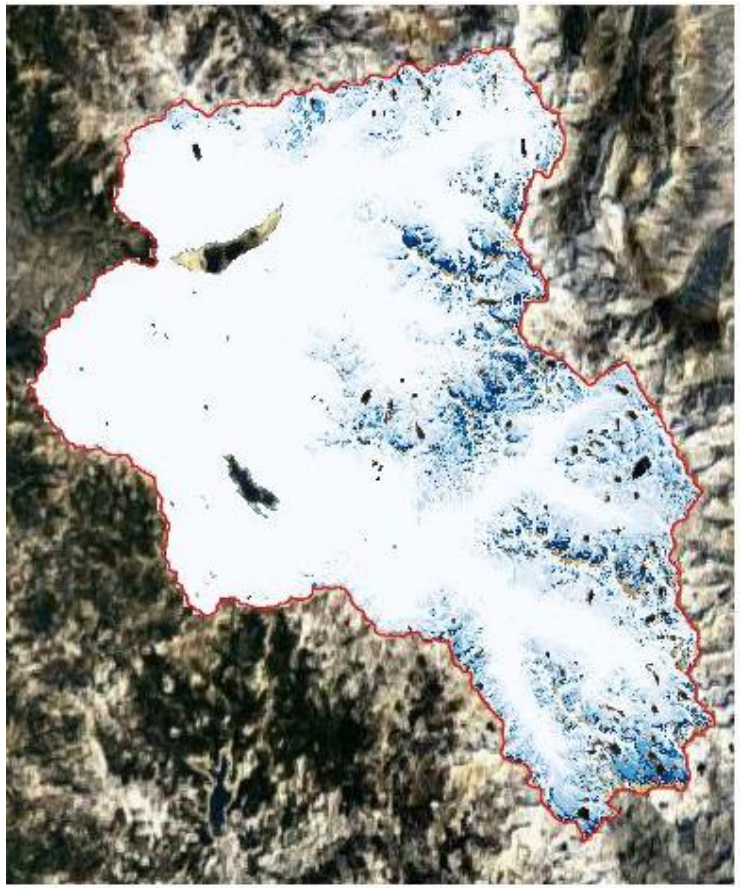
Evaluation metrics for 14 dates:
BIAS -40 mm
RMSE 216 mm
Correlation 0.729

Painter, T. H., Berisford, D. F., Boardman, J. W., Bormann, K. J., Deems, J. S., Gehrke, F., ... & Winstral, A. (2016). The Airborne Snow Observatory: Fusion of scanning lidar, imaging spectrometer, and physically-based modeling for mapping snow water equivalent and snow albedo. *Remote Sensing of Environment*, *184*, 139-152.

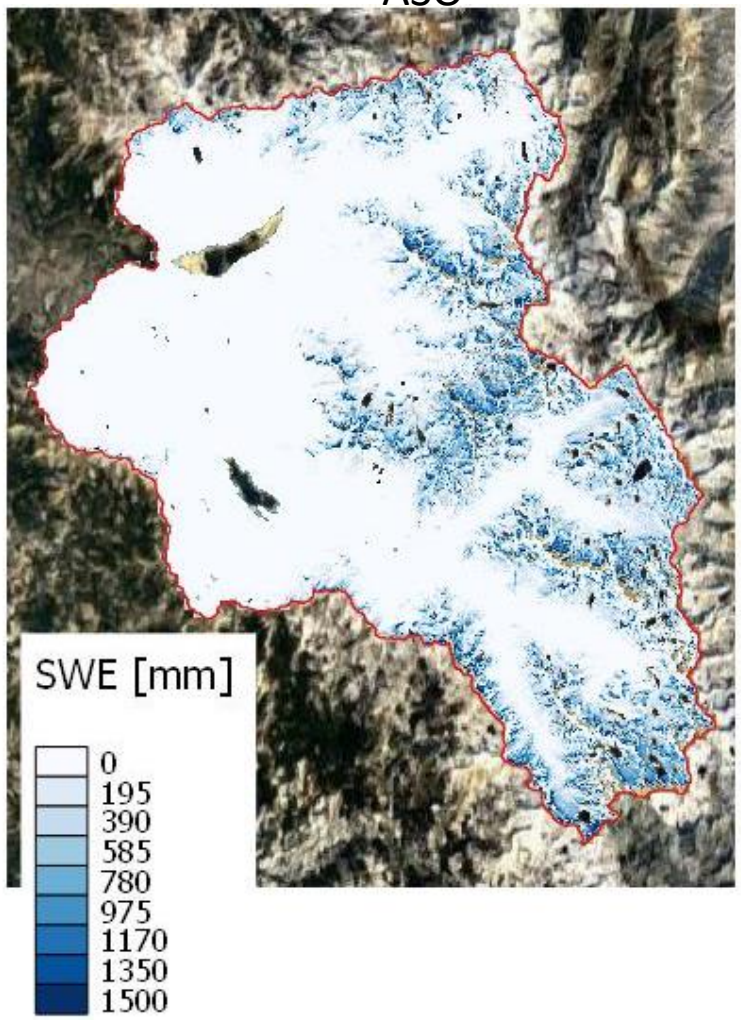
Results

South Fork of the San Joaquin River, Sierra Nevada, California (4th July 2019)

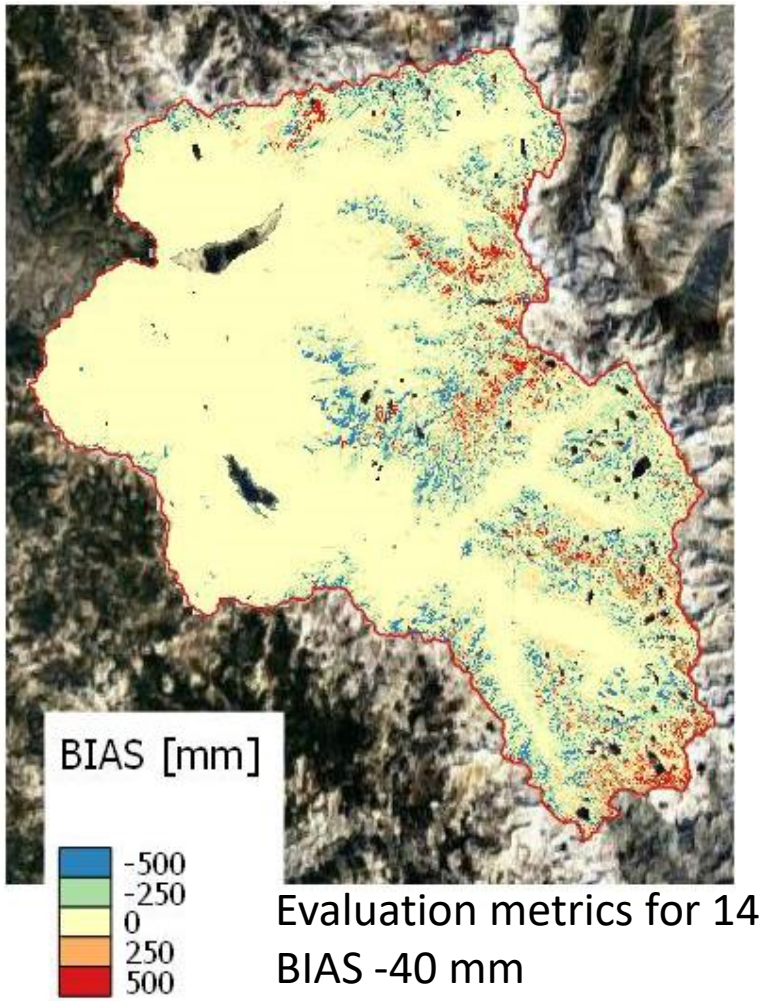
Proposed



ASO



BIAS



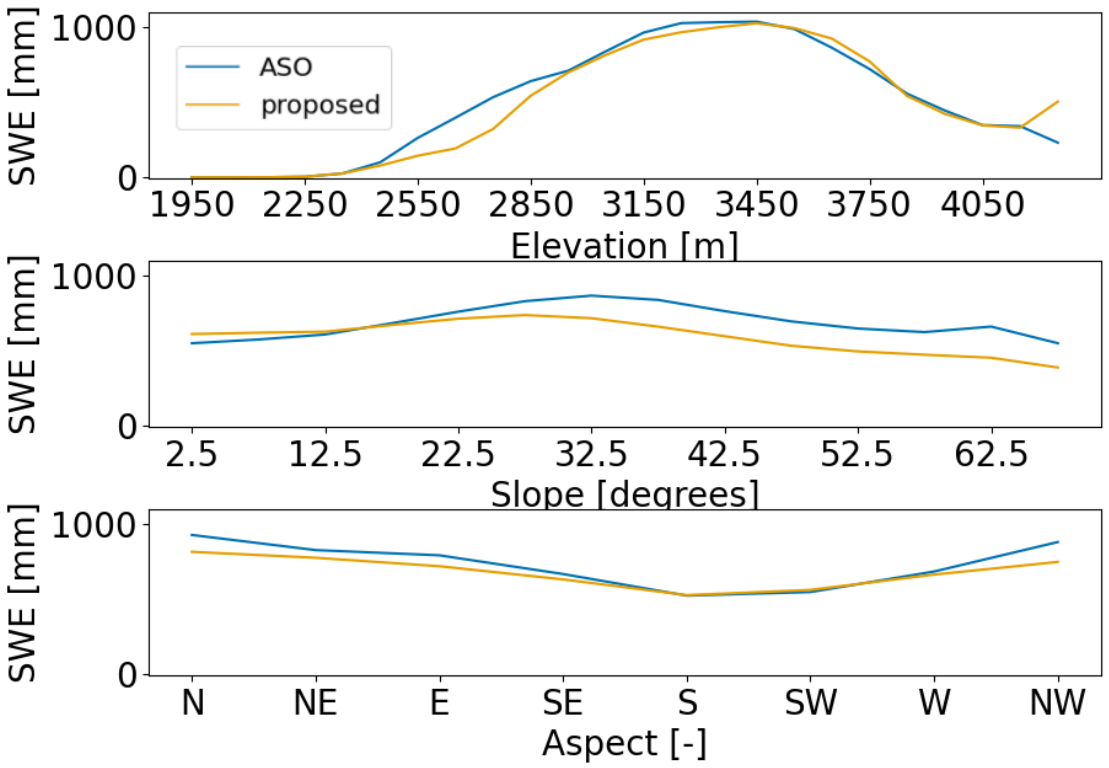
Evaluation metrics for 14 dates:
BIAS -40 mm
RMSE 216 mm
Correlation 0.729

Painter, T. H., Berisford, D. F., Boardman, J. W., Bormann, K. J., Deems, J. S., Gehrke, F., ... & Winstral, A. (2016). The Airborne Snow Observatory: Fusion of scanning lidar, imaging spectrometer, and physically-based modeling for mapping snow water equivalent and snow albedo. *Remote Sensing of Environment*, *184*, 139-152.

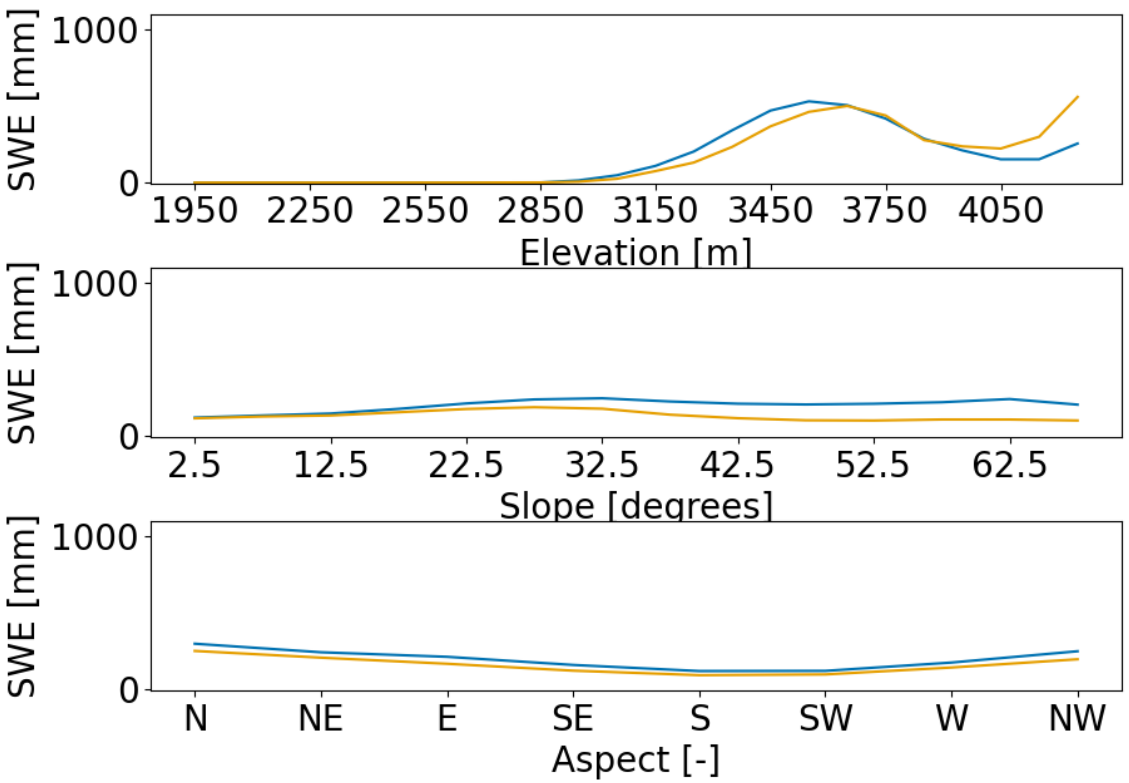
Results

South Fork of the San Joaquin River, Sierra Nevada, California

2nd May 2019

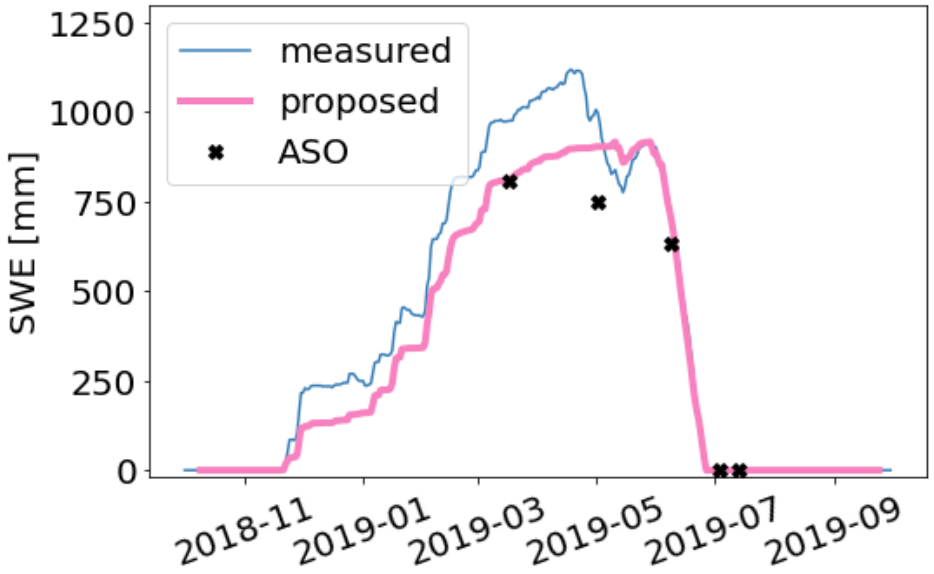


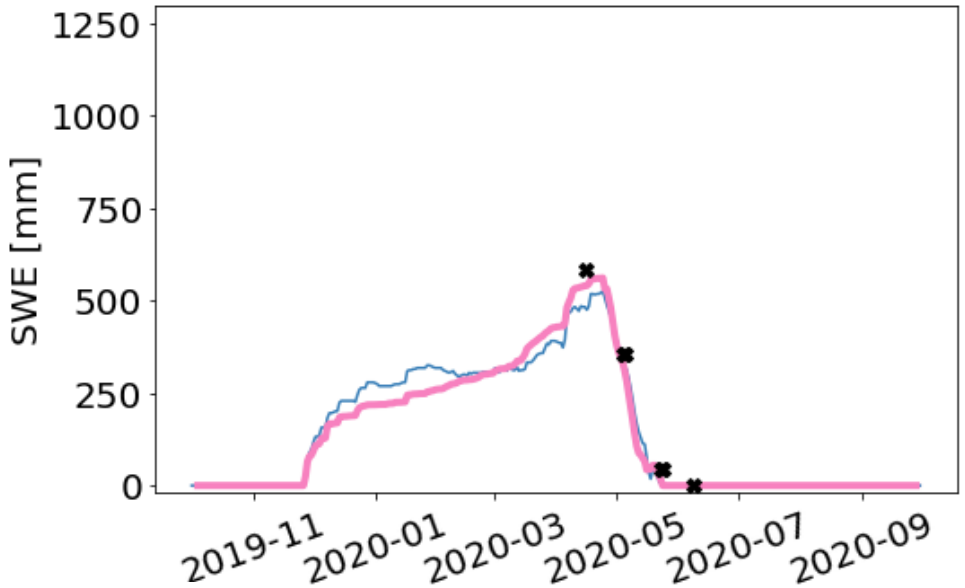
4th July 2019

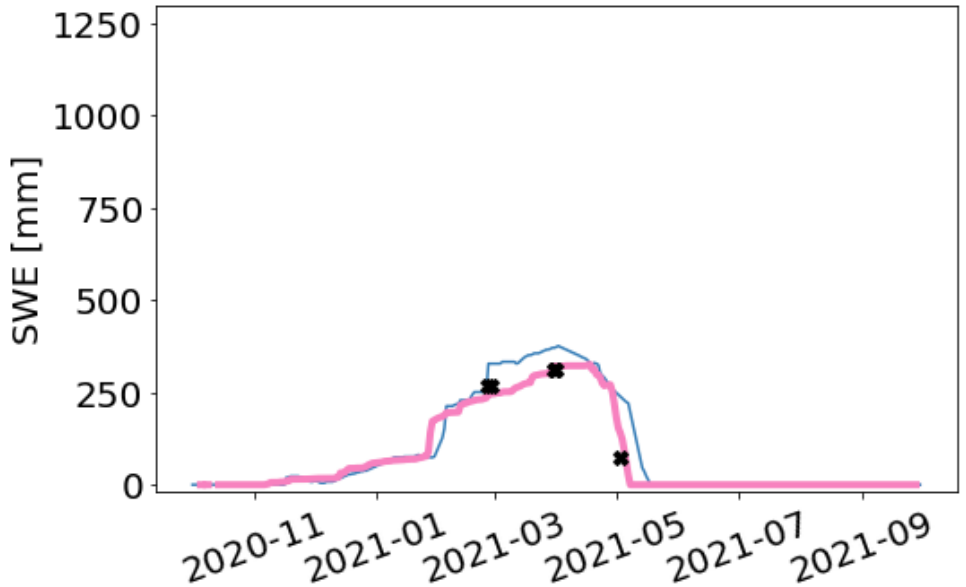


Results

South Fork of the San Joaquin River, Sierra Nevada, California

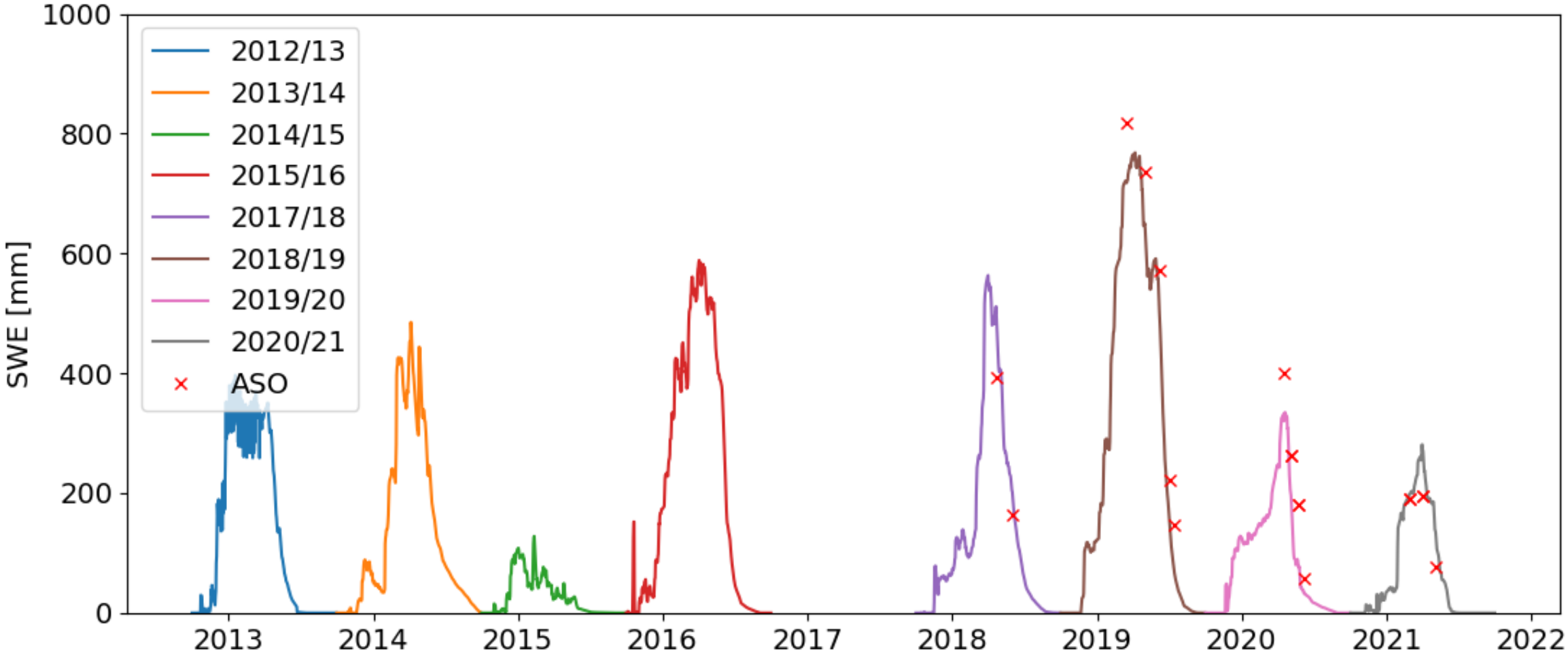






Results

South Fork of the San Joaquin River, Sierra Nevada, California



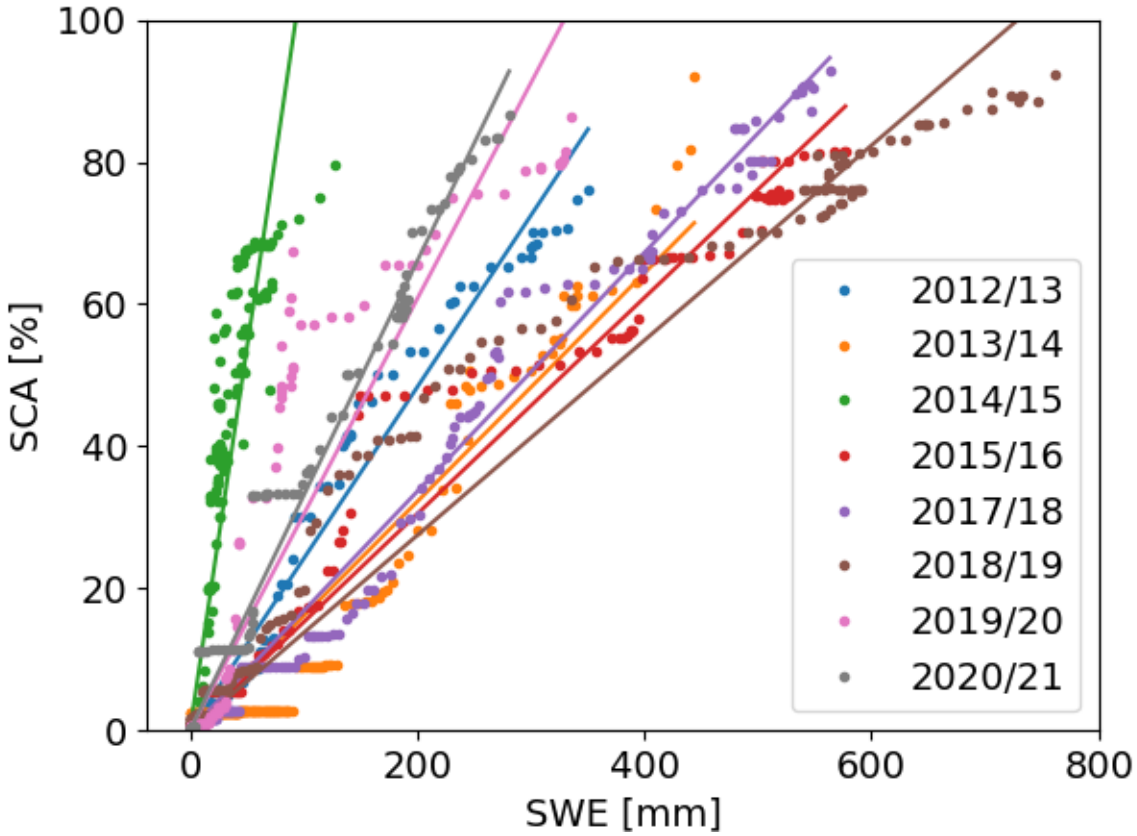
Conclusions

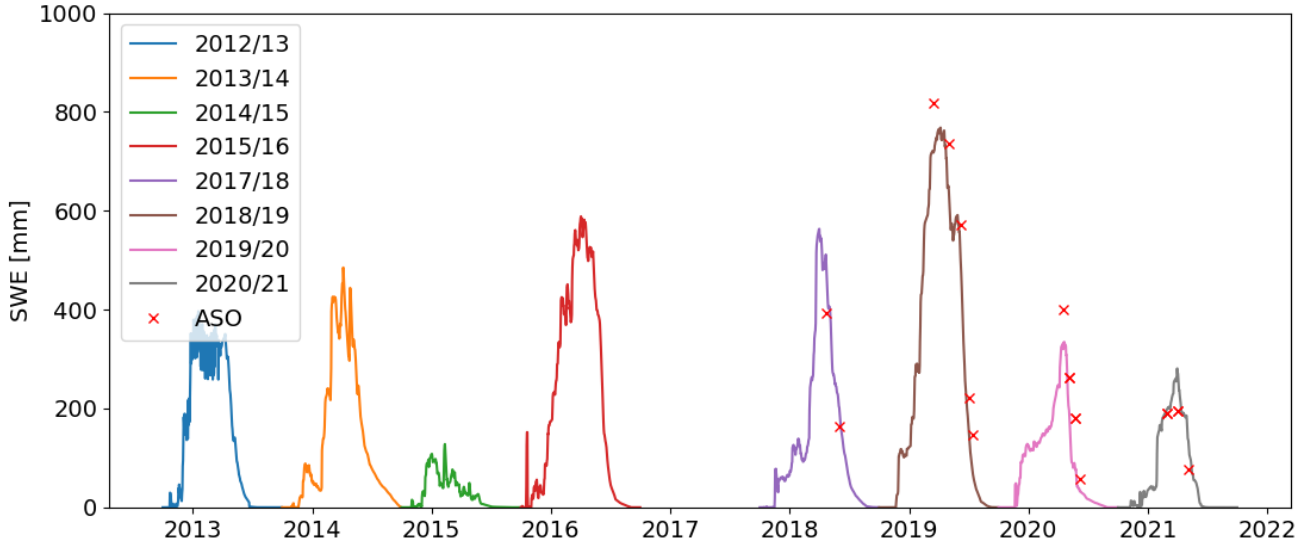
- Accurate daily and high spatial resolution SWE reanalysis product
- Innovative use of S-1 data to spatialize melting
- Innovative SCA correction
- Able to well represent spatial patterns
- Able to well represent inter-annual variability
- Agreement in terms of overall SWE balance

- To do: Fully independent from in-situ data (e.g., when determining the accumulation, potential melting)

Thank you for your attention

Towards a (near) real-time reconstruction





Negative correlation (ρ=-0.75) between the coefficient of the intercept *α* and maximum of SWE