Assimilation of Soil Moisture Data into an Integrated Terrestrial Model: Validation of Soil Moisture and Real-time Flood Forecasting

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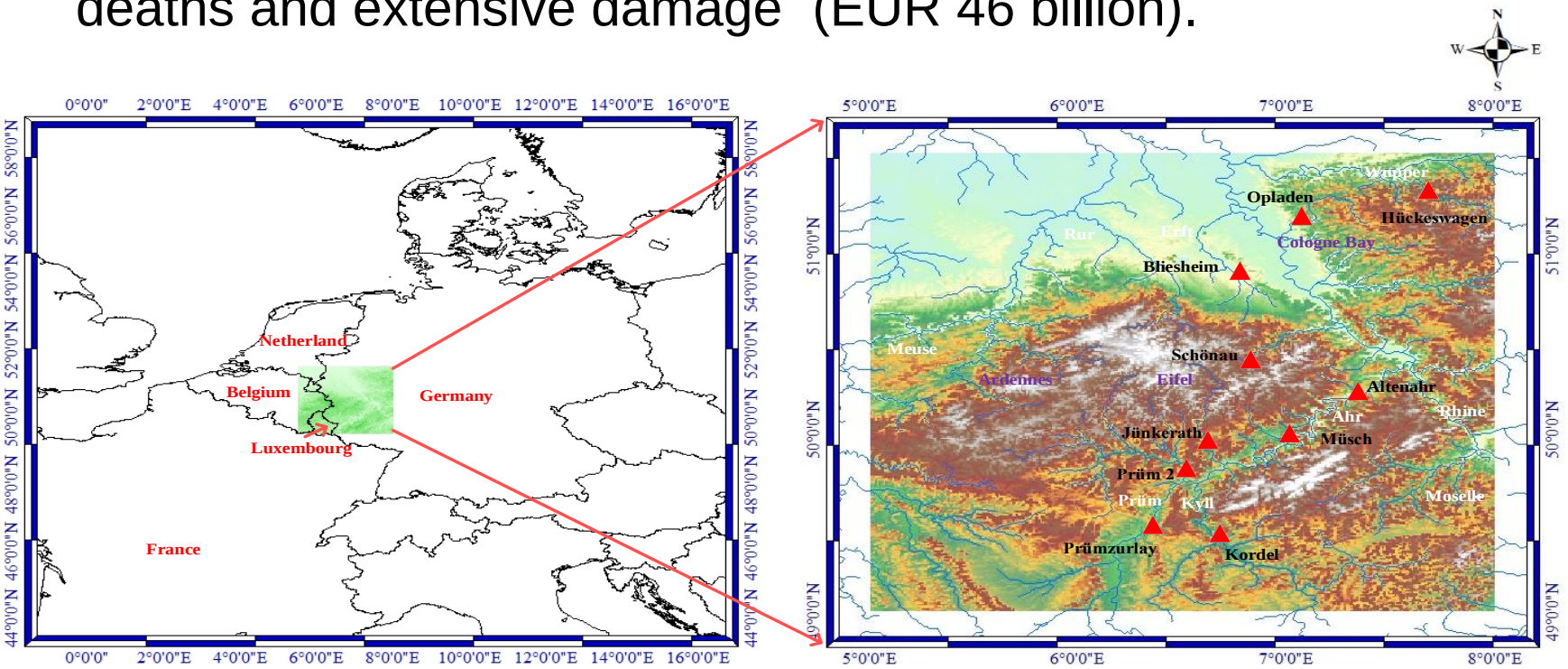
Research questions, Objectives

- Testing the EnKF capabilities in improvement of SWC and real-time flood forecasting.
- Does the performance of data assimilation vary between using different remotely-sensed observations (e.g., Sentinel-1 vs. CCI) in hydrological models?
- Proposing and implementing a novel application of the First Order Reliability Method (FORM) to validate the reliability of the DA performance.

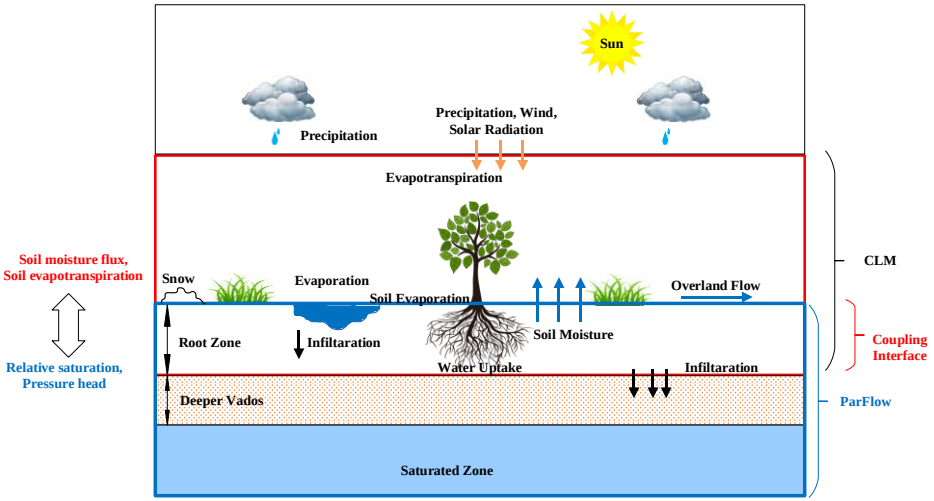
Case study description

- Situated in western Germany, eastern Luxembourg, and southeastern Belgium.
- Flood July 2021 (13-18 July): The flood in Germany led to 180 deaths and extensive damage (EUR 46 billion).

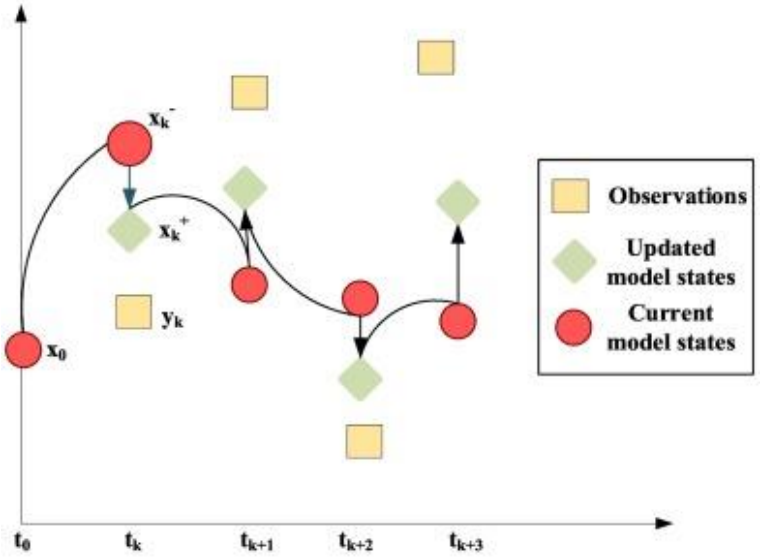


Methodology

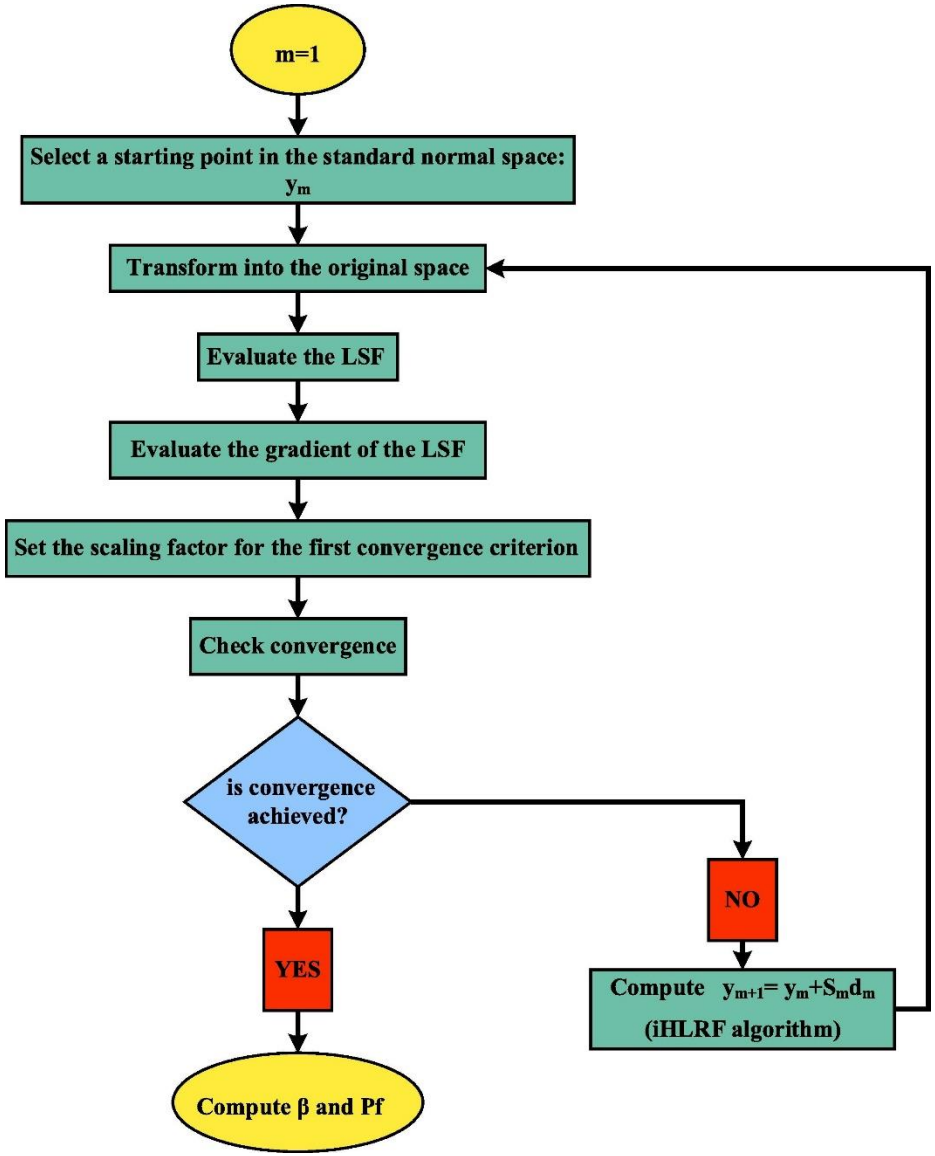
- **Modeling**
- **ParFlow-CLM**
  - Atmospheric forcing input : ECMWF data
  - Soil configuration: 15 layers (up to 50 m)
  - Spatial resolution: 0.0055◦ (~0.611 km)
  - Time period of simulation: June-July 2021



- **Data assimilation**
- **EnKF**
  - Generating 50 ensembles: error perturbation
  - for precipitation and initial pressure head.
  - Pressure head is updated (then it is converted to SWC).



Methodology: The FORM



Methodology: The LSF

$$RE_t = \frac{|y_{obs}{}^t - \hat{y}^t|}{y_{obs}{}^t} \times 100$$

"low relative error" with RE < 15%, "medium error" with 15% < RE < 35%, and "high error" with RE > 35%, as delineated.

$$CE = 1 - \frac{\sum_{t=1}^{n}(y_{obs}{}^t - \hat{y}^t)^2}{\sum_{t=1}^{n}(y_{obs}{}^t - \bar{y})^2}$$

CE < 0.50 indicating "unsatisfactory," 0.50 < CE < 0.65 signifying "sat isfactory," 0.65 < CE < 0.75 denoting "good," and 0.75 < CE < 1.00 re presenting "very good."

$$DAA = \frac{|y_{obs}{}^t - \hat{y}^t|}{\frac{1}{n}\sum_{t=1}^{n} P^t} > 0.2$$

DA Accuracy (DAA) is between 5% and 20% of corresponding avera ge precipitation.

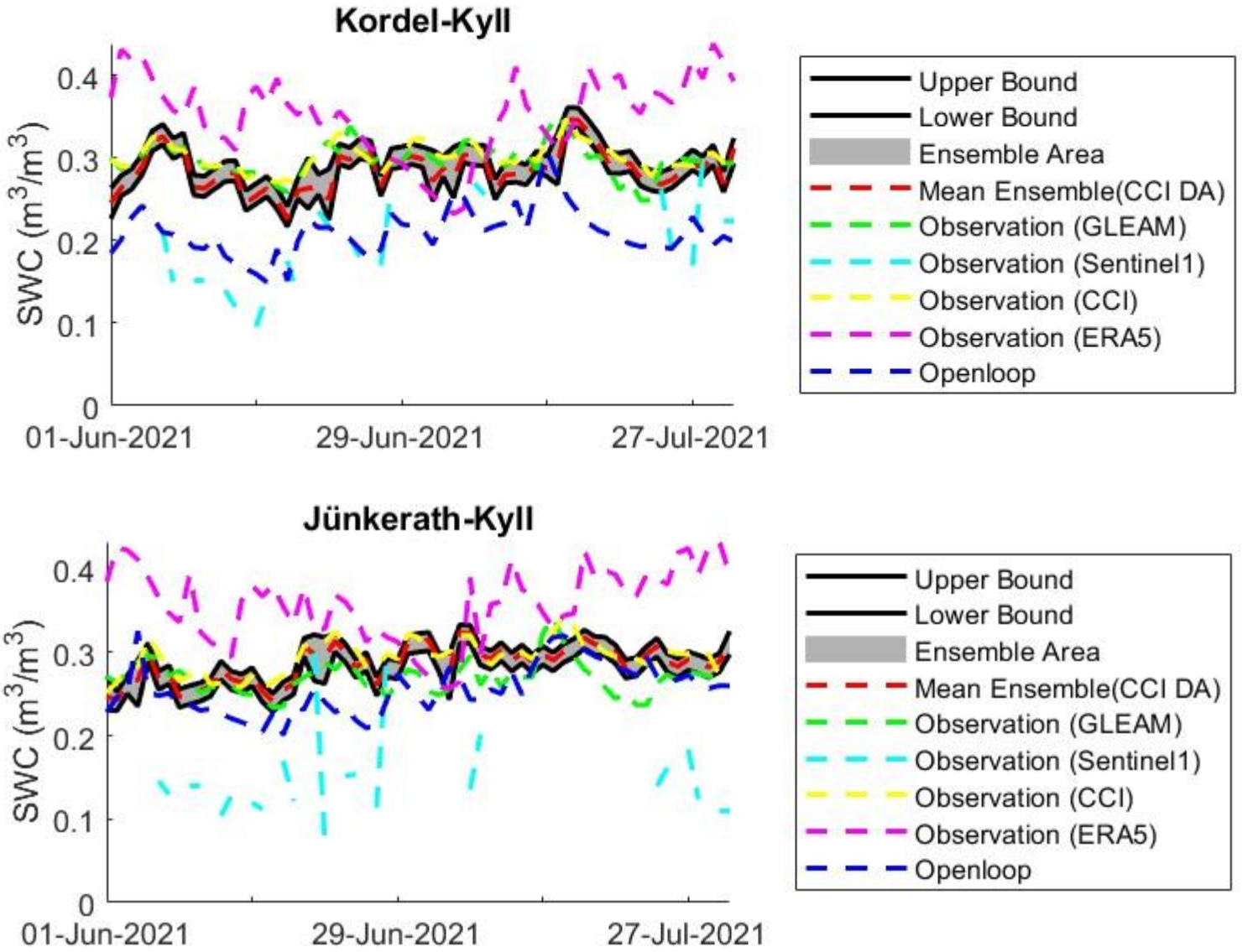
$$G(y) = 0.35 < RE$$

$$G(y) = 0.75 > CE$$

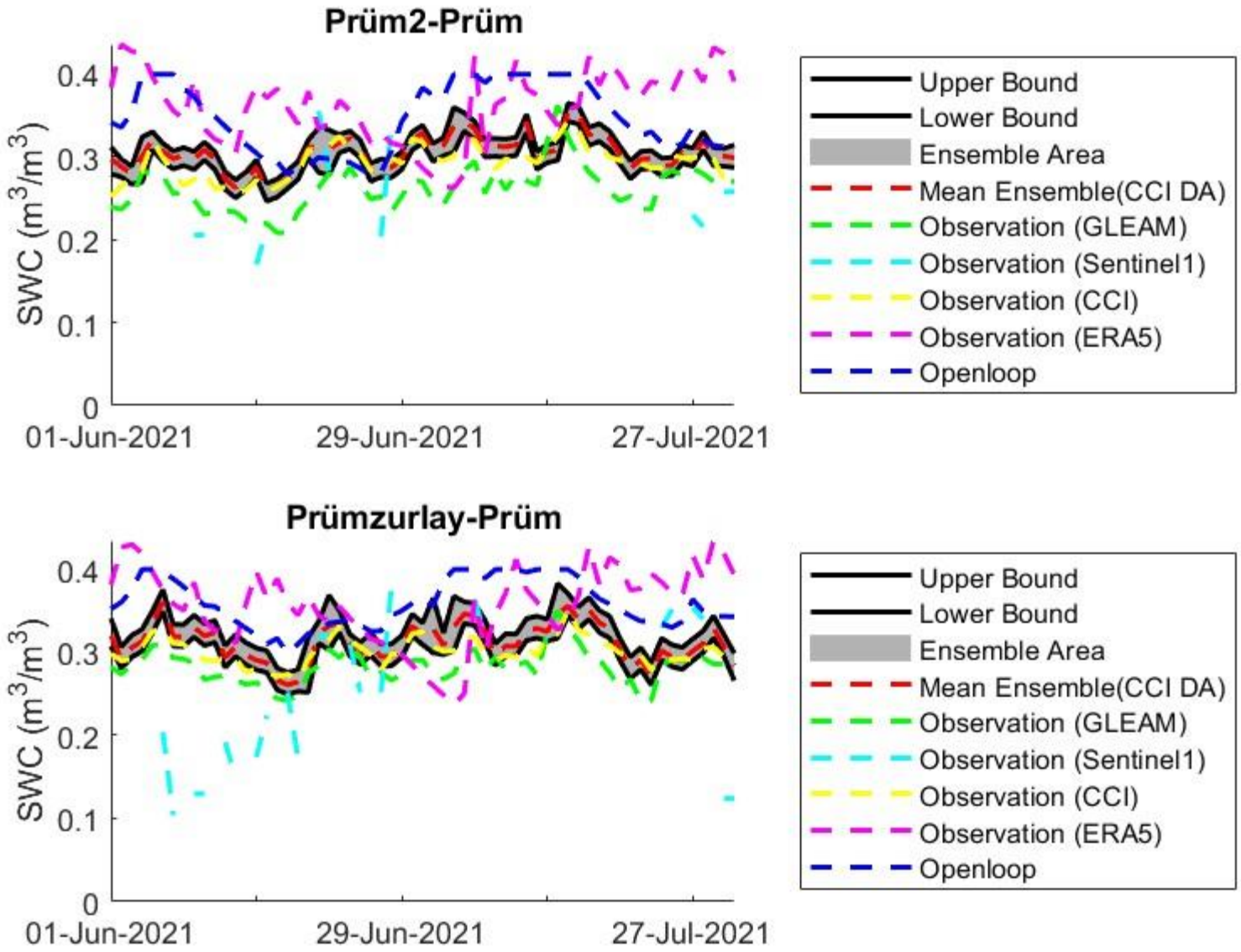
$$G(y) = DDA > 0.2$$

Results

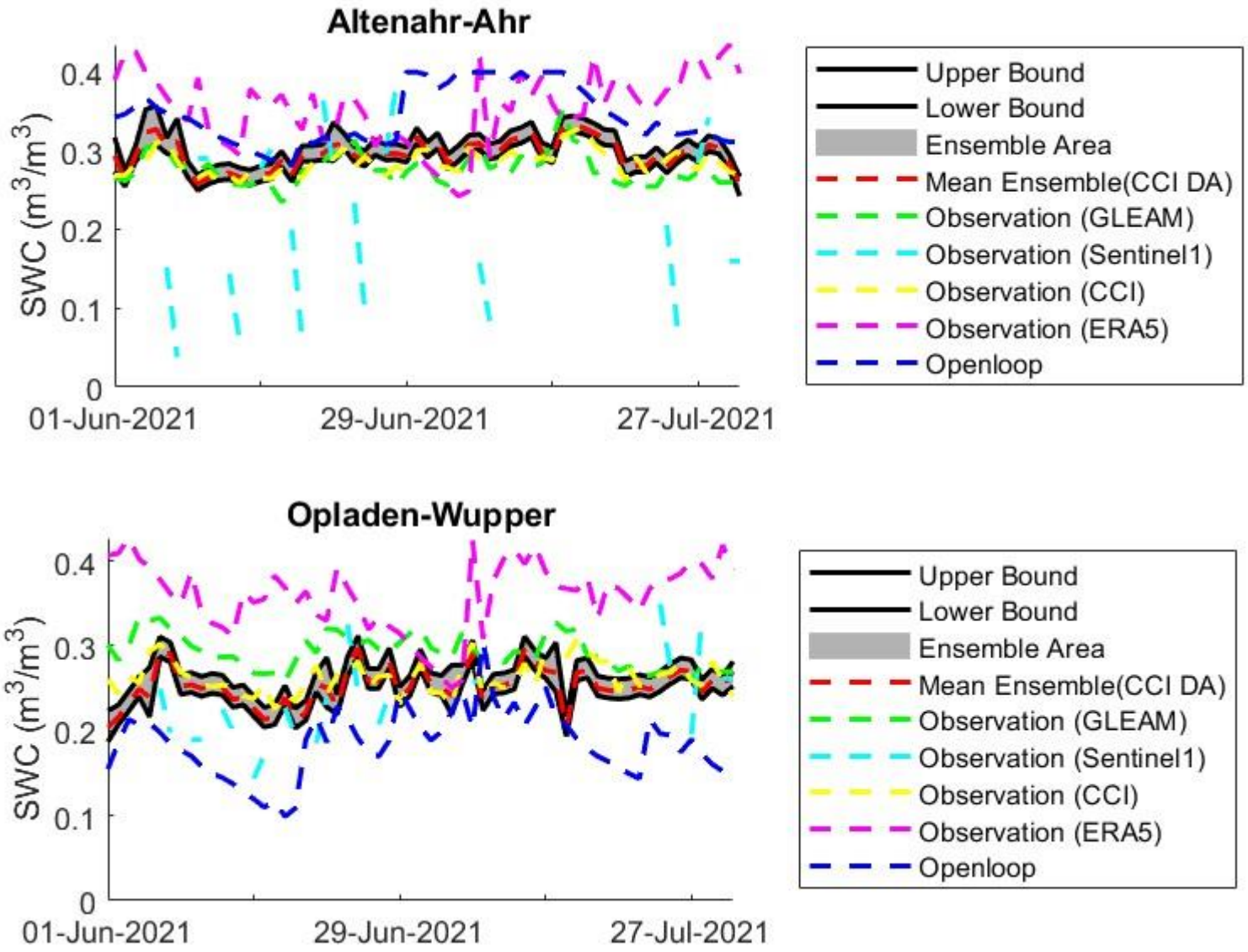
Time series of SWC; CCI DA



Time series of SWC; CCI DA



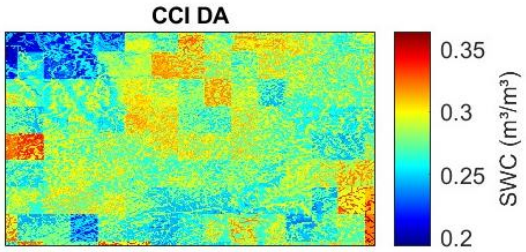
Time series of SWC; CCI DA

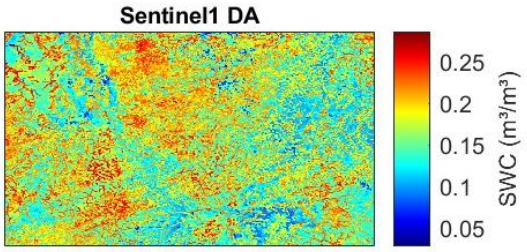


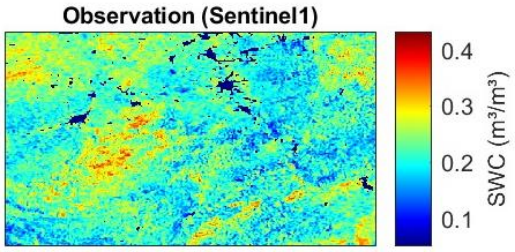
Findings: CCI DA

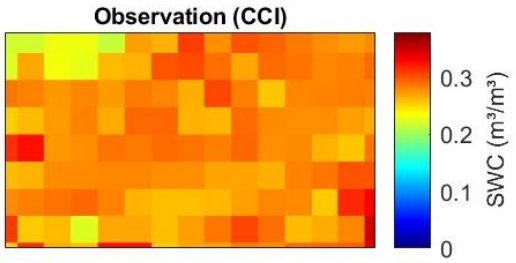
- CCI DA proves to be a robust approach for representing soil moisture dynamics (good agreement with GLEAM).
- It shows improvement over ERA5/GLEAM in capturing moisture spikes during rai nfall, such as the significant event in mid-July.
- Open-loop, on the other hand, generally underperforms by under/overestimating SWC levels during rainfall events, indicating a lack of responsiveness to precipit ation input.

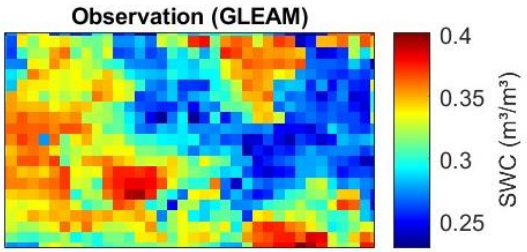
SWC, Spatial pattern

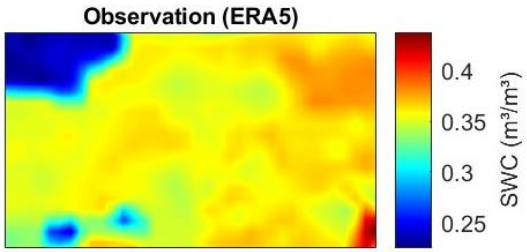


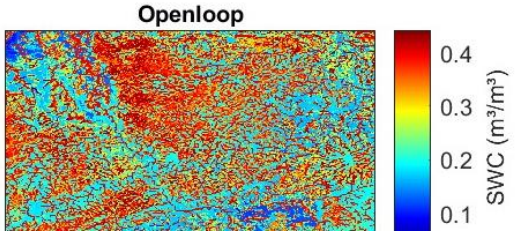






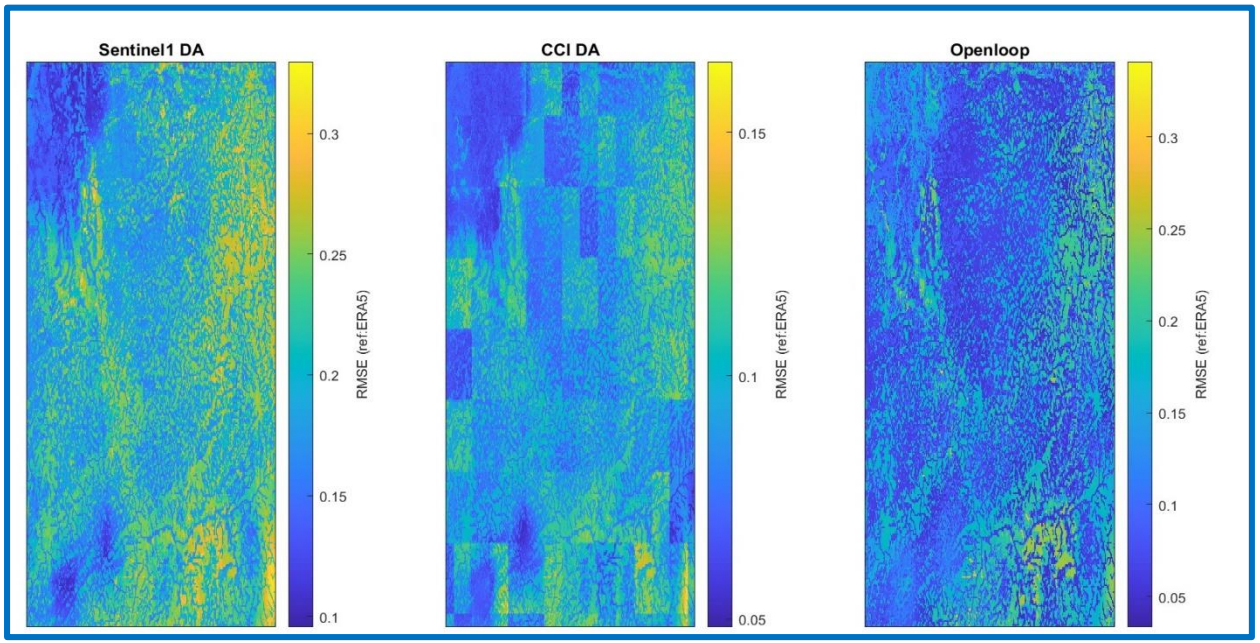




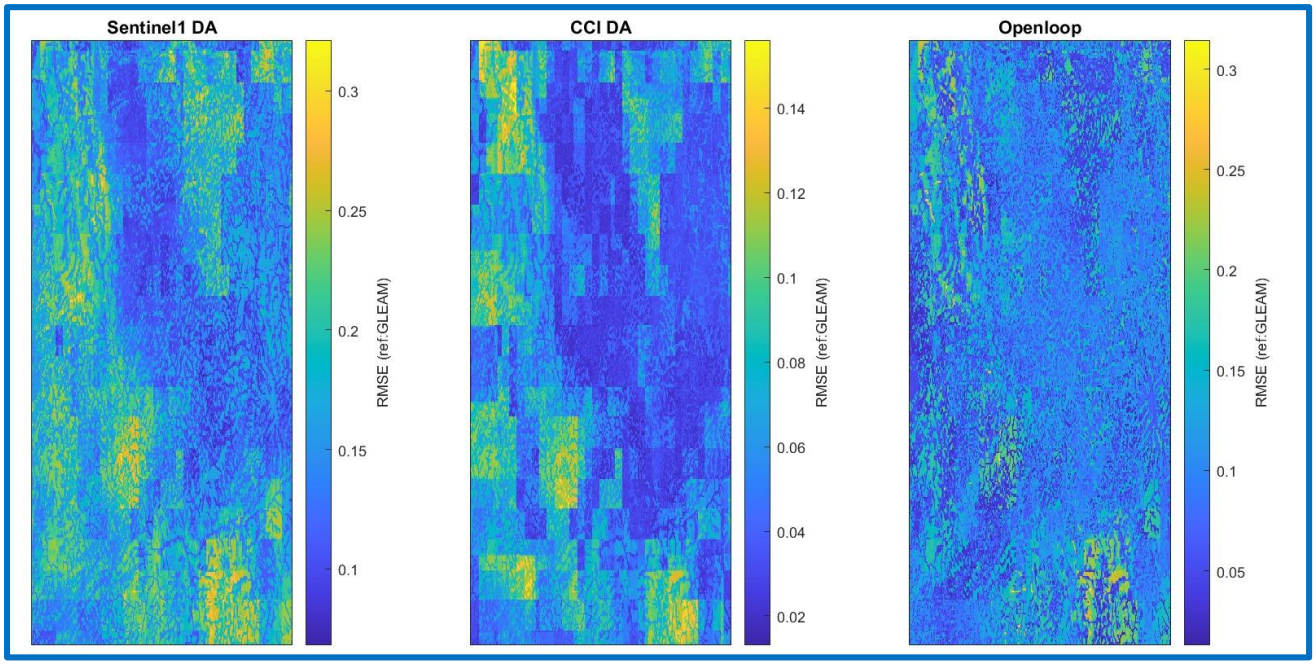


- GLEAM remains a better reference in this context, off ering a more accurate representation of both spatial he terogeneity and broad-scale trends.
- In contrast, ERA5's smoother approach works well for general insights but lacks the precision needed for mor e detailed hydrological assessments.

SWC, RMSE

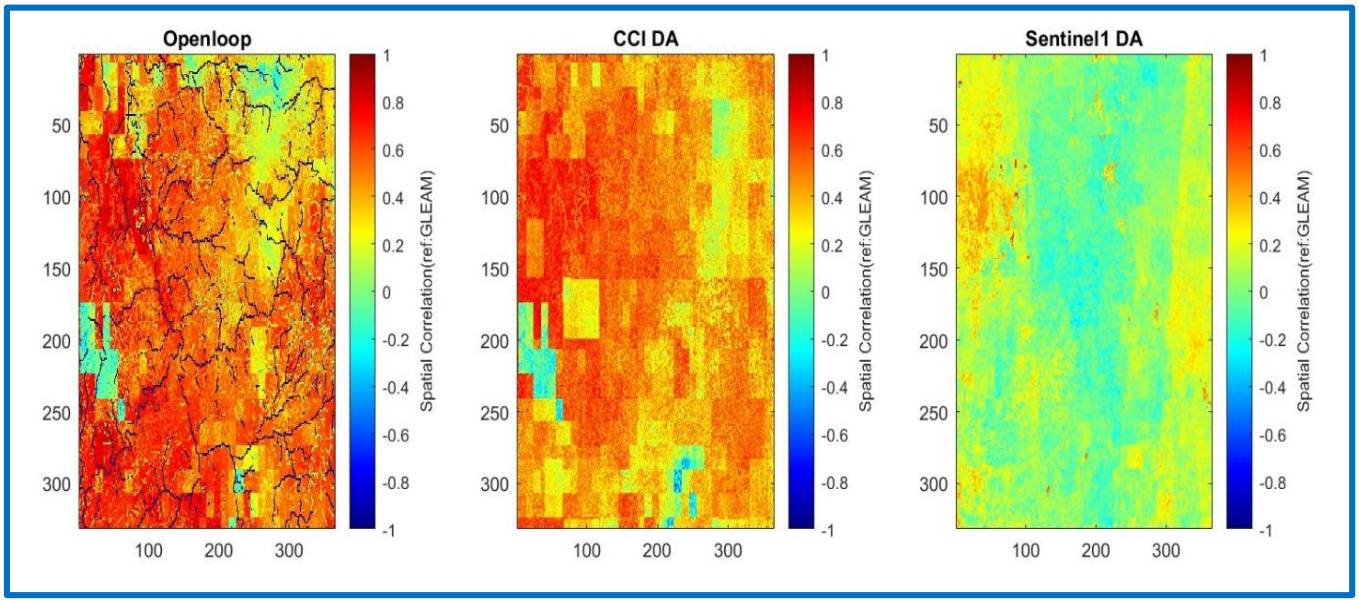


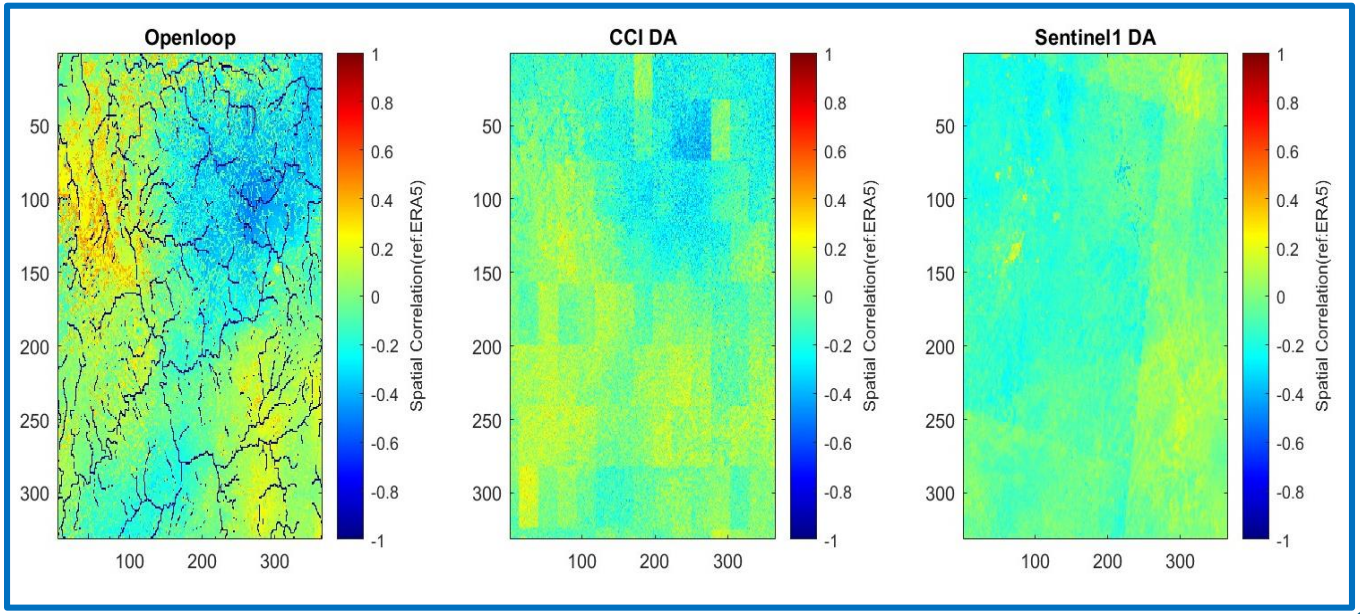
- RMSE for simulated SWC by CCI DA is lower than RMSE of simulated SWC by Sentinel-1 DA.



Spatially corrolation, SWC

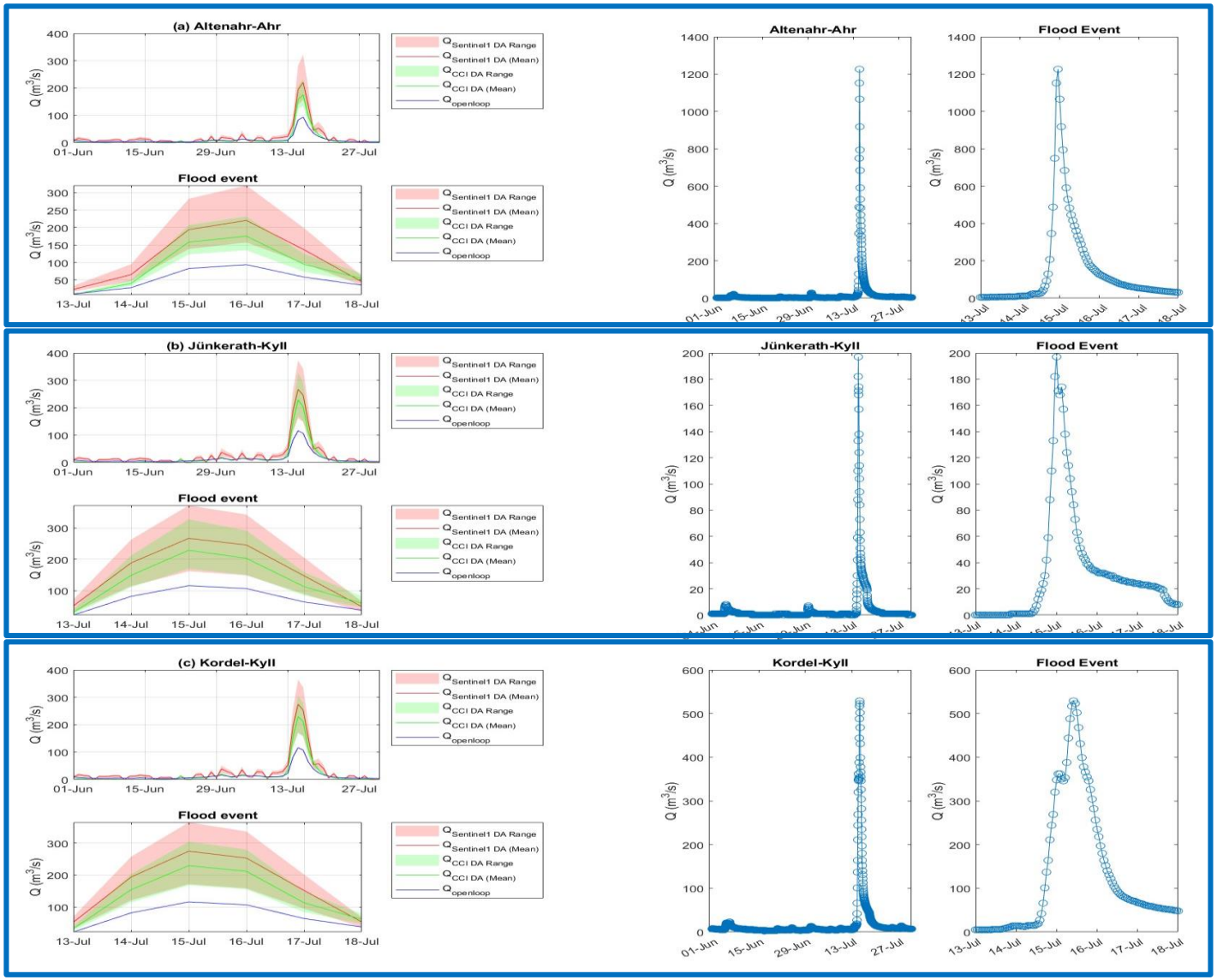
- The CCI DA shows better spatial correlation.
- Weak correlations of open-loop.
- The Sentinel-1 DA shows improved spatial correlation compared to the Open-loop, but it does not perform as consistently as CCI DA.





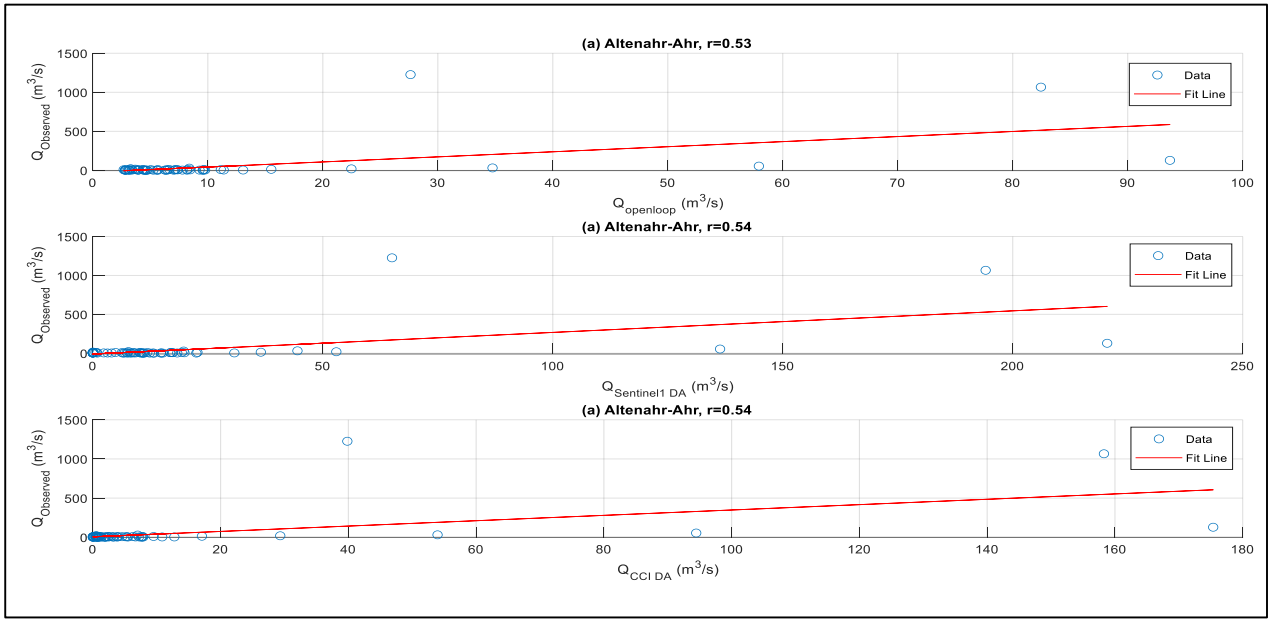
Time series of Streamflow

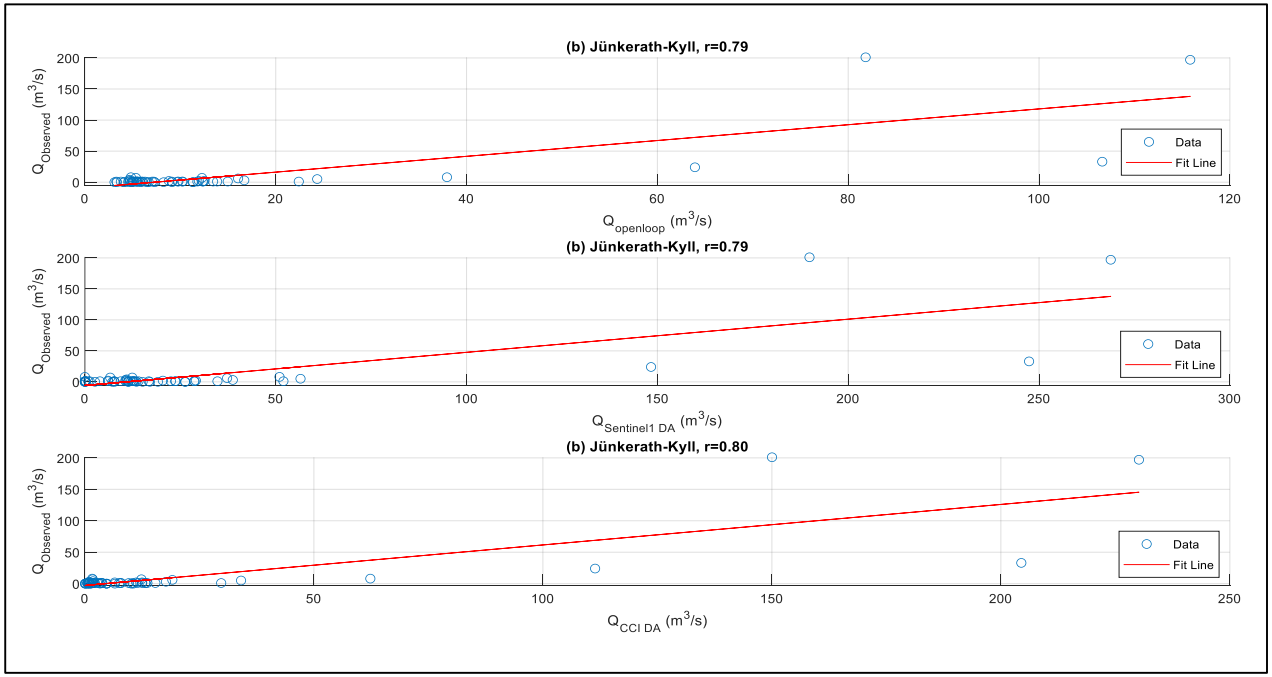
- Q simulated by Sentinel-1 DA (comparing to CCI DA) has better agreement with observation.



Streamflow: R

- DA resulting in slig htly higher R.
- SM-DA adjust the Q peak to be closer to the observed val ues.





Probabilistic evaluation: the FORM

SWC

	P_f					
	LSF					
	RE > 0.35		CE < 0.75		DDA > 0.2	
	Ref: GLEAM	Ref: ERA5	Ref: GLEAM	Ref: ERA5	Ref: GLEAM	Ref: ERA5
Sentinel-1-DA	12 %	15 %	11 %	14 %	7 %	11 %
CCI-DA	9 %	12 %	10 %	10 %	8 %	9 %
Open-loop	14 %	17 %	15 %	16 %	12 %	14 %

Streamflow

	P_f					
	LSF					
	DDA > 0.2					
	(a)	(b)	(c)	(d)	(e)	(f)
Sentinel-1-DA	13 %	10 %	7 %	10 %	9 %	7 %
CCI-DA	15 %	12 %	9 %	12 %	11 %	9 %
Open-loop	17 %	14 %	11 %	14 %	13 %	11 %

- Sentinel-1-DA shows the lowest probability of failure across all locations, indicating sup erior performance in reducing failure risk.
- CCI-DA, while performing better than the open-loop, shows moderately higher failure p robabilities.
- The open-loop exhibits the highest failure probabilities, highlighting the importance of d ata assimilation in improving the model's reliability.

Conclusions

- RMSE for simulated SWC by CCI DA is lower than RMSE of simulated SWC by Sentinel-1 DA.
- Q peak simulated by Sentinel-1 DA has better agreement with observation.
- Time lag in occurrence of Q peak is seen (between 1-3 days).
- Updating states + parameters (K and n) can be helpful for improving streamflow predictions. dx=0.611 km and obviously it is bigger than the width of river, which results lower value of pressure head and then streamflow.