Prognostic ParFlow integrated hydrologic model applications at stakeholder-scale over central Europe

2025-03-17 I Klaus Goergen[1,2], Alexandre Belleflamme[1,2], Suad Hammoudeh[1,2], and Stefan Kollet[1,2]

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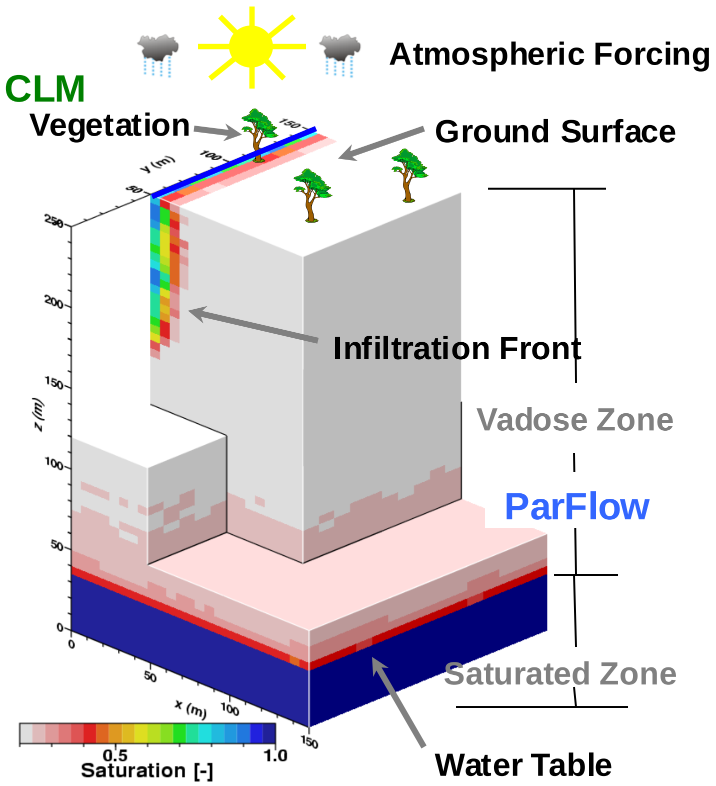
GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

Integrated modelling of terrestrial systems group (S. Kollet)

Our interest: Terrestrial water cycle functioning, interactions, feedbacks (G2A), and changes

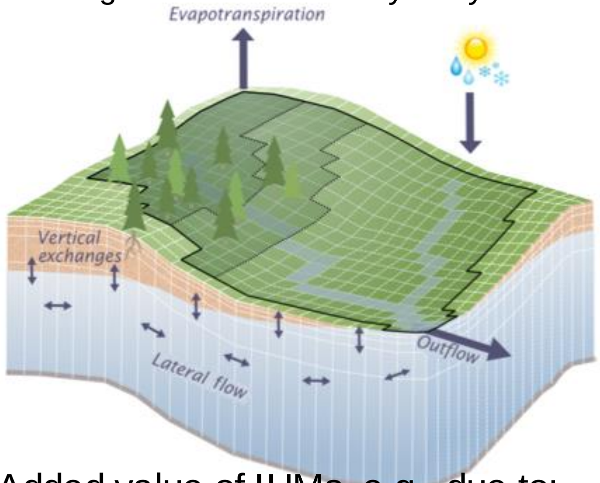


ParFlow overview: Kuffour et al. (2020, GMD)

ParFlow integrated hydrological model (github.com/parflow)

- Physically based model, explicit representation of transport processes and feedbacks
- 2D/3D surface and subsurface hydrodynamics are treated in continuum approach
- Land-atmosphere interactions through Common Land Model (CLM)
- Consistent terrestrial water cycle representation

Integrated HM with 3D hydrodynamics



Condon and Maxwell (2017, HESS)

Added value of IHMs, e.g., due to: **Redistribution of surface and groundwater**, **streamflow aquifer interactions**, **ponding / flowing water in convergence zones**, evolution of river networks, km-scale heterogeneity, hill-slope processes

Realistic process representation

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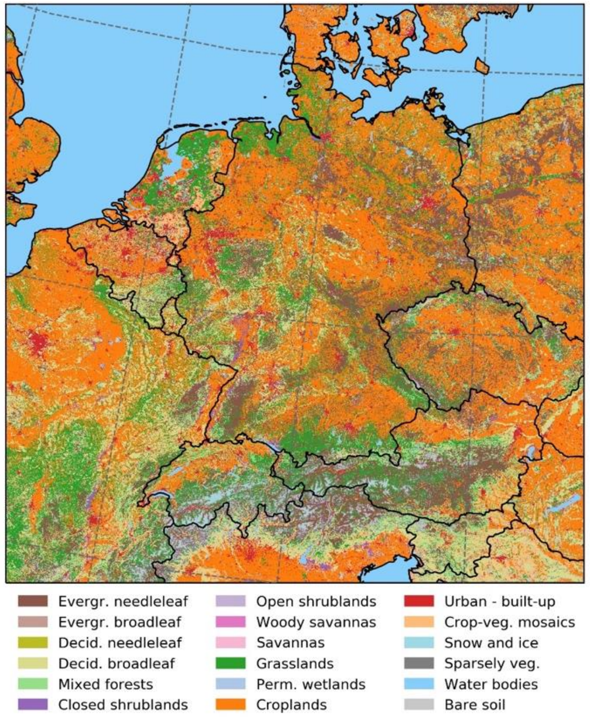
Prognostic ParFlow simulations for water resources

DE06: “Hydrologic Germany”, 611m resolution, 2000x2000x15 grid points, to 60m depth w/ ParFlow/CLM

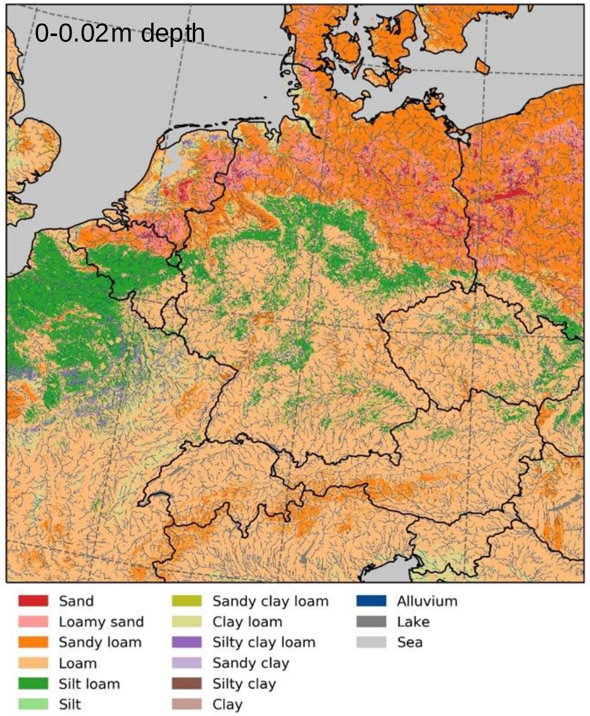
After 2018/2019 droughts:
Setup DE06 in co-design approach with agriculture stakeholders for water resources

- Careful setup of hydro-facies distributions and soil hydraulic properties
- Extensive spinup
- **No calibration or tuning**

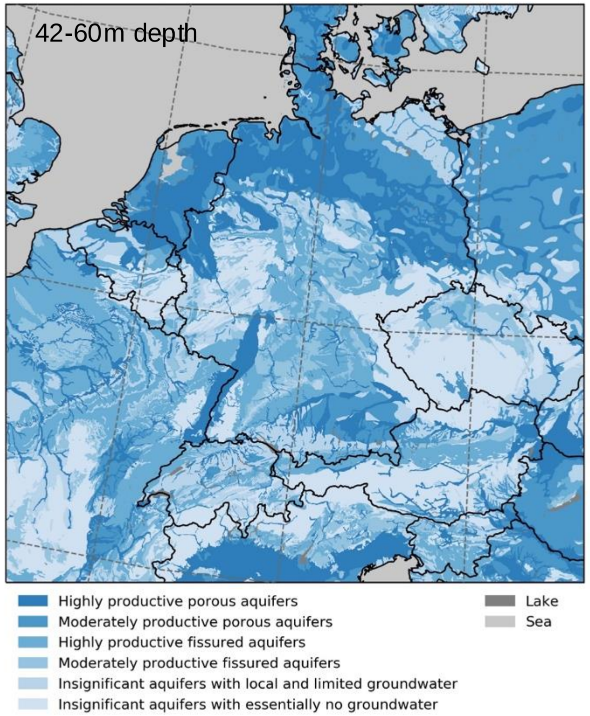
IGBP type land cover from CORINE



USDA soil types from SoilGrids textures



IHME hydrogeological types

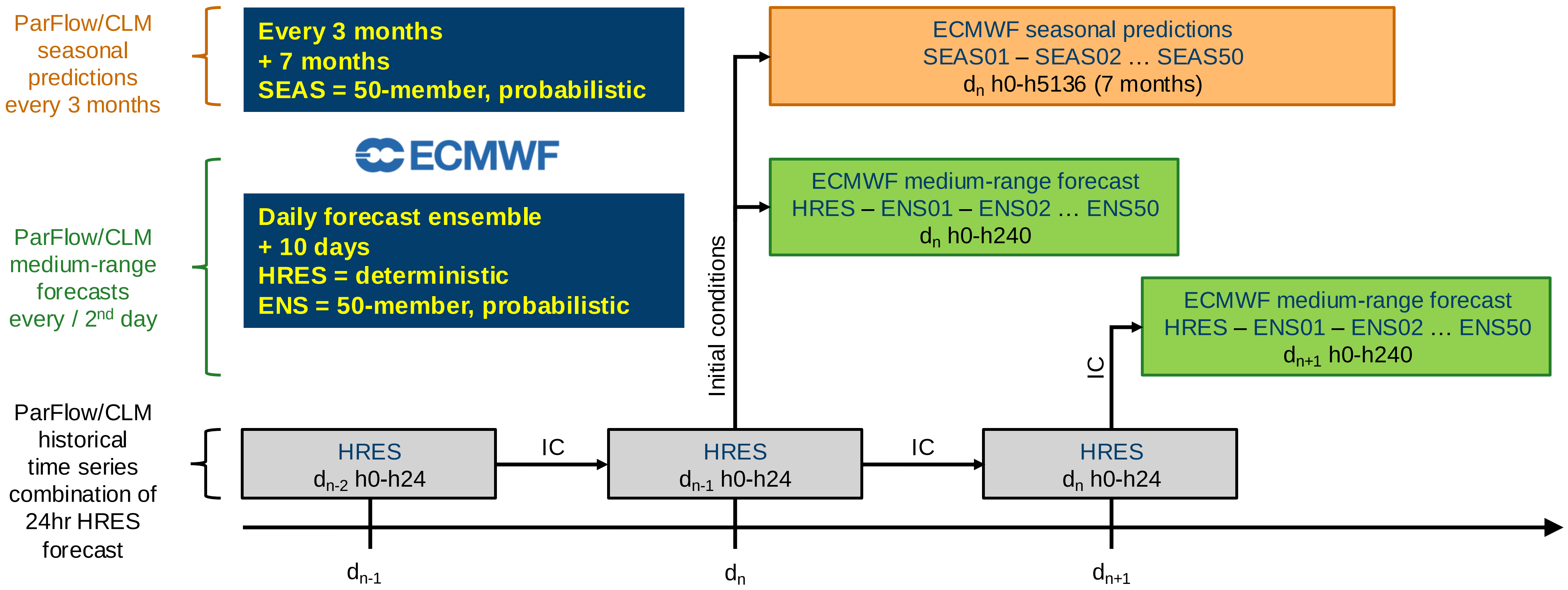


Van Genuchten parameters from ROSETTA

Belleflamme et al. (2023, Frontiers in Water)

System for daily DE06 quasi-operational monitoring/forecasting runs

Also available: HRES-driven climatology is from 2011, workflow is on JSC/JUWELS HPC GPU Booster



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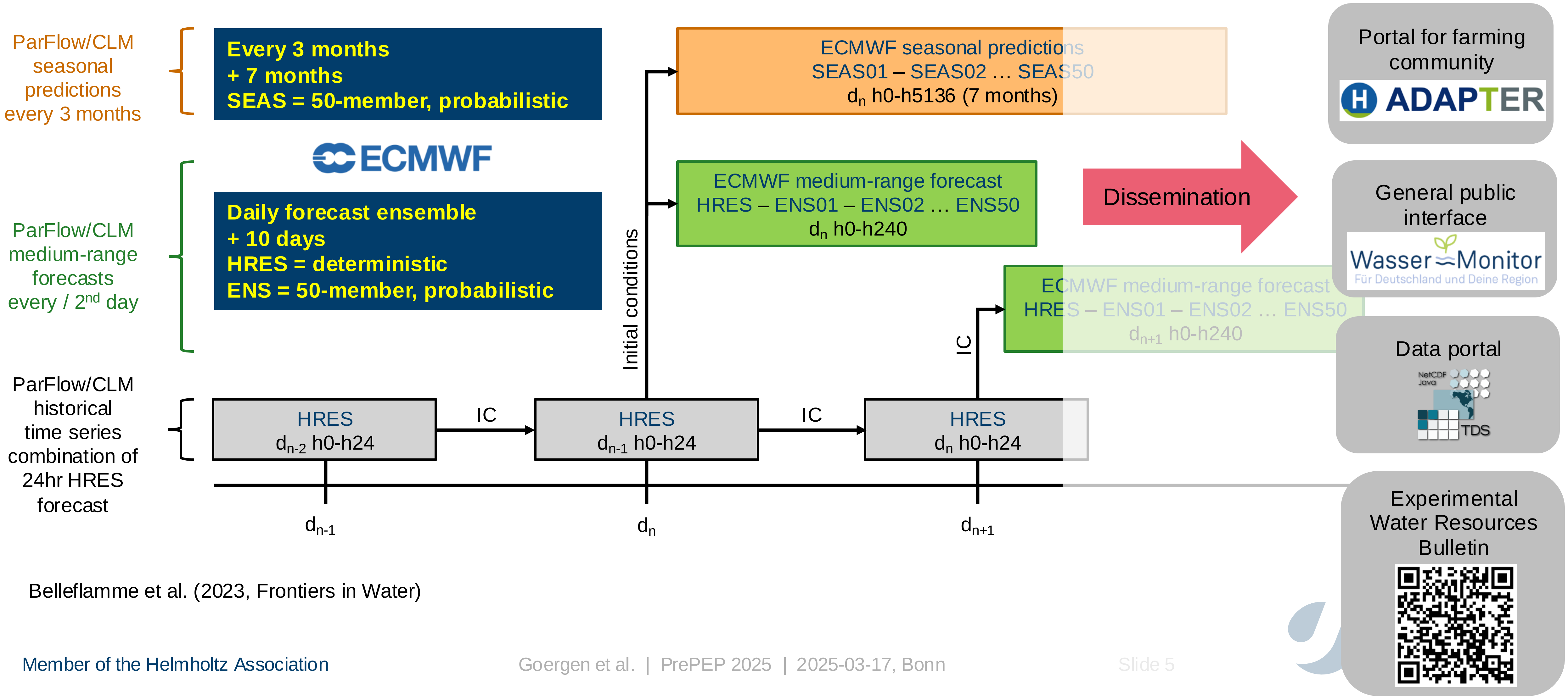


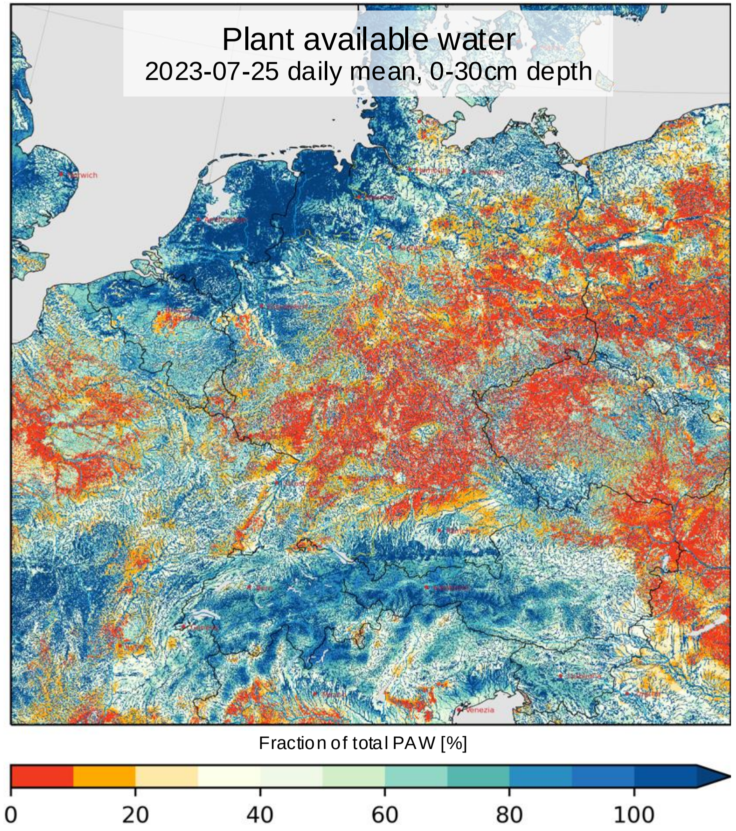
Belleflamme et al. (2023, Frontiers in Water)

Agriculture stakeholder information needs define our products

Towards a more weather extremes-resilient agriculture

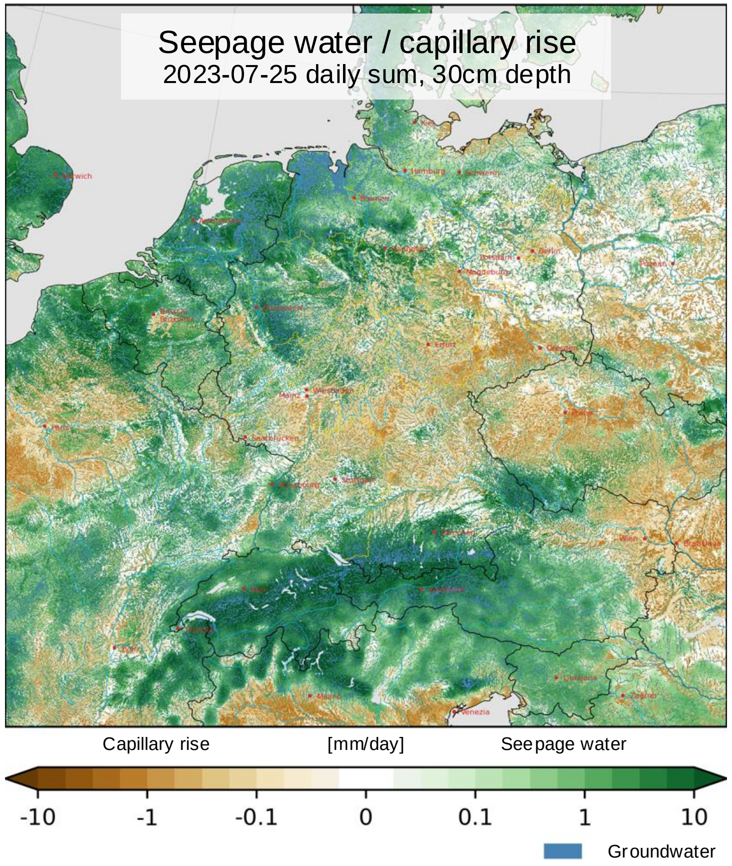
www.adapter-projekt.de

e.g., water stress impacts

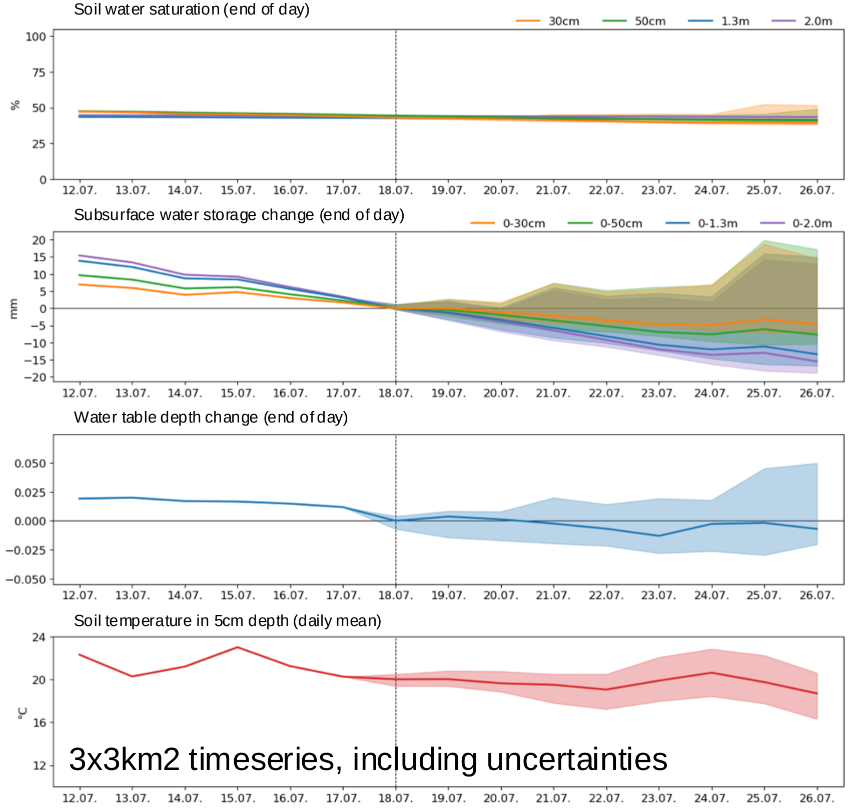


Belleflamme et al., (2023, Frontiers in Water)

e.g., leakage of nutrients, GW recharge



e.g., 8+ diagnostics daily

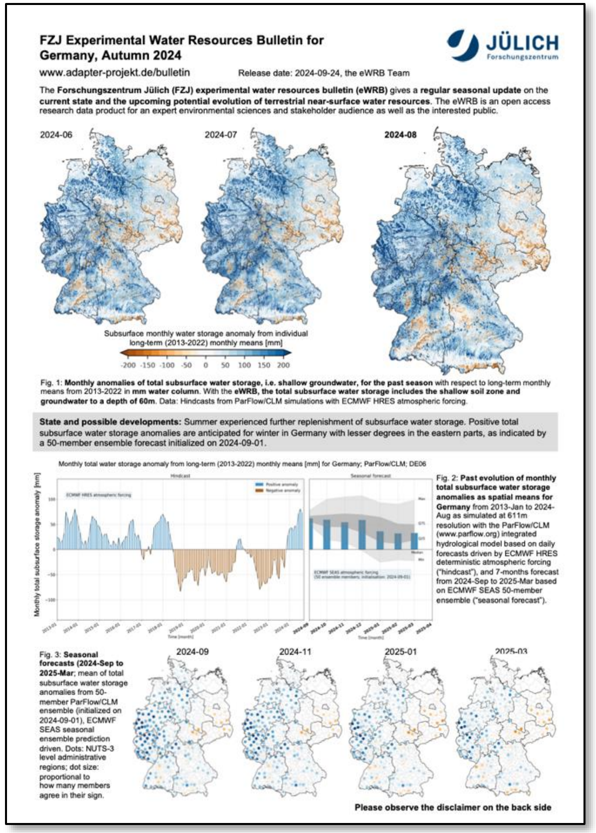


3x3km2 timeseries, including uncertainties

Experimental Water Resources Bulletin (eWRB)

Seasonal predictions of subsurface water storage

www.adapter-projekt.de/bulletin/index_en.html


FZJ Experimental Water Resources Bulletin for Germany, Autumn 2024

www.adapter-projekt.de/bulletin Release date: 2024-09-24, the eWRB Team

The **Forschungszentrum Jülich (FZJ) experimental water resources bulletin (eWRB)** gives a **regular seasonal update** on the **current state and the upcoming potential evolution of terrestrial near-surface water resources**. The eWRB is an open access research data product for an expert environmental sciences and stakeholder audience as well as the interested public.

2024-06 2024-07 2024-08

Subsurface monthly water storage anomaly from individual long-term (2013-2022) monthly means [mm]

-200 -150 -100 -50 0 50 100 150 200

Fig. 1: **Monthly anomalies of total subsurface water storage, i.e. shallow groundwater, for the past season** with respect to long-term monthly means from 2013-2022 in **mm water column**. With the **eWRB, the total subsurface water storage includes the shallow soil zone and groundwater to a depth of 60m**. Data: Hindcasts from ParFlow/CLM simulations with ECMWF HRES atmospheric forcing.

State and possible developments: Summer experienced further replenishment of subsurface water storage. Positive total subsurface water storage anomalies are anticipated for winter in Germany with lesser degrees in the eastern parts, as indicated by a 50-member ensemble forecast initialized on 2024-09-01.

Monthly total water storage anomaly from long-term (2013-2022) monthly means [mm] for Germany; ParFlow/CLM; DE06

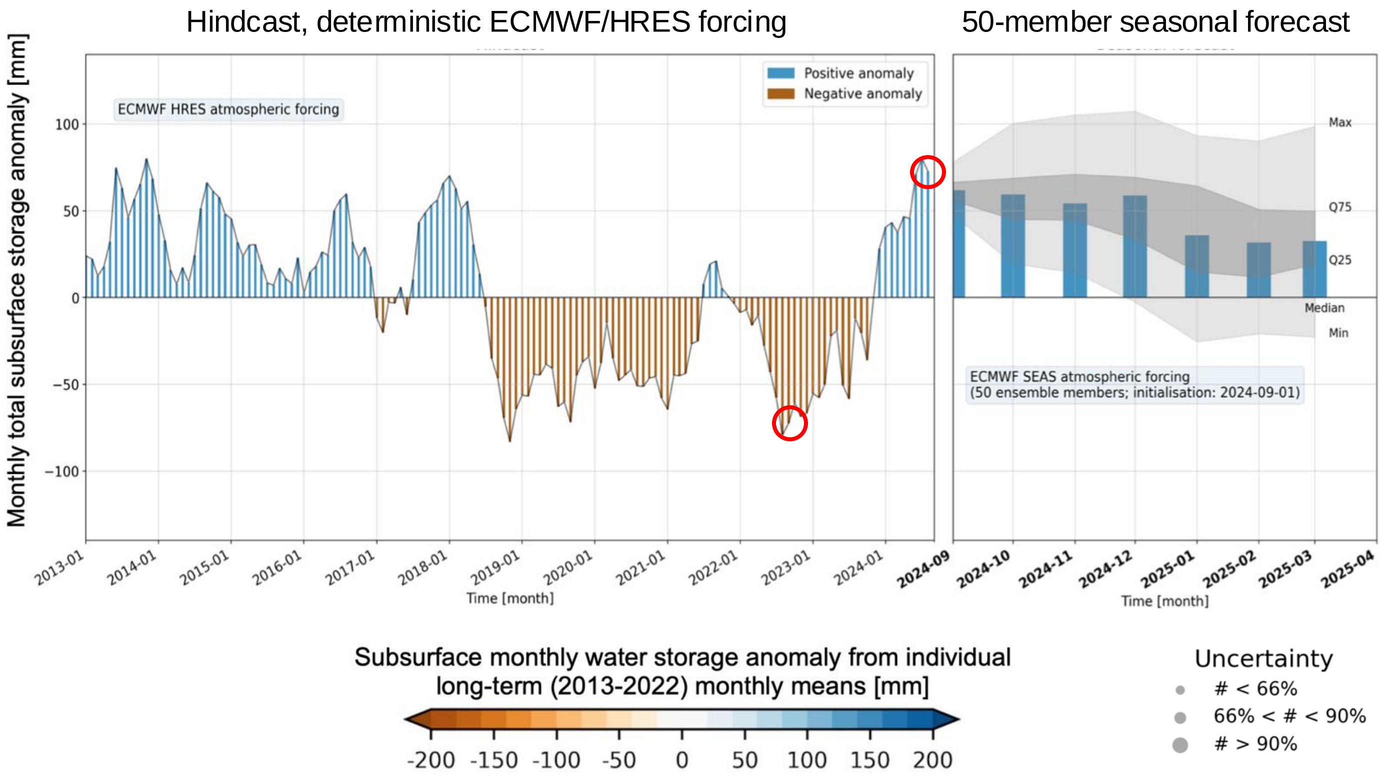
Fig. 2: **Past evolution of monthly total subsurface water storage anomalies as spatial means for Germany** from 2013-Jan to 2024-Aug as simulated at 611m resolution with the ParFlow/CLM (www.parflow.org) integrated hydrological model based on daily forecasts driven by ECMWF HRES deterministic atmospheric forcing ("hindcast"), and 7-months forecast from 2024-Sep to 2025-Mar based on ECMWF SEAS 50-member ensemble ("seasonal forecast").

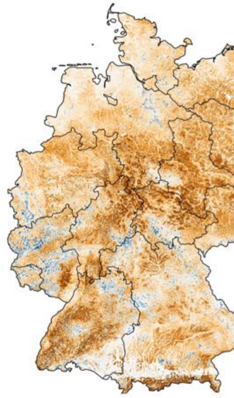
Fig. 3: **Seasonal forecasts (2024-Sep to 2025-Mar**; mean of total subsurface water storage anomalies from 50-member ParFlow/CLM ensemble (initialized on 2024-09-01), ECMWF SEAS seasonal ensemble prediction driven. Dots: NUTS-3 level administrative regions; dot size: proportional to how many members agree in their sign.

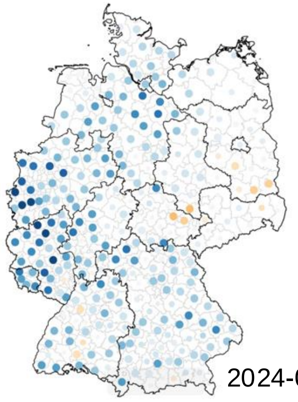
2024-09 2024-11 2025-01 2025-03

Please observe the disclaimer on the back side

Hydrometeorological extremes, recent severe droughts, well captured




2022-09


2024-08

Belleflamme et al. (under prep.), Hammoudeh et al. (under prep.)

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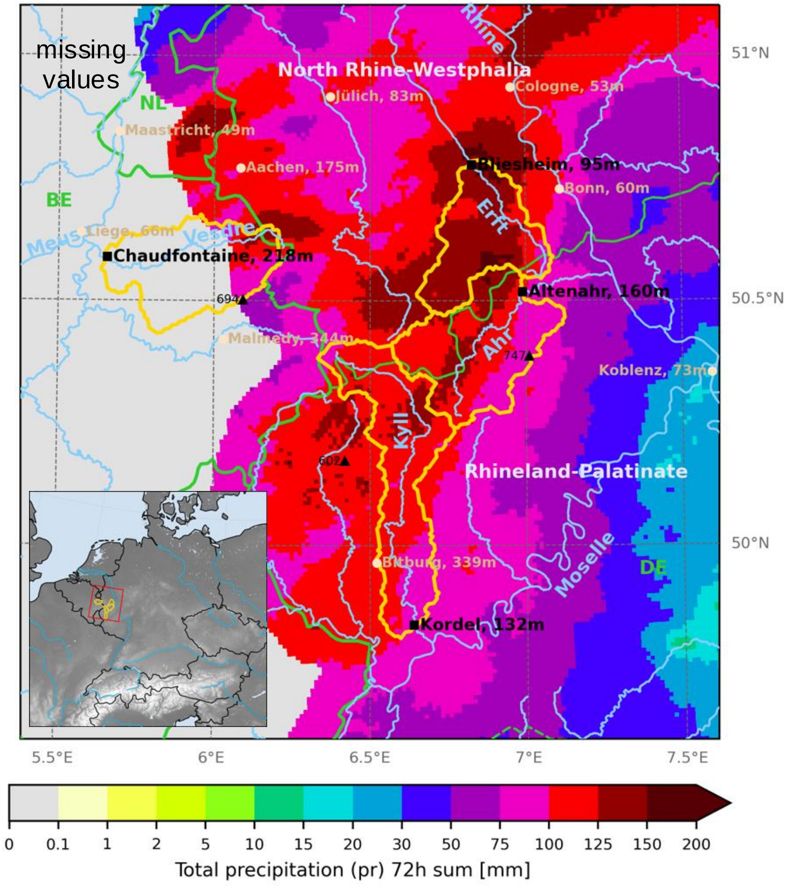
w/ DE06: Analyse unprecedented Central Europe 2021-07-14/15 flood

Goal: Process-based analysis to demonstrate the prognostic capabilities of ParFlow/CLM DE06 ensemble

72h (-07-12 to 14) radar precipitation sum RADKLIM



Domain subset: ≈150x150km^2

Heavily affected catchments:
Ahr, Vesdre, Kyll, Erft

- **Sustained, intense, widespread rainfall from a quasi-stationary low**
- **Rainfall event affected complete Eifel-Ardennes low mountain ranges drainage network**
- NWP models predicted July ‘21 precipitation extremes
- Major natural hazard in north-western Europe (many casualties, high damages)
- E.g., Ahr catchment:
  - 70mm July long-term mean,
  - 115mm/72h from 2021-07-12 to 14,
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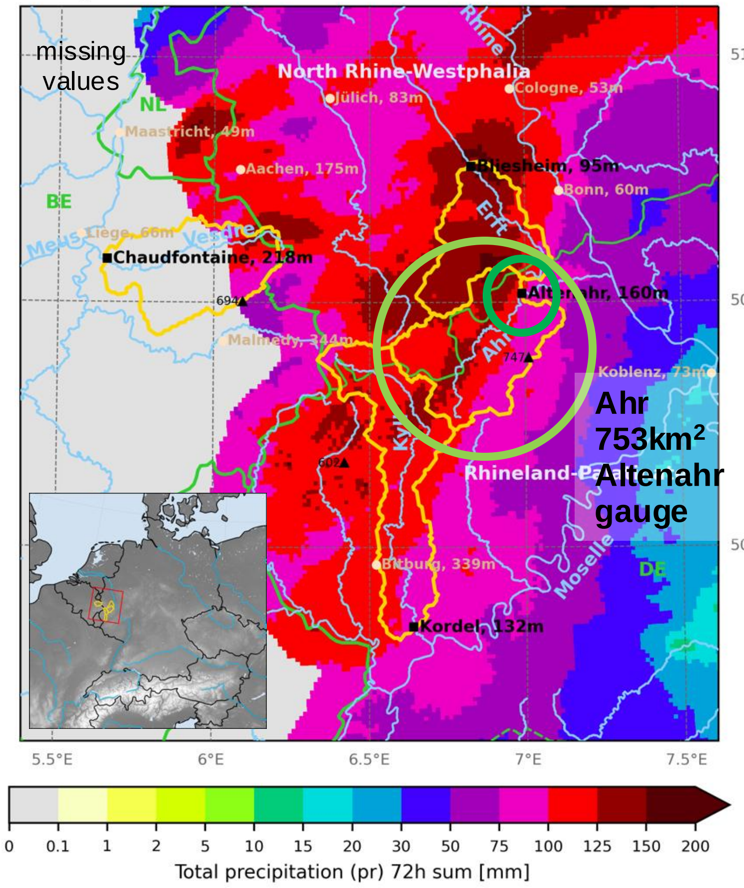

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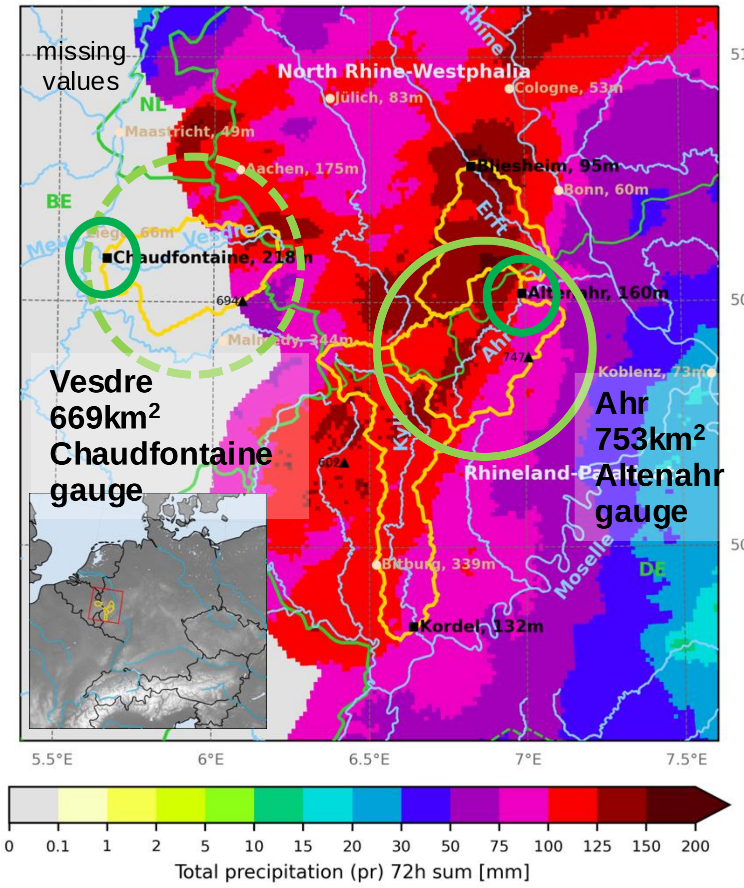

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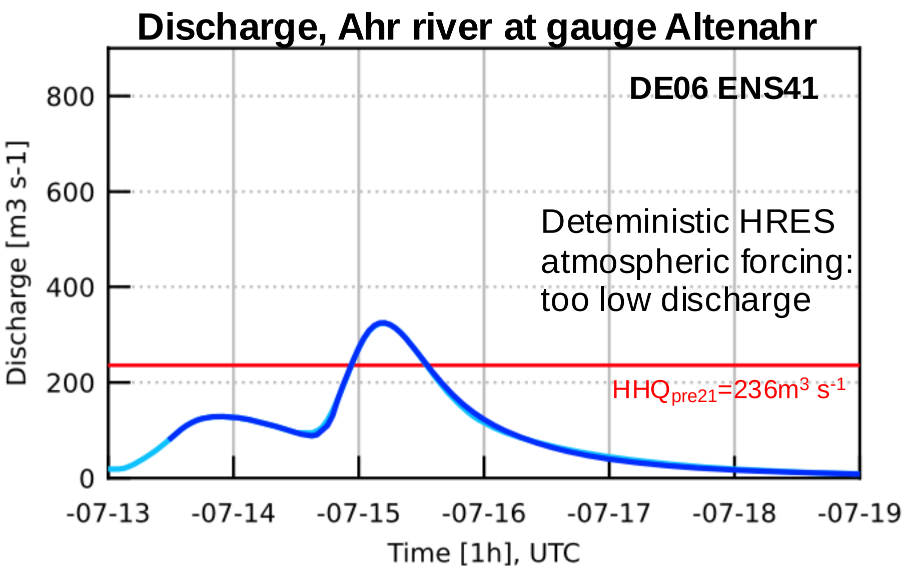
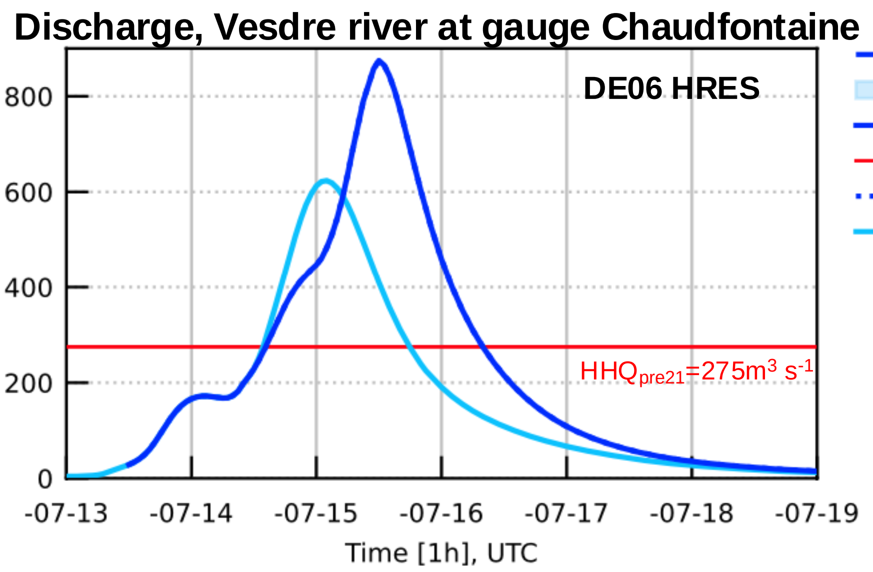
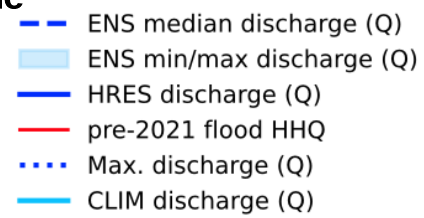
Dynamics and order of magnitude of discharge can be reproduced

Use DE06 as-is for process analysis; no focus on forecast skill or an exact event reproduction







Based on Parflow overland flow

ParFlow/CLM DE06
ECMWF HRES, ENS forcing
Initialisation: 2021-07-13_12UTC

Reconstructed: Q_{peak}=1000-1200m^{3}s^{-1} at Altenahr (Roggenkamp Herget, 2022, HYWA); **Q_{peak}=680m^{3}s^{-1}** at Chaudf. (pers. comm. Uni Lüttich)

- Large precipitation bandwith leads to highly differing discharge peaks; same with QPEs from radar observations (Saadi et al., 2023)
- Tuning, e.g., possible via streamflow parametrisations (Manning's coefficient, but roughness unknown or not represented)
- **The DE06 water resources forecast "as is" captures extreme flood event w/o additional calibration / tuning**

Goergen et al. (under rev.)

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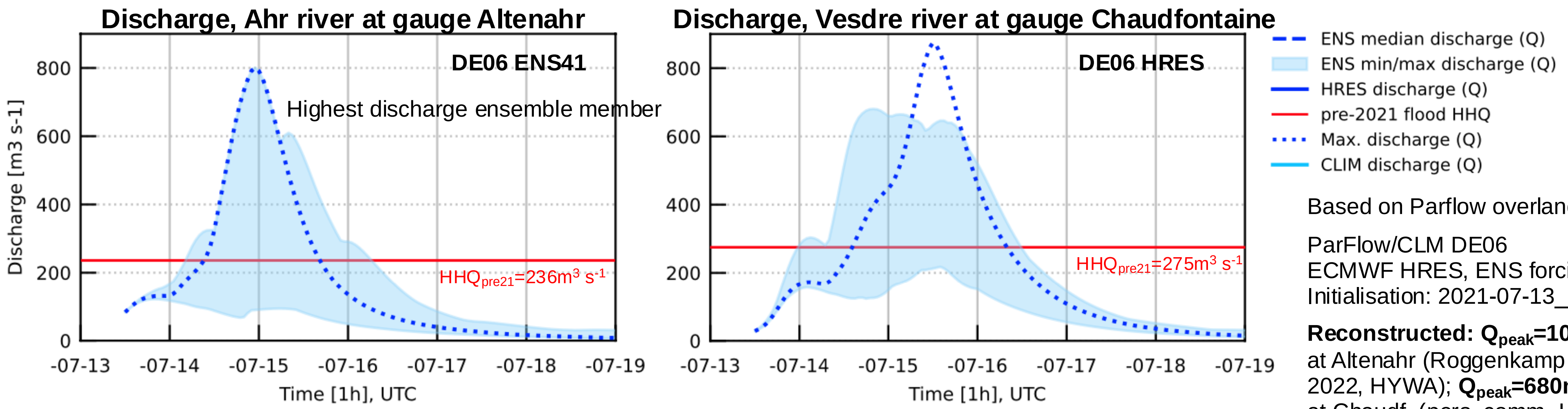

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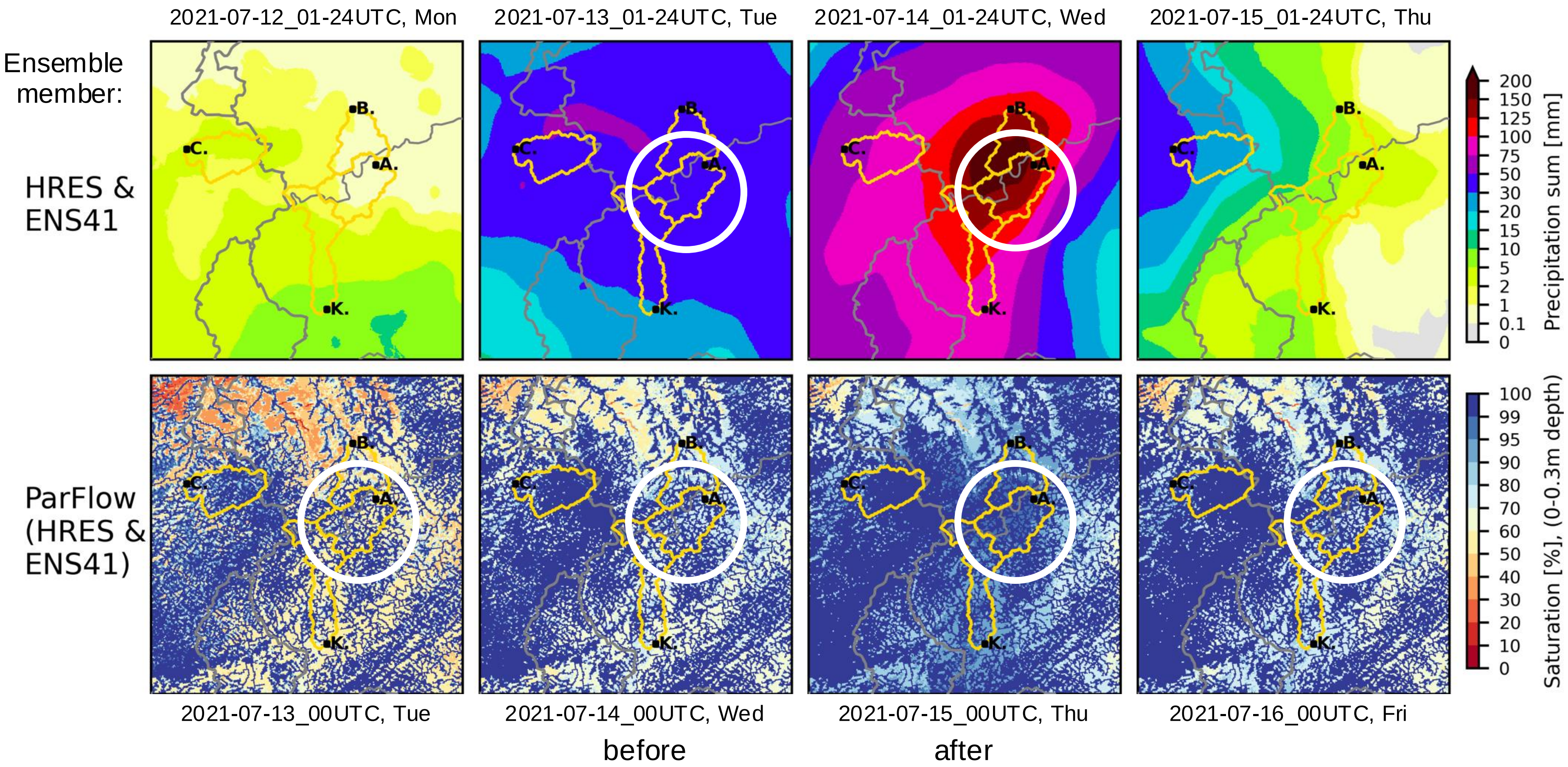
Goergen et al. (under rev.)

The soil almost reached saturation during the event

Maximum average soil saturation (0-30cm) over the 4 catchments is 91-97%

- Our interest is in the physical processes
- No infiltration excess overland flow
- Very low overland flow outside river channels
- High exfiltration in the valleys
- **We hypothesize that there was a strong pressure response of the system**



Relatively homogeneous soil hydraulic properties between catchments

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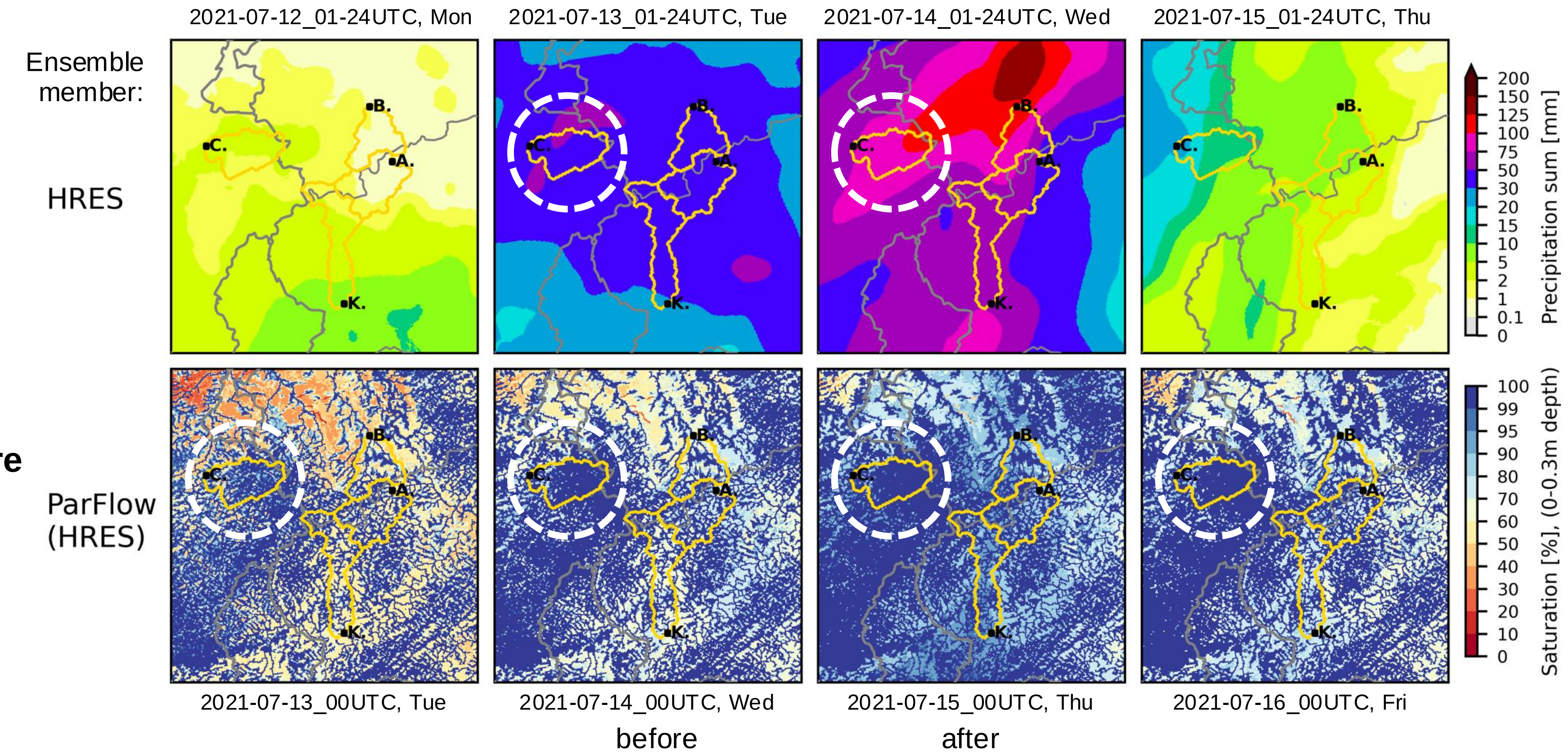
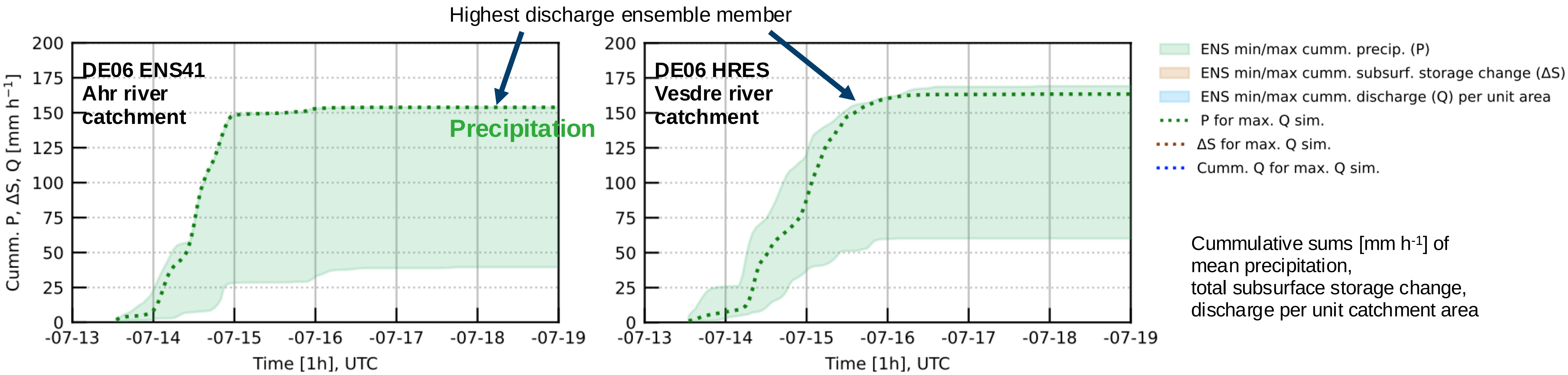
- Vesdre: Different preconditioning; higher saturation at the onset



Relatively homogeneous soil hydraulic properties between catchments

Strong buffer effect through subsurface storage

Up to 1/3 of the precipitation can infiltrate in the Ahr catchment, avoiding even higher discharge peaks



Cummulative sums [mm h^{-1}] of
mean precipitation,
total subsurface storage change,
discharge per unit catchment area

- Ahr catchment: **Increase in subsurface storage mitigates stream flow response**, despite 70% saturation (14.7. 00UTC)
- Vesdre catchment: Initially higher saturation, **less subsurface buffer, about all precipitation transformed into discharge**
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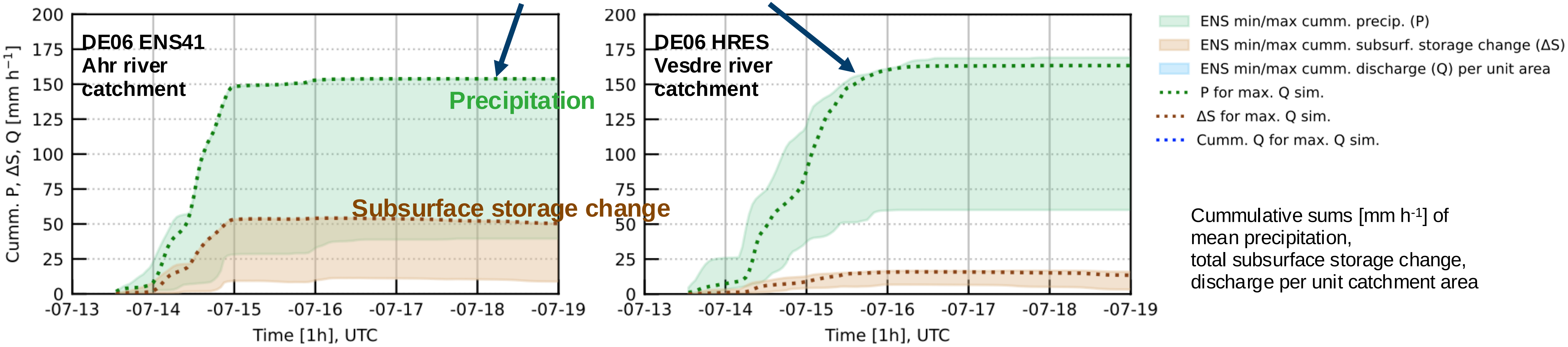

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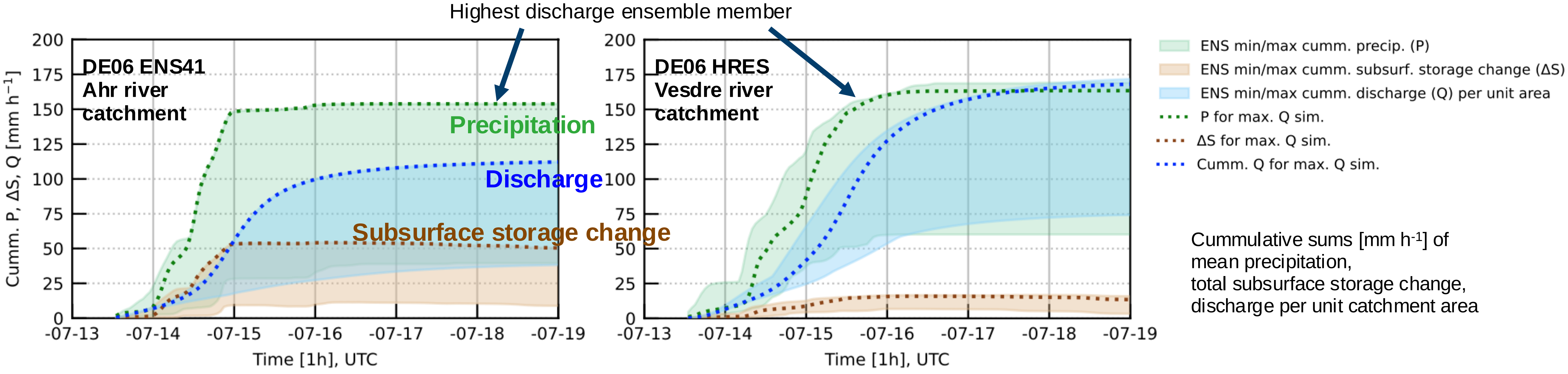

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Conclusions and outlook

IHM ParFlow/CLM with DE06 setup is an applied, highly versatile monitoring and forecasting system

- Use for **water resources** applications and **hydrometeorological extreme events**
- **Uncalibrated physics-based ParFlow IHM** can capture dynamics and magnitude the July 2021 flood event
- For the Ahr, the **subsurface** could absorb **about 1/3 of the precipitation**, mitigating the stream flow response

Outlook

- The physical representation of **groundwater-surface water interactions** affords **hypothesis** testing and will be used for **more in-depth process analysis of the 2021 flood event**
- With new exascale JSC/JUPITER HPC a **pan-European forescast domain** (EU06) seems feasible
- Combination of **added value of ParFlow IHM** and **high-resolution atmospheric models** in **coupled ESMs**