Integrated simulation of the terrestrial water cycle with the coupled Terrestrial Systems Modelling Platform (TSMP)

(Evolution of 2018 to 2020 European terrestrial water resources anomalies from coupled COSMO-CLM-ParFlow (TSMP) forecast simulations)

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A B C/J geoverbund aachen bonn köln jülich

HPSC TerrSys

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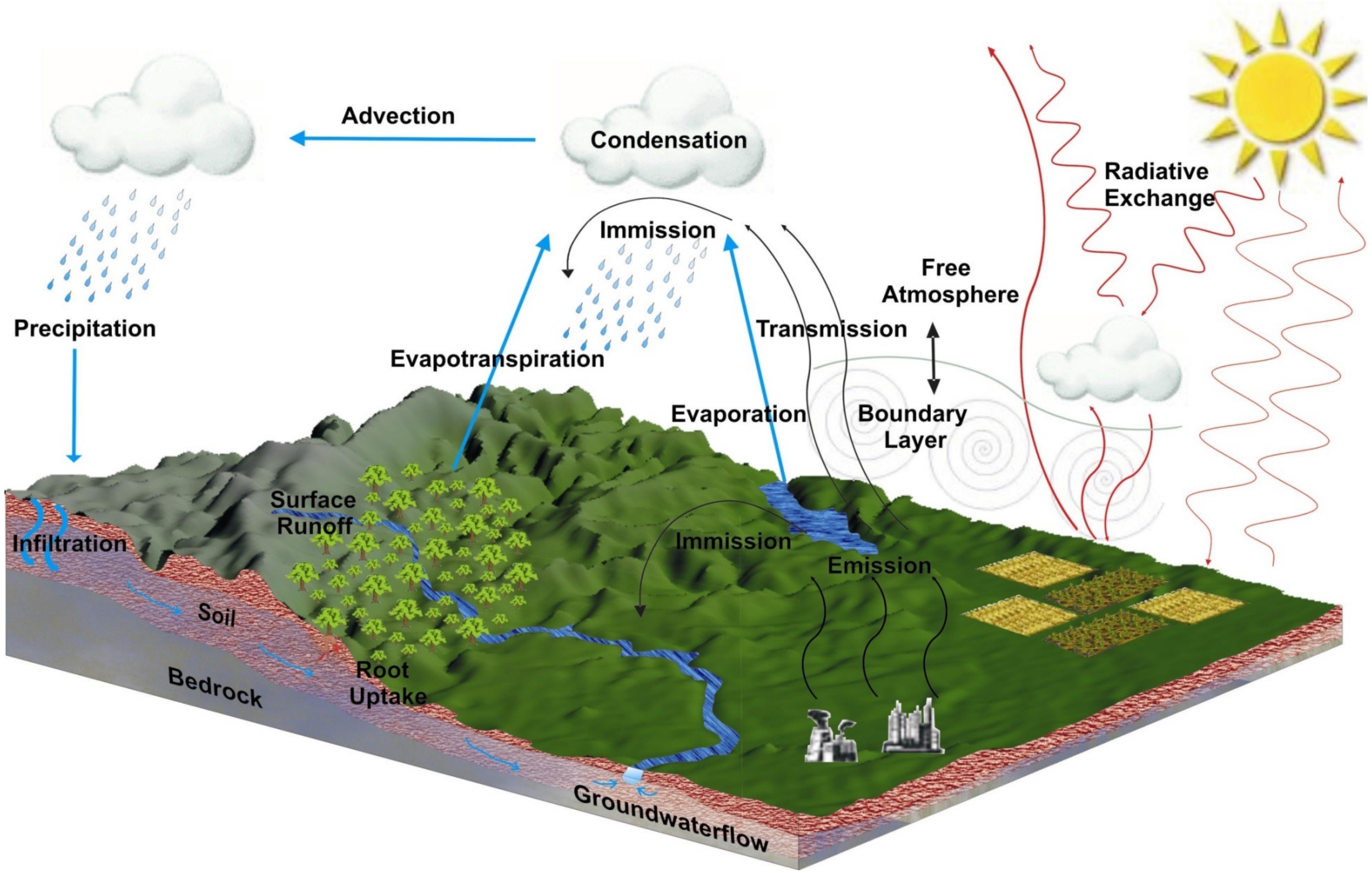
The terrestrial system

Our focus: Terrestrial water cycle and groundwater-to-atmosphere (G2A) interactions and feedbacks



- Complex interactions and feedbacks between various sub-systems of the coupled geo-ecosystem, many drivers
- Linkages through energy, mass and momentum transfers
- Multiple spatio-temporal scales
- Anthropogenic physical system changes modify land surface and ecosystem processes and services with many socio-economic impacts

Motivation

Intensification of the hydrological cycle under climate change

- Global (**climate**, land use) **change** has an **impact** on **water as a resource,** its sustainable use, and affects water security

- Better **understanding** and **prediction** of (increasing) **extreme hydroclimatic events** (e.g., droughts, heatwaves) and **related feedbacks** for informed adaptation (e.g., irrigation) or mitigation options, but:
  - Observations: Scarce/inconsistent at the European scale
  - Climate models: Often simplified groundwater representation
  - Hydrological models: Often simplified surface-subsurface interactions and neglect two-way feedbacks with the atmosphere: terrestrial water cycle not closed

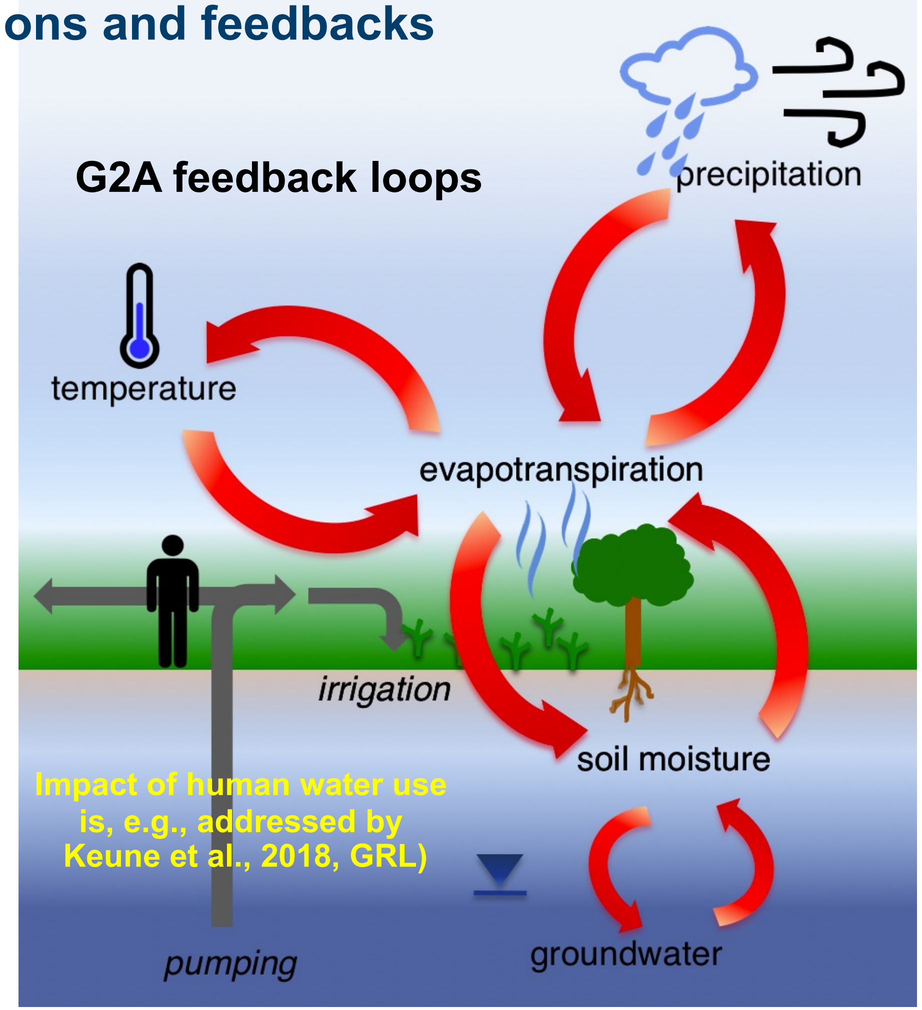
- In addition: **Human water use** has multiple local and non-local (climatic) effects (groundwater recharge/storage, discharge, ET/P recycling, etc.) … not addressed today

Some research questions and goals

Assess the groundwater-terrestrial system-atmosphere interactions and feedbacks

1. What are **drivers of hydroclimatic extremes** (droughts, heatwaves) in the context of land-atmosphere coupling? How does groundwater alleviate extremes? (*processes*)
2. Provide a **physically consistent groundwater-to-atmosphere climatology** as a basis to assess how extreme weather events and climate change affect groundwater (*application*)
3. What is the **impact of extreme hydrometeorological conditions** (e.g., drought of 2018) on **water resources** in Europe? (*resources*)

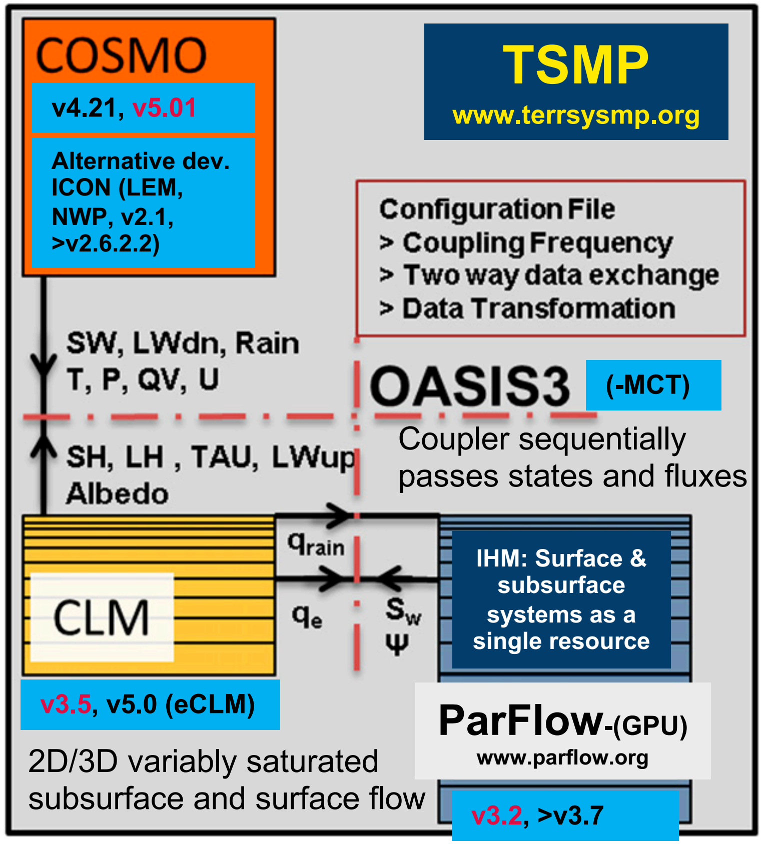
Need for integrated groundwater-to-atmosphere simulations – the coupled land surface/subsurface and atmospheric water and energy cycles are impacted



Courtesy J. Keune (2018), Uni Ghent

Terrestrial Systems Modelling Platform (TSMP) model system

Closure of the terrestrial water and energy cycle from groundwater to the atmosphere

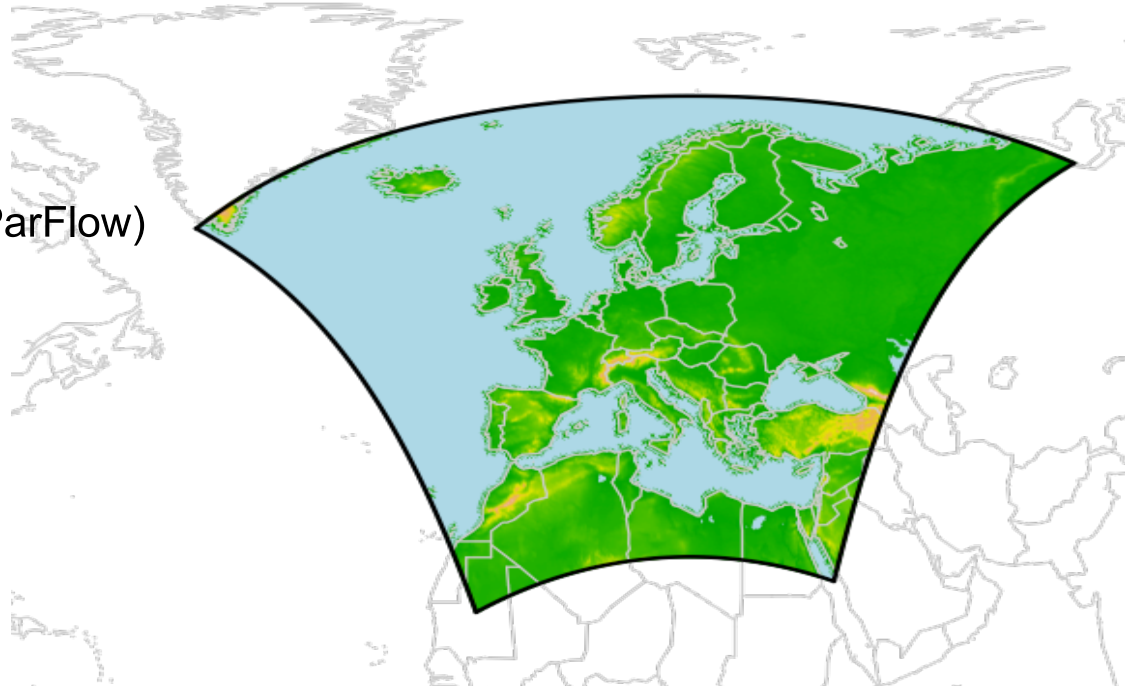


Shrestha et al. (2014, Mon Weather Rev); Gasper et al. (2014, GMD); Kurtz et al. (2016, GMD); Burstedde et al. (2018, Comput Geosc); Hokkanen et al. (2021, Comput Geosc)

- A scale-consistent highly modular fully integrated soil-vegetation-atmosphere numerical modelling system using COSMO, Community Land Model and ParFlow
- Physically-based representation of transport processes of mass, energy and momentum across scales down to sub-km resolutions, explicit feedbacks between compartments (focus: terrestrial hydrological cycle), including irrigation and pumping
- Optimized for latest massively parallel HPC systems; Parallel Data Assimilation Framework (TSMP-PDAF)

TSMP pan-European model setup

In line with the WCRP Coordinated Regional Downscaling Experiment (CORDEX) project



- CORDEX EUR-11 Gutowski et al. (2016, GMD)
  - Resolution: 0.11° (about 12km), 436 x 424 gridpoints
  - Vertical levels: 50 (COSMO), 10 (to -3m) (CLM), 15 (to -60m) (ParFlow)
  - Time steps: 60s (COSMO), 900s (CLM), 900s (ParFlow)
- Input data Keune et al. (2016, JGR)
  - Atmosphere: ERA-Interim
  - Land surface: MODIS data (4 plant functional types / grid cell)
  - Subsurface: FAO soil types (and Gleeson/BGR data base)
- Experiments
  1. **Sensitivity studies, year 2003 (European heat wave)** 1D vs 3D groundwater physics Keune et al. (2016, JGR)
  2. **EURO-CORDEX evaluation**: 1989-1995 spinup, 1996-2019 analysis Furusho-Percot et al. (2019, Sc Data) + Hartick et al. (2021, WRR)
  3. **Probabilistic water resources prediction,** heatwave and drought impacts, 3 water years Hartick et al. (2021, WRR)

A “pristine” groundwater climatology, no human impacts

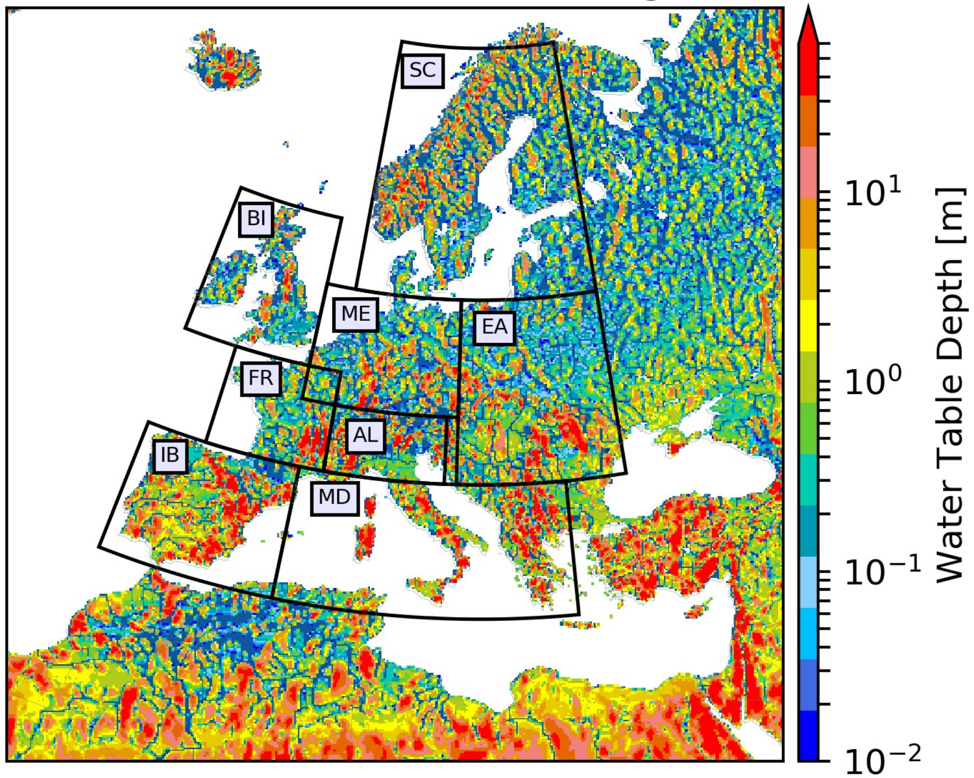
ERA-Interim driven TSMP evaluation run (with 3D ParFlow) 1996/01 to 2019/08

- Typical large scale patterns (coastal plains, mountains, etc.)
- River networks start to evolve
- Redistribution of surface and groundwater in continuum approach
- Surface runoff and subsurface hydrodynamics are linked
- Physically consistent with atmospheric forcing

Basis for assessment of weather and regional climate change impacts on groundwater

Towards actionable information

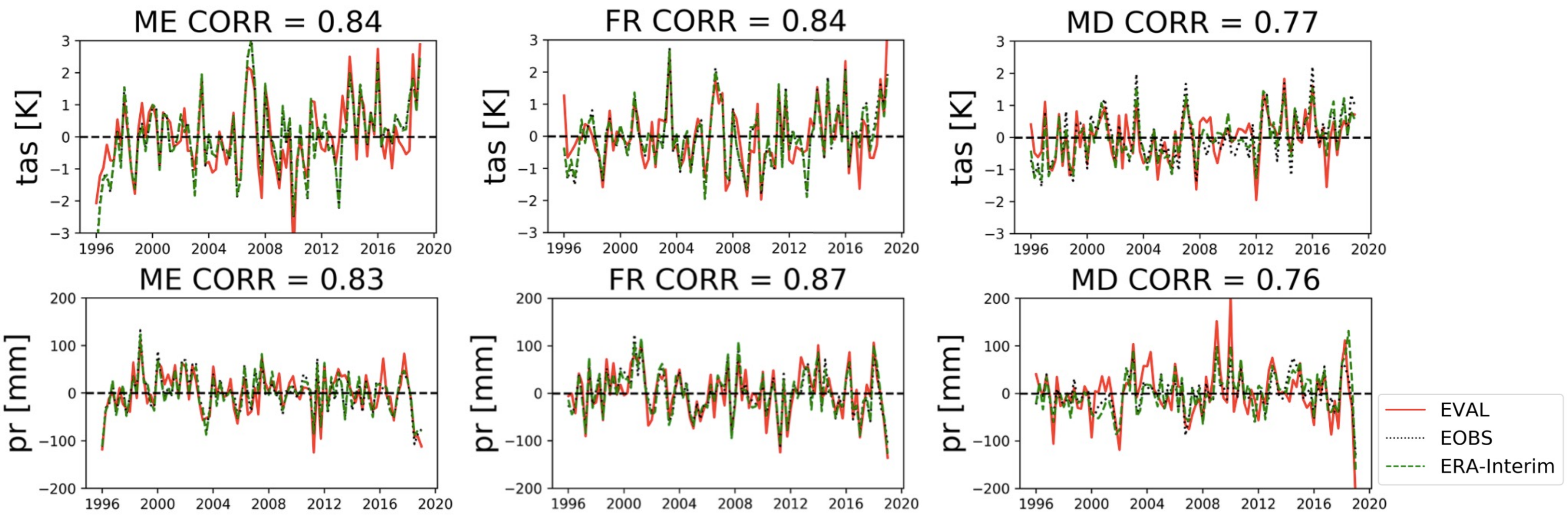
TSMP mean water table depth, 1996/Sep to 2018/Aug



Furusho-Percot et al. (2019, Sc Data)

Well represented interannual variability in TSMP evaluation run

TSMP seasonal precipitation and air temperature anomalies 1996-2018 wrt E-OBS v19 and ERA-Interim



Furusho-Percot et al. (2019, Sc Data)

Representation of the terrestrial system without human water use (e.g., Keune et al., 2018, GRL)

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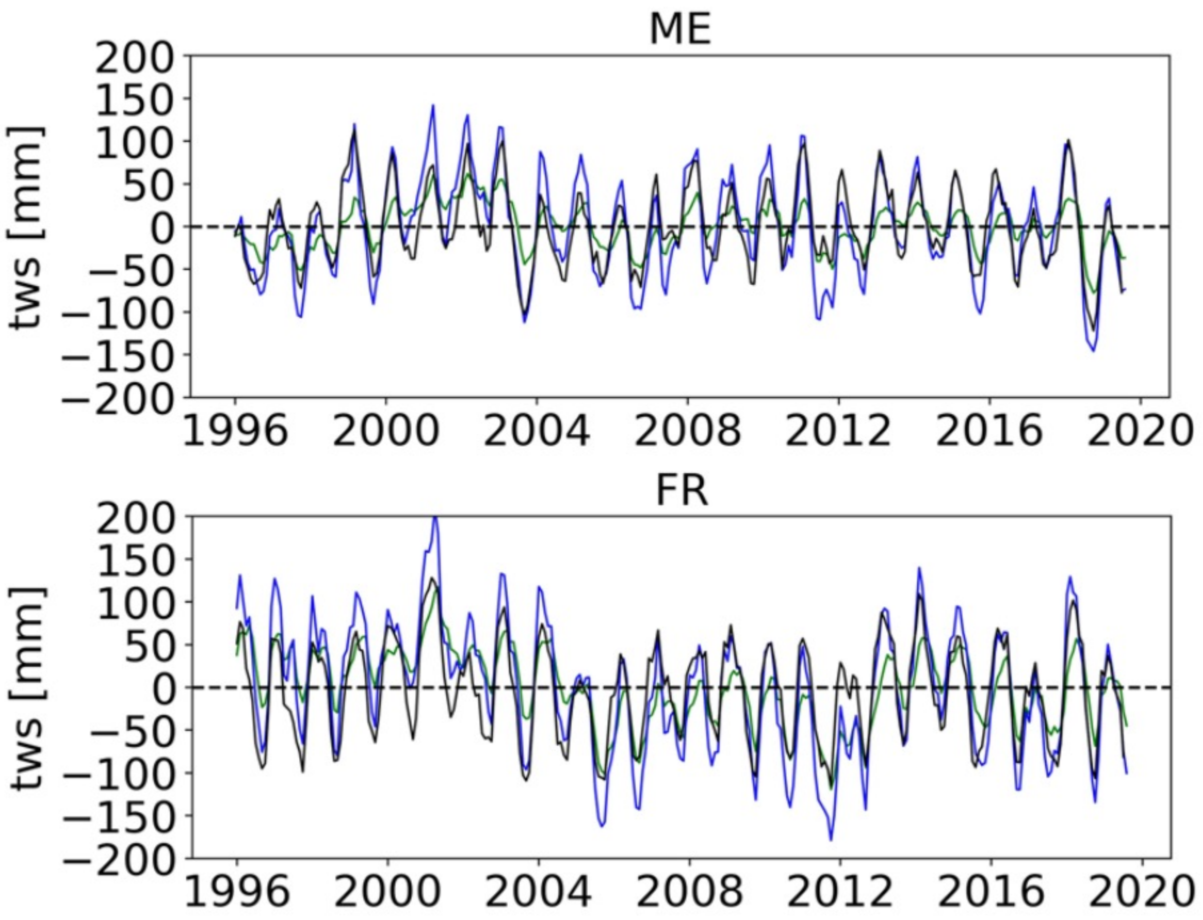
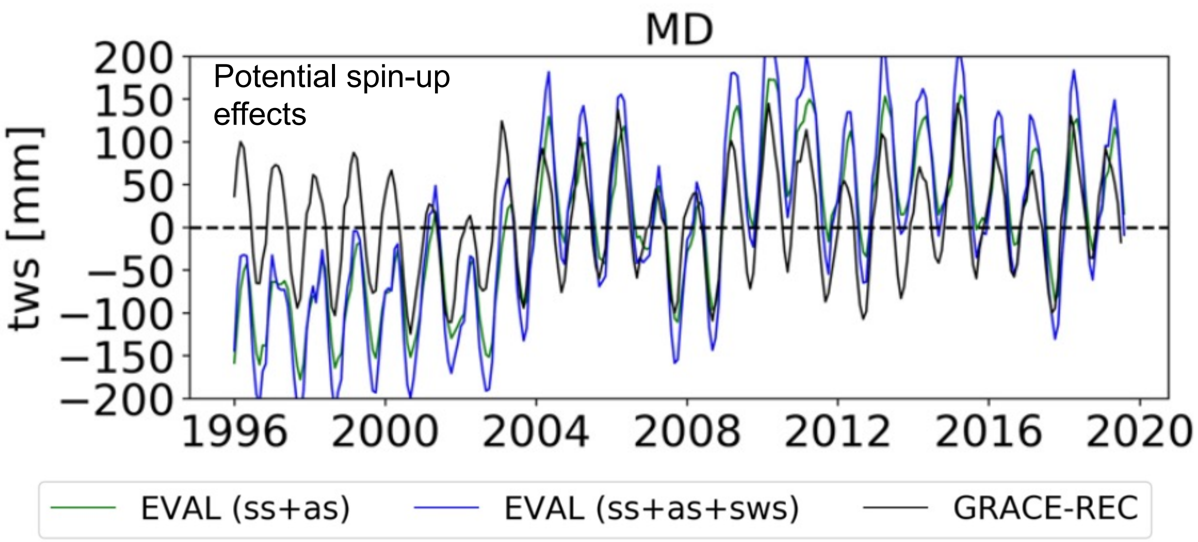
Water storage variability over Prudence regions reproduced

TSMP monthly total column water storage, deviation from mean, 1996-2019 wrt GRACE-REC dataset





soil storage, aquifer storage, surface water storage

$$s_{i,j} = \sum_{k}^{nz} sat_{i,j,k} \, por_{i,j,k} \, dz \, k$$

Hartick et al. (2021, WRR)

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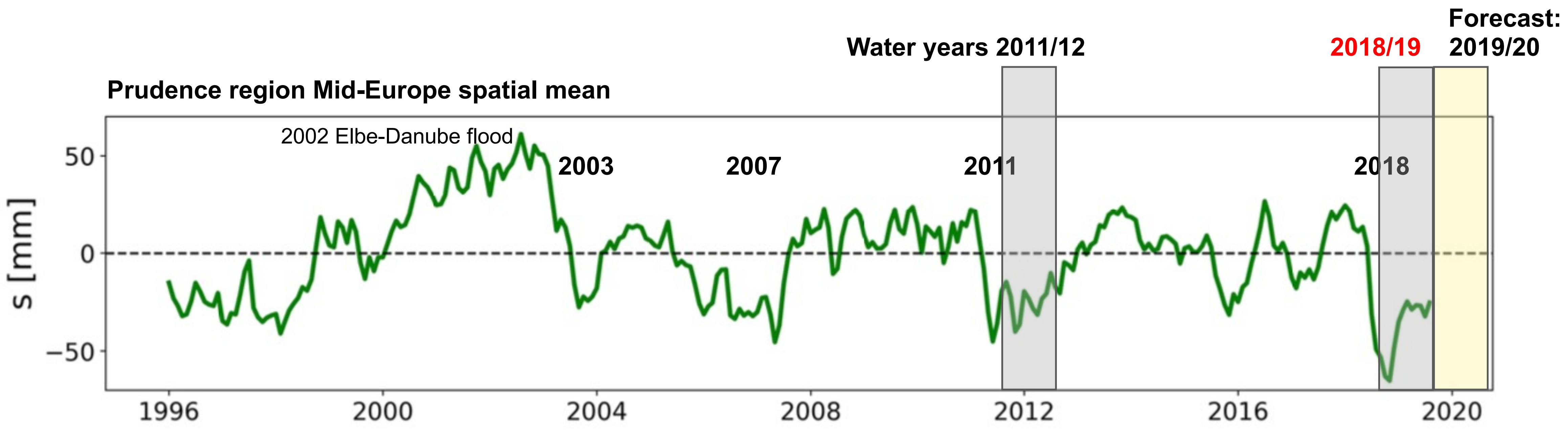
Hydroclimatic extremes

Monthly column water storage anomalies 1996/Jan to 2019/Aug from TSMP groundwater climatology



Main drought and water scarcity events are captured
Drought as strong anomaly in subsurface water storage wrt climatology

Hartick et al. (2021, WRR)

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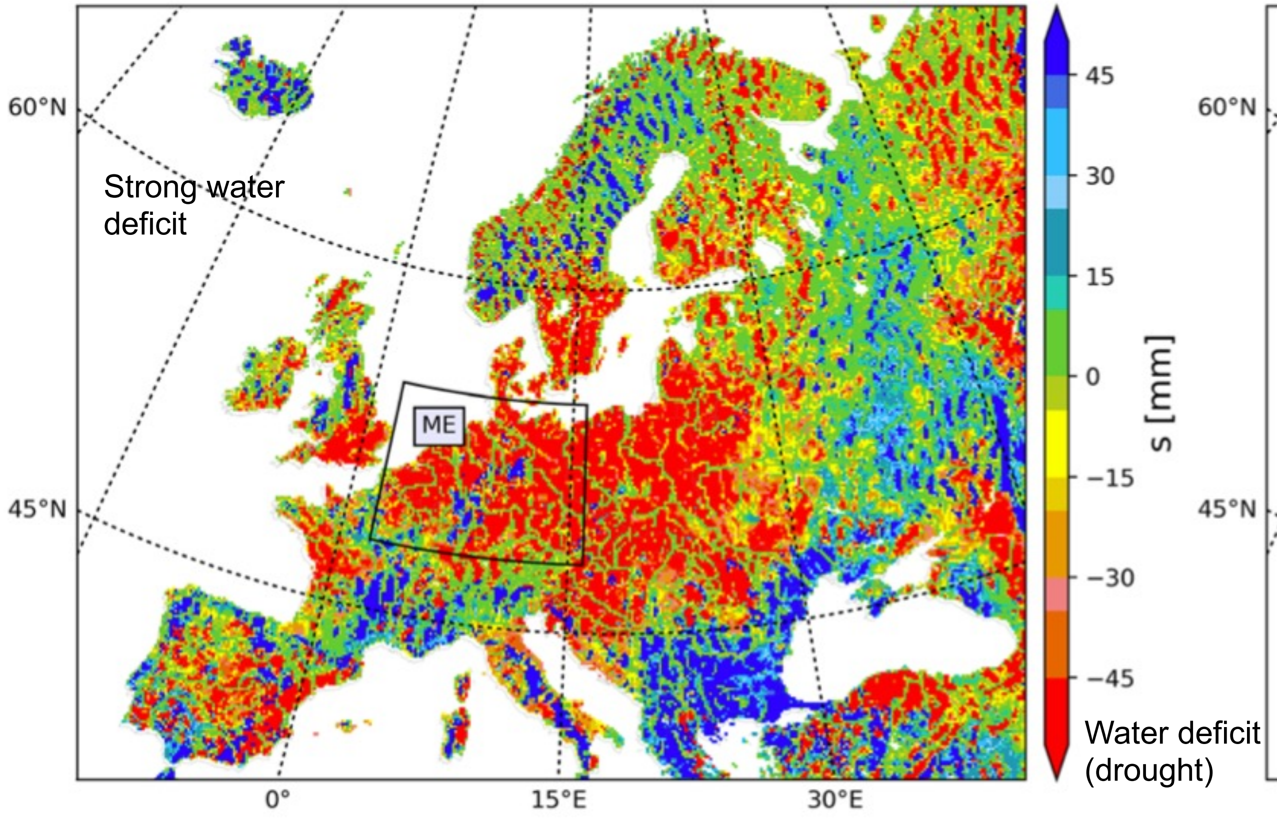
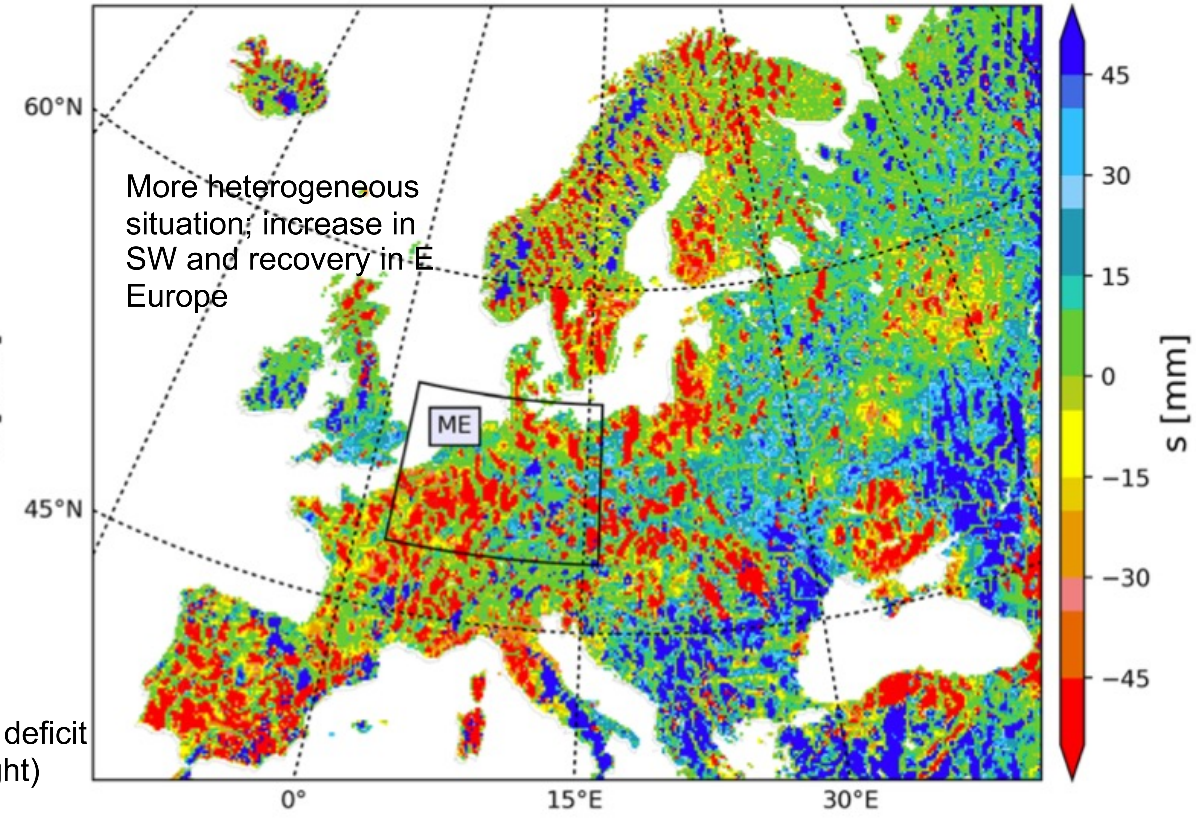
Hydroclimatic extremes

https://datapub.fz-juelich.de/slts/

Subsurface monthly water storage anomalies, s, from TSMP groundwater climatology



August 2018



August 2019

Hartick et al. (2021, WRR)

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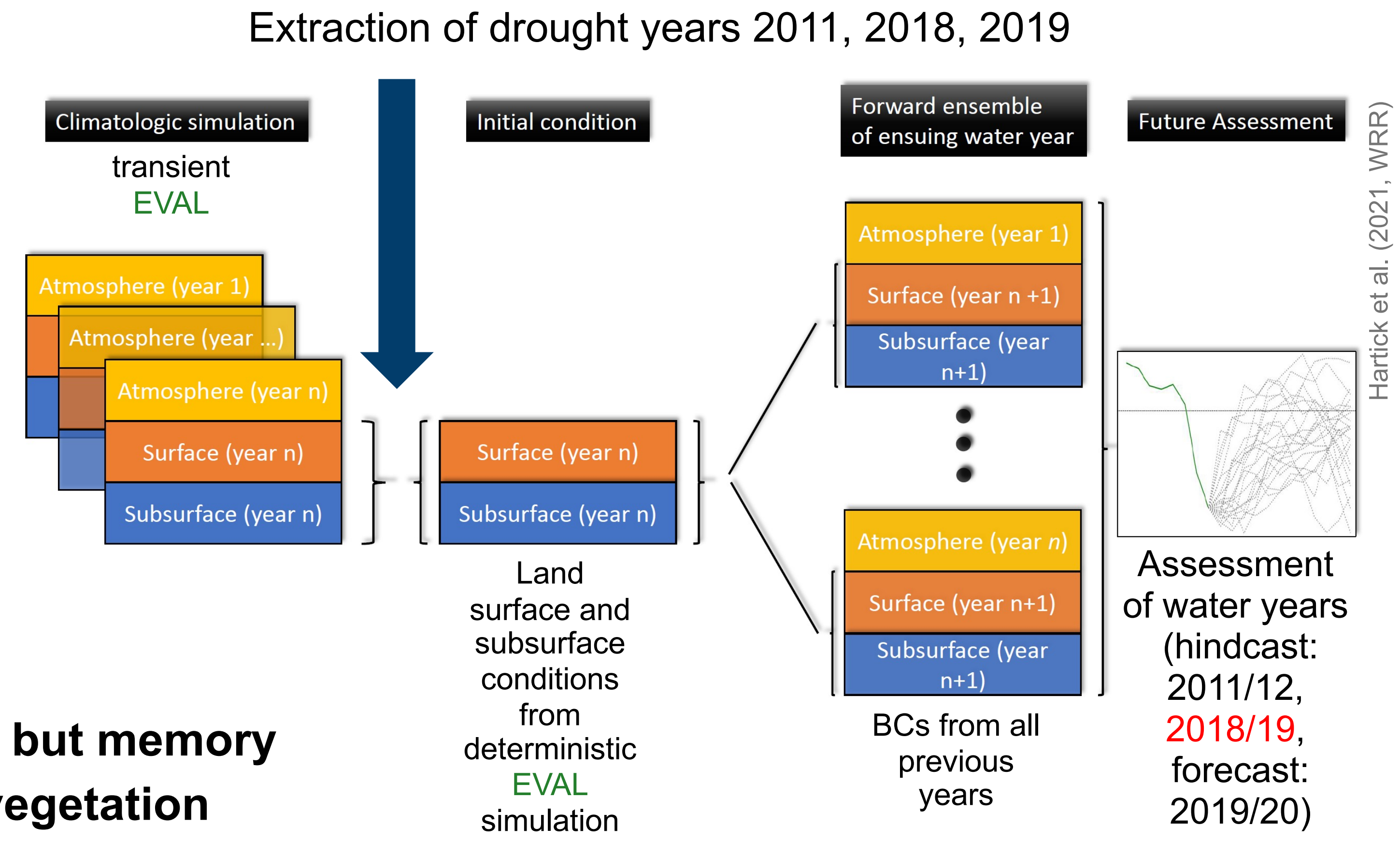
Interannual probabilistic subsurface water assessment, method

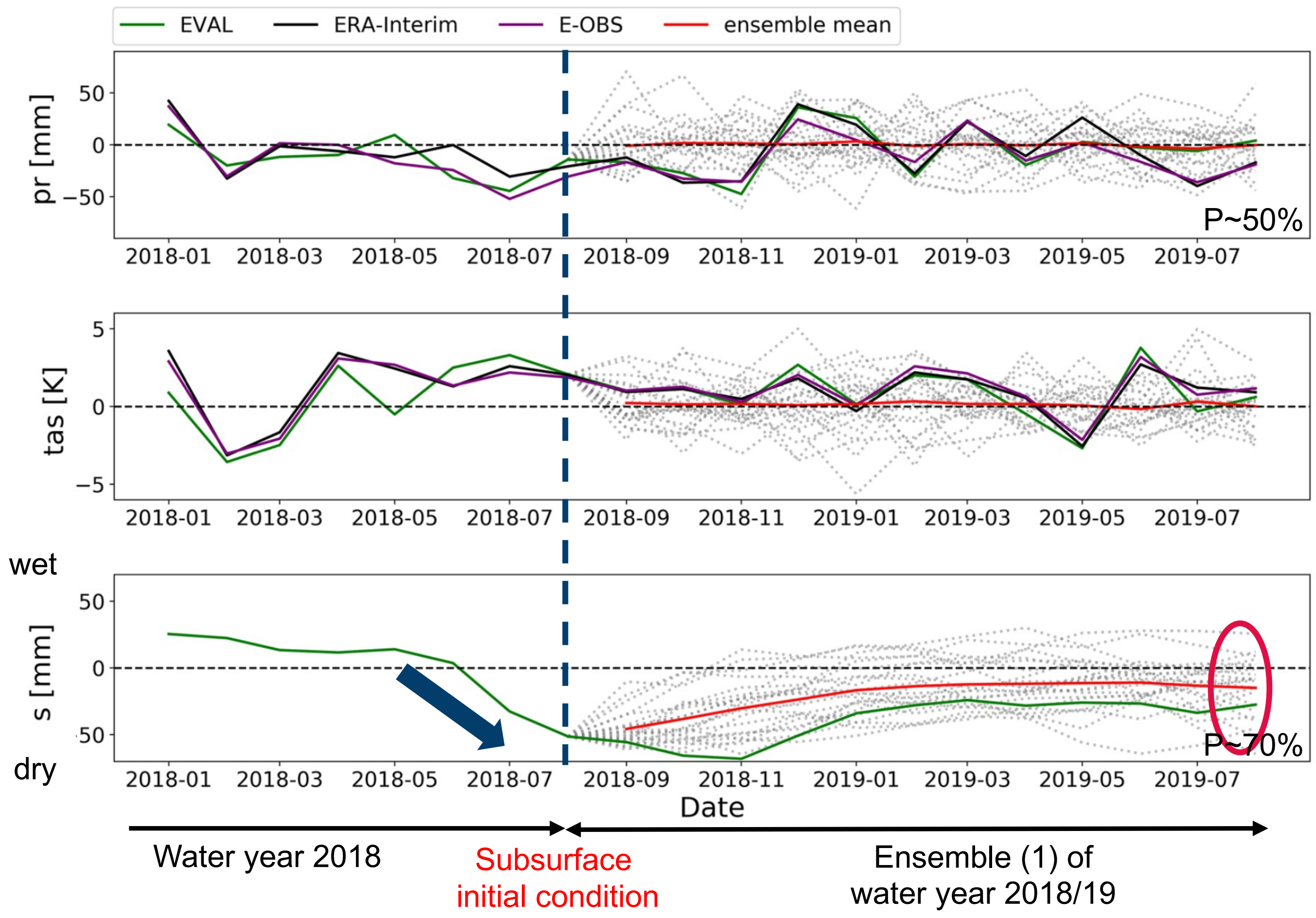
What is the impact of meteorological conditions on water resources in subsequent water years?

- Approach
  - Use last day of the water year as initial condition: e.g., 2018-08-31
  - Simulate 2018/19 water year, with atmospheric conditions from all preceding years (climatologic ensemble) to produce a "probabilistic" forecast, accounting for uncertainty and natural variability
  - Inspection of forecasted probabilities of water storage anomalies
- Rationale: **Uncertain atmospheric forcing, but memory effects due to slow dynamics in gw-soil-vegetation system: initial value problem**



Hindsight assessment of water year 2018/Sep-2019/Aug, ME

Impact of memory effects of subsurface hydrodynamics on the evolution of water storage anomalies



- Heat wave with positive temperature and negative precipitation anomalies
- Evolution of dry (negative) subsurface water storage anomaly, s
- Stabilisation of s towards August 2019, s_mean=-15mm, s_SD=22mm
- Reduction of dry anomaly with most ensemble members, but Weibull probability estimation P~70% for continuing water deficit (P_pr~50%)
- Severe drought 2018: EVAL s=-28mm 08/2019 → continuously dry conditions

Hartick et al. (2021, WRR)

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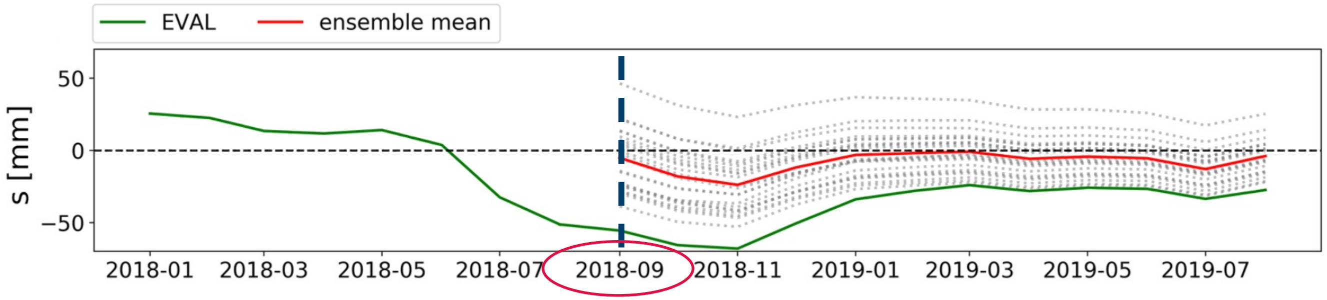
Hindsight assessment of water year 2018/Sep-2019/Aug, ME

Impact of memory effects of subsurface hydrodynamics on the evolution of water storage anomalies

What is the impact of the initial condition, memory effect?

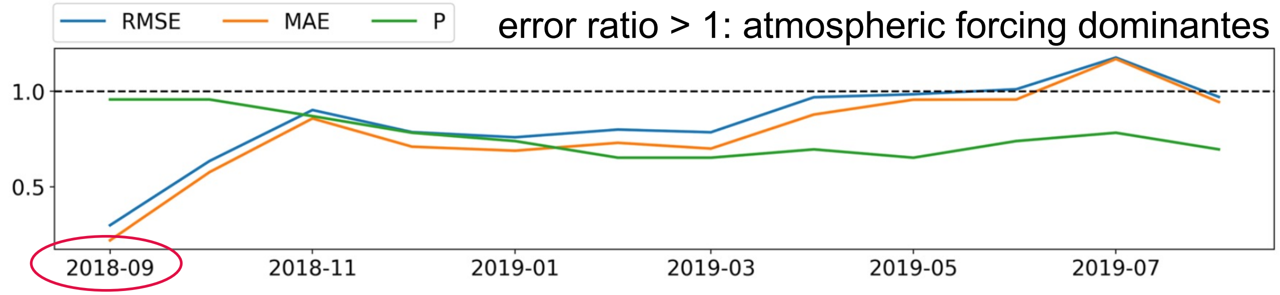


Reverse ensemble assessment

- 2nd ensemble (2): All available initial conditions driven with atmospheric forcing of 2018/19 (EVAL), ParFlow/CLM only
- Convergence of ensemble members; spread reduces by 55%

Relative influence of initial condition vs atmospheric forcing on predictability? → anomaly strength

error ratio > 1: atmospheric forcing dominantes



error ratio < 1: initial condition dominates

Hartick et al. (2021, WRR)

Ensembles error ratios of s

- MAE of each ensemble to EVAL
  RMSE of each ensemble
- error ratio = error of assessment ens. (1) / error of reverse assessment ens. (2)
- **Initial condition more important than forcing**

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Summary and conclusions

Bridge gap between hydrology and meteorology; exploration of feedback pathways and machanisms

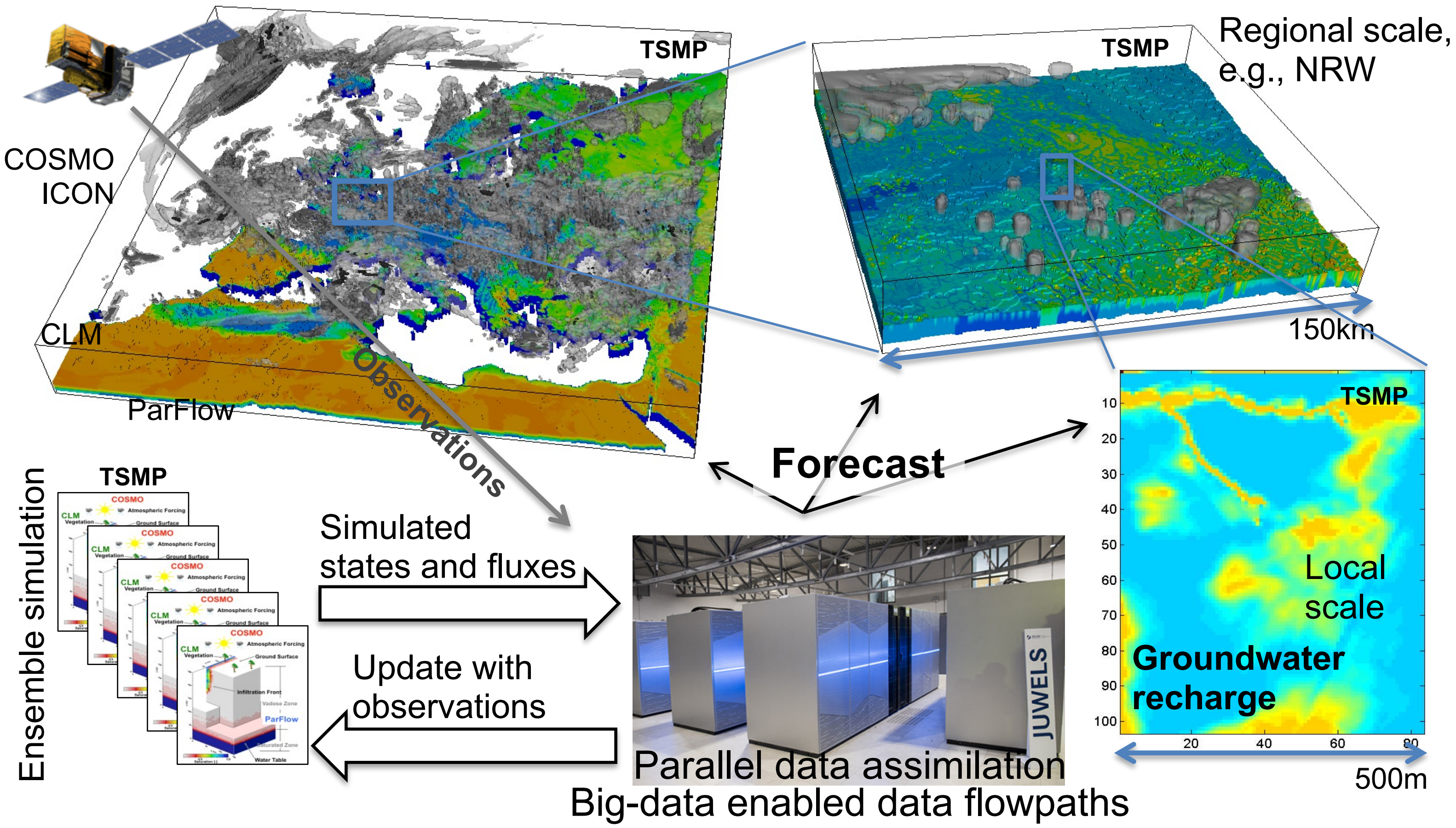
- COSMO+CLM+ParFlow **(TSMP)** allows to simulate **states** and **fluxes** of the **terrestrial water** and **energy cycle**
- **Shallow water tables** simulated with a physics-based gw model can **alleviate temperature extremes** by 1°C
- **Groundwater processes** may play a **crucial** role for climate and the **evolution of heatwaves** and **droughts**

- “Natural” **groundwater climatology** consistent with the atmospheric forcing generated by TSMP for **Europe**
- Good representation of spatio-temporal variability of interannual anomalies wrt observations and reanalysis
- **Baseline dataset** to **assess hydro-climatic extremes** and the **impact of human water use**

- **Water scarcity** and **droughts** are **detectable** and **predictable** (towards real-world resources applications)
- **Increased probability for water deficit in regions with strong previous year deficit**, predictability up 8 months
- Models need to account for **long-term memory effects** in terrestrial water cycle over large spatial scales

Ongoing and outlook: Longer EVAL run w/ ERA-5; TSMP in CLMcom EURO-CORDEX CMIP6 downscaling

Our concept of a fully coupled terrestrial monitoring system



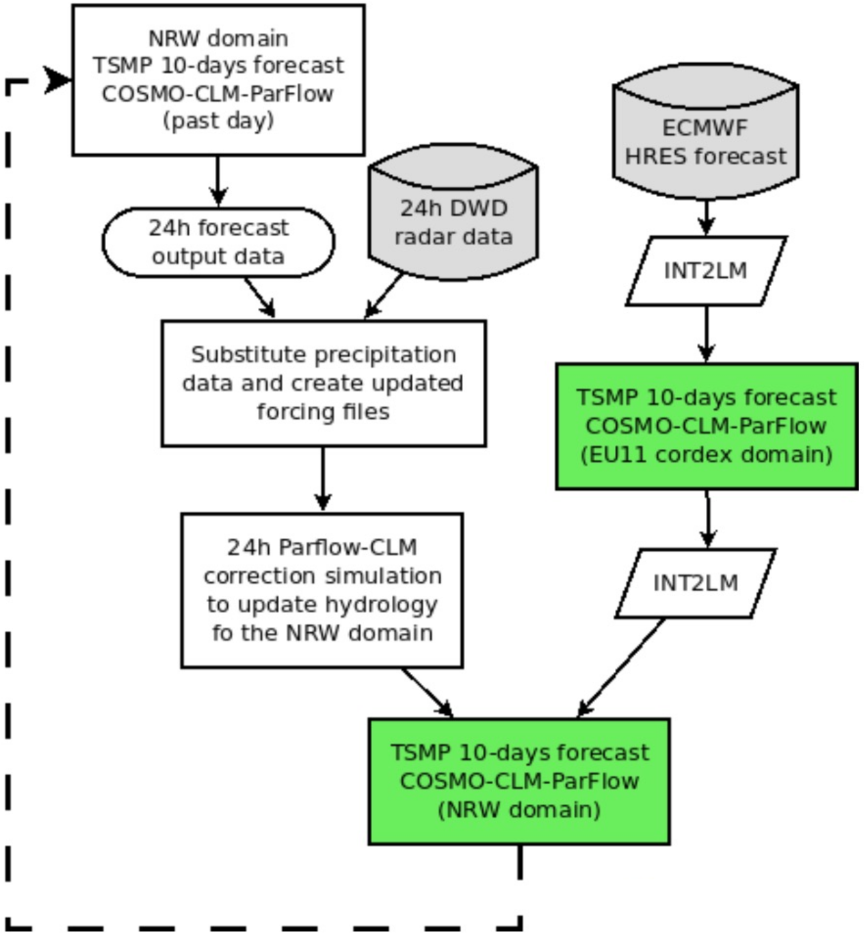
See, e.g., Kollet et al. (2018, Water)

TSMP-M(onitoring)

Daily deterministic simulations, schematic workflow at Jülich Supercomputing Centre

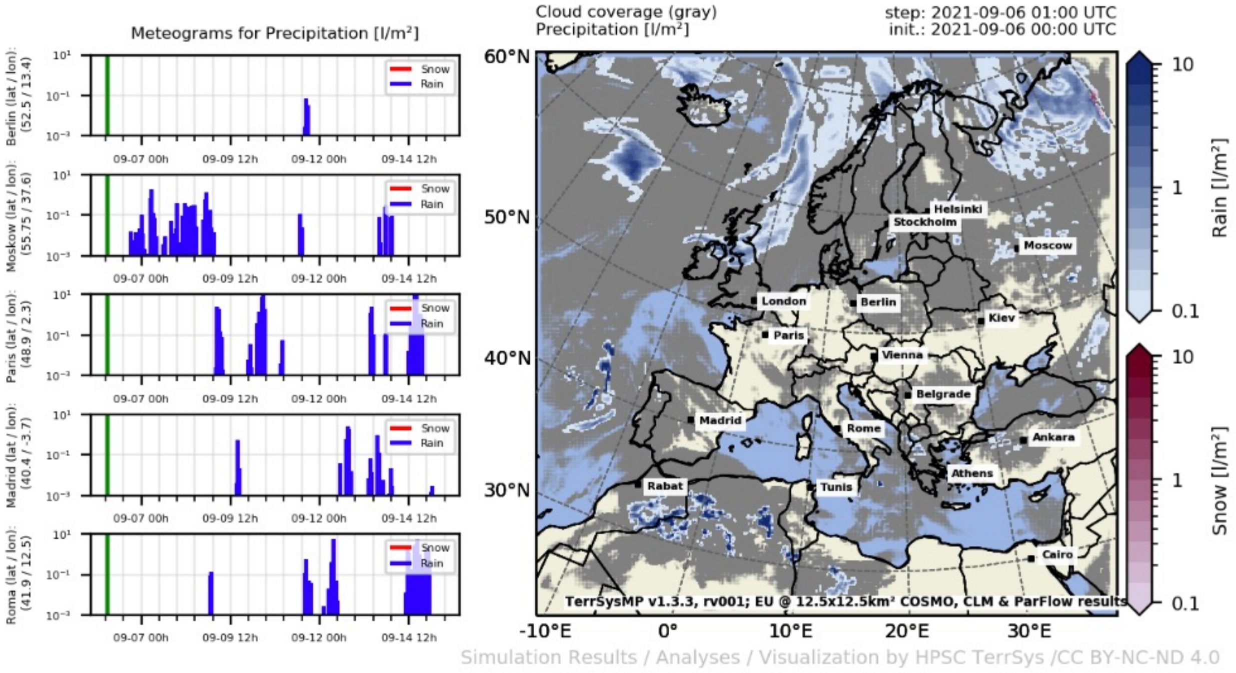
1. 10-days European forecast driven by ECMWF-forecast;
2. DWD (German Meteorological Service) precipitation radar data used for a short 24 hours TSMP simulation that is aimed on updating soil moisture data in the model ("correction" simulation);
3. 10-days forecast over NRW domain based on EU-forecast and correction simulation.

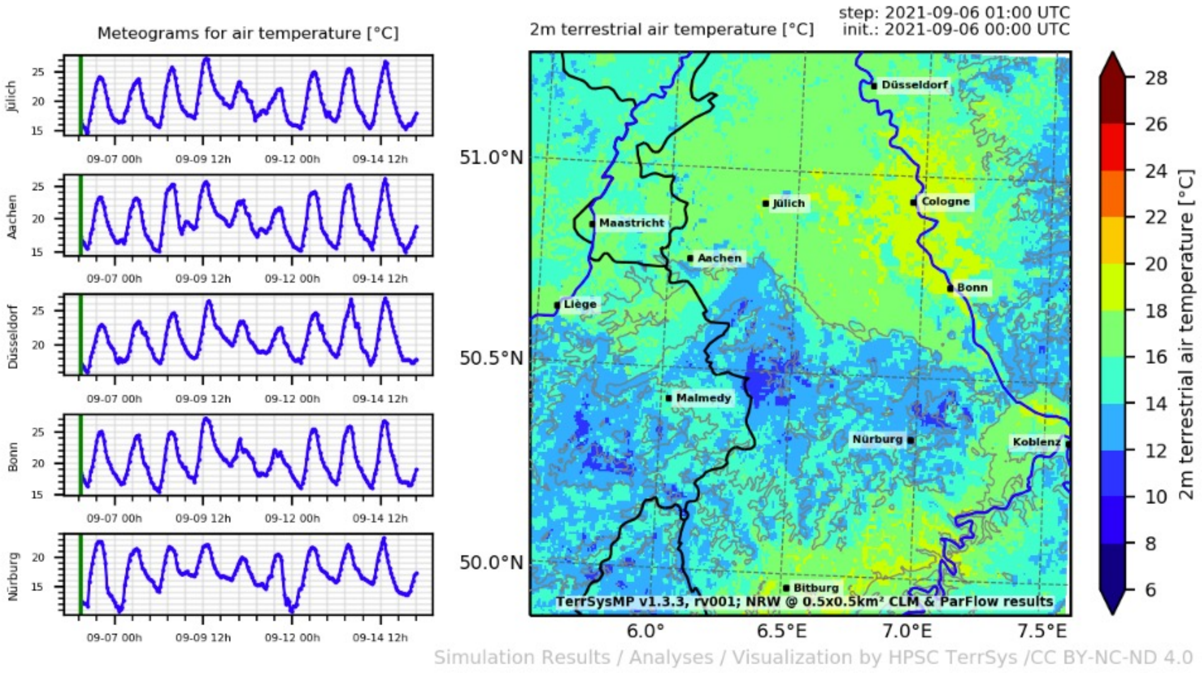
Outputs available at:
`www.terrsysmp.org/forecast/index.html`



TSMP-M(onitoring)

https://www.terrsysmp.org/forecast/index.html





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