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

2019-10-16 I **K. Goergen[1,2], C. Furusho-Percot[1,2], C.Hartick[1,2], J. Keune[1,2,*], M. Eltahan[1,2], S. Kollet[1,2]**

[1]Institute of Bio-Geosciences (IBG-3, Agrosphere), Research Centre Jülich, Jülich, Germany

[2]Centre for High-Performance Scientific Computing in Terrestrial Systems, Geoverbund ABC/J, Jülich, Germany

[*]Now at Department of Environment, Ghent University, Belgium

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HPSC TerrSys

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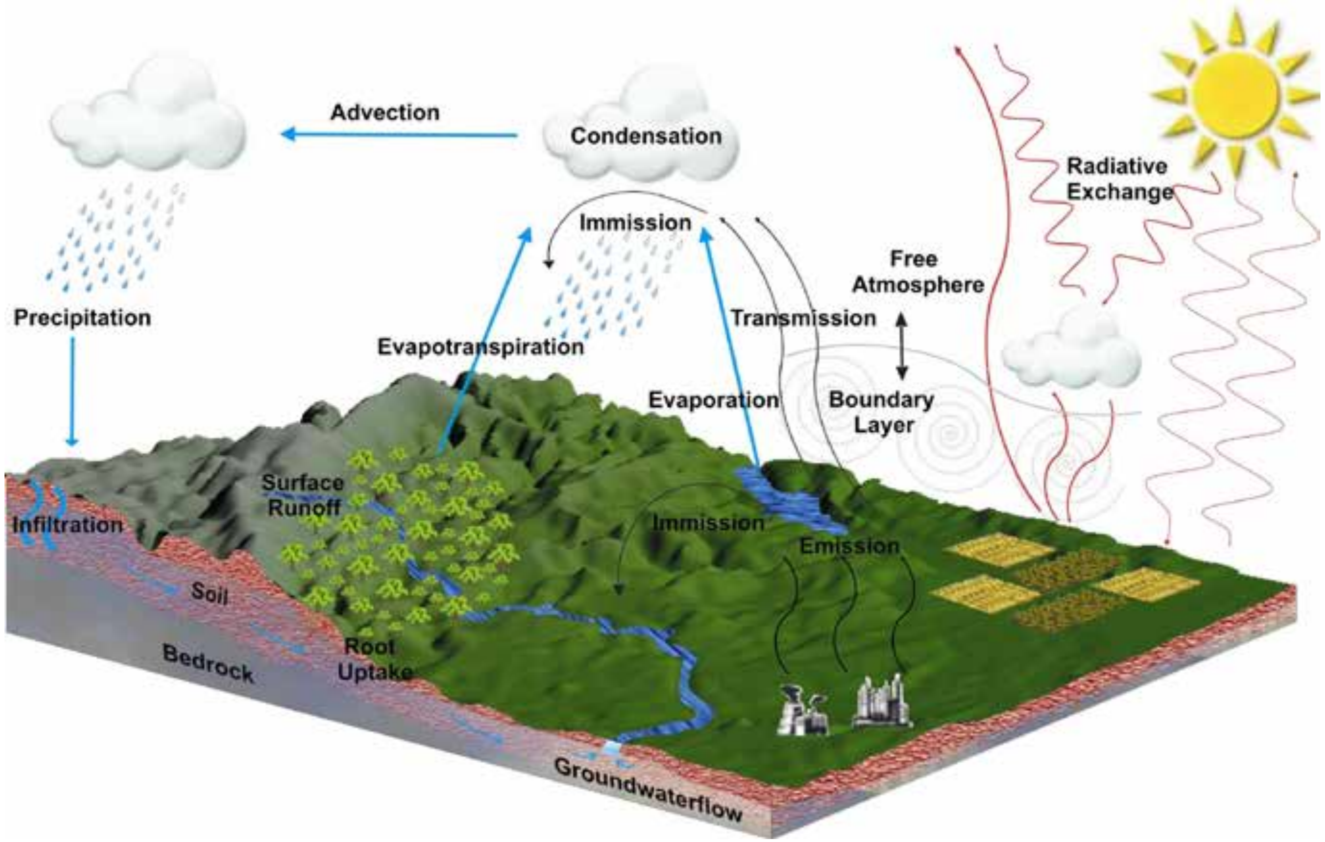
The terrestrial system

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: Do not include or highly simplify groundwater
  - Hydrological models: Usually simplify surface-subsurface interactions and neglect two-way feedbacks with the atmosphere: terrestrial water cycle not closed

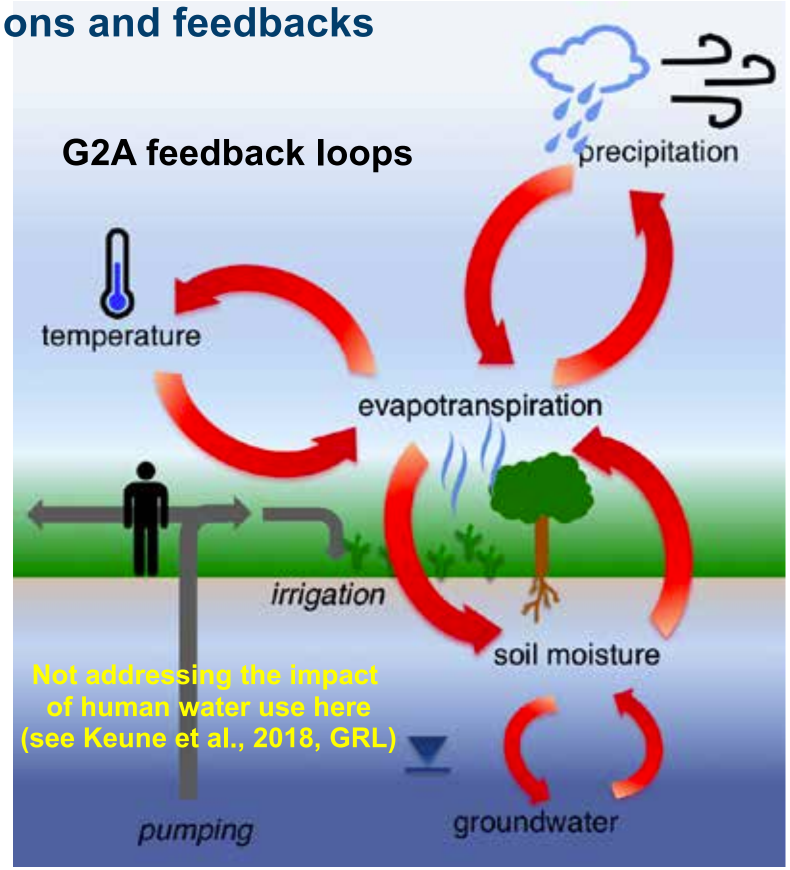
- <u>In addition:</u> **Human water use** has multiple local and non-local (climatic) effects (groundwater recharge/storage, discharge, ET/P recycling, etc.) … not addressed today

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** (here: drought 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)

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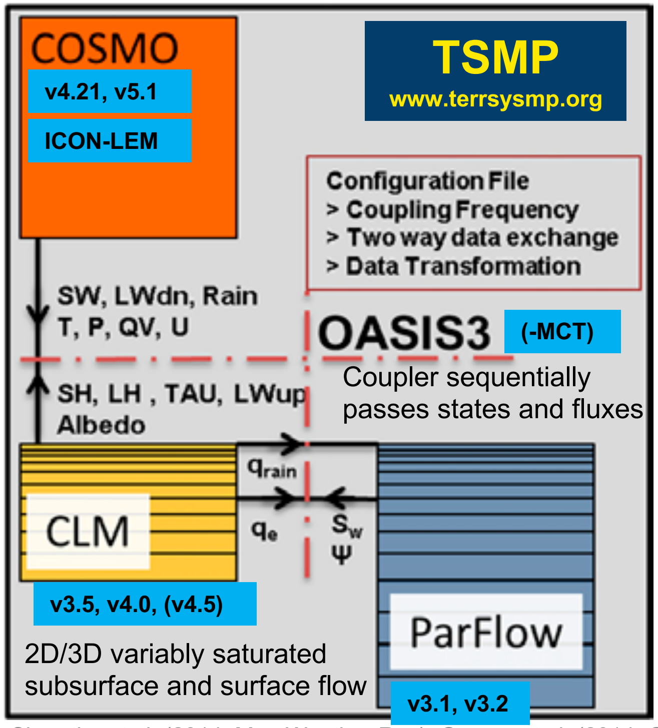
Terrestrial Systems Modelling Platform (TSMP) model system

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

- 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)

Towards a holistic representation of complex interactions among the compartments in the geo-ecosystem



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

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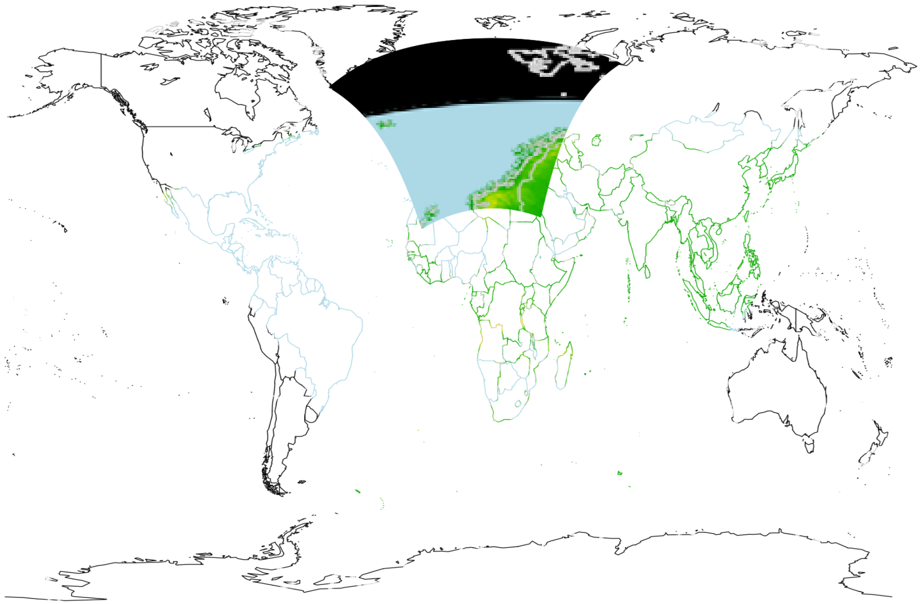
TSMP pan-European model setup

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

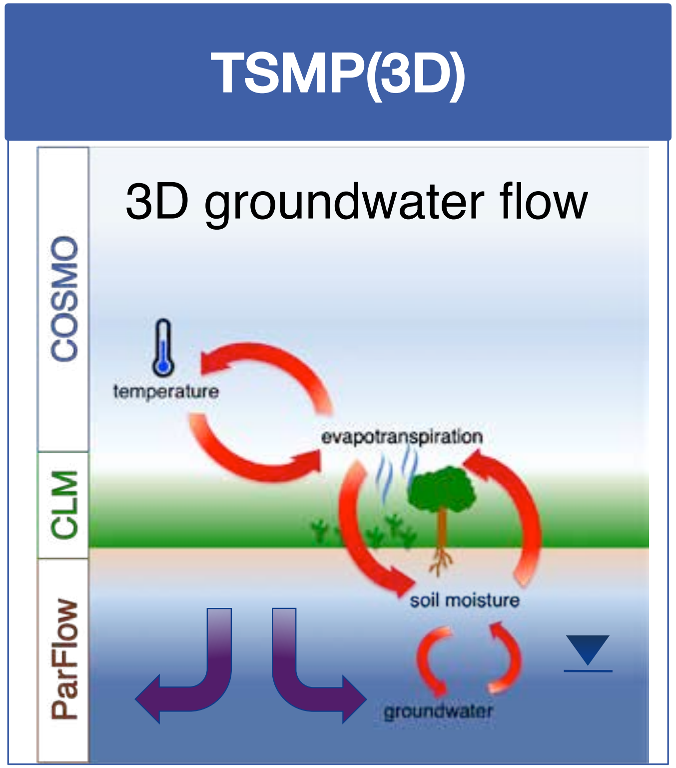


- CORDEX EUR-11 Gutowski et al. (2016, GMD)
  - Resolution: 0.11° (about 12km), 436 x 424 gridpoints
  - Vertical levels: 50 (COSMO), 10 (CLM), 15 (ParFlow)
  - Time steps: 60s (COSMO), 180s (CLM), 180s (ParFlow)
- Input data Keune et al. (2016, JGR)
  - Atmosphere: ERA-Interim
  - Land surface: MODIS data (4 plant functional types / grid cell)
  - Subsurface: FAO soil types (and Gleeson 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, 1996-2018 analysis, pristine conditions Furusho-Percot et al. (revision)
  3. **Pobabilistic water resources prediction,** heatwave and drought 2018 impacts on 2018/19 Hartick et al. (revision)

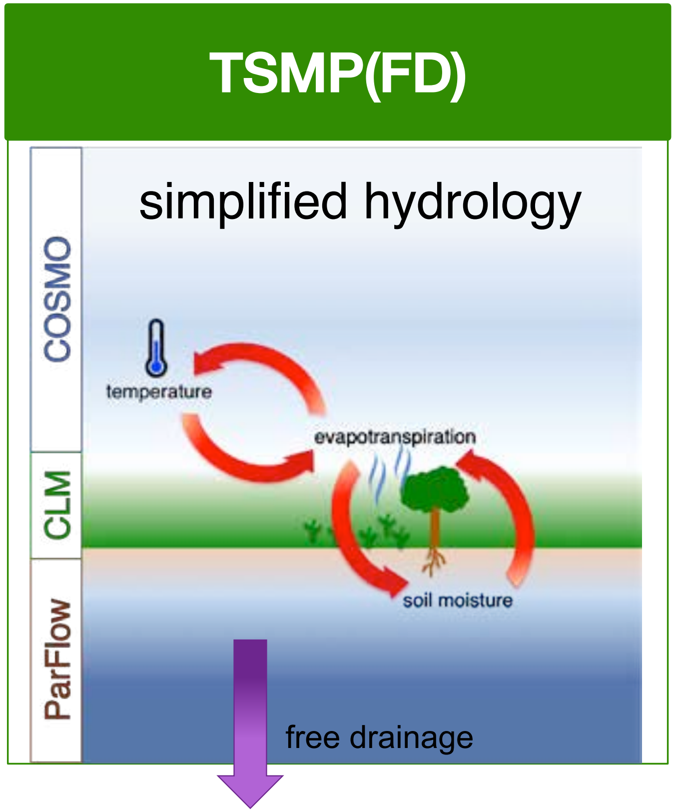
Impact on land-atmosphere (L-A) coupling

Impact of groundwater on soil moisture-temperature feedback? Test case summer 2003

- To which extent might groundwater alleviate extreme temperatures during droughts and heatwaves?
- Impact of groundwater representation in regional climate simulations
- Hypothesis: Groundwater dynamics have a significant impact on L-A coupling on continental scale; dual boundary layer concept



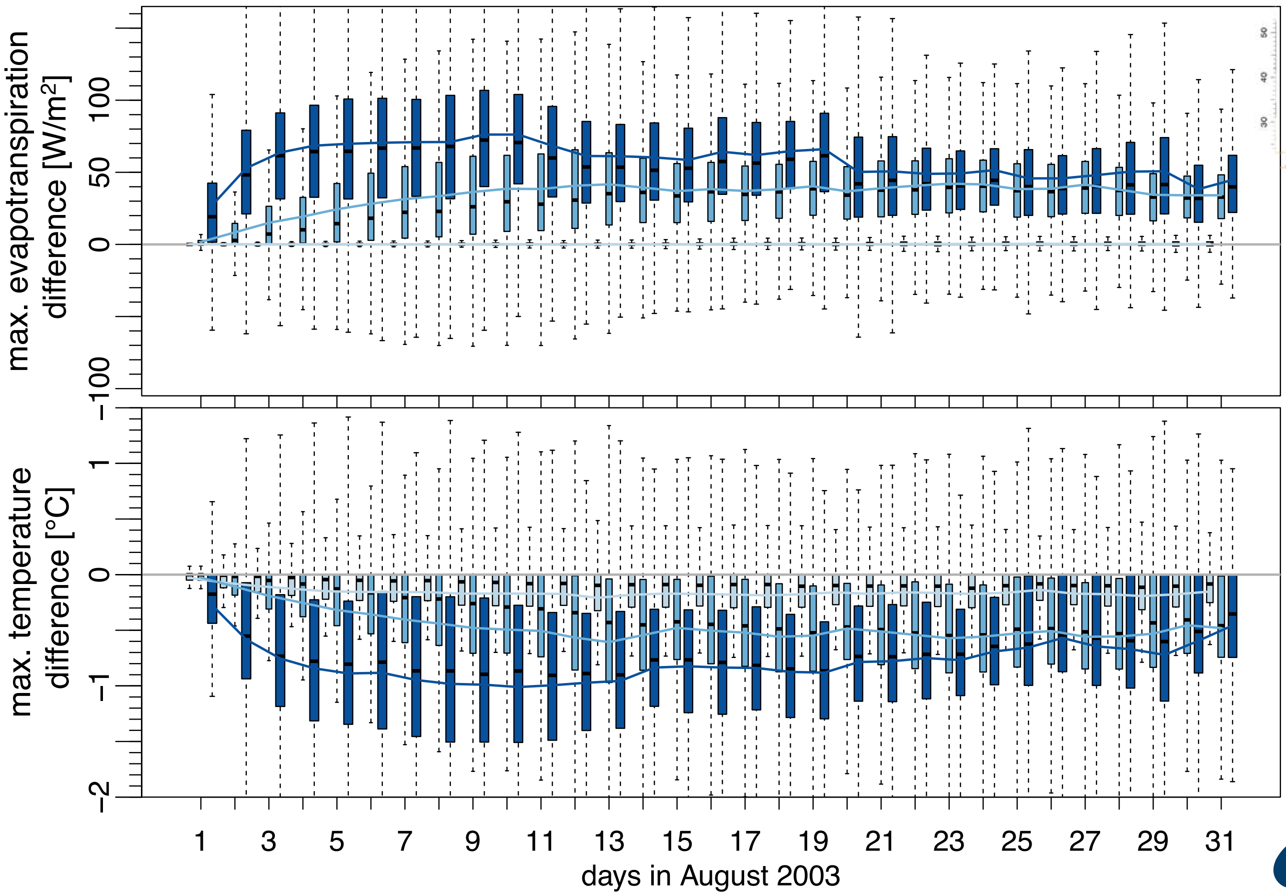
Courtesy J. Keune (2018)

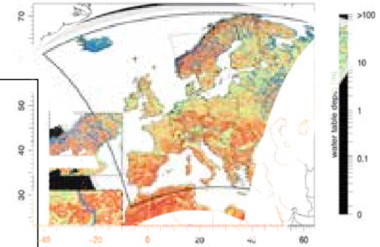


Groundwater-to-atmosphere feedbacks

△ = TerrSysMP(3D) – TerrSysMP(FD)

- Simulation of heatwave 2003 with 3D GW formulation and 1D free drainage; daily COSMO reinitialization, transient ParFlow+CLM
- Lower temperature / higher latent heat flux in 3D groundwater simulation; higher evaporative fraction





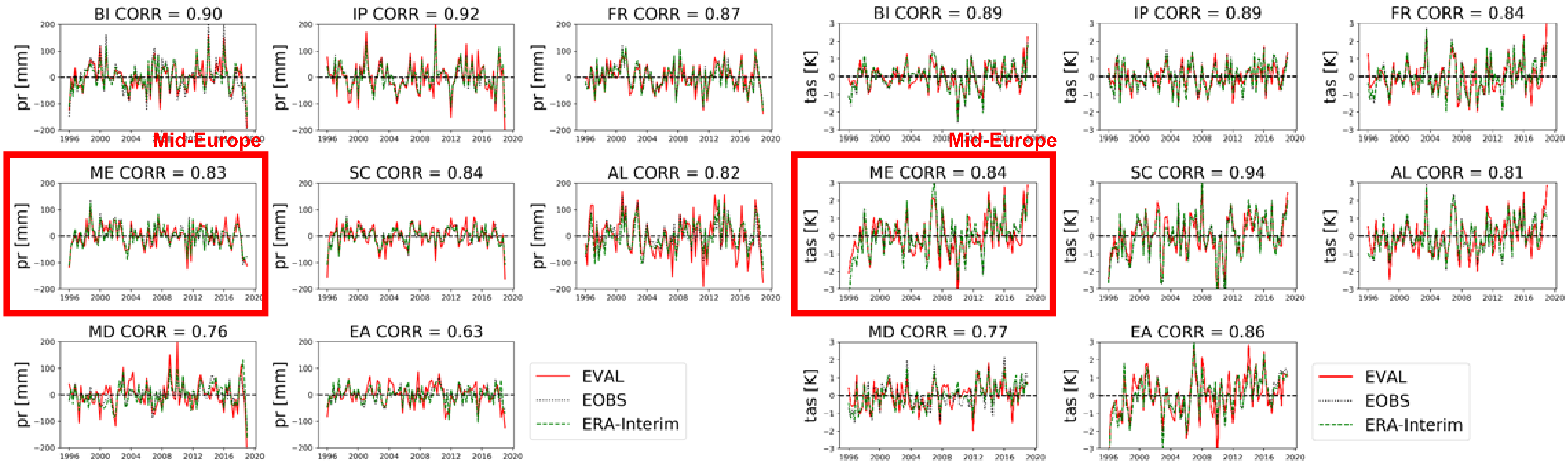
Complete focus domain

- **shallow WTD (<1m)**
- **medium WTD (1m<WTD<5m)**
- **deepWTD (>5m)**

Keune et al. (2016, JGR)

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. (under revision, Sc Data)

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

A “pristine” groundwater climatology, no human impacts

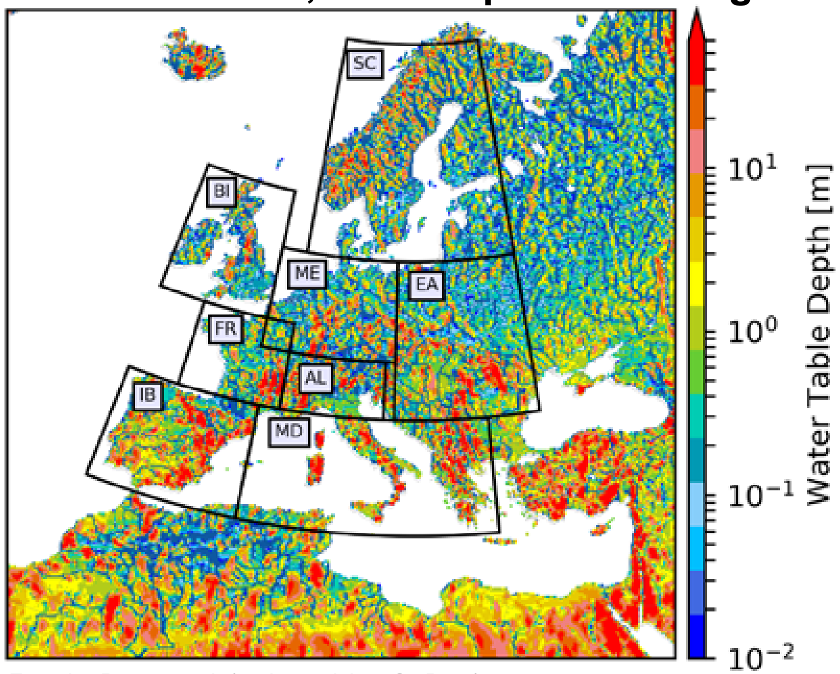
Simulated water table depth (WTD) with fully coupled TSMP (3D ParFlow)

- 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 WTD, 1996/Sep to 2018/Aug



Furusho-Percot et al. (under revision, Sc Data)

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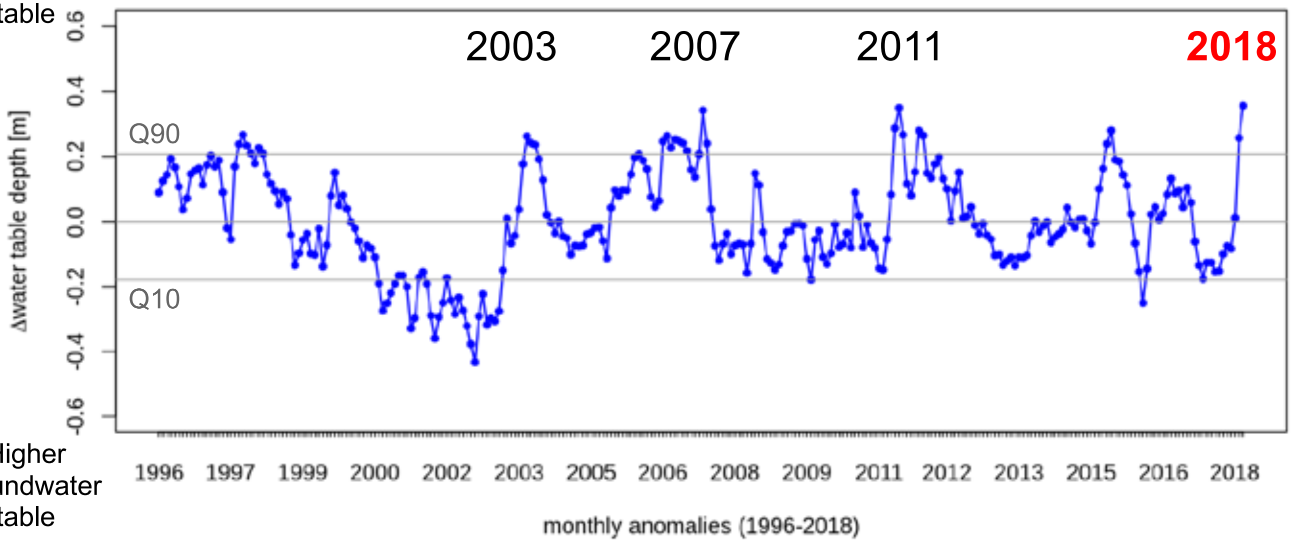
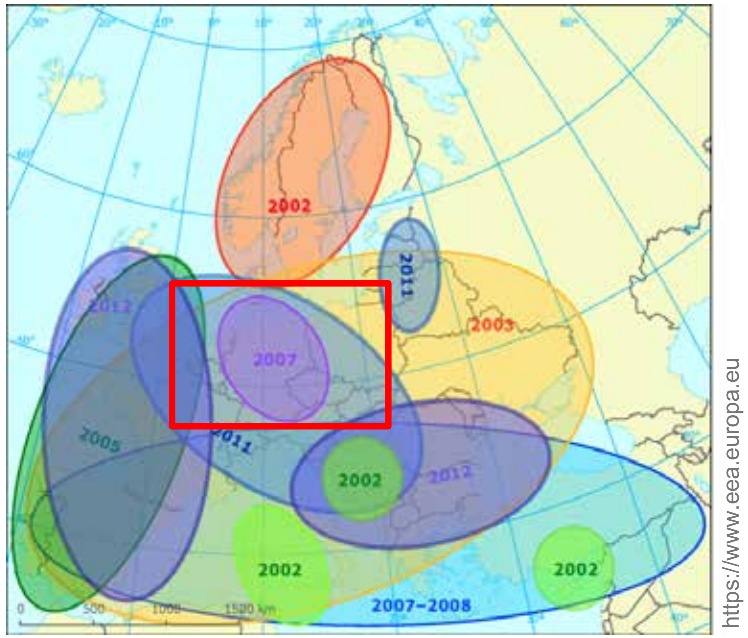
Hydroclimatic extremes

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

Water table depth, monthly anomalies January 1996 to August 2018, TSMP



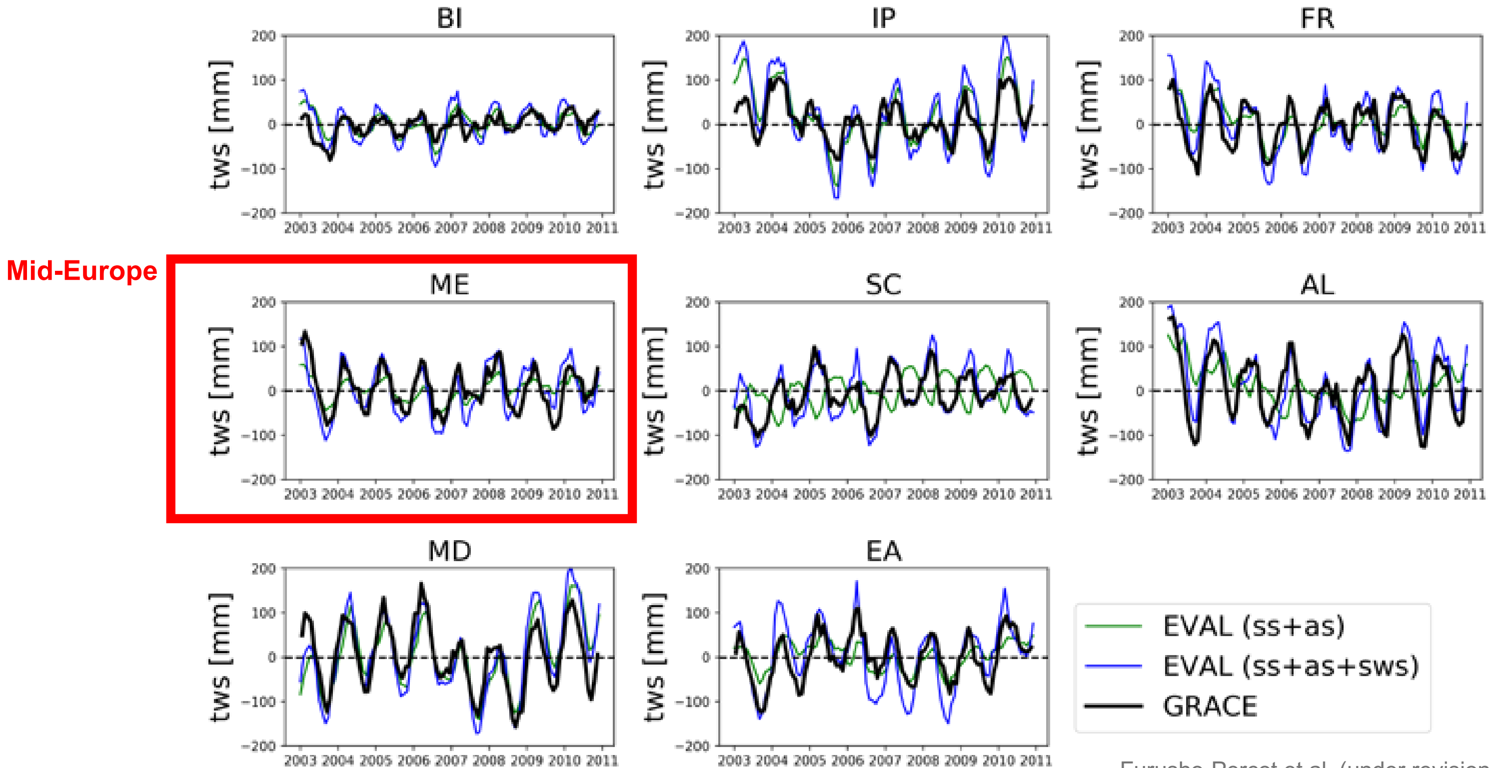
Furusho-Percot et al. (under revision, Sc Data)



Main drought and water scarcity events between 2002 and 2011

Water storage variability over Mid-Europe reproduced

TSMP monthly total column water storage, deviation from mean, 2003-2011 wrt GRACE mascon



$$_{i,j} = \sum_{k}^{nz} sat_{i,j,k}\, por_{i,j,k}\, dz_k$$

Furusho-Percot et al. (under revision, Sc Data)

Prediction of future conditions: The year 2019

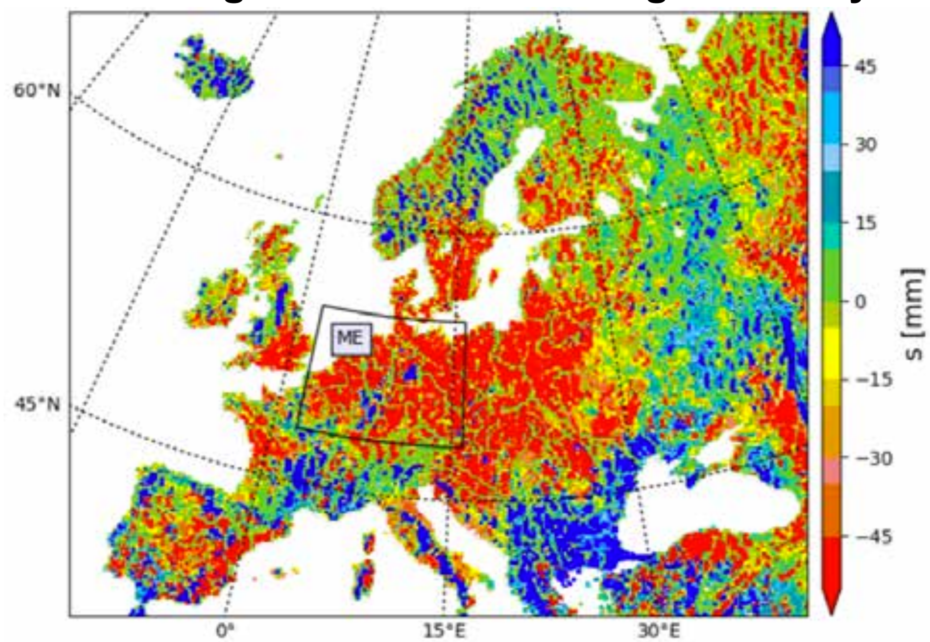
What is the impact of the 2018 central European meteorological conditions on water resources in 2019?

- Challenge

  Extremely uncertain seasonal precipitation forecasts

- Approach
  - Use last day of the water year as initial condition: 2018-08-31
  - Simulate 2019, with atmospheric conditions from all preceding years to produce a "probabilistic" forecast covering the "full" uncertainty range
  - Inspection of forecasted probabilities of water storage anomalies

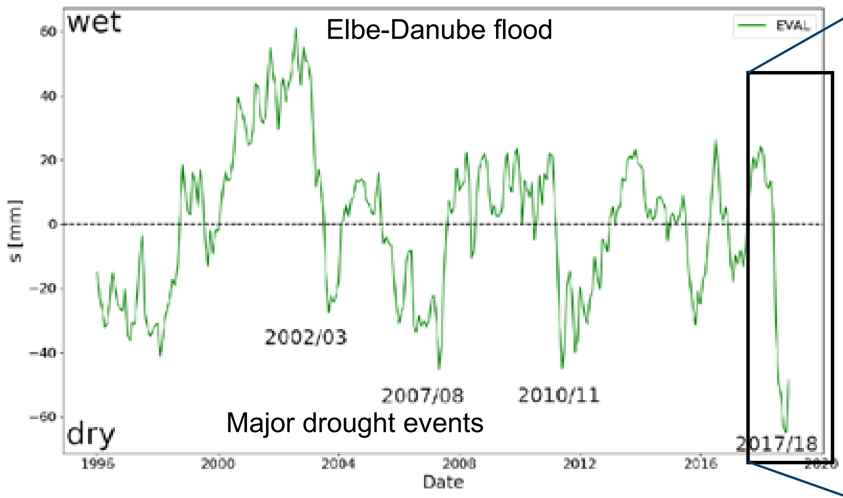
TSMP August 2018 water storage anomaly



Hartick et al. (under revision)

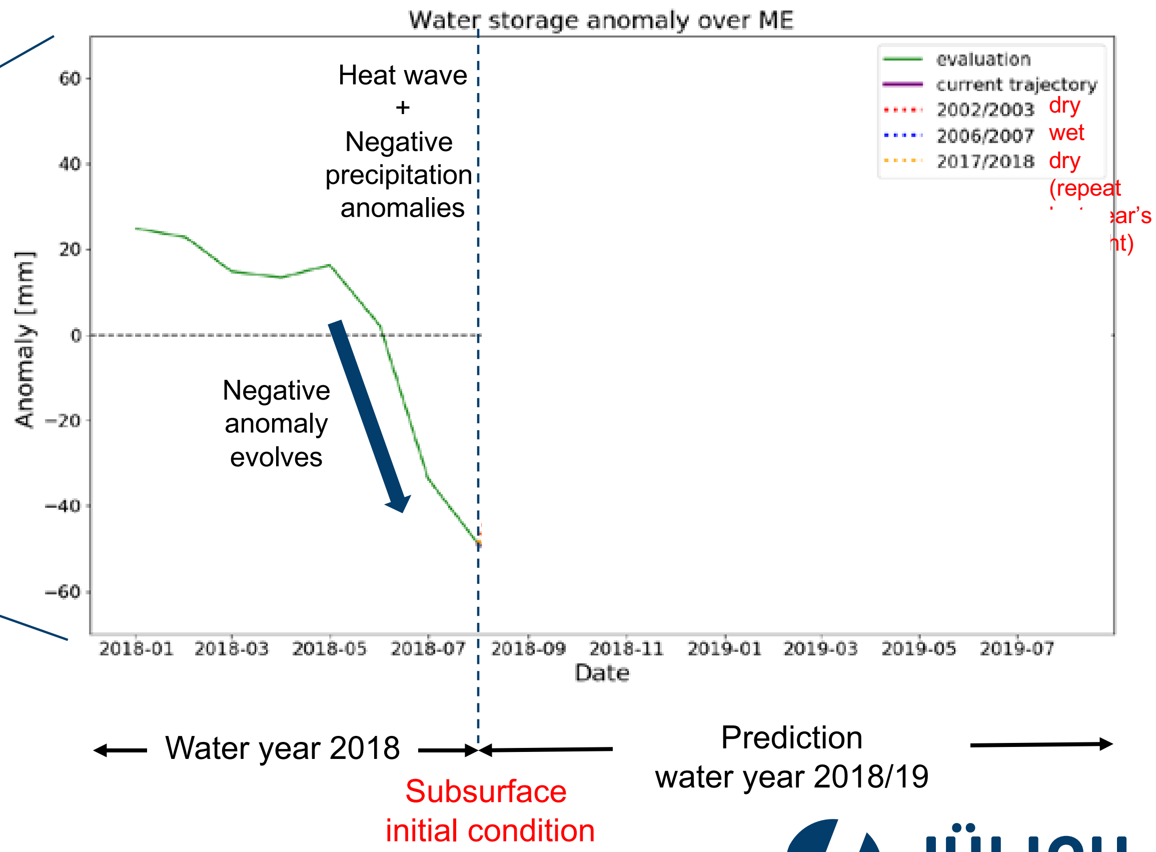
Probabilistic forecast of water year 2018/19 (Sep-Aug)

Most ensemble members reduce the dry anomaly, but negative anomalies prevail, drought might continue



TSMP water storage anomalies, ME

Hartick et al. (under revision)



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Summary and conclusions

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

- **TSMP** allows to simulate **all 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)**
- **Ensemble forecast** indicates a high probability of a **very dry water year 2018/19** over Central Europe

Outlook / Ongoing: TSMP regional climate change projections; human water use, convection permitting resolution, improved input datasets; integrated modelling for monitoring and forecasting water resources

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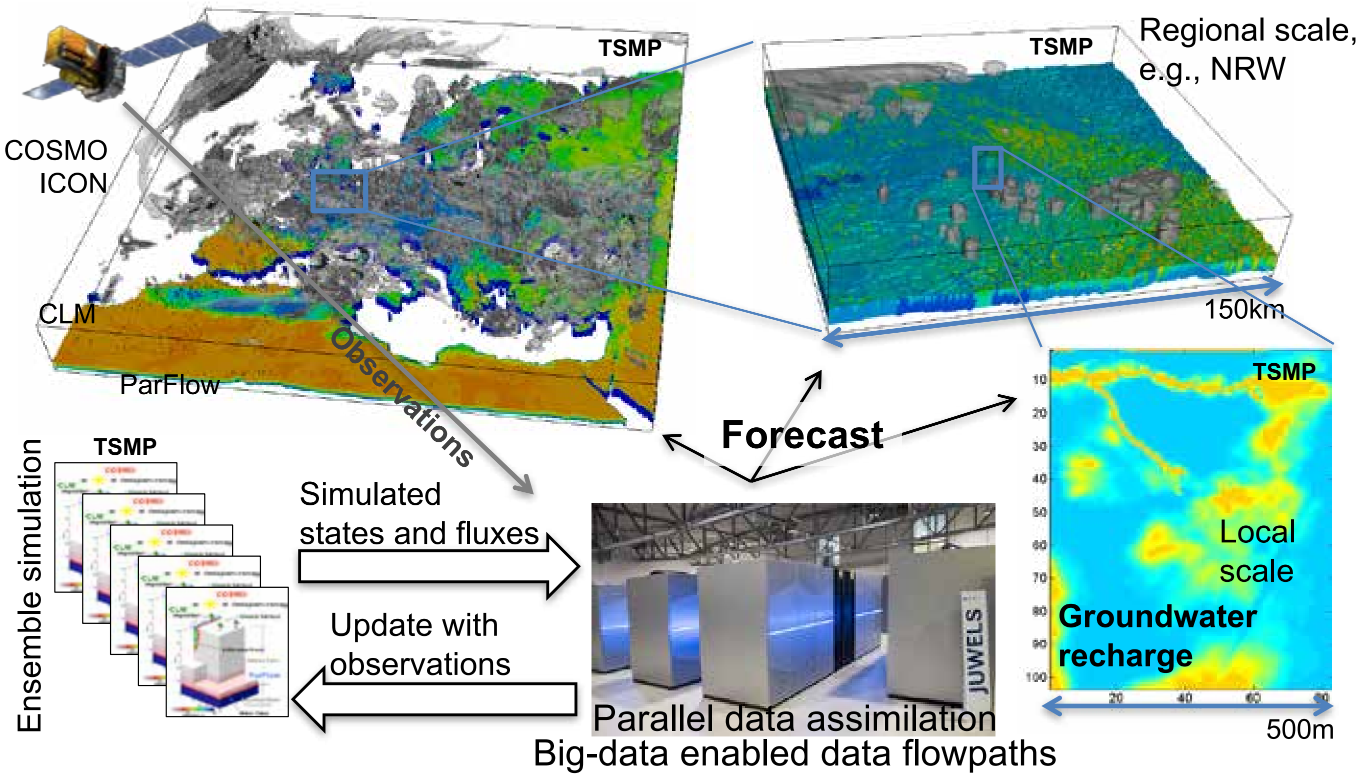
Our concept of a fully coupled terrestrial monitoring system



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

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