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

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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 subsystems 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

- 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 (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
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)
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. **Probabilistic 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

![Diagram](TSMP(3D))

3D groundwater flow

![Diagram](TSMP(FD))

simplified hydrology

Courtesy J. Keune (2018)
Groundwater-to-atmosphere feedbacks

\[ \Delta = \text{TerrSysMP(3D)} - \text{TerrSysMP(FD)} \]

- 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

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

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
Hydroclimatic extremes

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

Main drought and water scarcity events between 2002 and 2011

Furusho-Percot et al. (under revision, Sc Data)
Water storage variability over Mid-Europe reproduced

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

\[ n_z = \sum_{i,j,k} \text{sat}_{i,j,k} \text{por}_{i,j,k} dz_k \]

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)
Summary and conclusions

Summary and conclusions
Bridge gap between hydrology and meteorology; exploration of feedback pathways and mechanisms

- **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
Our concept of a fully coupled terrestrial monitoring system

- Regional scale, e.g., NRW
- Local scale

Parallel data assimilation
Big-data enabled data flowpaths

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


Hartick, C., C. Forusho-Percot, K. Goergen, and S. Kollet (under revision) Interannual, probabilistic prediction of water resources over Europe following the heatwave and drought 2018.


