Integrated simulation of the European water cycle including human water use

2019-02-28 I **K. Goergen[1,2], J. Keune[1,2,*], C. Furusho-Percot[1,2], S. Kollet[1,2]** with

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HPSC TerrSys

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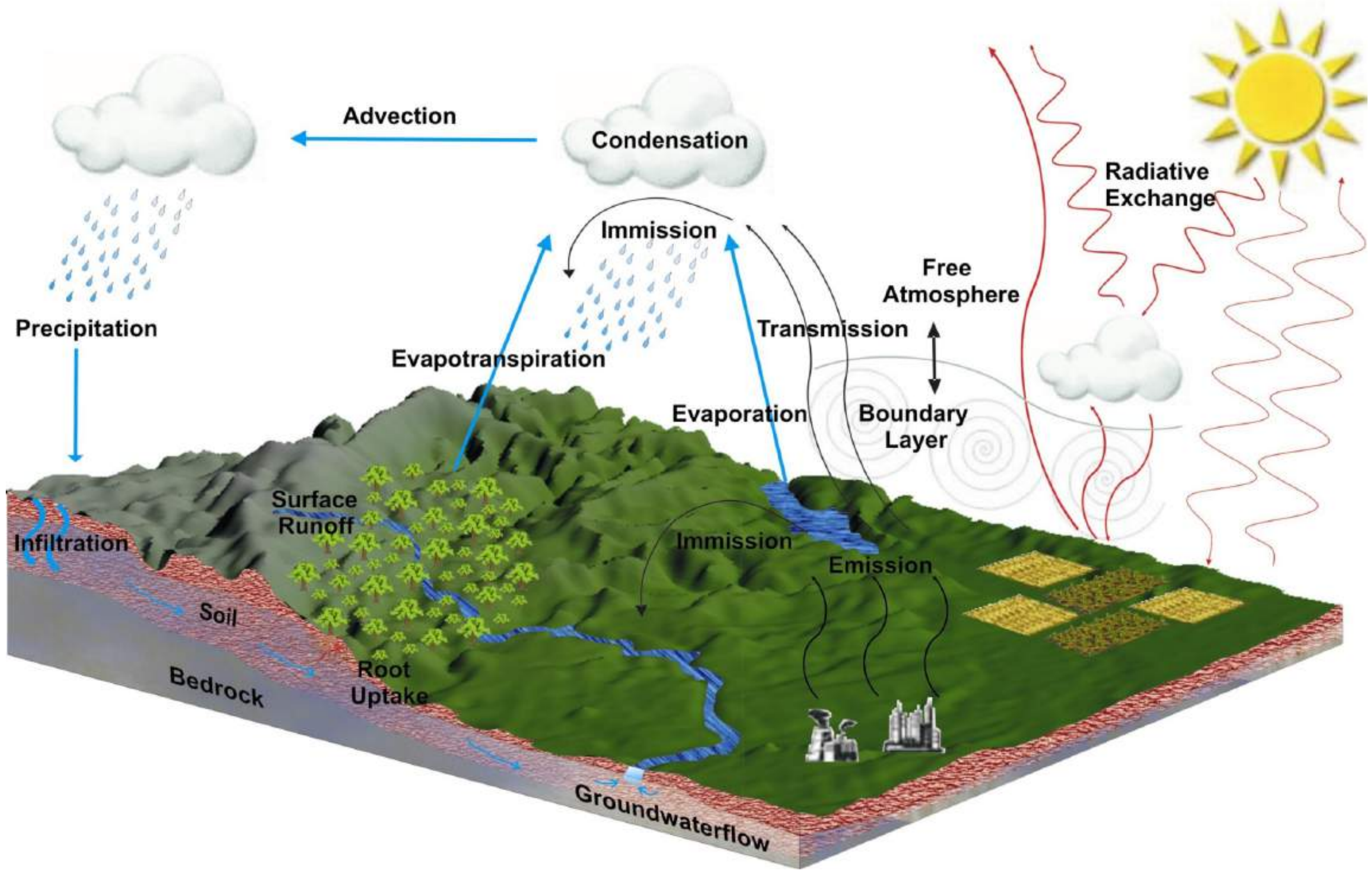
The terrestrial system

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

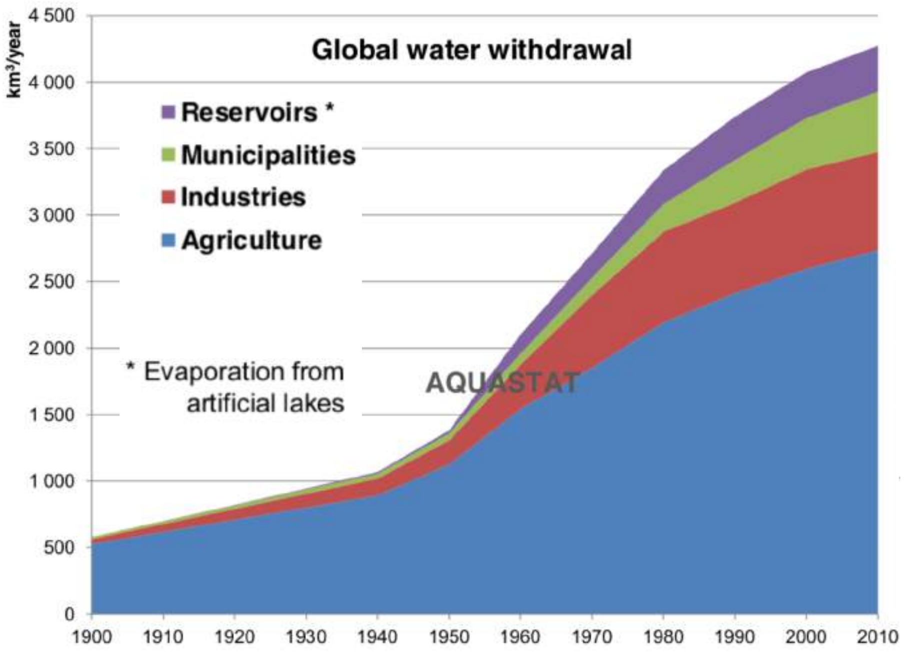


- Complex interactions and feedbacks between various sub-systems of the coupled geo-ecosystem
- Linkages through energy, mass and momentum transfers
- Multiple spatio-temporal scales
- Anthropogenic physical system changes modify land surface and ecosystem processes and services with many socio-economic 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
- Human water use has multiple local and non-local (climatic) effects (groundwater recharge/storage, discharge, ET/P recycling, etc.)
- Better understanding and prediction of (increasing) extreme hydro-climatic 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



http://www.fao.org/nr/water/aquastat/water_use/index.stm

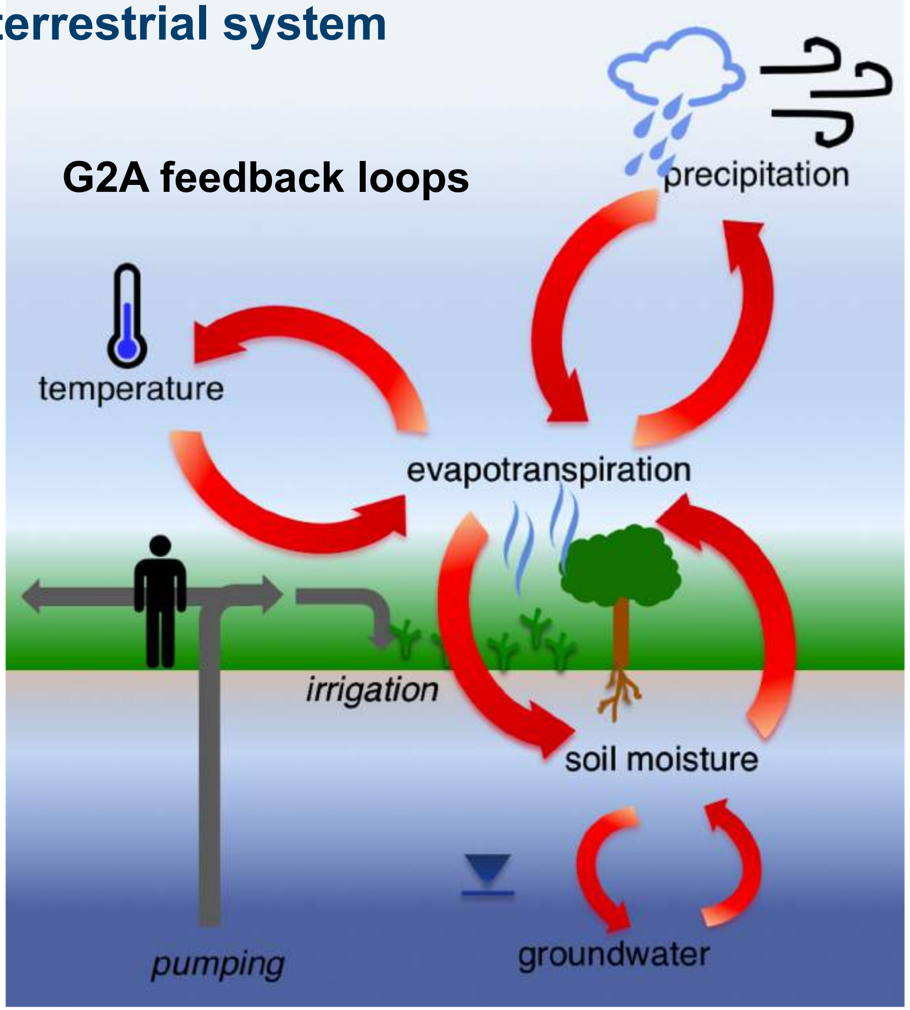
Mean global water use footprint in the order of magnitude of the global groundwater flux and constantly increasing

Research questions and goals

Assess the impact of groundwater and human water use on the terrestrial system

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 climate change affects groundwater (*application*)
3. How does human water use affect atmospheric processes, like the continental moisture sink; and how do these processes in turn affect water resources? (*resources*)

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



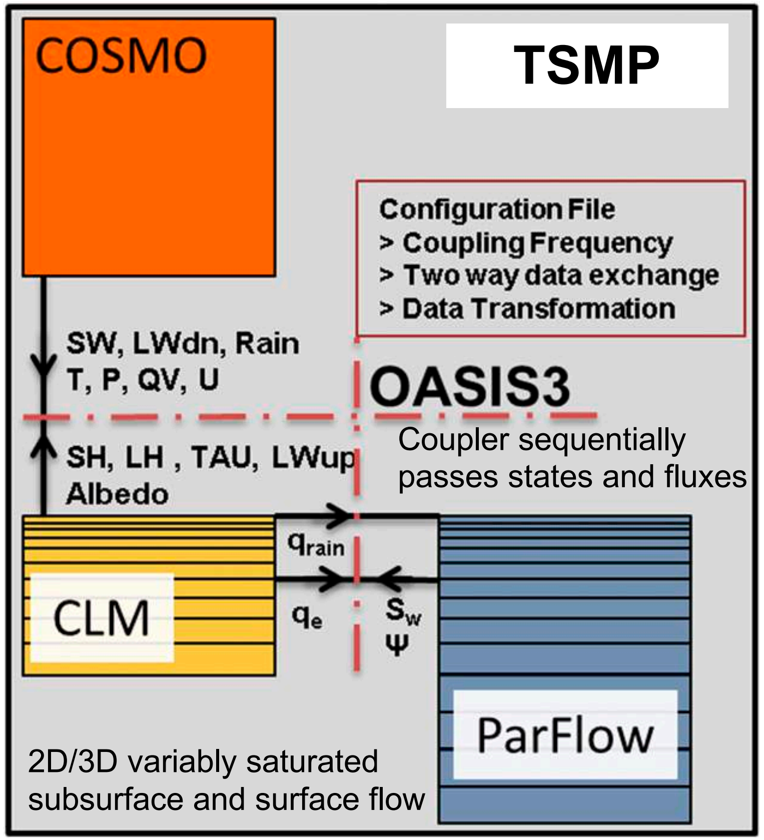
Courtesy J. Keune (2018)

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)
- Massively parallel code, extensive porting and tuning efforts on latest HPC systems, true big data challenge

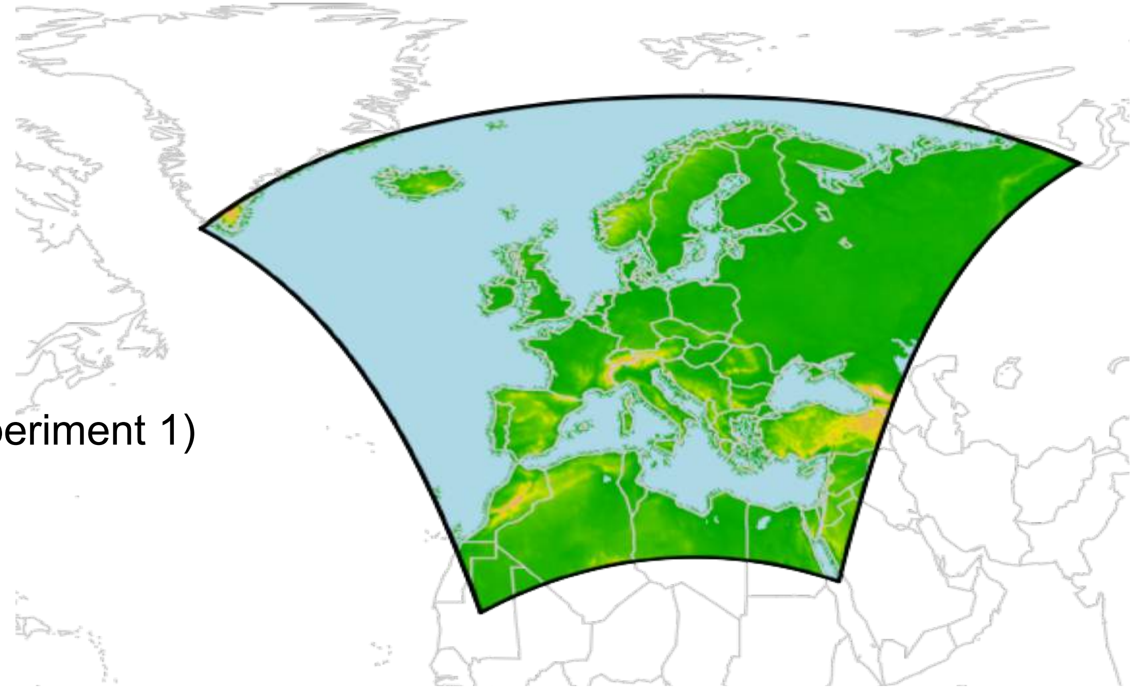
→ **Holistic representation of complex interactions among the compartments in the geo-ecosystem**



Shrestha et al. (2014, Mon Weather Rev)
Gasper et al. (2014, GMD)

TSMP pan-European model setup

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

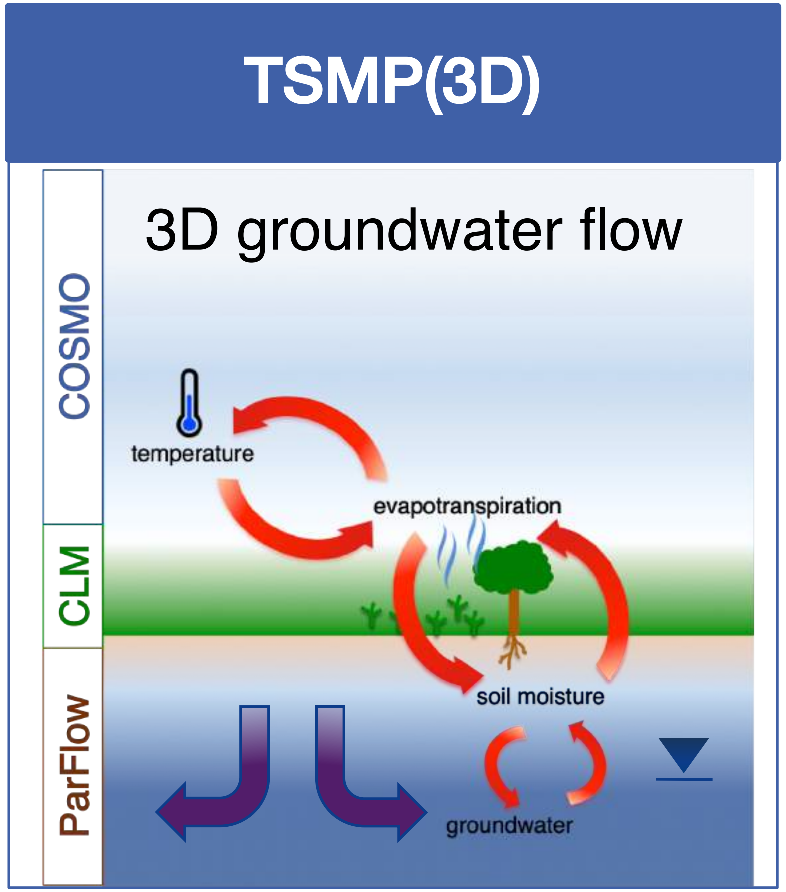


- CORDEX EUR-11 Gutowski et al. (2016, GMD)
  - Resolution: 0.11° (about 12km), 436 x 424 gridpoints
  - Vertical levels: 50 (COSMO), 10 (CLM), 15 (ParFlow)
  - Time steps: 60s (COSMO), 180s (CLM), 180s (ParFlow)
- Input data Keune et al. (2016, JGR)
  - Atmosphere: ERA-Interim (spectral nudging above 850hPa, experiment 1)
  - 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 free-drainage vs 3D groundwater physics, different hydrofacies distributions Keune et al. (2016, JGR)
     - Water use simulations: No water use vs explicit pumping (shallow/deep aquifers) and irrigation Keune et al. (2018, GRL)
  2. **EURO-CORDEX evaluation**: 1989-1995 spinup, 1996-2018 analysis, pristine conditions Furusho-Percot et al. (submitted)

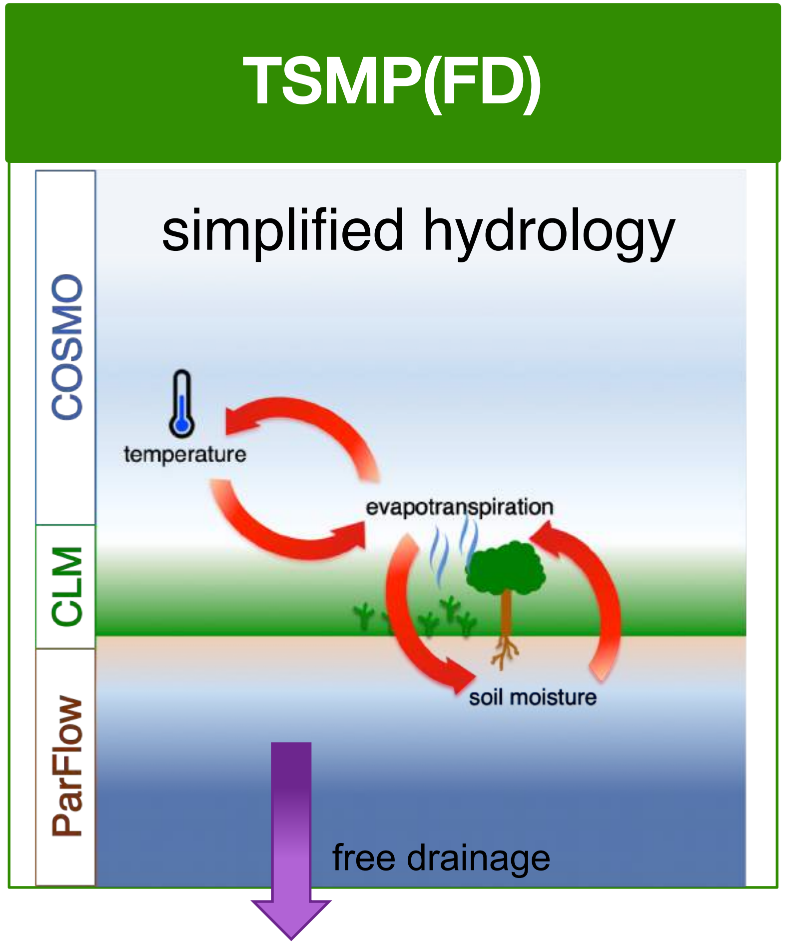
Impact on land-atmosphere (L-A) coupling

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



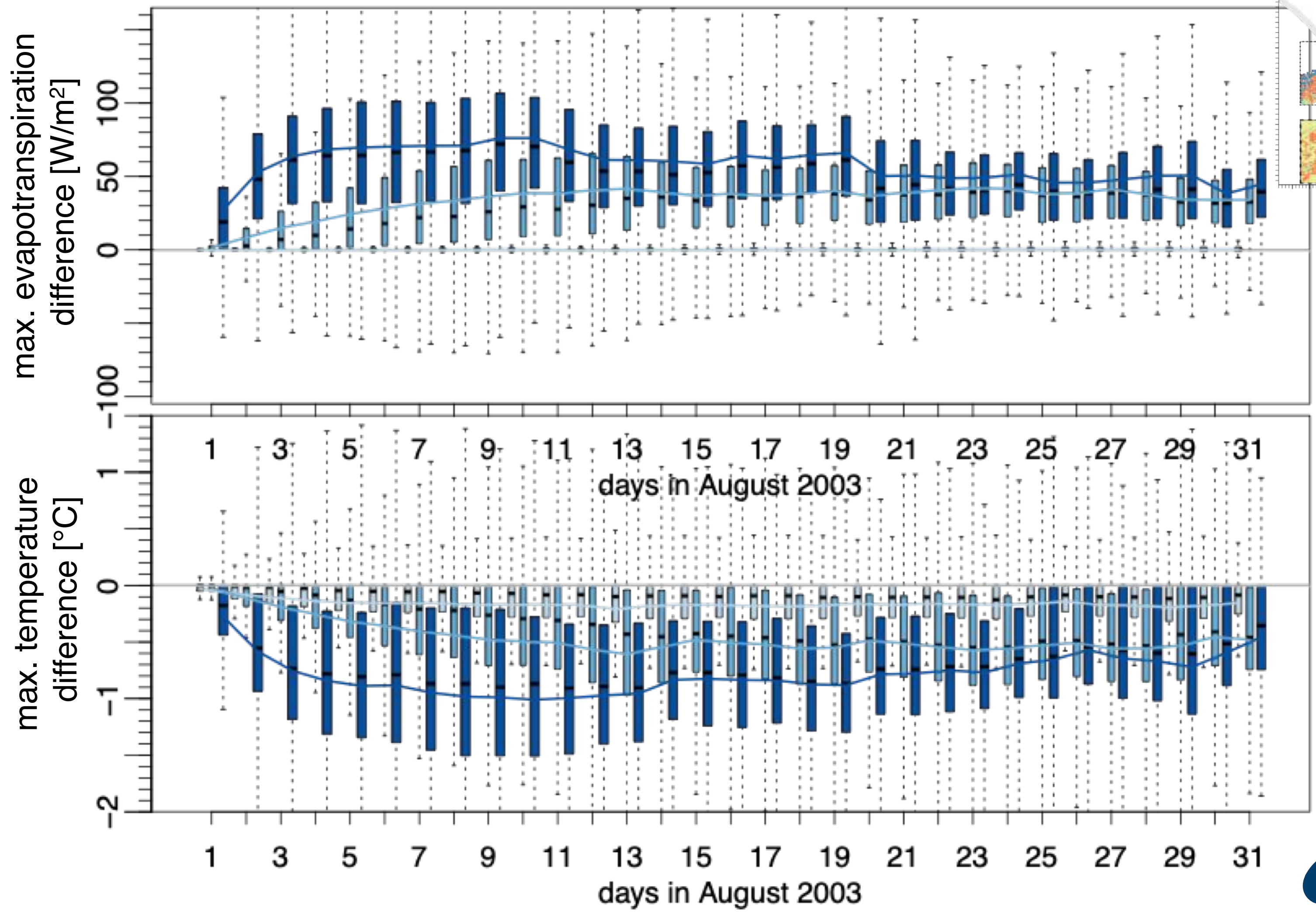
Courtesy J. Keune (2018)

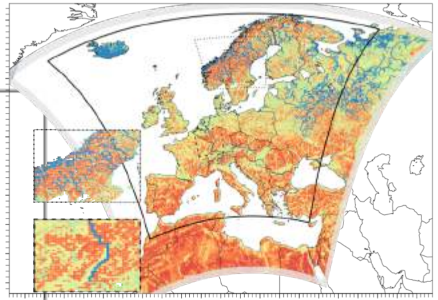


Groundwater-to-atmosphere feedbacks

△ = 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





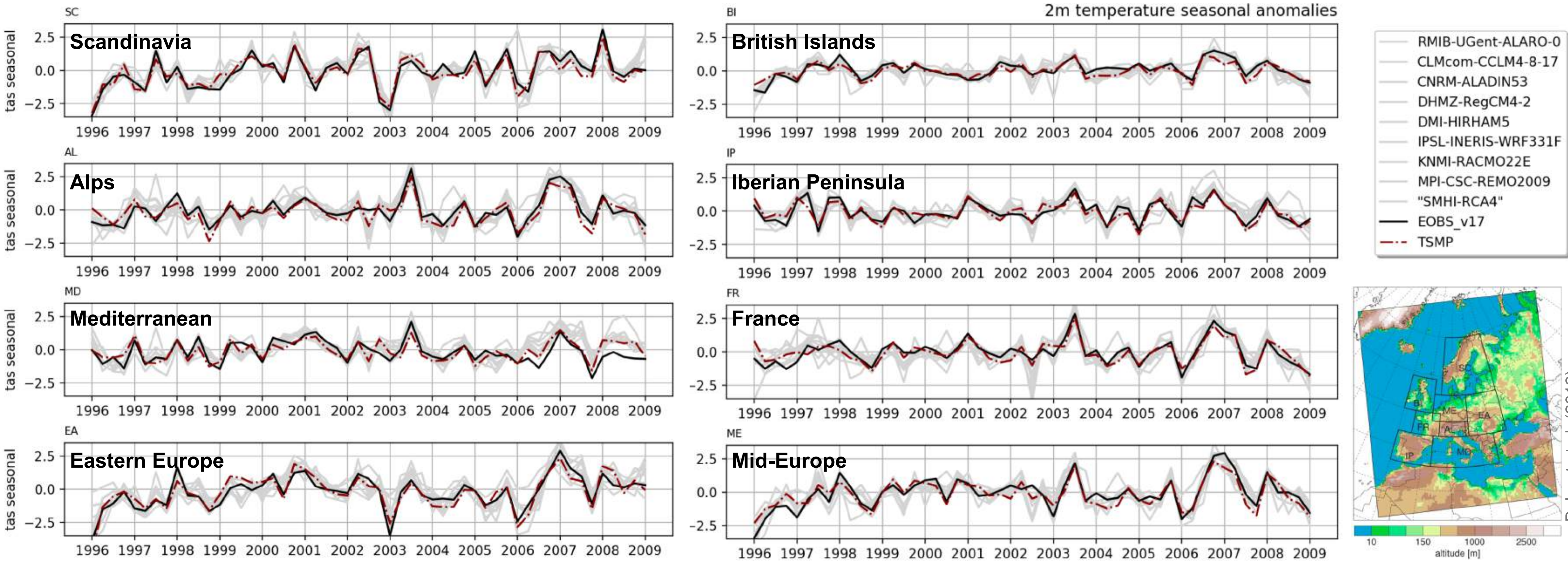
Complete focus domain

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

Keune et al. (2016, JGR)

Added value of coupled simulations in reproducing anomalies

Seasonal air temperature, EURO-CORDEX evaluation runs and TSMP 1996-2008 wrt E-OBS v17



Furusho-Percot et al. (submitted)

Belprat et al. (2012)

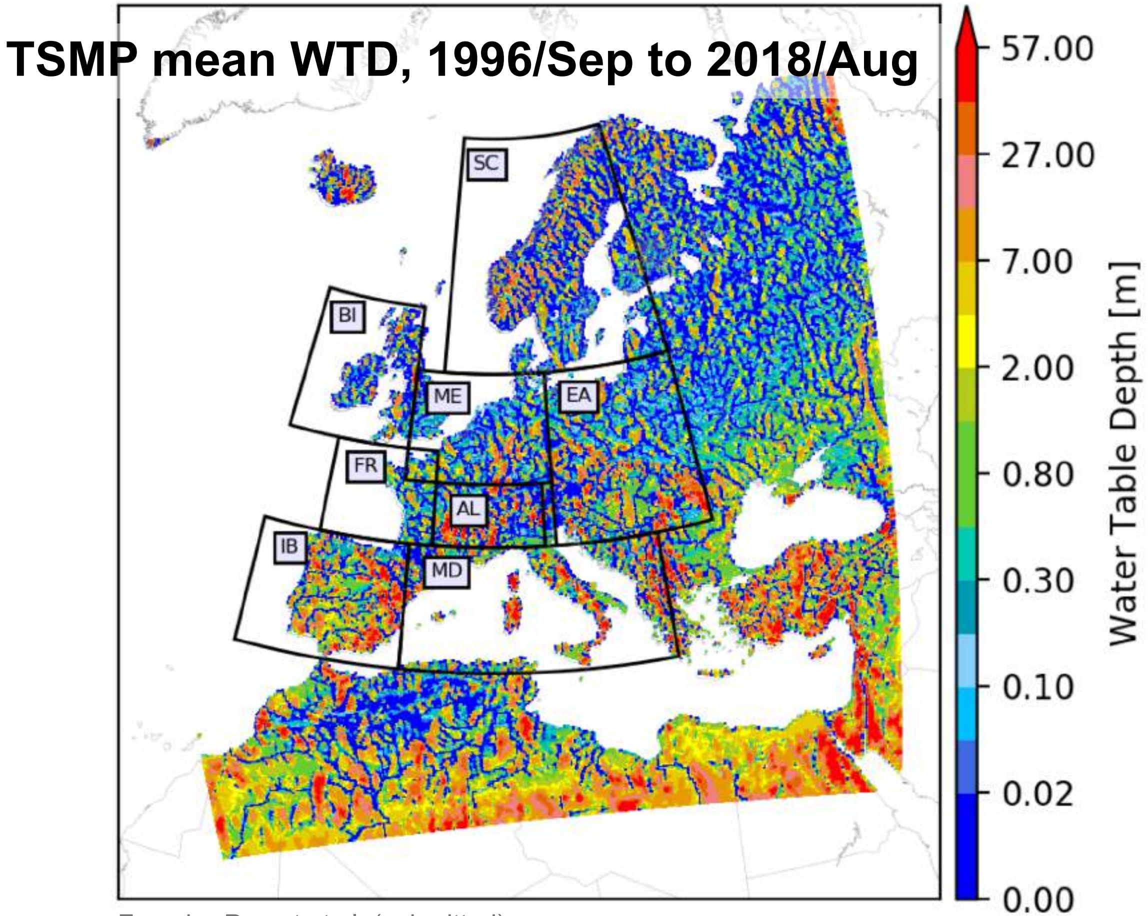
A “pristine” groundwater climatology, no human impacts

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

- 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 regional climate change impacts on groundwater

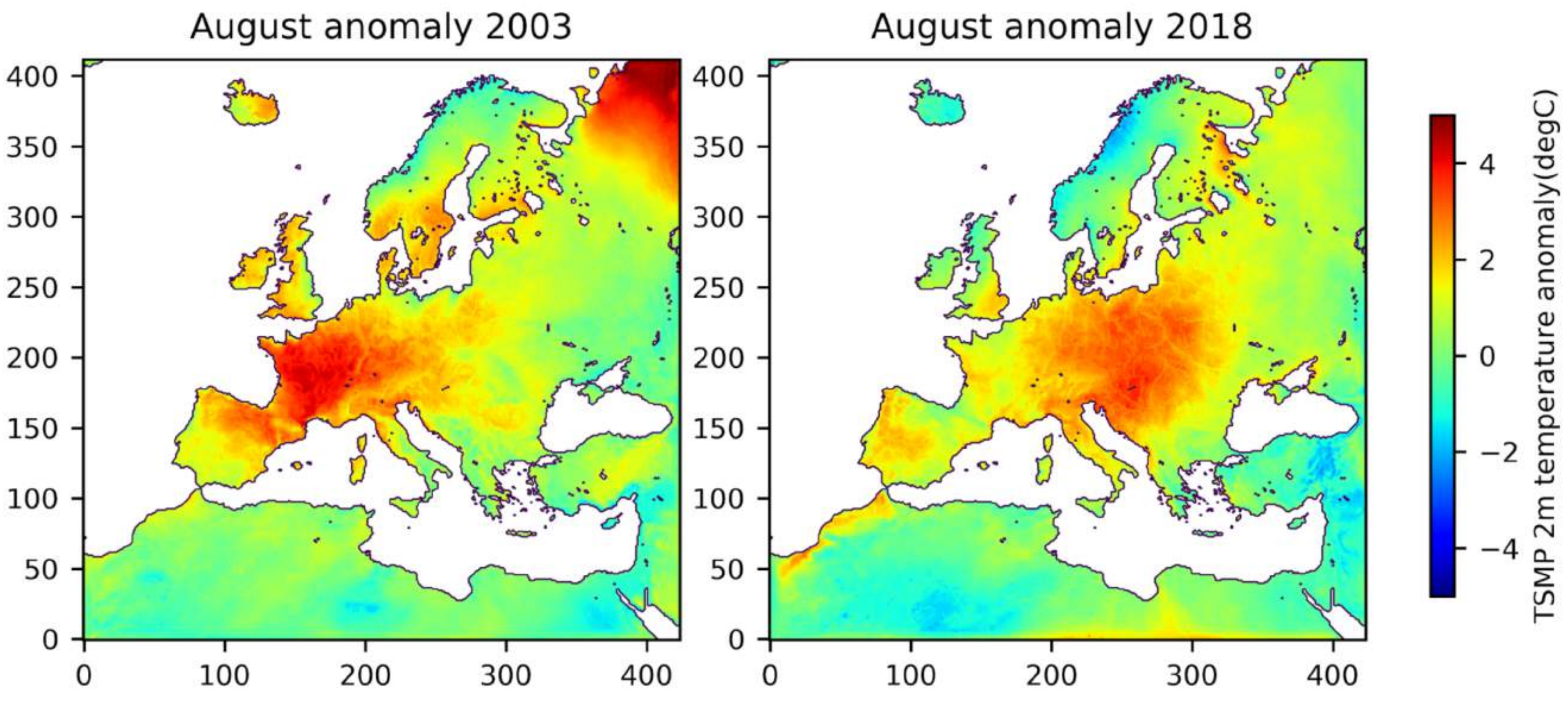
→ Towards actionable information



Furusho-Percot et al. (submitted)

Hydroclimatic extremes

August 2003 and 2018 2m air temperature monthly anomalies

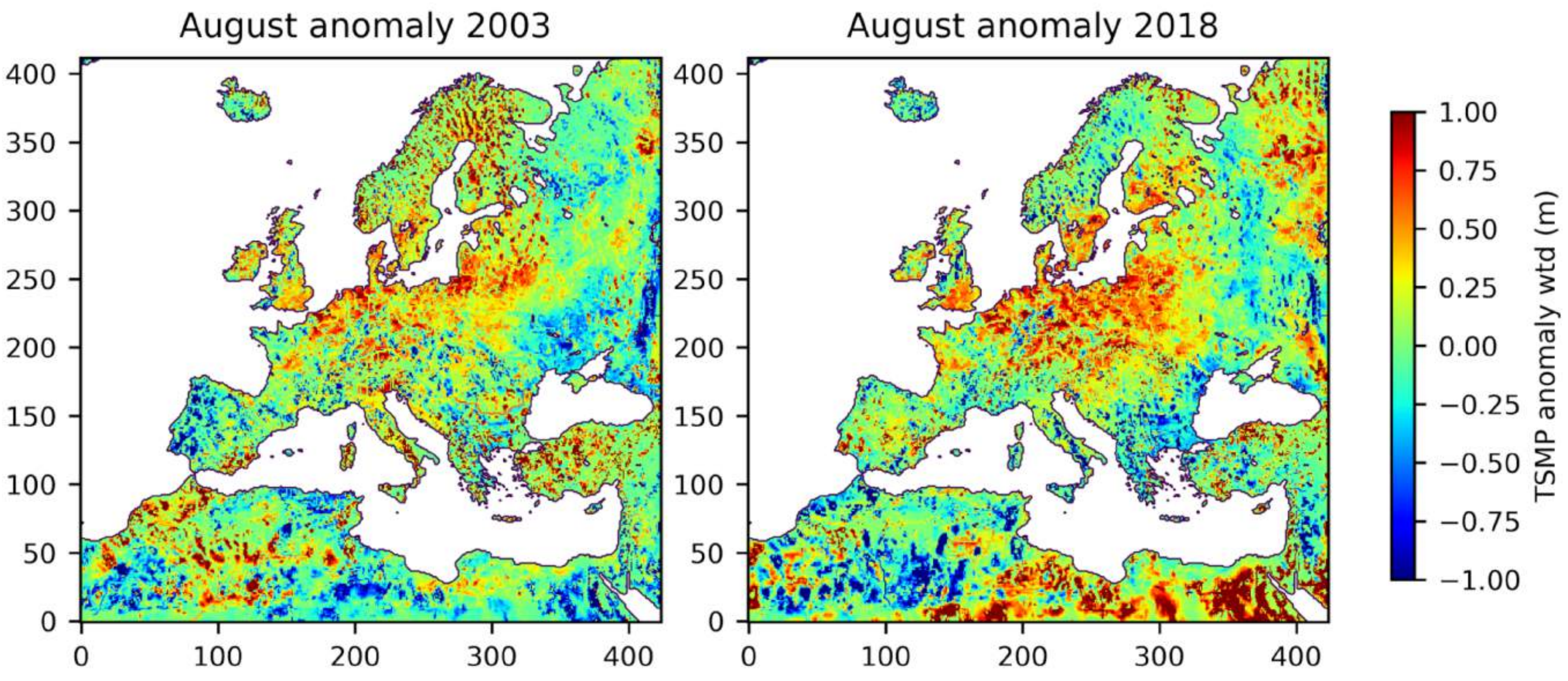


Furusho-Percot et al. (submitted)

Hydroclimatic extremes

August 2003 and 2018 water table depth monthly anomalies

Portugal: Positive precipitation anomaly in 2003



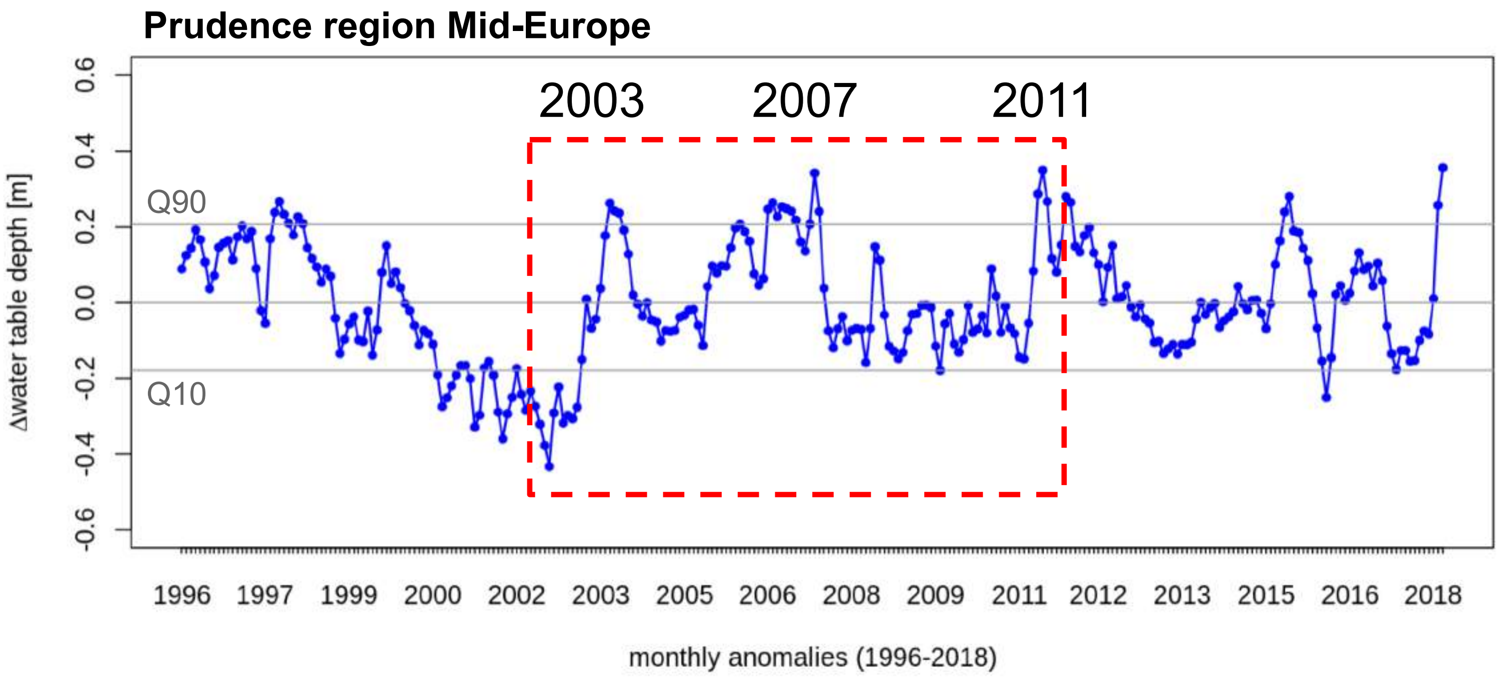
Lower groundwater table, deeper

Higher groundwater table, more shallow

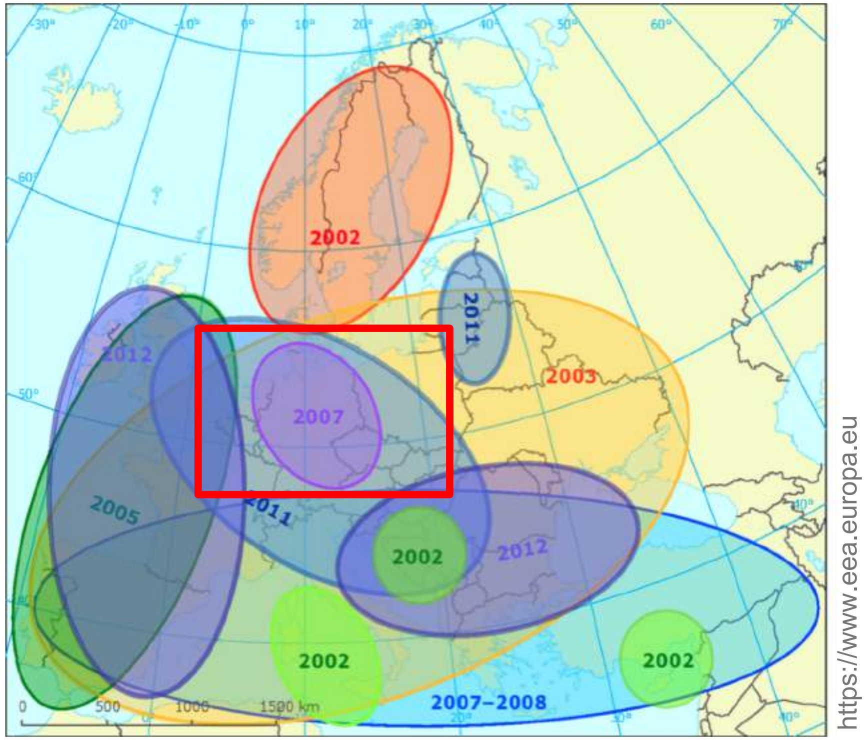
Furusho-Percot et al. (submitted)

Hydroclimatic extremes

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



Furusho-Percot et al. (submitted)



Main drought and water scarcity events between 2002 and 2011

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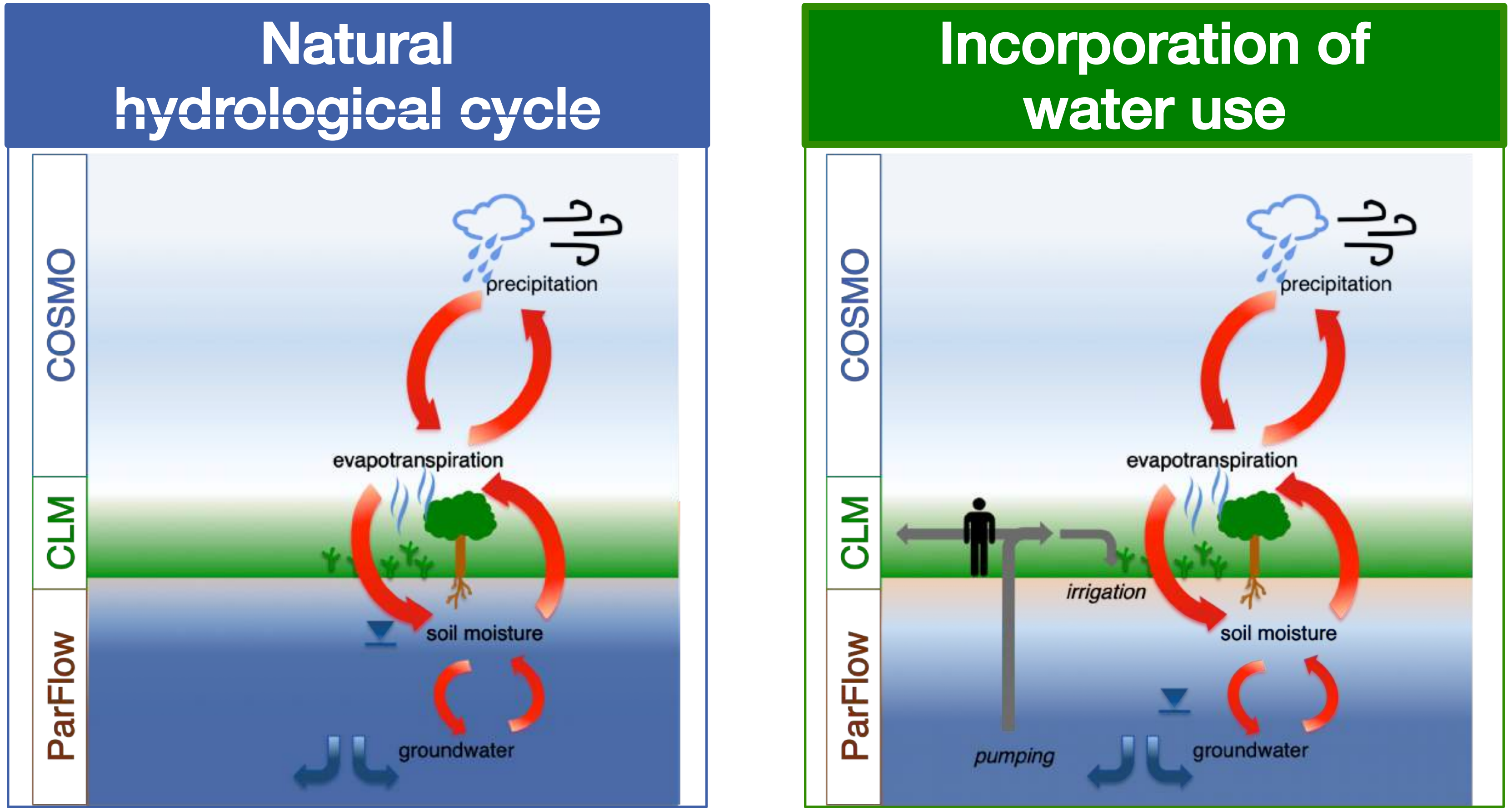
Consideration of human water use (HWU) in TSMP simulations

How does human water use affect atmospheric processes, how do these affect water resources?

Does groundwater abstraction/irrigation systematically change the strength of the continental sink for atmospheric moisture leading to a continuous drying (or wetting) of continental regions?

Five simulations for 2003:

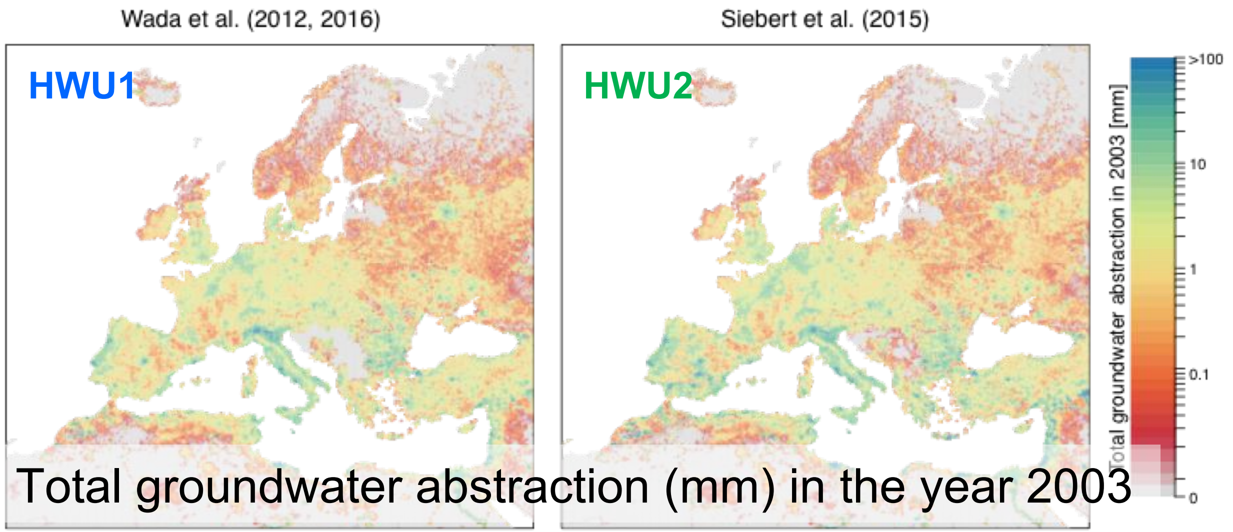
- One reference, no water use
- Two water use datasets and two irrigation schedules each, daytime and nighttime

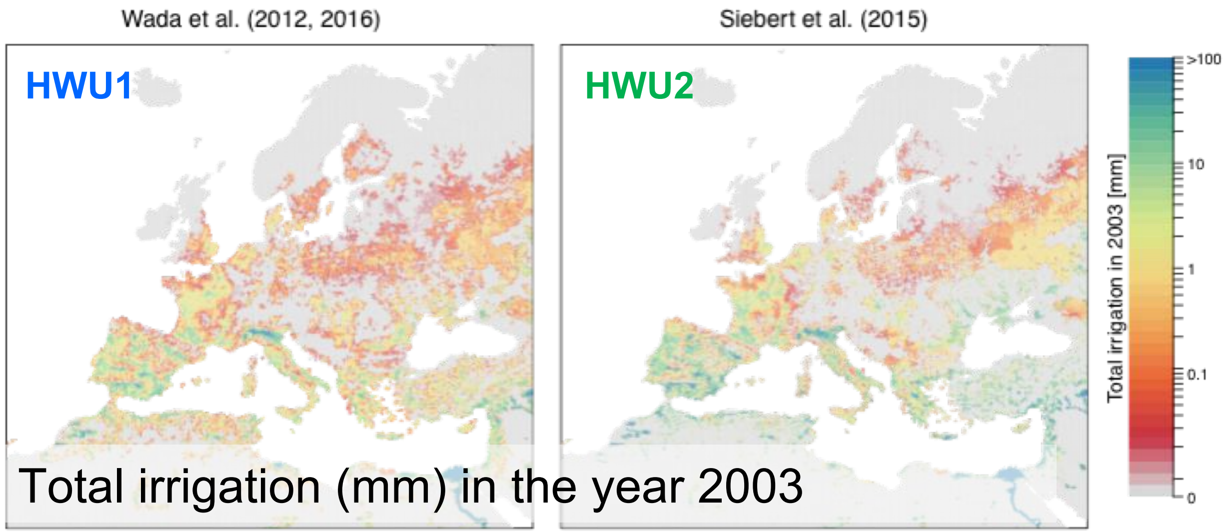


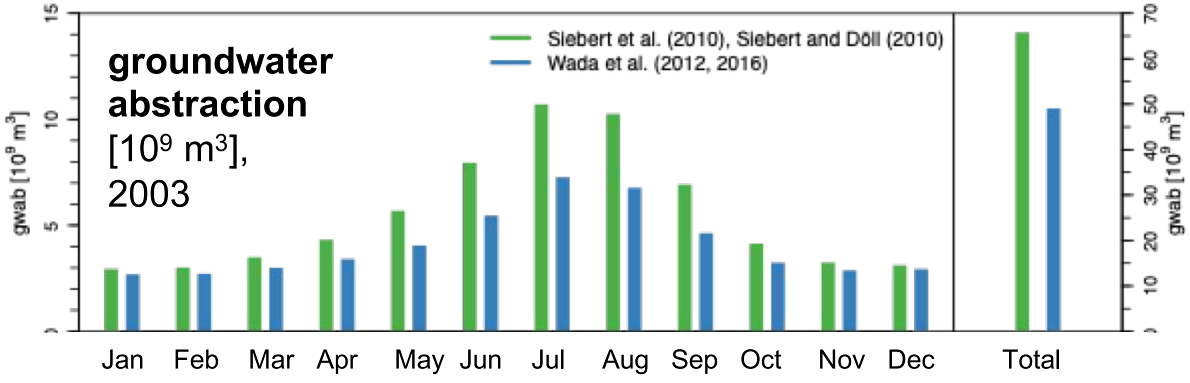
Courtesy J. Keune (2018)

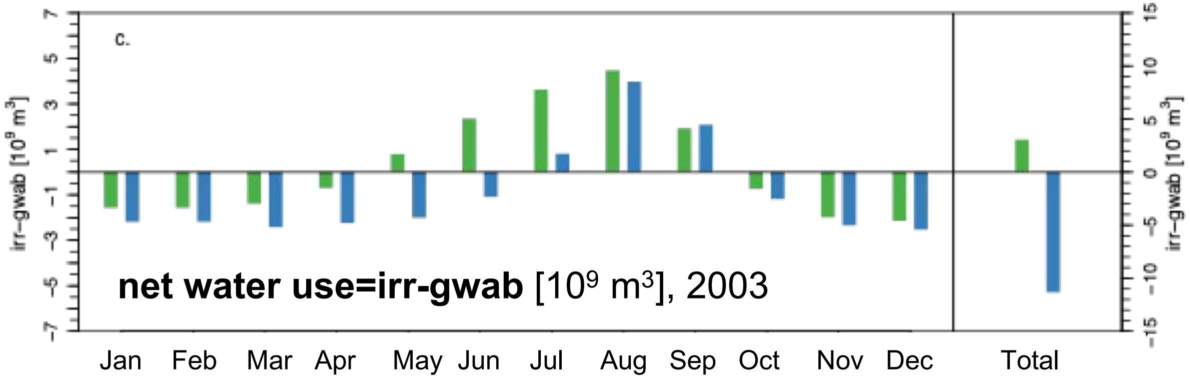
Spatial distribution of groundwater abstraction and irrigation

Daily estimates, large uncertainties, Wada et al. (2016) (HWU1) and Siebert et al. (2010) (HWU2) datasets









Keune et al. (2018, GRL)

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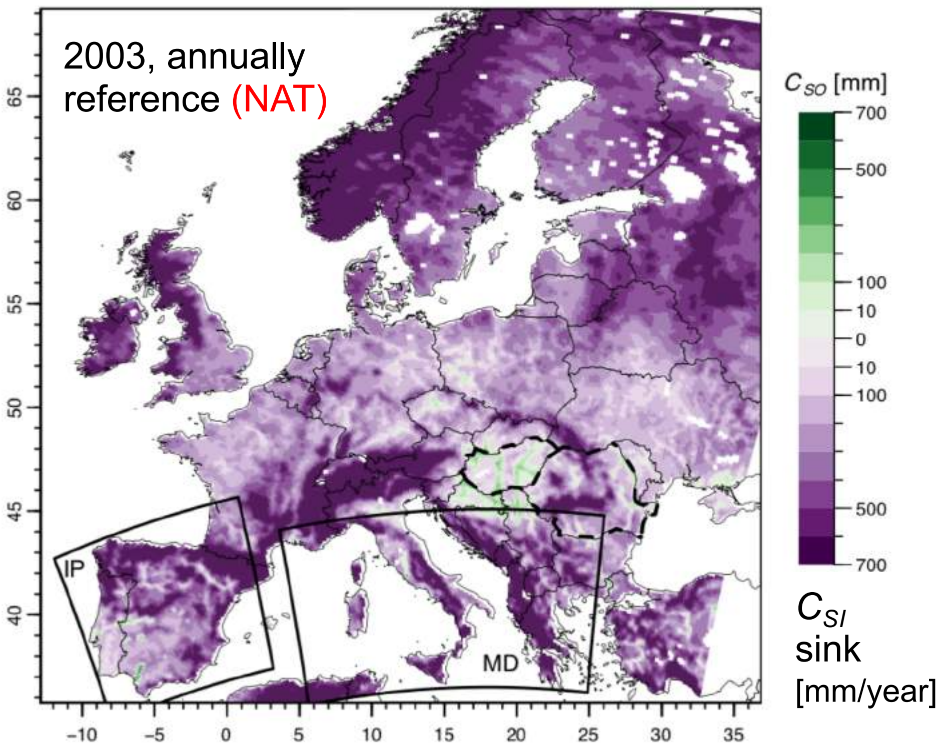
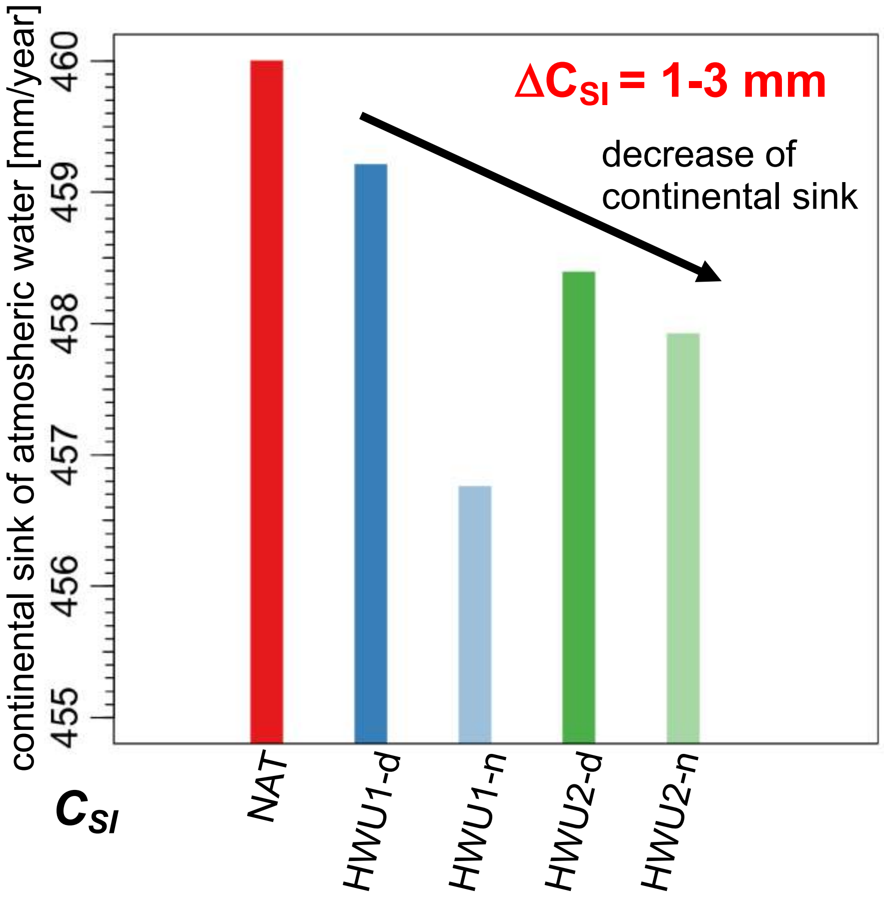
HWU impact on continental sink for atmospheric water

Strength of the continental moisture sink is measured by atmospheric divergence: C_{SI} = -div(Q) = P-ET





Human water use impacts on the continental sink of water (decrease) are on the same order of magnitude as sea level rise studies, i.e., impact of gw on sea level Konikow & Kendy 2005; Wada et al. 2016

Manifold reasons: Increase in ET, decrease in P, etc.

Continental sink: P > ET (net atm. import of water)

Continent is net source of water to atmosphere

C_{SO}=div(Q)=ET-P: ET> P (e.g. during summer)

Keune et al. (2018, GRL)

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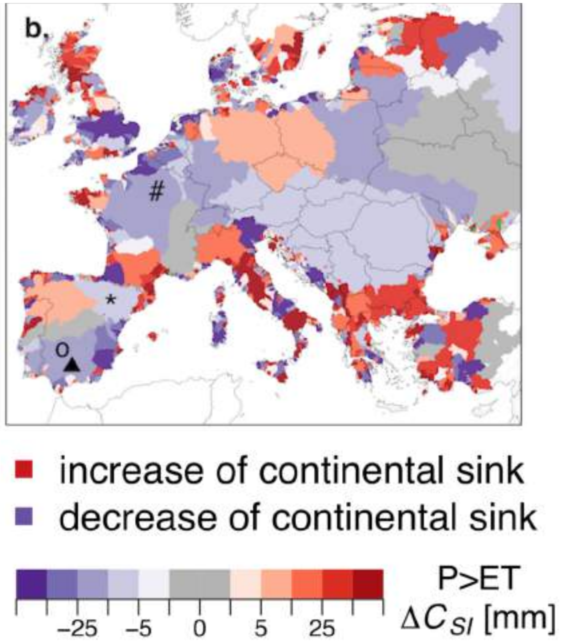
Contribution to subsurface water storage change

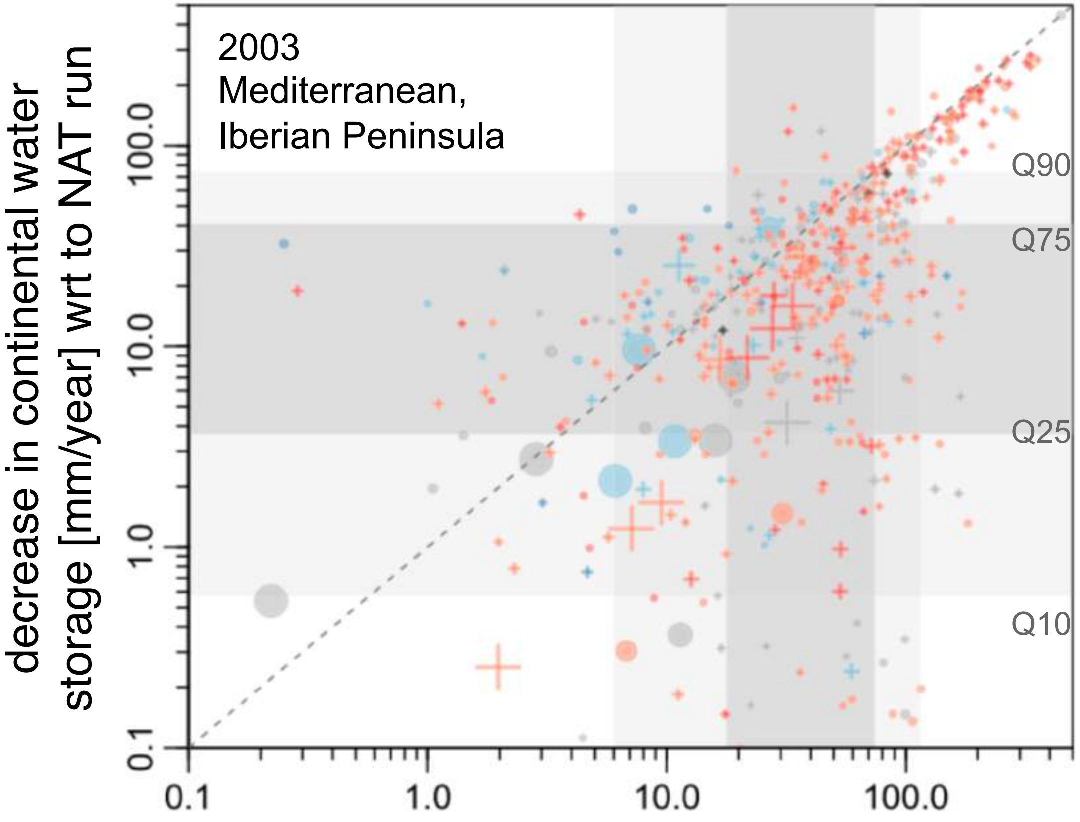
Changes in strength of the continental sink mainly manifest themselves as continental storage changes

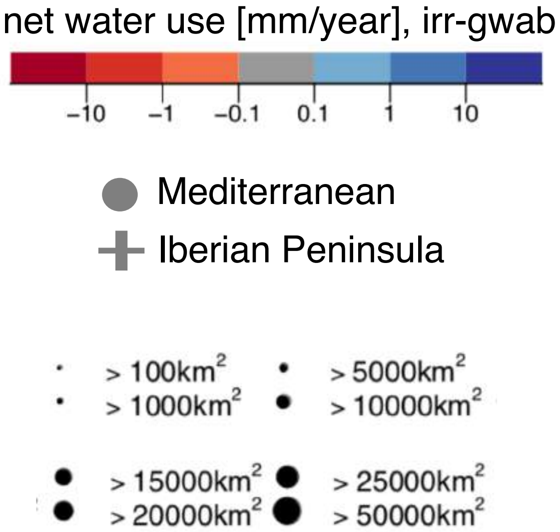
HWU1-n - NAT, 2003, example



HWU induced C_{SI} alteration

Atmospheric feedbacks consistent with water use; decrease of C_{SI} in arid watersheds, increase in ET





Atmospheric feedbacks to human water use are drivers of subsurface water storage changes, rather than net water use

Keune et al. (2018, GRL)

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Summary and conclusions

Groundwater and human water use impact the terrestrial system at the continental scale

- **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 RCMs
- **Baseline dataset** to **assess hydro-climatic extremes** and the **impact of human water use**

- **Human water use** induces systematic **atmospheric feedbacks**, systematically changing the **strength** of the **continental sink** for atmospheric water, and these feedbacks …
- are **drivers** of **terrestrial water storage changes**, potentially aggravating the drying of arid watersheds

Outlook

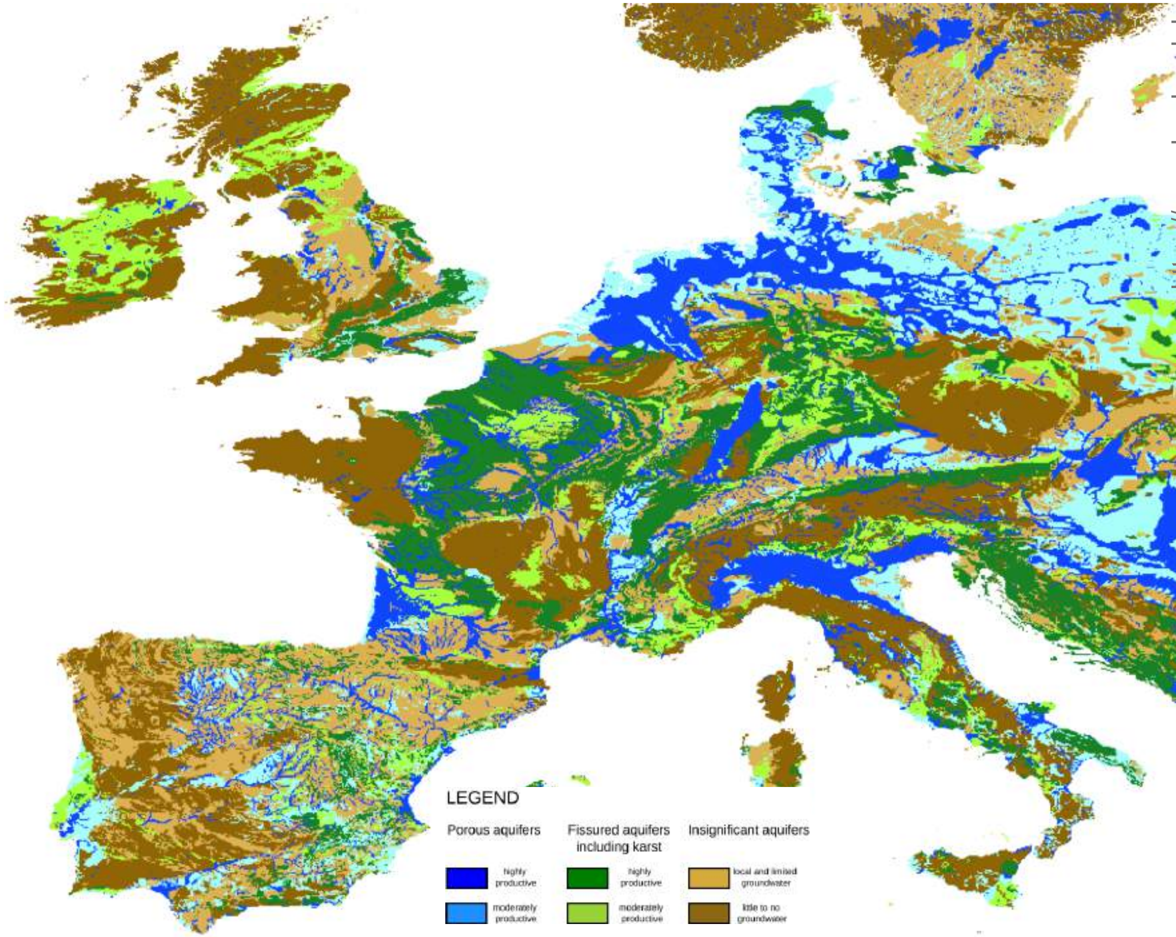
Integrated simulations as tools to develop adaptation strategies, securing freshwater availability

- Enhance knowledge on feedbacks and uncertainties in the climate system

- TSMP climate change projections without/with HWU
- Use integrated modelling for monitoring and forecasting water resources; improvement of weather forecasts, drought and flood forecasts, early warnings

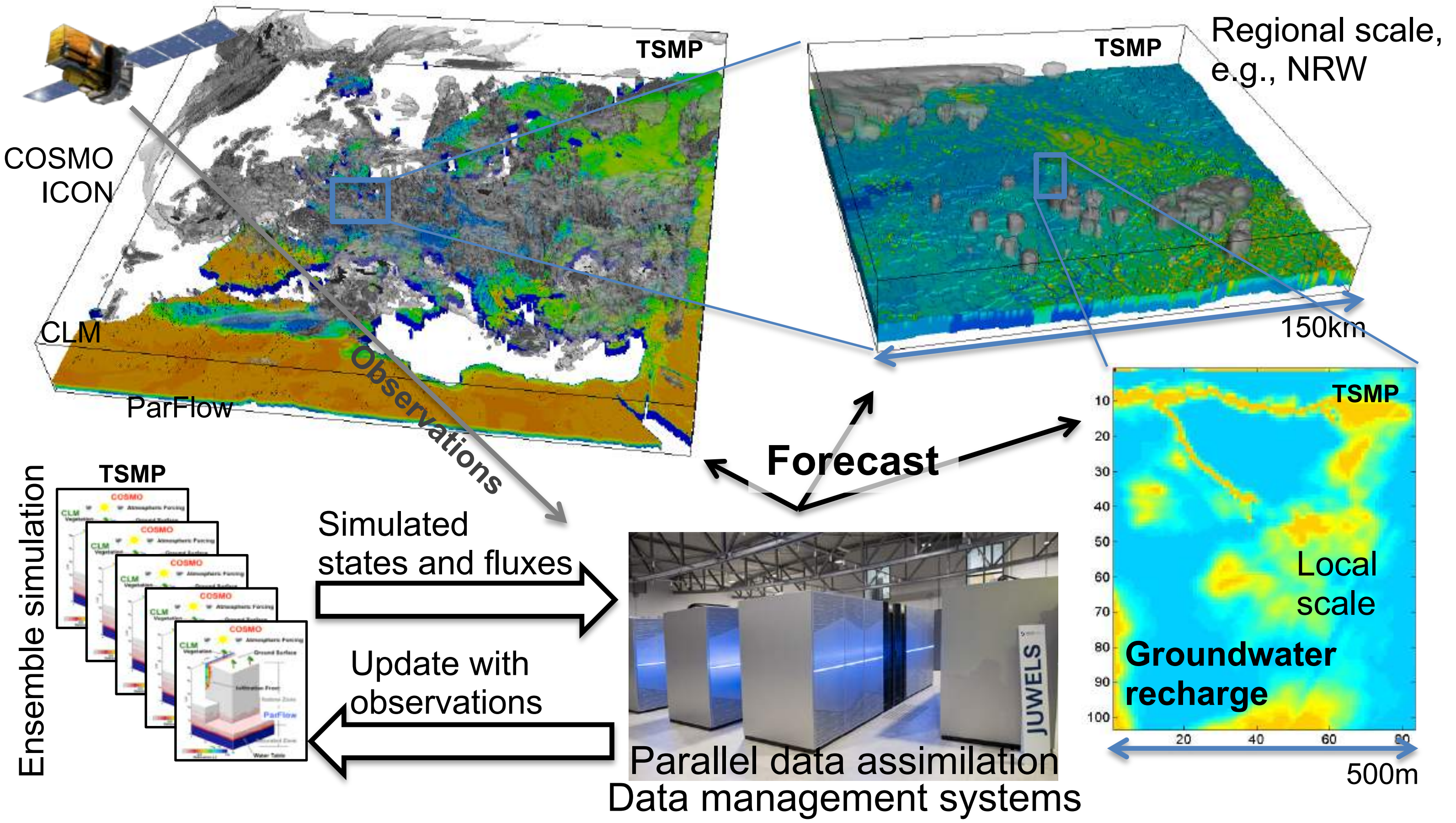
- Added value through convection-permitting, continental-scale simulations, more detailed hydrogeology – ongoing work

- **Bridge the gap between hydrology and atmospheric sciences; exploration of full HWU feedback pathways and machanisms**



https://www.bgr.bund.de

Our concept of a fully coupled terrestrial monitoring system



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