Coupled groundwater-to-atmosphere simulations with the regional climate system model TSMP as a contribution to the new European CORDEX-CMIP6 ensemble

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CLM Community

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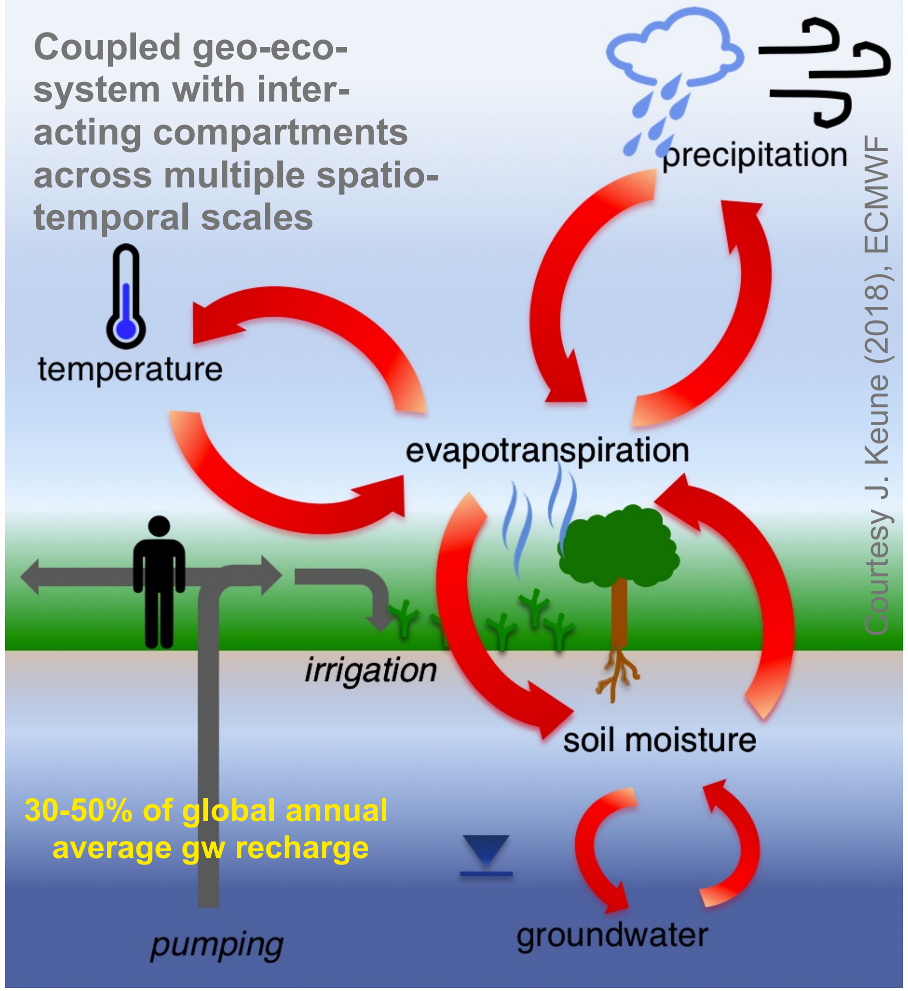
State-of-the-art and motivation

Our interest: Terrestrial water cycle interactions and feedbacks incl. human interventions



Numbers: Aeschbach-Hertig and Gleeson (2012)

- **Intensification of the hydrological cycle** under climate change with impacts on water as a resource, sustainable use, water security (e.g., Huntington, 2006, J Hydrol; Wada and Bierkens, 2014, ERL)
- Conceptually many feedback effects are understood, but the **strength** and **sensitivity of feedbacks** to changes in system state are in parts unclear
- **Observed patterns of hydrological change** can often be explained only insufficiently, e.g. water storage trends in Europe (e.g., Jensen et al., 2019, JGR-A)

Research questions

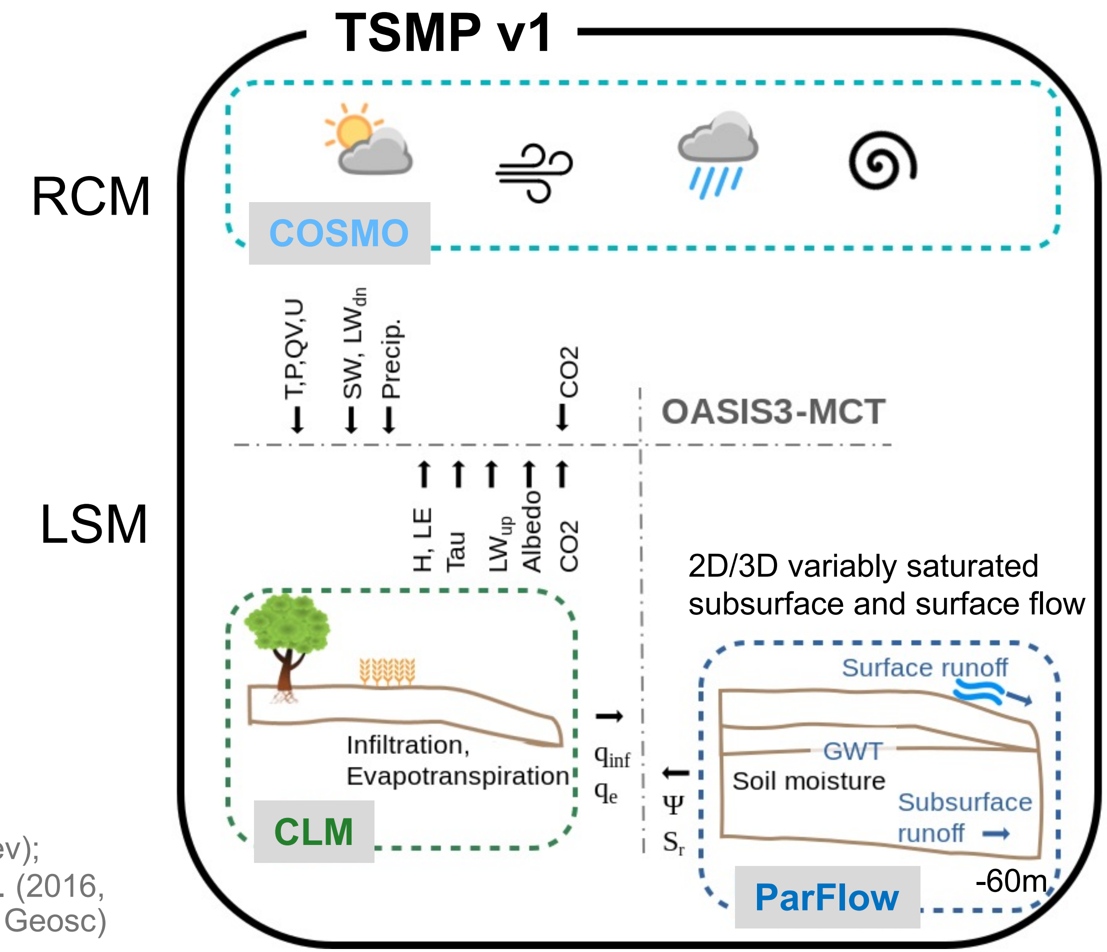
- What are **drivers of hydroclimatic extremes** (droughts, heatwaves) when groundwater is considered in L-A coupling; impacts on **water resources**?
- How did **human water use (HWU)** and **land use and land cover change (LULCC)** have contributed to **modifications** of **water** and **energy cycles** with multiple (non-)local (hydro-climatic) effects?

Our modelling framework: TSMP

Physically based representation of transport processes and feedbacks across scales and sub-systems

Terrestrial systems modelling platform
www.terrsysmp.org

- Modular coupling design
- Component models can have different resolutions
- Massively parallel
- With data assimilation option



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

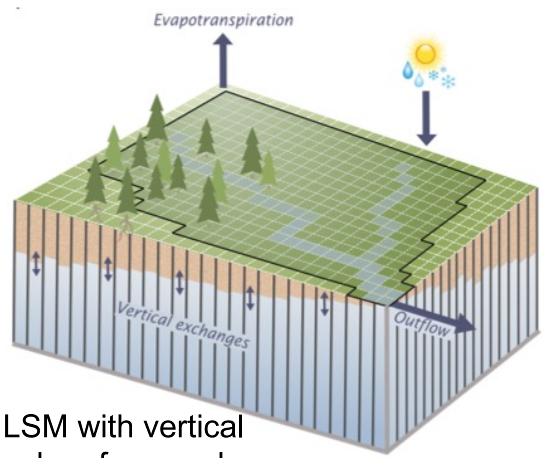
Active development towards TSMPv2: **ICON-eCLM-ParFlow**

IHM Surface and subsurface systems are treated as a single resource

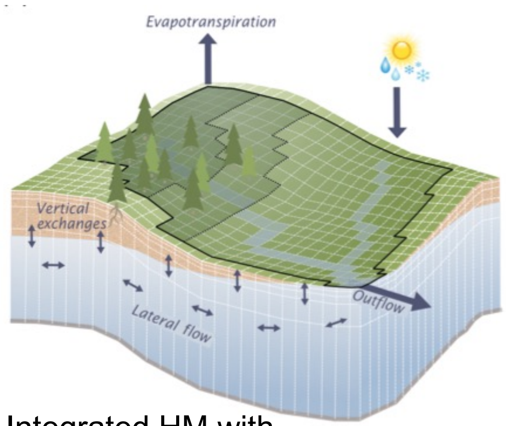
ParFlow can also be run as a GPU variant
www.parflow.org

Groundwater-to-atmosphere similations (G2A) w/ RCM+IHM

More realistic process representation and a basis for VIACS applications



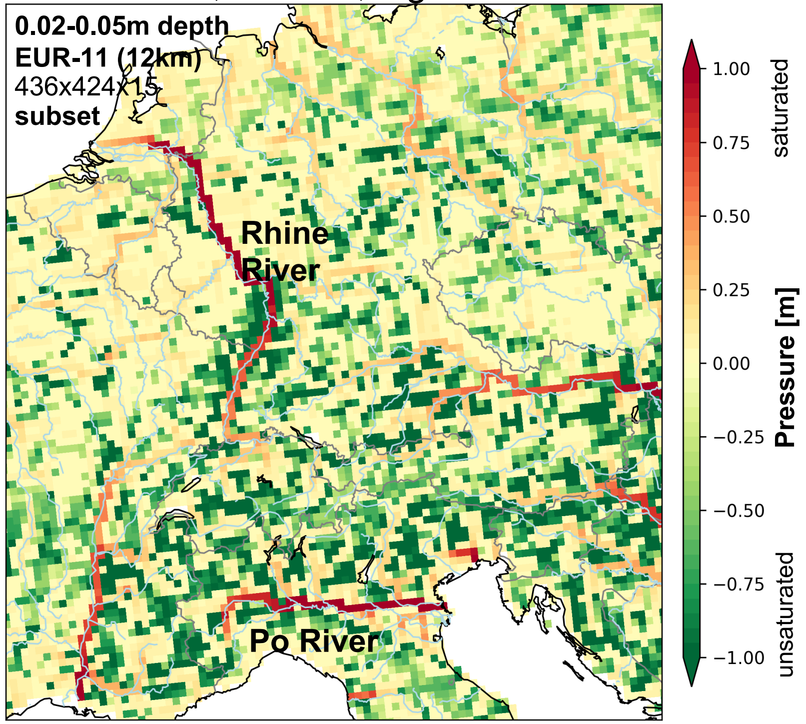
LSM with vertical subsurface exchanges



Integrated HM with 3D hydrodynamics

Sub-surface and surface hydro-dynamics are linked; IHMs can resolve km-scale heterogenity, hill slope processes

TSMP / ParFlow, 2020-01-23, 23 UTC
ERA5-driven, test run, high initial soil moisture



Redistribution of surface and groundwater in continuum approach, ponding / flowing water in convergence zones, evolution of river networks

- Groundwater affects L-A coupling, land water balance, hydrometeorology in RCMs (e.g., Keune et al., 2016, JGR-A; Furusho-Percot et al., 2022, GRL; Poshyvailo et al., 2022, ESDD; Barlage et al., 2021, GRL)
- Scale-dependent feedbacks: km-scale requires 3D hydrodynamics (e.g., Barlage et al., 2021, GRL)
- Closed terrestrial water cycle: water resource investigations, incl. HWU (e.g., Hartick et al., 2021, WRR; Keune et al., 2018, GRL; Furusho-Percot et al., 2019, Sc Data)

Schematic: Condon and Maxwell (2017, HESS)

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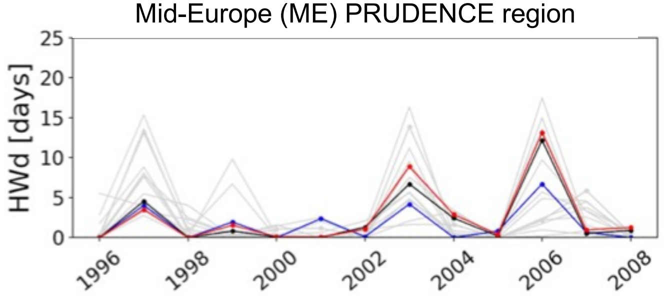
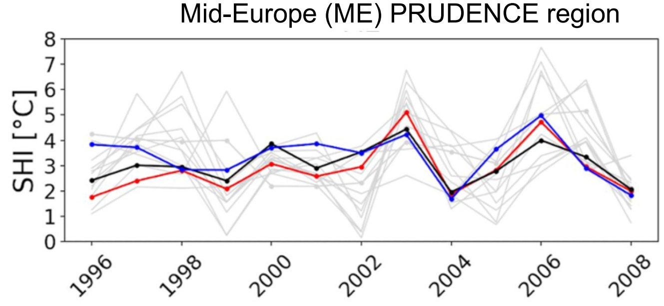
GW treatment affects heatwaves, TSMP w.r.t. CORDEX RCMs

ERA-Interim evaluation runs, TSMP vs 12 EURO-CORDEX RCMs, ERA-Land, E-OBS, GLEAM (=reference)

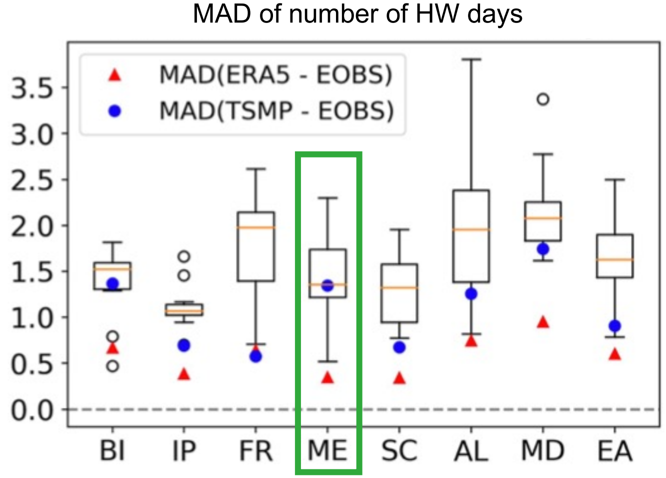
Annual number of heat wave days (HWd), accumulated days per JJA, spatial means

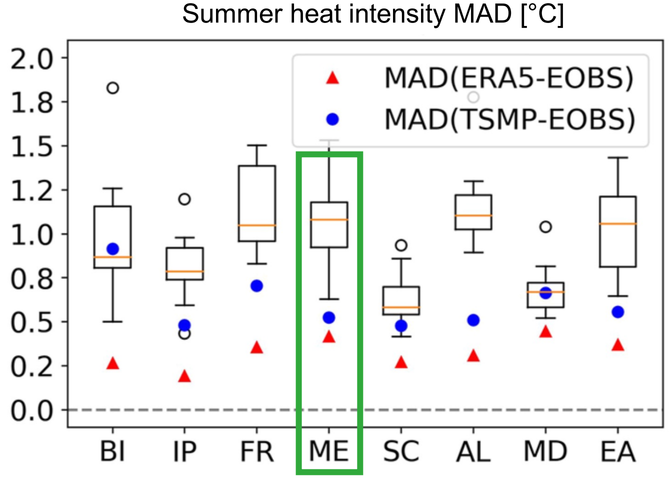


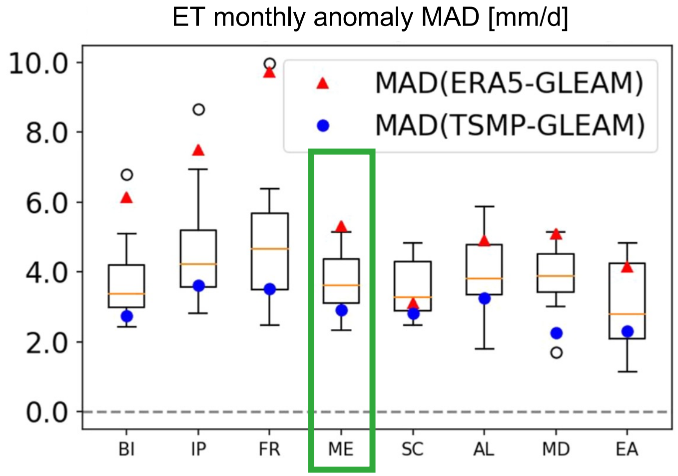


Summer heat intensity (SHI) (amplitude between highest summer tas and multi-annual summer 90th percentile of each model)

Multi-annual mean absolute deviation (MAD) of HWd w.r.t. E-OBS







Heat wave:
daily mean tas > 13-year JJA P90 tas for more than 6 consecutive days

- Coupled TSMP (3D gw) has tendency towards reduced deviations of HW metrics from E-OBS

Furusho-Percot et al. (2022, GRL)

Human water use impacts in coupled TSMP

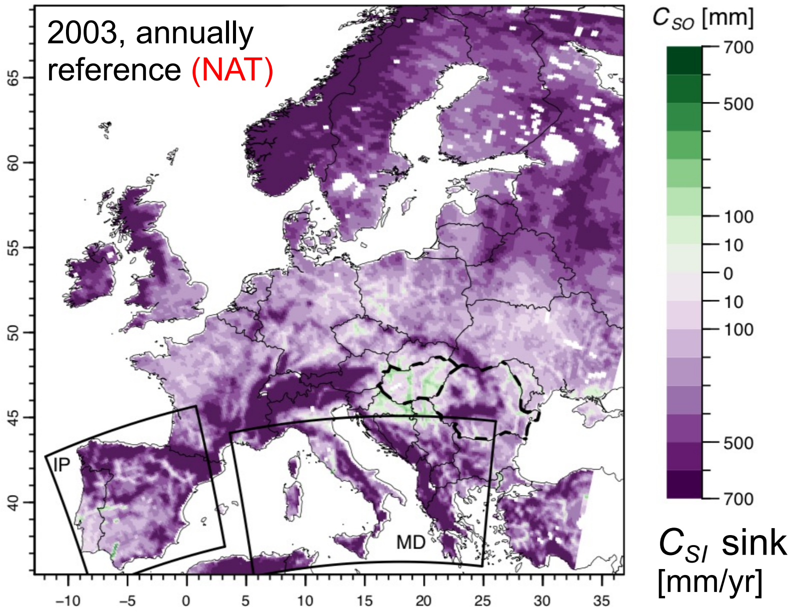
Impacts of HWU on atmospheric water budget and leads to changes of terrestrial water resources

TSMP @ EUR-11 w/ spectral nudging, ERA-I

HWU ensemble: no HWU (NAT) & 2 gw abstraction and irrigation datasets (Wada et al. 2016, JAMES; Siebert et al. 2010, HESS); strong annual cycle

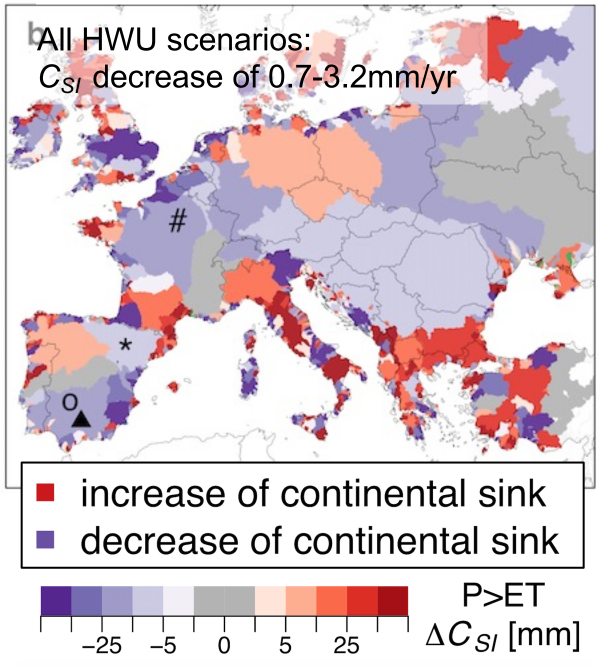
Shown scenario: Wada et al.; for EUR-11 domain: gw abstraction≈ $50*10^9 m^3/yr$ irrigation≈ $38*10^9 m^3/yr$

Atm. water budget, strength of C_{SI}: div(Q) = ET-P



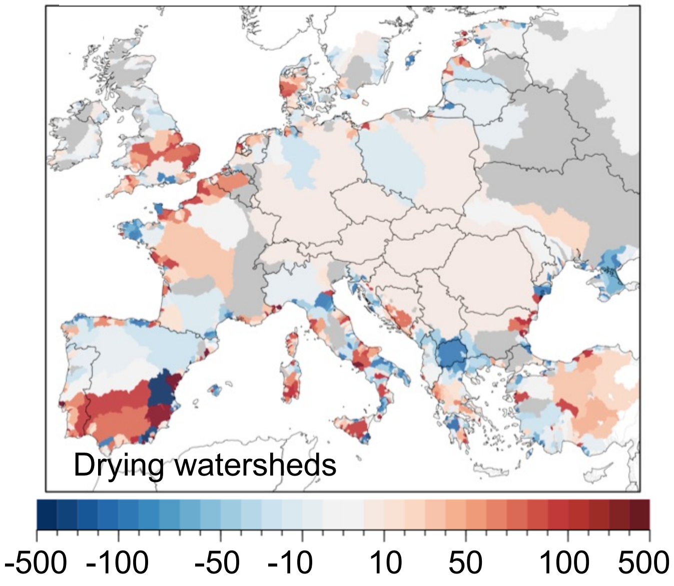
Continental sink C_{SI}: P > ET (net import)
Source C_{SO}=div(Q)=ET-P: ET> P (summer)

HWU1-n - NAT, 2003, example



HWU-induced C_{SI} alteration

NAT - HWU1-n, 2003, example



ΔWTD [mm]: groundwater table **rise** or **decline**

Keune et al. (2018, GRL)

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Climate Limited-area Modelling Community coupled RCM ensemble in CORDEX-CMIP6

Adding an “increased complexity” ensemble to the balanced GCM-RCM matrix of EURO-CORDEX

GCM / RESM	Coupling Area	ERA5+ORAS5 Reanalysis	EC-Earth3-Veg r1i1p1f1	MPI-ESM1-2-HR r1i1p1f1	MIROC6 r1i1p1f1	CMCC-CM2-SR5 r1i1p1f1
COSMO-CLM (0.11°)						

More about CLM-Community coupled or and/or high resolution simulations

A1-P-06:
Hagemann et al. “Regional Earth System Models for CMIP6 downscaling over the EURO-CORDEX domain”

A1-P-12:
Maurer et al. “Calibration of the new ocean-atmosphere model based on ICON and NEMO for the EURO-CORDEX domain”

A2-P-01:
Ahrens et al. “On convective enhancement of Vb-events in present and warmer climate”

A2-P-22:
Poll et al. “Flux exchange over heterogeneous land surfaces”

Summary, conclusions, and outlook

Coupled RCMs w/ IHMs can simulate all **states and fluxes of the terrestrial water and energy cycles**, G2A

Through **L-A coupling**, **groundwater processes** and **3D hydrodynamics** affect **hydroclimatic extremes** and **water resources**, including memory effects

Impacts of **human interventions** and their **impact on the water cycle can be simulated**, making novel information available for multiple **VIACS applications**

A **range of coupled simulations** will be contributed through the **CLM-Community** to **CORDEX-CMIP6,** including ongoing **TSMP** (COSMO5-01-CLM3-5-0-ParFlow3-12-0) **CORDEX-CMIP6**

Next steps

- Analyses on **the impact of HWU**, and **1D vs 3D hydrodynamics** for 30-year evaluation time spans
- **Evolution of European water resources in climate change projections** (challenge: long subsurface spinups needed)
- Mid-term (enhanced model systems): transient **land use and land cover change**, **ocean coupling**, biogeochemistry

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Additional slides

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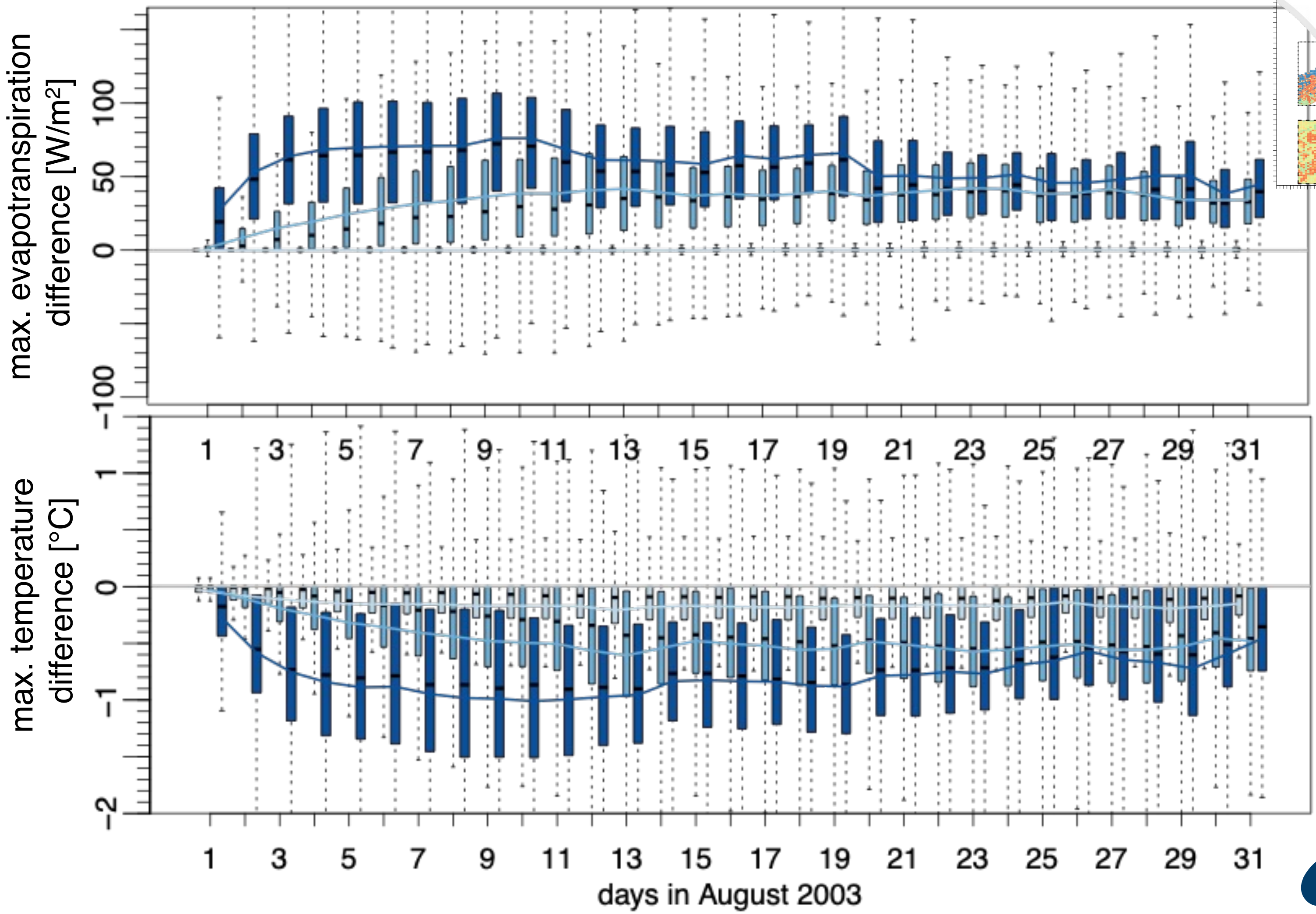
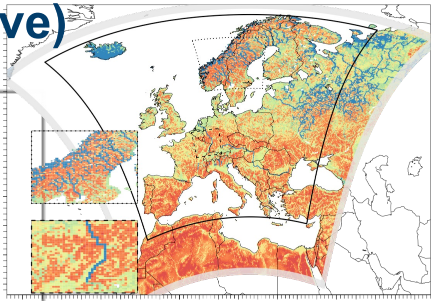
Impact of 3D vs 1D hydrodynamics

GW affects L-A coupling and alleviates heatwave (and drought) extremes (2003 heatwave)

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





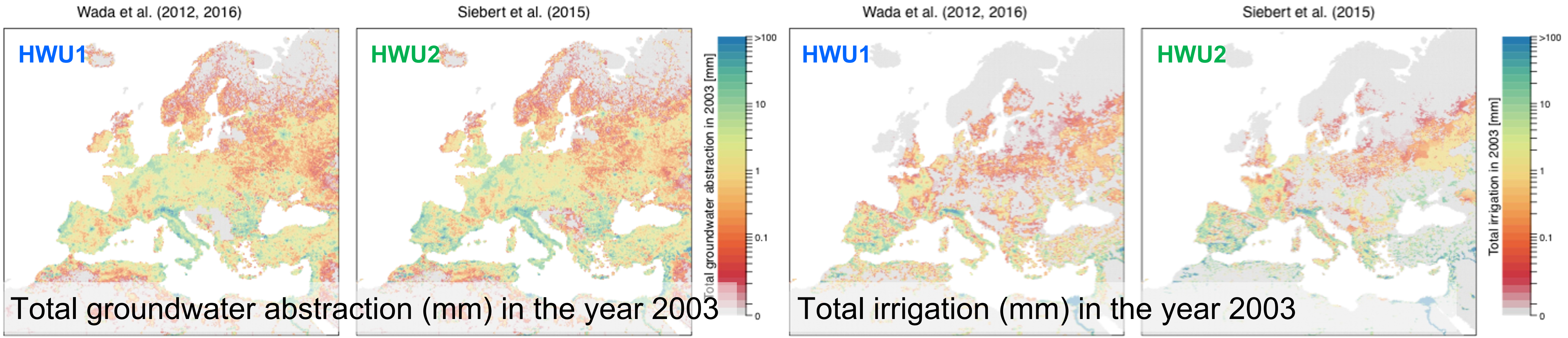
Complete EUR-11 focus domain

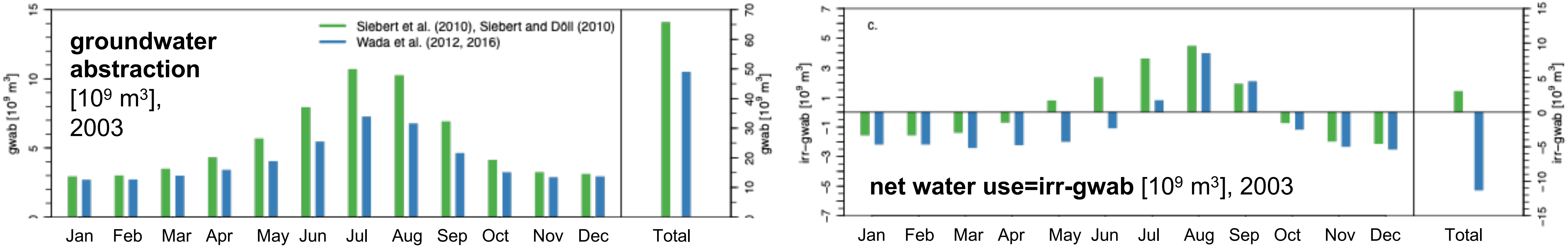
- shallow WTD (<1m)
- medium WTD (1m<WTD<5m)
- deepWTD (>5m)

Keune et al. (2016, JGR)

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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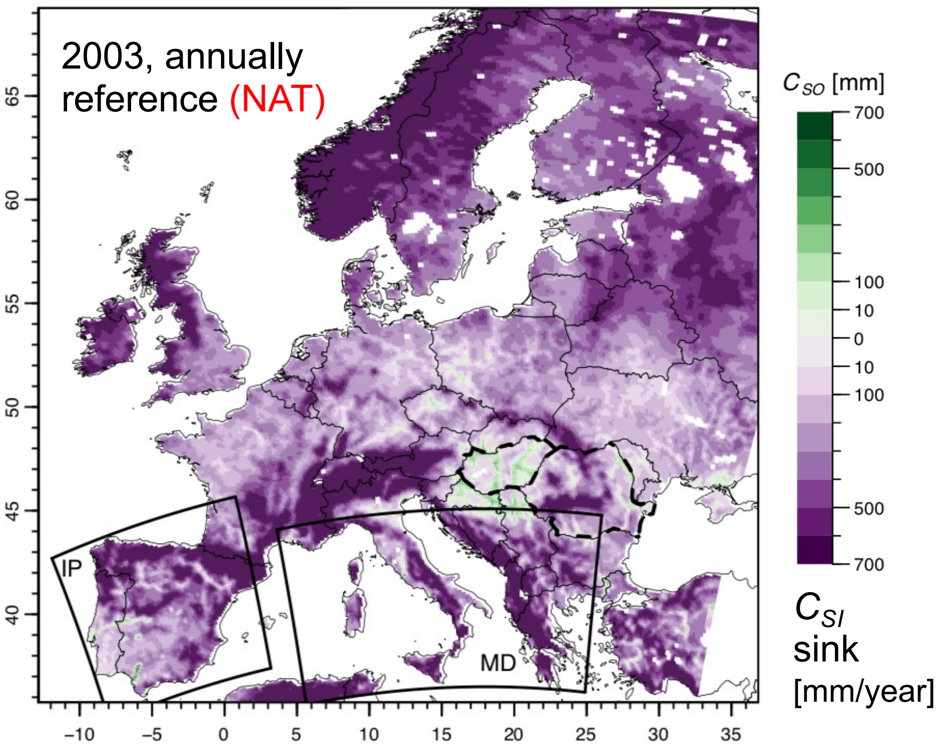
HWU impact on continental sink for atmospheric water

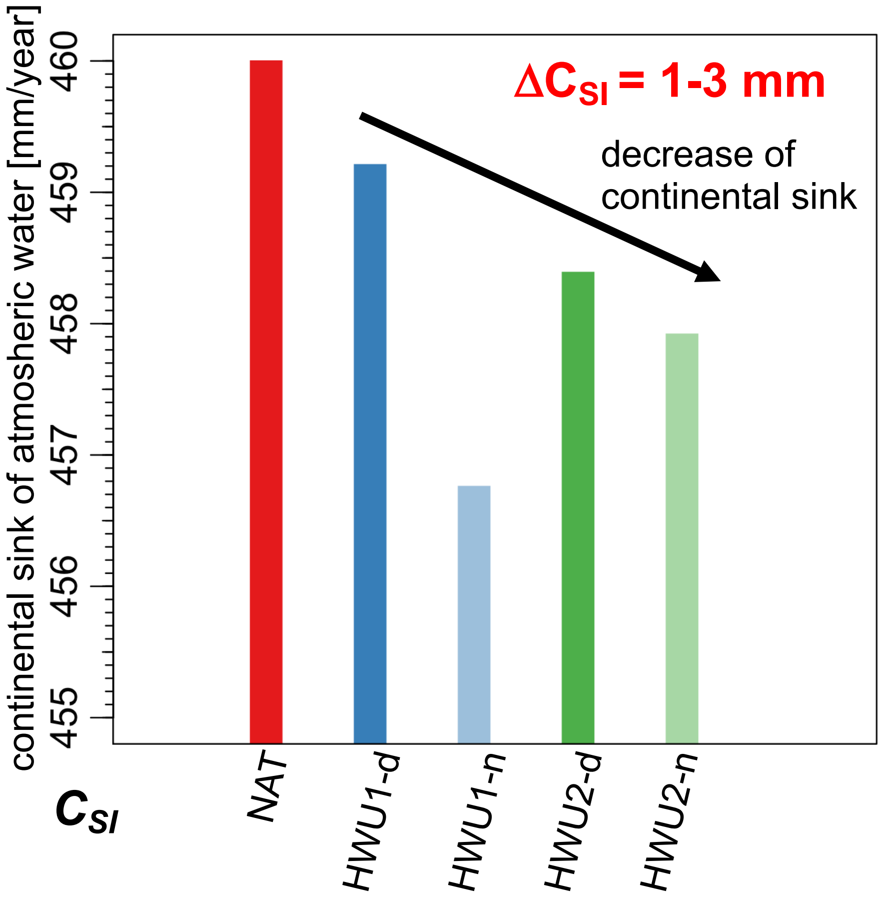
Strength of the continental moisture sink is measured by atmospheric divergence: C_{SI} = -div(Q) = P-ET



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)

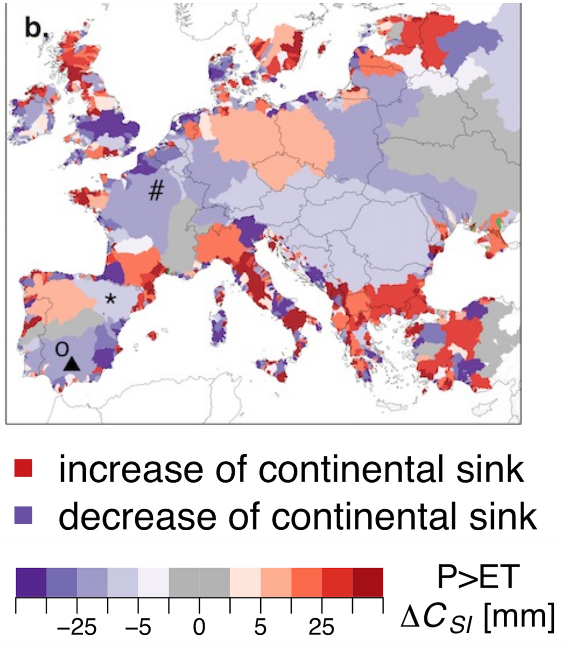
Human water use impacts on the continental sink of water (decrease) are on the same order of magnitude as sea level rise studies, i.e., impact of gw on sea level Konikow & Kendy 2005; Wada et al. 2016

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

Contribution to subsurface water storage change

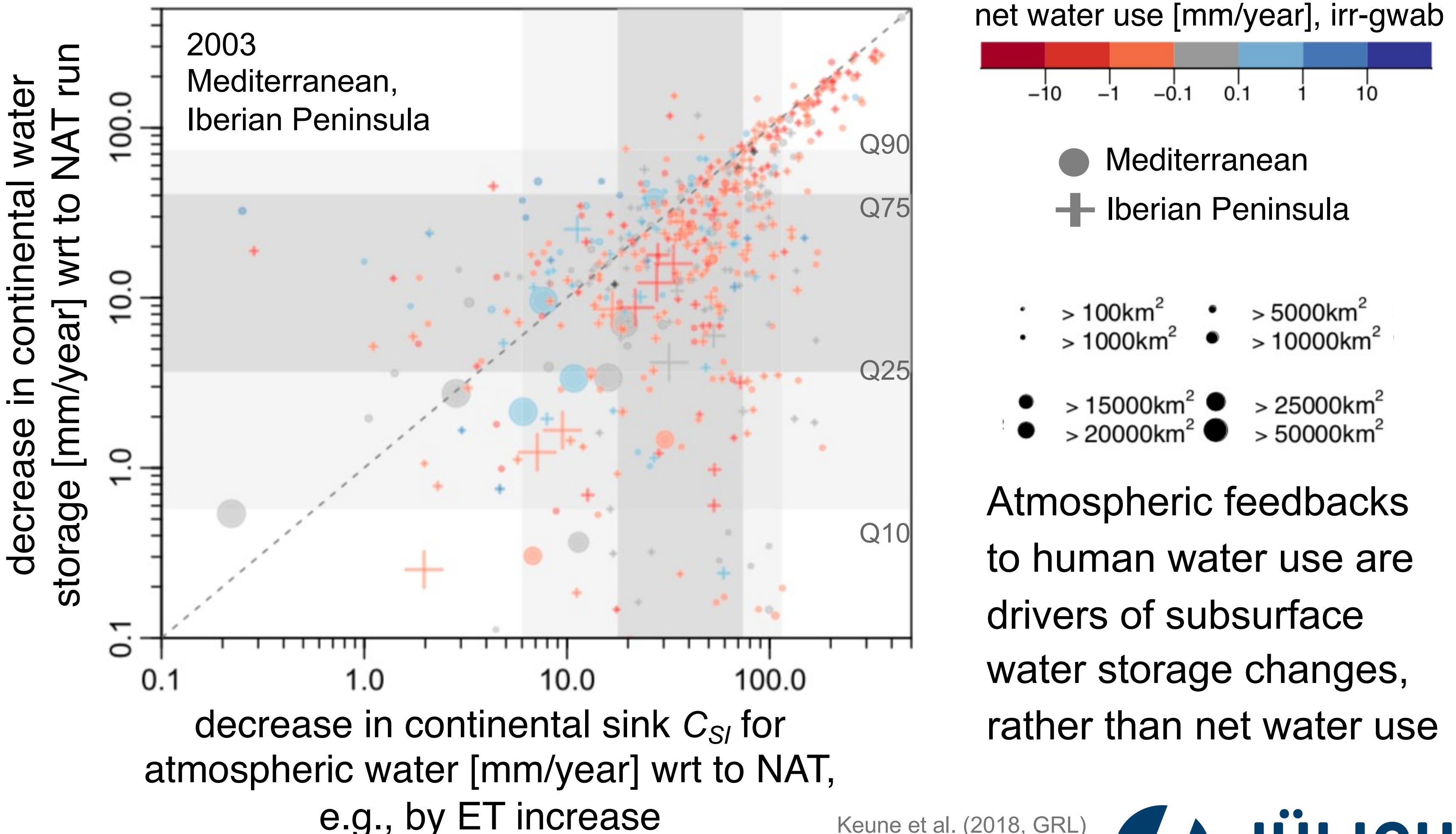
Changes in strength of the continental sink mainly manifest themselves as continental storage changes

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



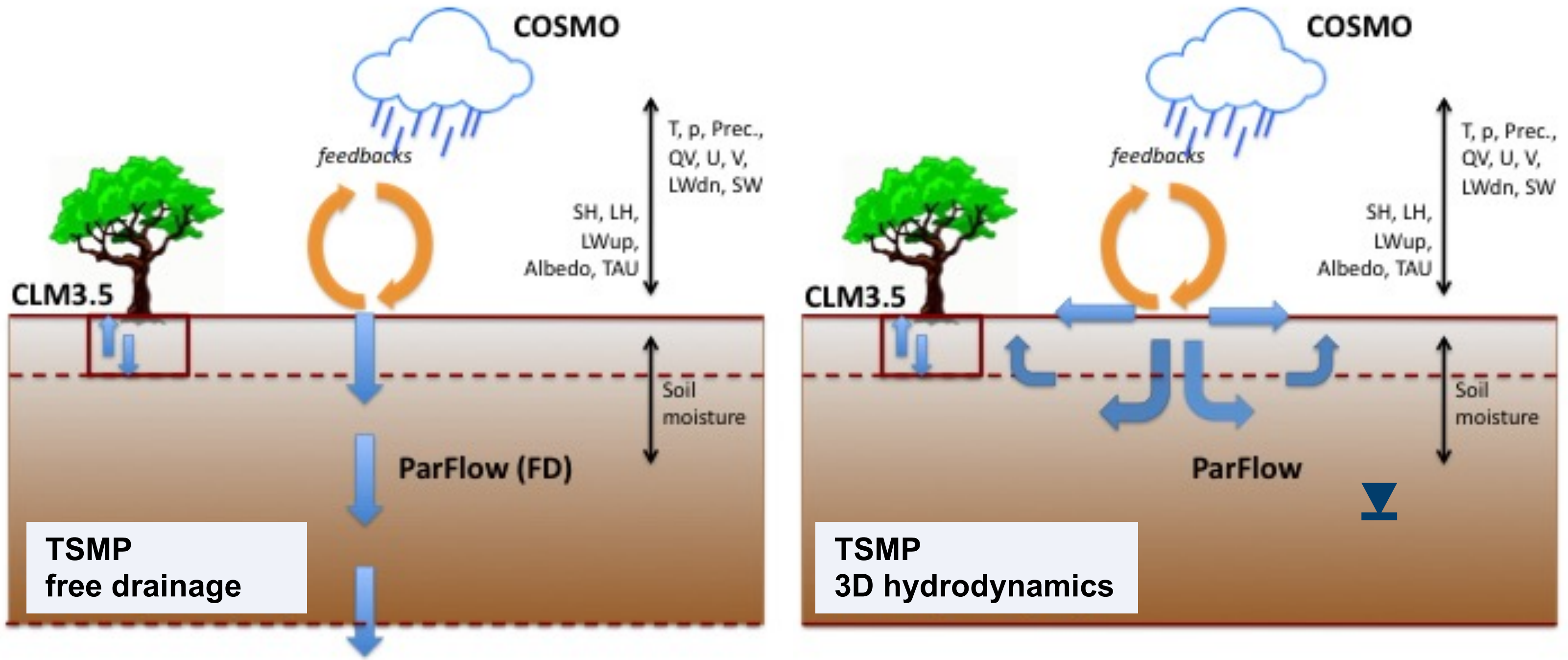
Atmospheric feedbacks to human water use are drivers of subsurface water storage changes, rather than net water use

Keune et al. (2018, GRL)

Use integrated hydrological models in coupled RCSMs

3D subsurface hydrodynamics and overland flow vs “free drainage” approach (here: ParFlow IHM w/ TSMP)

TSMP: CCLM5-01-CLM3-5-0-ParFlow3-12-0 (OASIS3-MCT2)



Keune et al. (2016, JGR)

Added value of explicit groundwater treatment

- Groundwater affects L-A coupling, land water balance, hydrometeorology in RCMs (e.g., Keune et al., 2016, JGR-A; Furusho-Percot et al., 2022, GRL; Poshyvailo et al., 2022, ESDD; Barlage et al., 2021, GRL; Schlemmer et al., 2018, JAMES)
- Closed terrestrial water cycle: water resource investigations, incl. HWU (e.g., Hartick et al., 2021, WRR; Keune et al., 2018, GRL; Furusho-Percot et al., 2019, Sc Data)
- Scale-dependent feedbacks, needed: 3D hydrodynamics w/ km-scale (e.g., Barlage et al., 2021, GRL)

Example results from 12km TSMP ERA-Interim simulations (2)

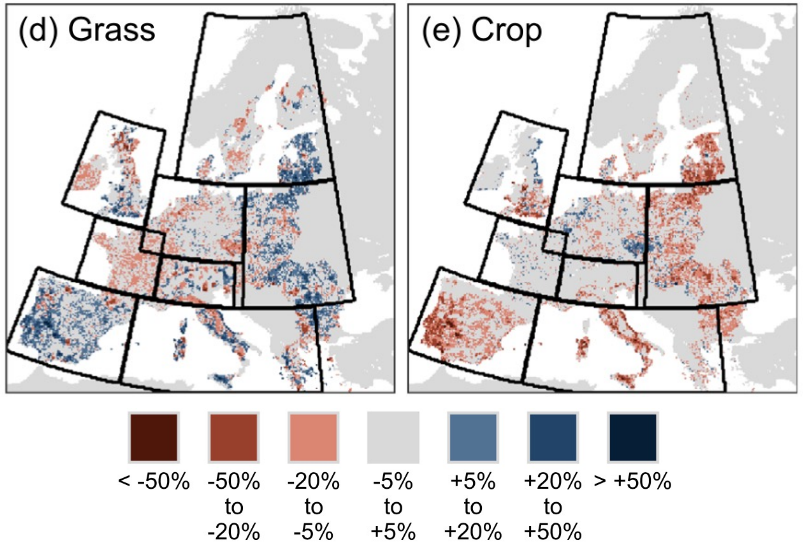
Impacts of LULCC on heat (and drought) in Europe (Zipper et al., 2019, ERL)

TSMP
w/ spectral nudging

Sensitivity study of 2003 (after ParFlow and ParFlow-CLM spinups)

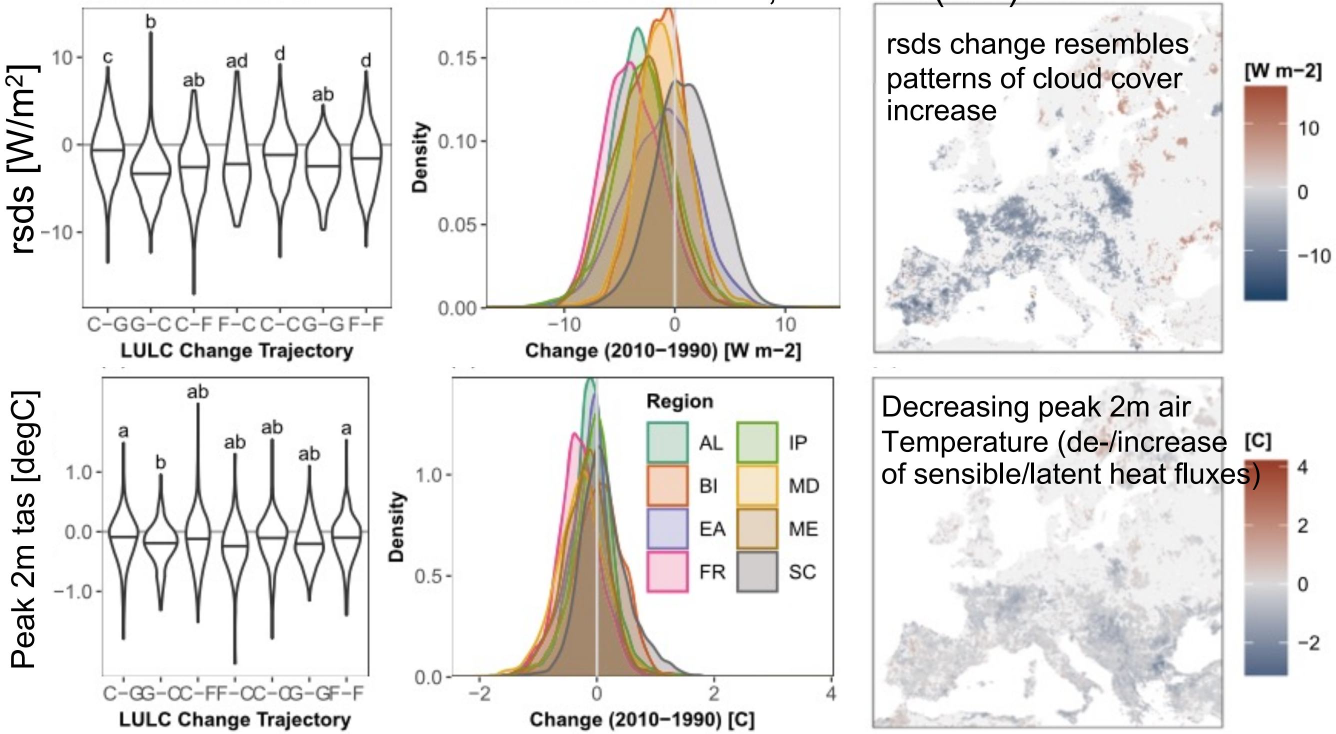
LULCC ensemble:
- 2 land cover datasets 1990 and 2010,
- 3 vegetation parametri-sations each

Analyses for 2003 JJA



Changes in % land cover/use from 1990 to 2010; seven LULCC trajectories overall

Differences LULC2010-LULC1990, summer (JJA)



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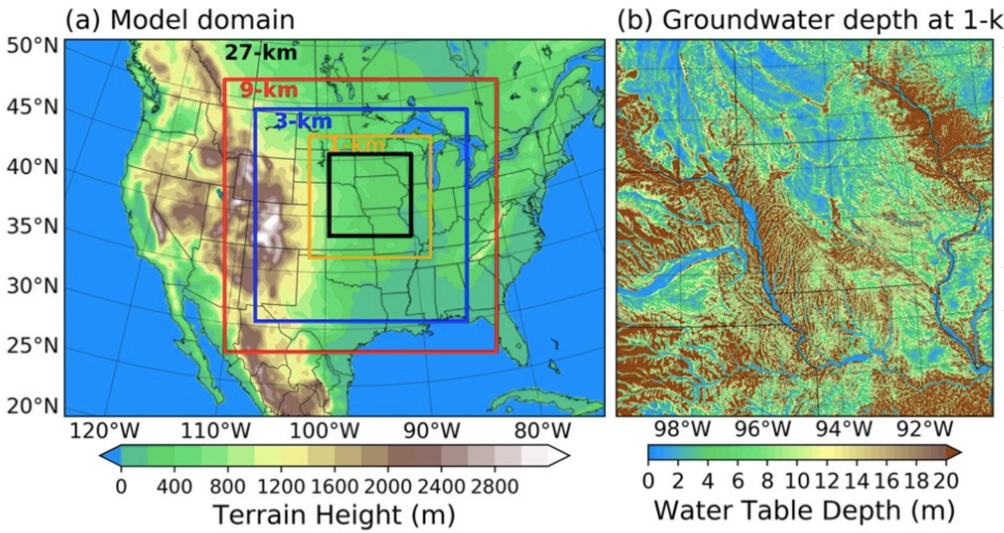
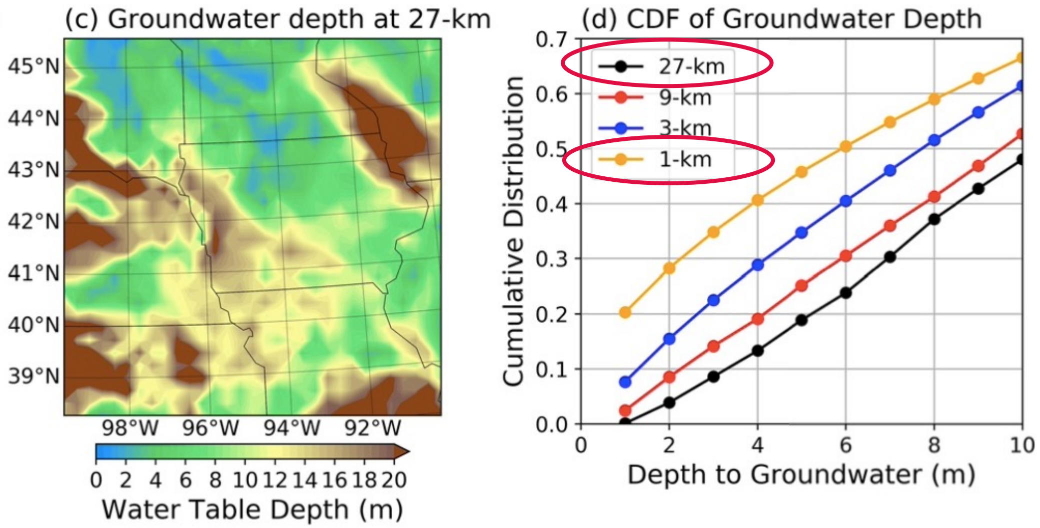
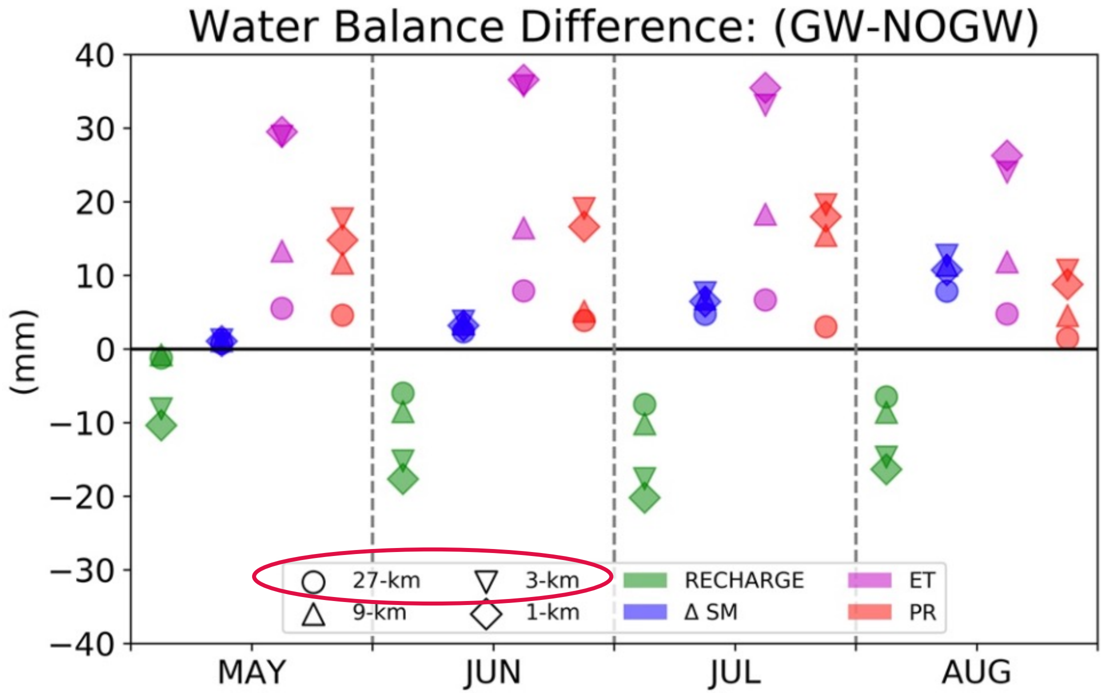
Impact of subsurface hydrodynamics is resolution dependent

GW processes modify land-surface water balance and hydrometeorology: Barlage et al. (2021, GRL)



WRF RCM w/ Noah-MP, JJA 2012-14, 27/9/3/1km grid spacing, **w/ 3D gw w/ 1D free drainage gw**





Considering GW physics leads, e.g., to:
- Realistic water table pattern (depending drainage, convergence, etc.)
- Higher evaporative fraction, lowering of tas bias
- 3km or less: Realistic gw processes (shallow water tables in convergence zones with alluvia) and water redistribution

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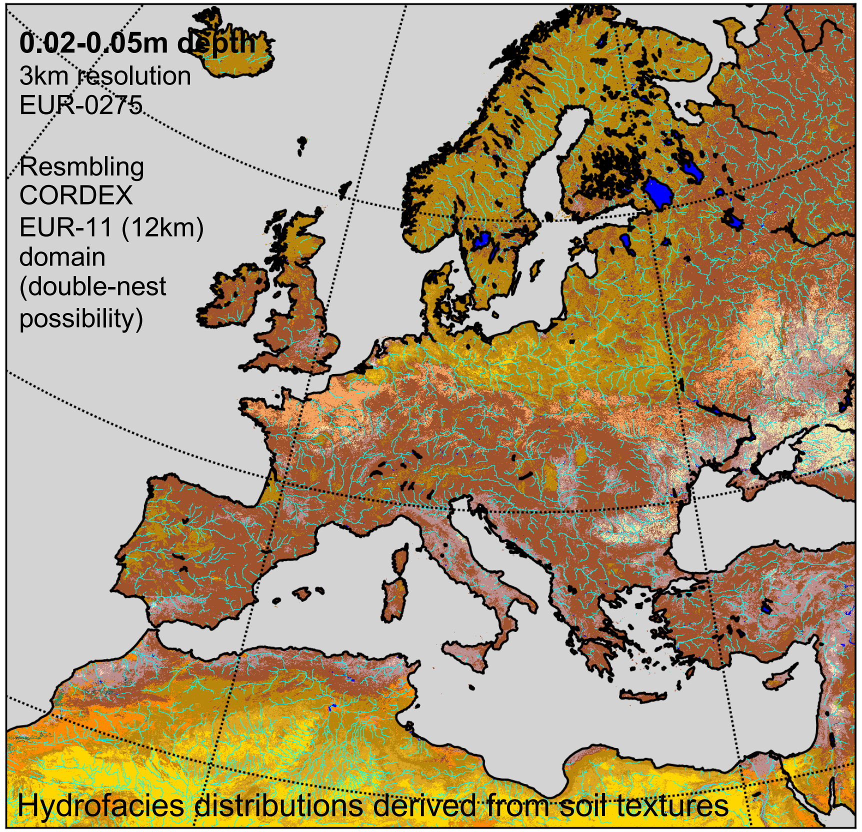
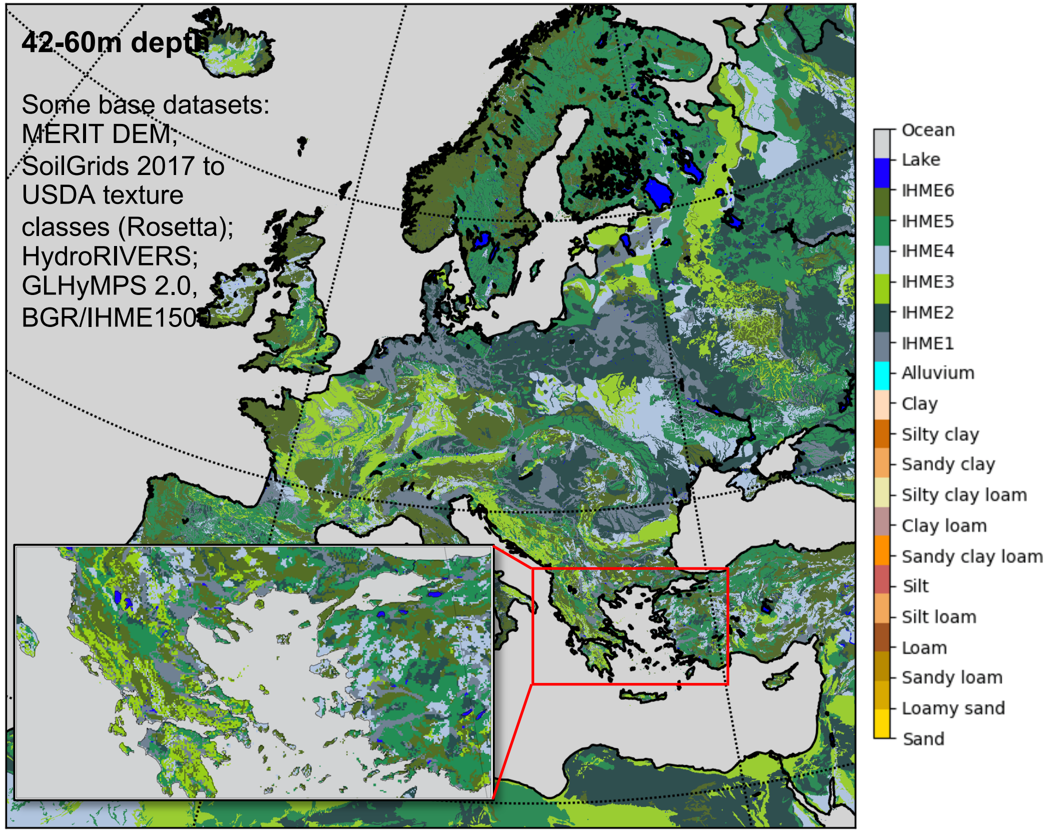
New TSMP setup for CORDEX-CMIP6, external parameters

Improved hydrogeology, spinup: loop x3 over 1970-1979 w/ fully coupled model





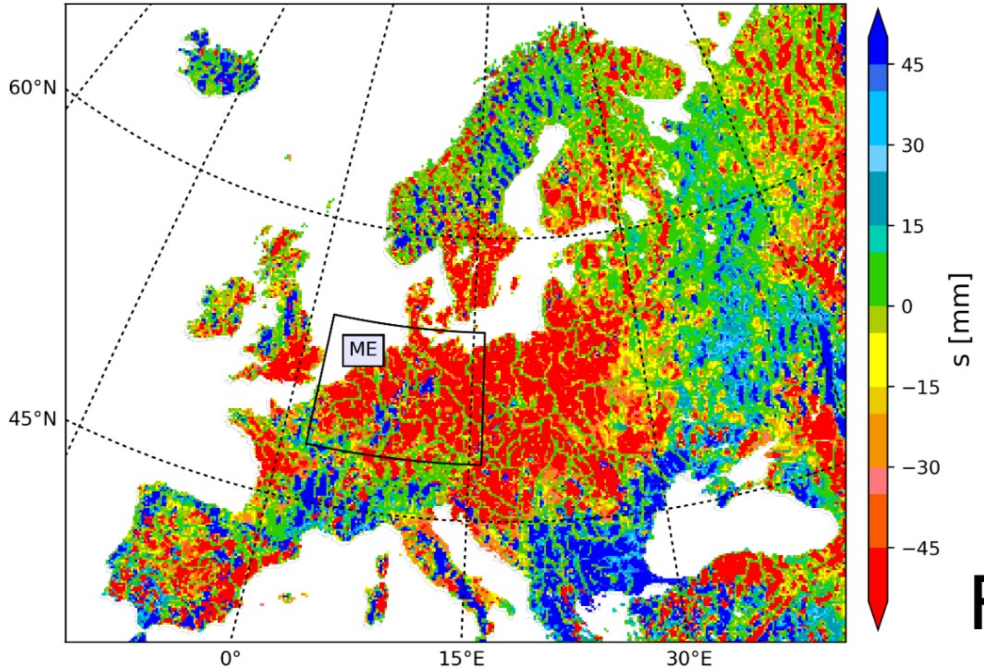
ParFlow indicators for soil hydraulic properties (permeability, specific storage, porosity, van Genuchten parameters)

Drought Conditions Accelerate the Energy Cycle over Continental Europe in a Fully Coupled Terrestrial Model

Carl Hartick[1,2], Carina Furusho-Percot[1,2], Klaus Goergen[1,2], Stefan Kollet[1,2] and Martyn P. Clark[3]
[1]Institute of Bio- and Geosciences (Agrosphere, IBG-3), Research Centre Jülich, Germany
[2]Centre for High-Performance Scientific Computing in Terrestrial Systems, Geoverbund ABC/J, Jülich, Germany
[3]University of Saskatchewan Coldwater Laboratory, Canmore, Canada

Hartick et al. (2022, GRL)

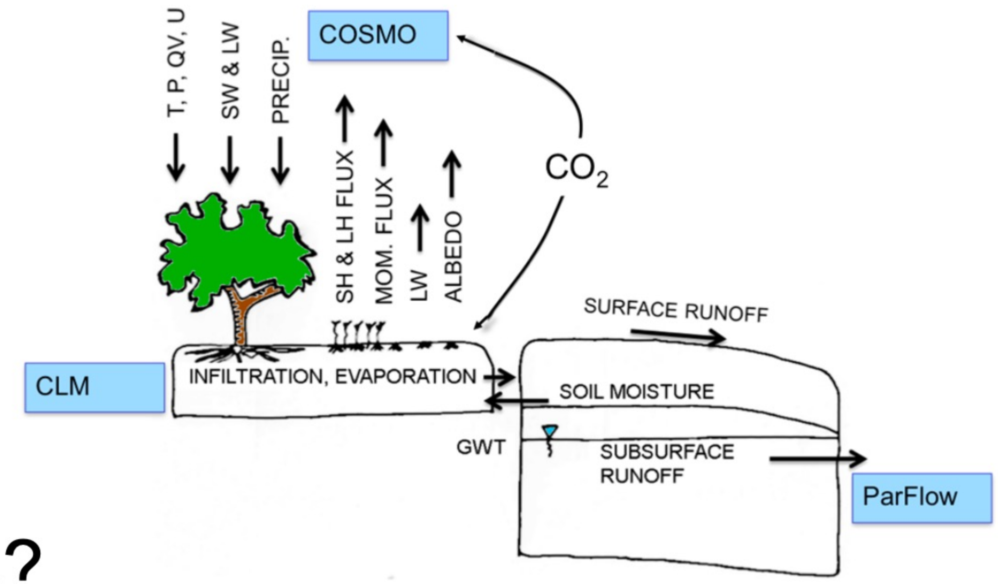
Motivation: Drought period 2018-2020



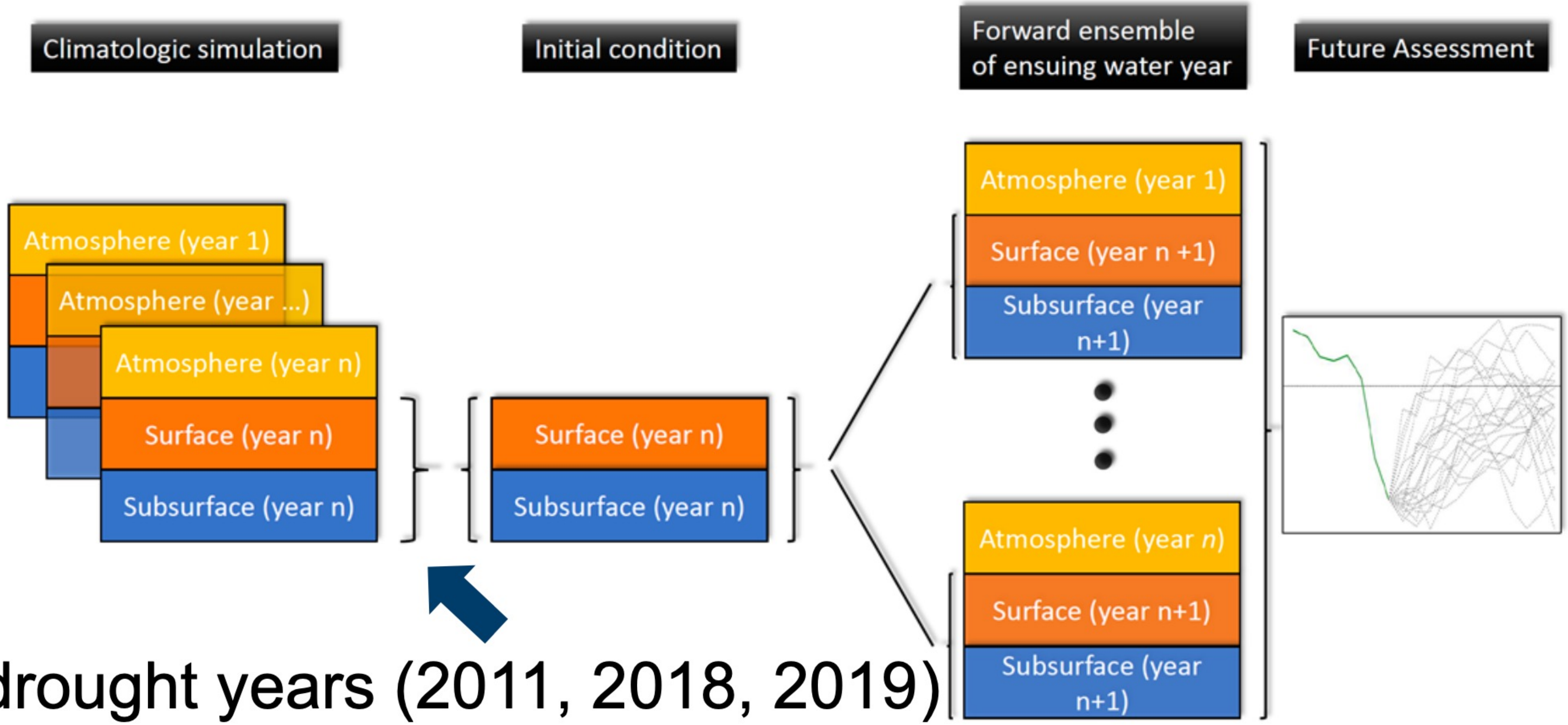
Subsurface water storage anomaly August 2018

Feedbacks?

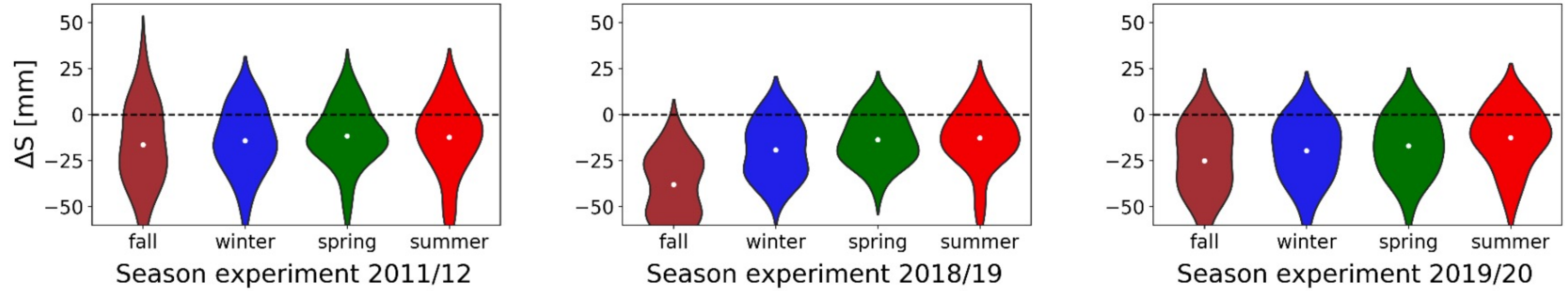
Model: TSMP



Ensemble simulations influenced by drought conditions



Extracting drought years (2011, 2018, 2019)



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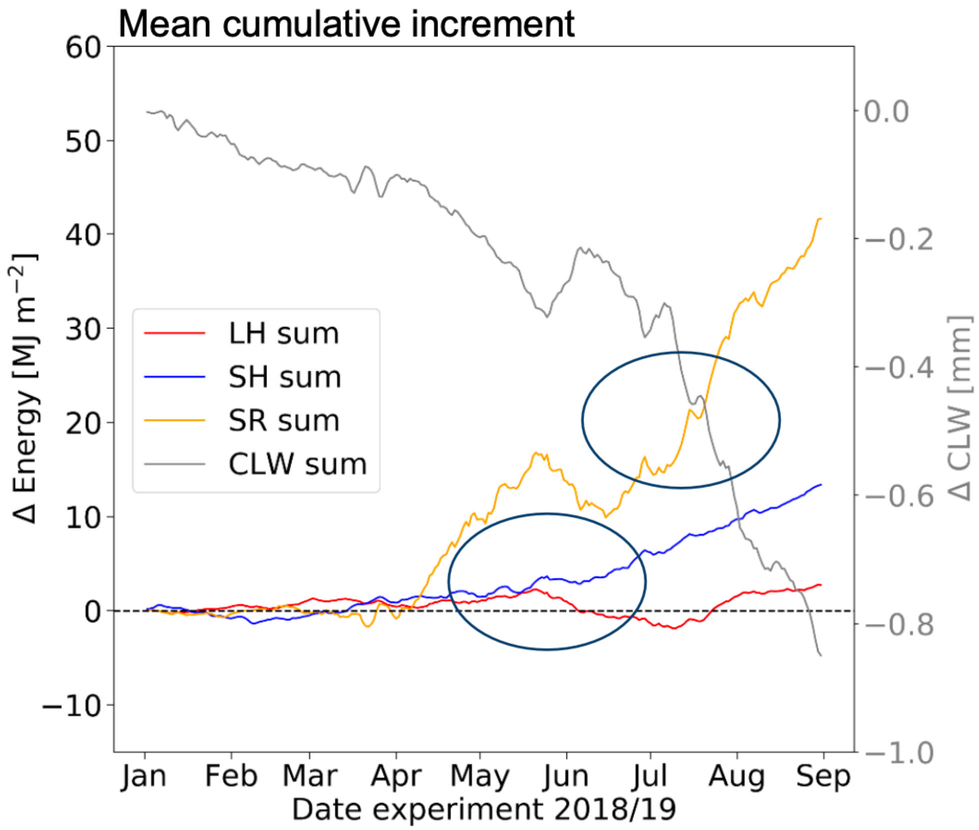
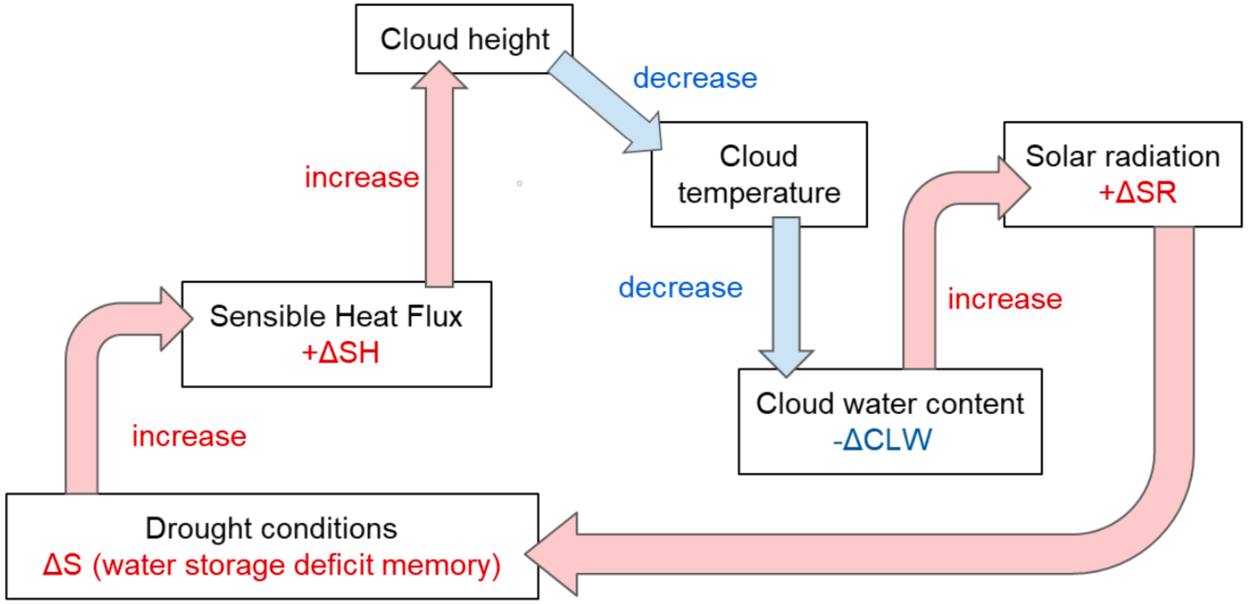
Results and Conclusion

Changes in the energy budget and cloud properties





Drought conditions accelerate the energy cycle via altered clouds

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Added value of incorporating HWU

Validation study, Keune et al. 2019 JAMES