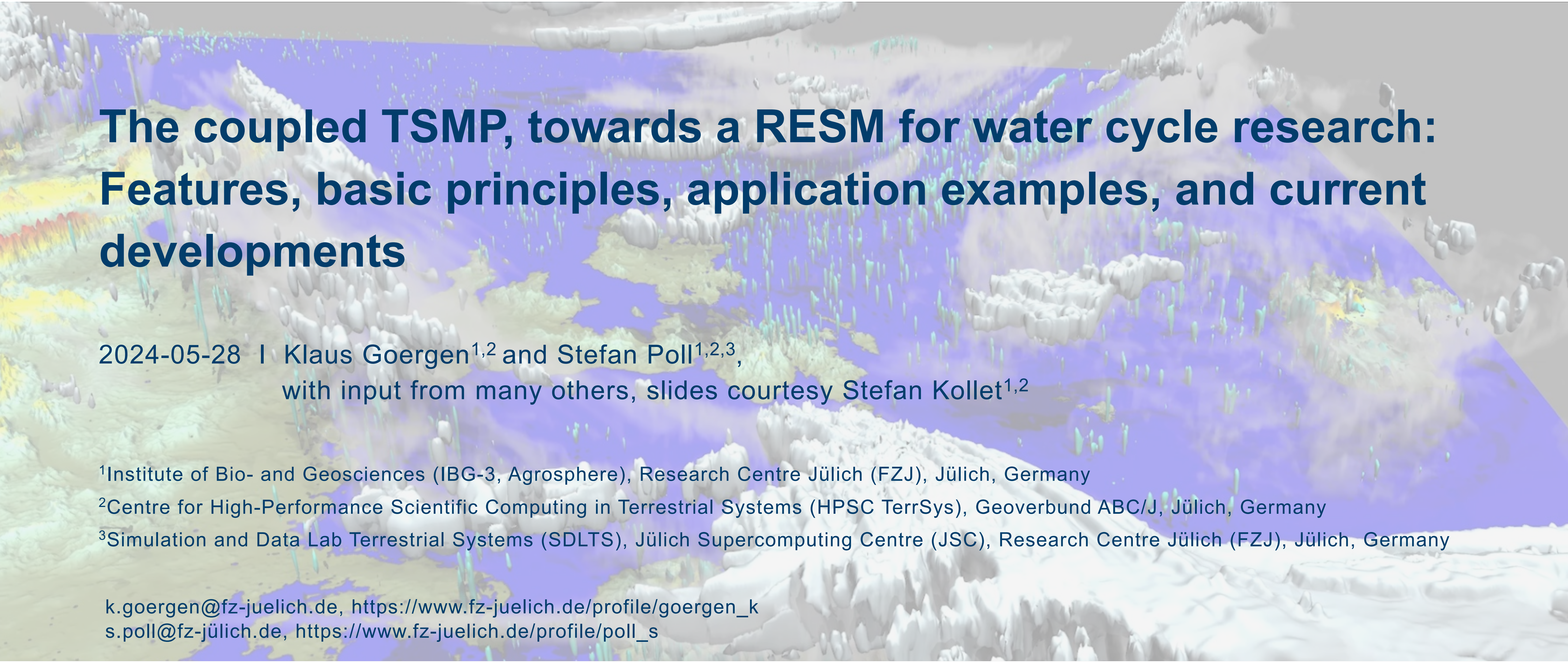

The coupled TSMP, towards a RESM for water cycle research: Features, basic principles, application examples, and current developments

2024-05-28 I Klaus Goergen[1,2] and Stefan Poll[1,2,3],
with input from many others, slides courtesy Stefan Kollet[1,2]

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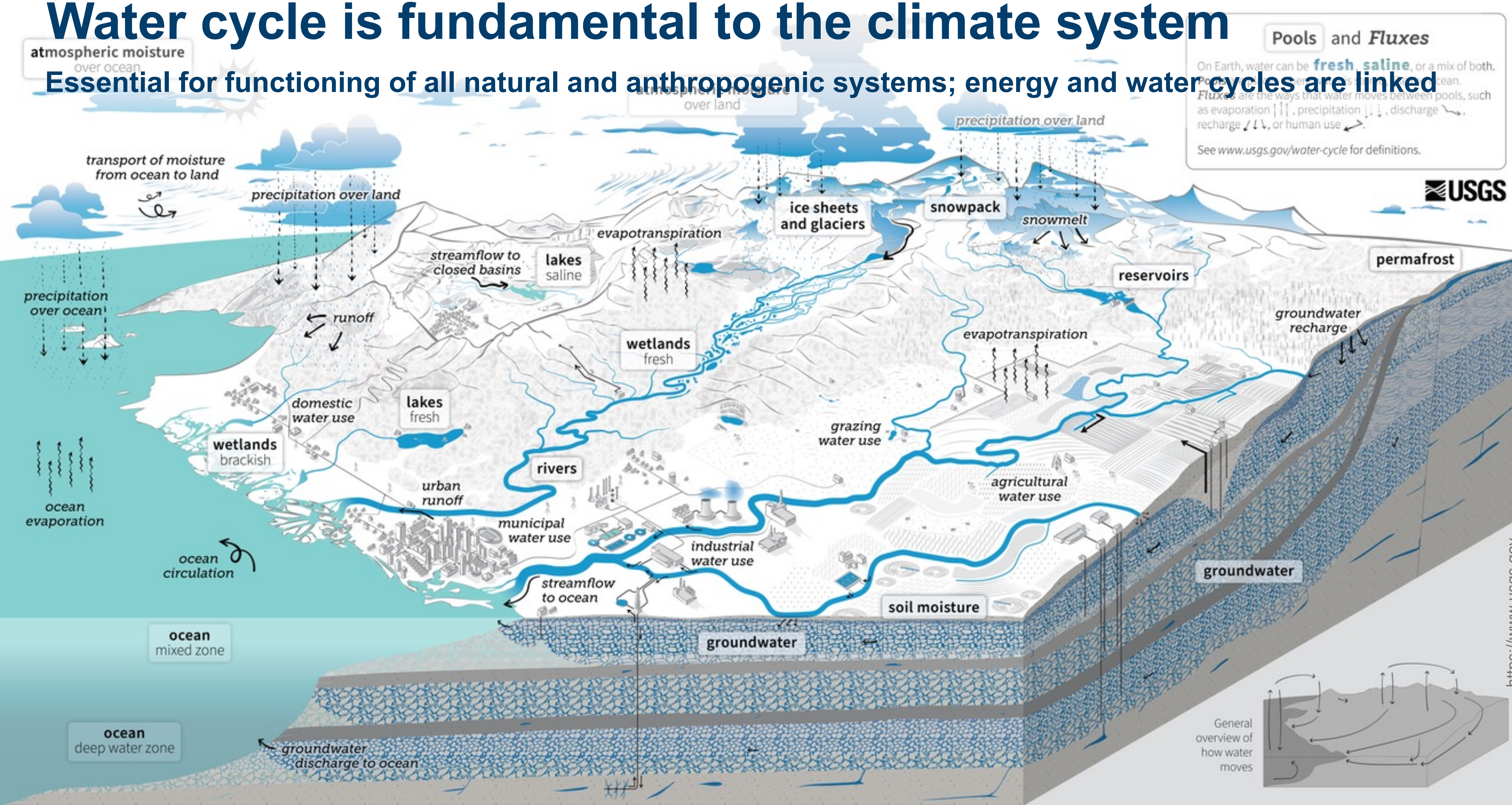
CRC1502
DETECT
sfb1502.de

Setting the scene for the day

Our interest is in the terrestrial water cycle,
how it functions, how it changes, how it is impacted

Water cycle is fundamental to the climate system

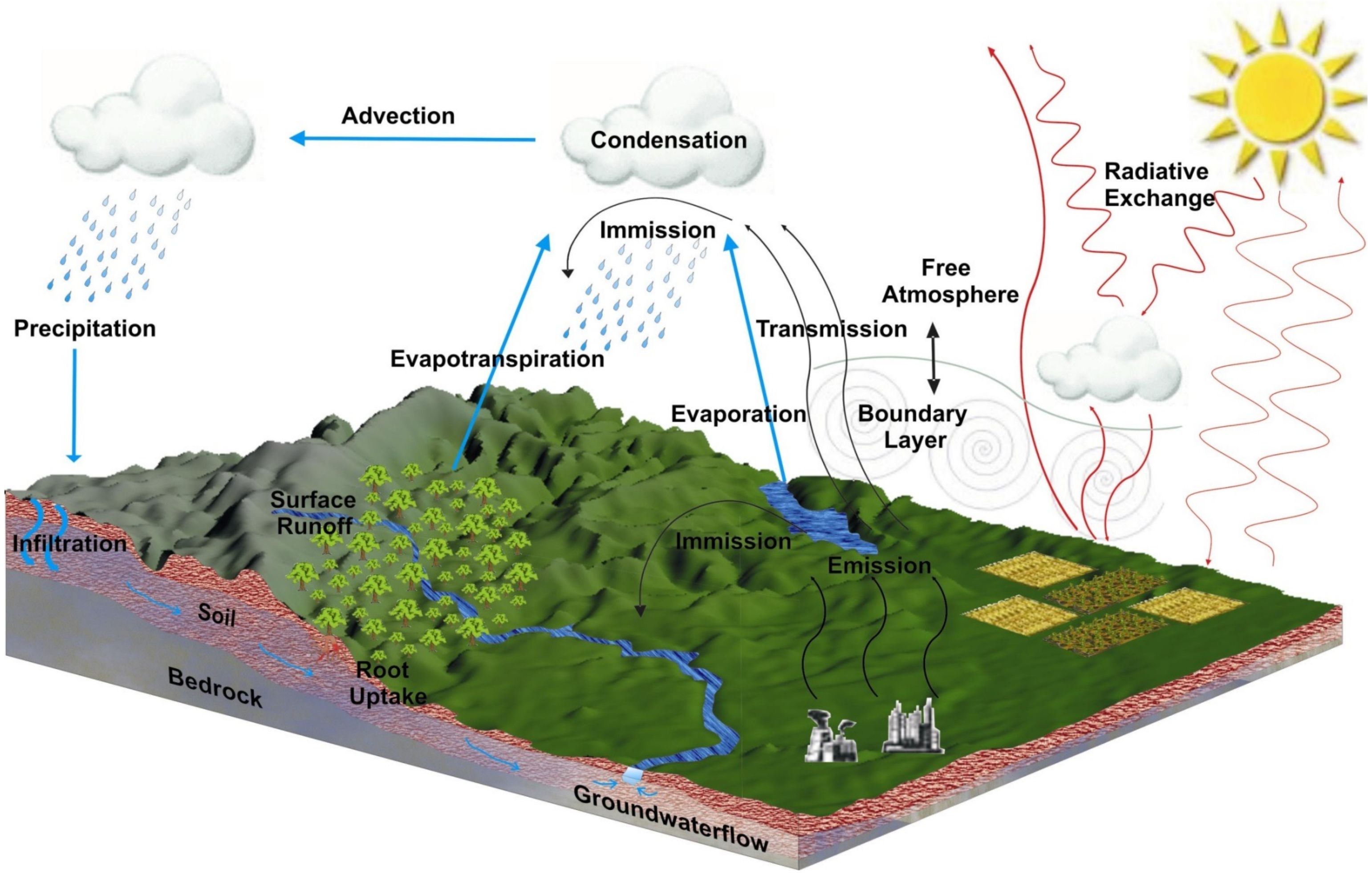
Essential for functioning of all natural and anthropogenic systems; energy and water cycles are linked



https://www.usgs.gov

Integrated modelling of terrestrial systems group (S. Kollet)

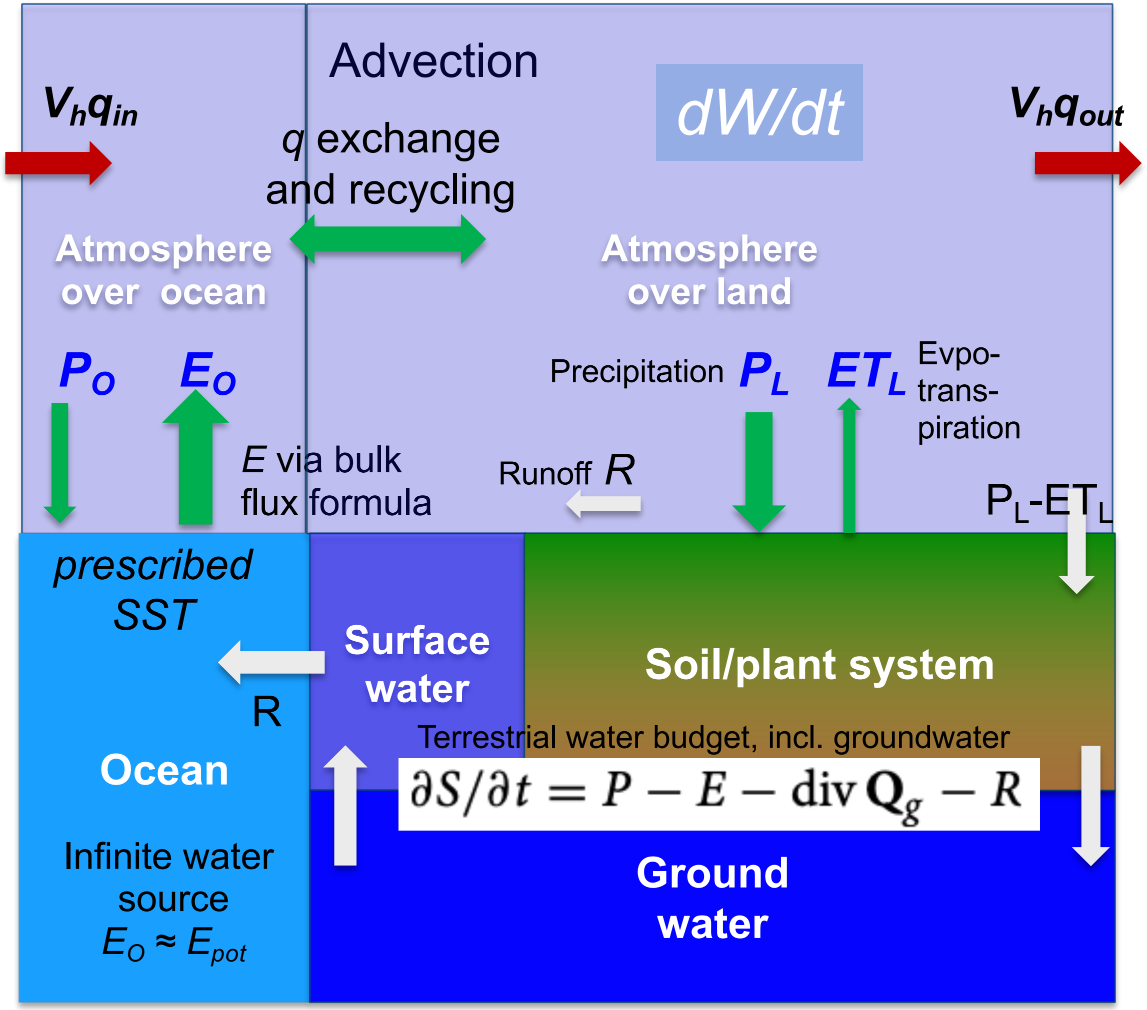
Our interest: Terrestrial water cycle and groundwater-to-atmosphere (G2A) interactions and feedbacks



- 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

Water cycle, groundwater-to-atmosphere

Subsurface budget needs to be considered



Time-averaged total atmospheric water balance:

dW/dt = - div(Q_a) – P + ET

$$\operatorname{div} \mathbf{Q} = -\nabla \cdot 1/g \int_0^{p_s} q \mathbf{V}_h dp$$

Atmospheric storage change over long time scales, (here: dt=1yr): dW/dt ≈ 0

Over relative long time scales the atm. divergence equals the continental sink; simplified atmospheric water budget for a control volume:

div(Q_a) = – P + ET = C_s

Terrestrial and atmospheric water budgets are linked:

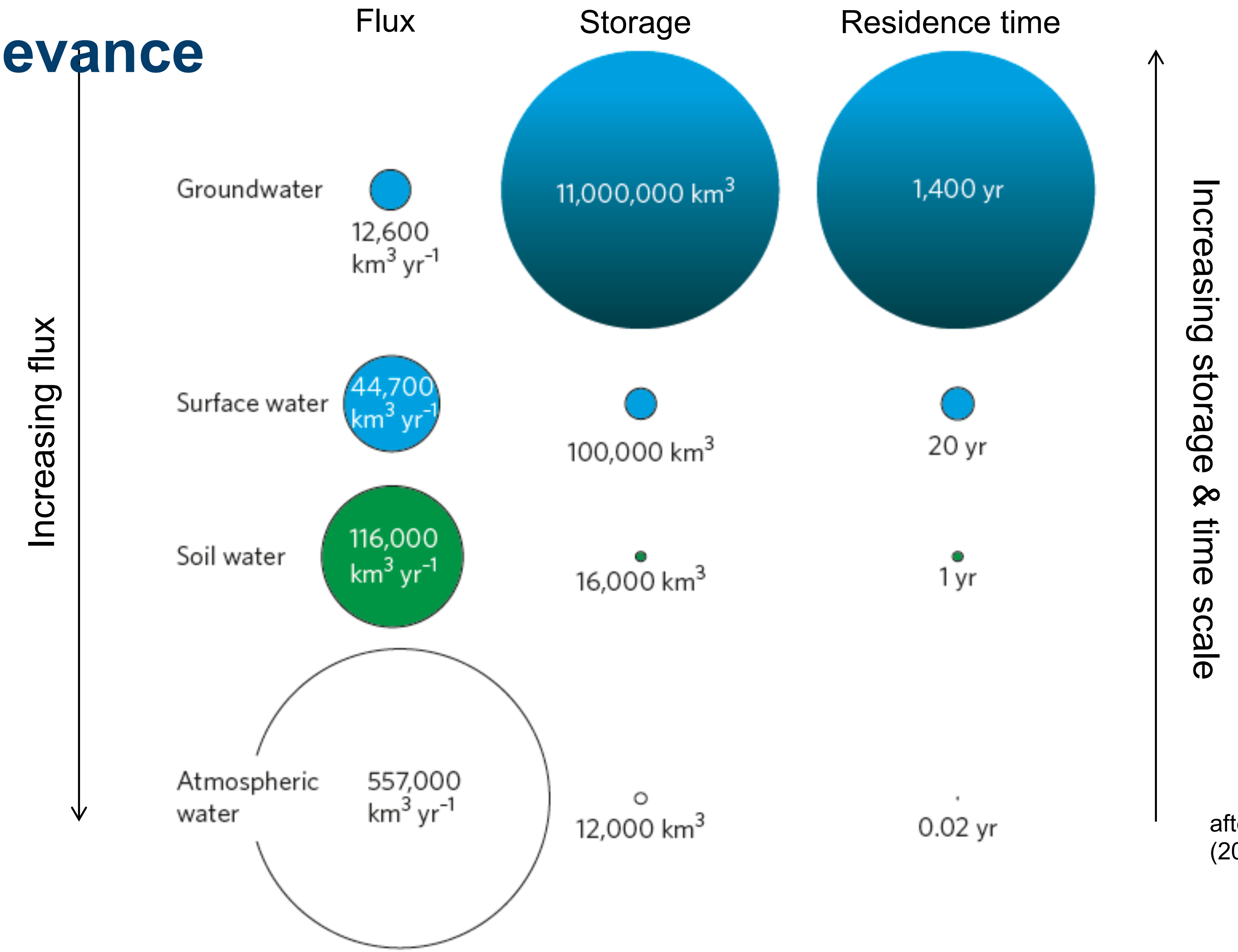
dS/dt = – div(Q_a) – R

Terrestrial water budget:

dS/dt = P – ET – R

Assumptions: closed continental basin (div(Q_{lg}) = 0)

GW relevance

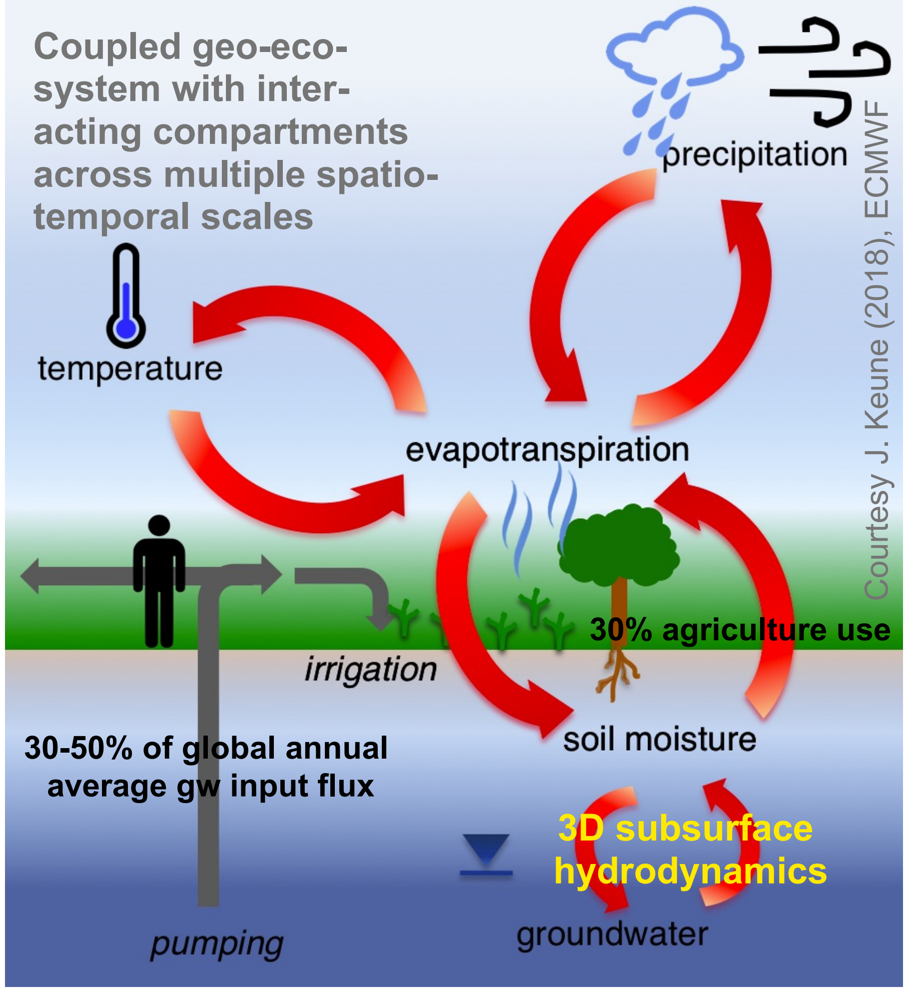


Volumes and rates of the hydrologic cycle

after Aeschbach-Hertig & Gleeson (2012, Nat.Geosc)

Motivation

Intensification of the hydrological cycle under climate change (e.g., Huntington, 2006, J Hydrol; Wada and Bierkens, 2014, ERL)



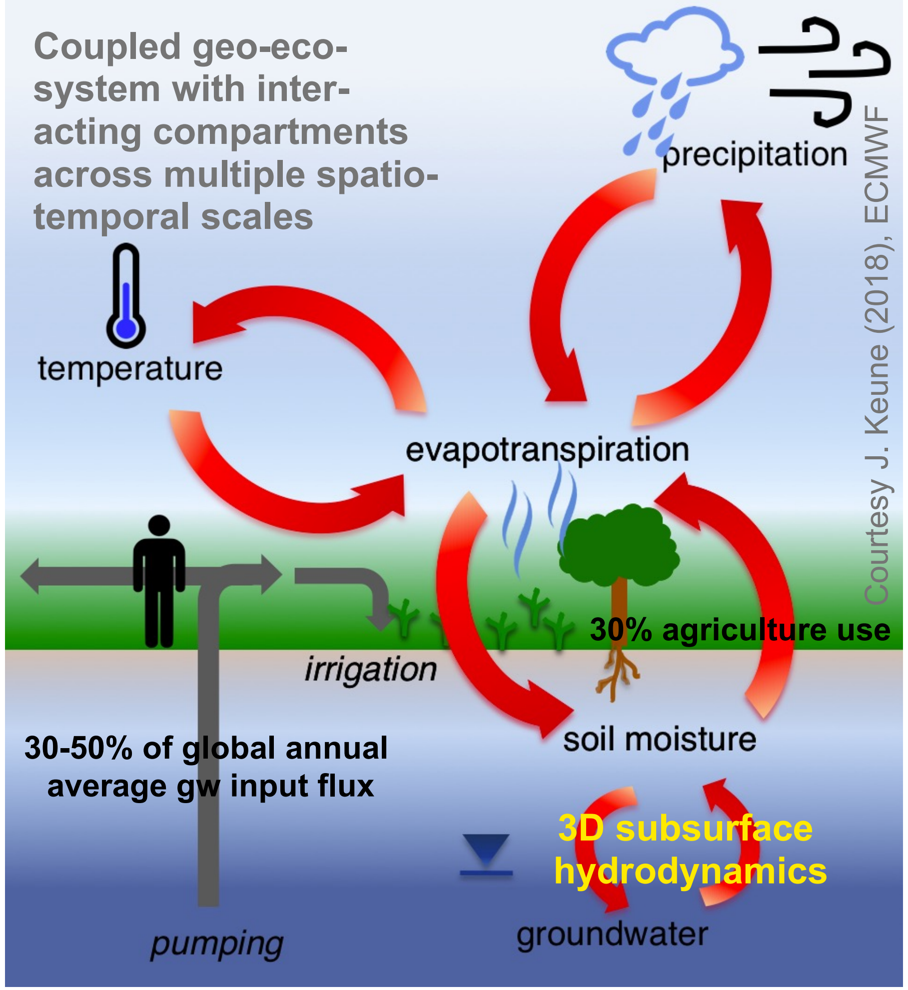
Numbers: Aeschbach-Hertig and Gleeson (2012); Klein Goldewijk et al. (2017)

- Global (climate, land use) change has an impact on water as a resource, its sustainable use, and affects water security
- 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., Jensen et al., 2019, JGR-A)
- 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

Some research questions and goals

DFG CRC DETECT (www.sfb1502.de)

Assess the groundwater-terrestrial system-atmosphere interactions and feedbacks

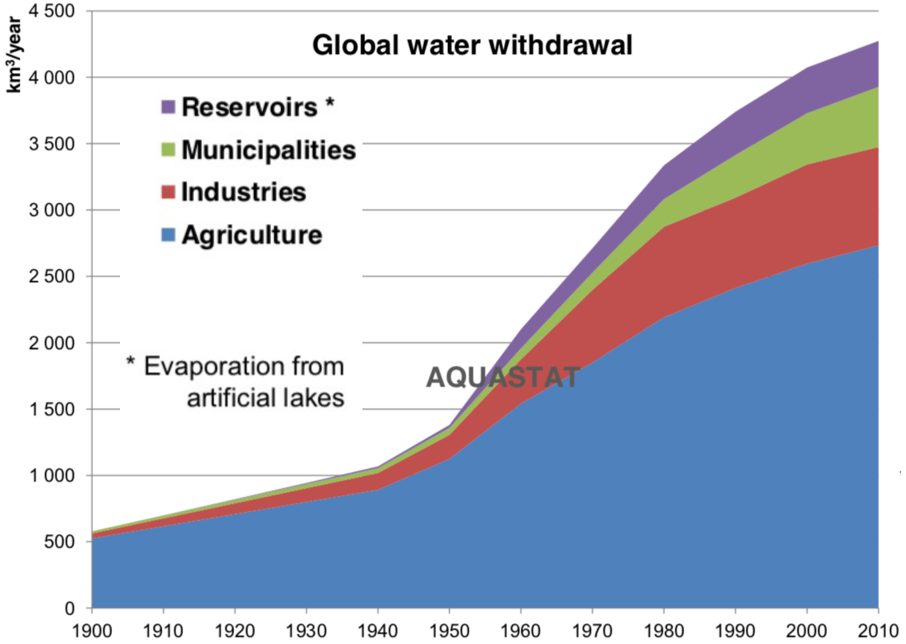


Numbers: Aeschbach-Hertig and Gleeson (2012); Klein Goldewijk et al. (2017)

- What are **drivers of hydroclimatic extremes** (droughts, heatwaves) in the context of land-atmosphere coupling? How does groundwater alleviate extremes? (*processes*)
- Provide a **physically consistent groundwater-to-atmosphere climatology** as a basis to assess how extreme weather events and climate change affect groundwater (*application*)
- What is the **impact of extreme hydrometeorological conditions** (e.g., drought of 2018 in Europe) on **water resources** in Europe? (*resources*)
- What is the **added value of coupled RCSMs** w.r.t. interactions and feedbacks? (*model development*)
- Aside from GHG forcing and natural variability, also **human water use** (HWU) and **land use and land cover change** (LULCC) have led to **persistent modifications of the coupled water and energy cycles** of land and atmosphere with multiple (non-)local (hydro-climatic) effects, contributing to observed regional water storage trends.

Human vs natural water cycle, human water use matters

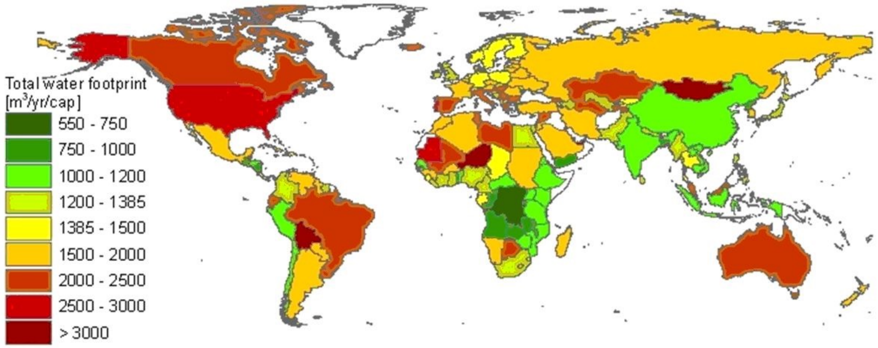
Mean global water use footprint in the order of magnitude of the global groundwater flux and increasing



https://www.fao.org/aquastat/en/overview/methodology/water-use

FAO’s Information System for Water and Agriculture

Total water use per capita including agriculture, industry, domestic, water transfers, etc.



Mekonnen and Hoekstra (2011), www.waterfootprint.org, https://sswm.info/node/7612

Water footprint: about 1400 m3yr-1 per capita

Contents and narrative of today

Talk about why/how we are moving towards coupled RCSMs / RESMs, Groundwater-2-Atmosphere, G2A

- Simulation, is the third pillar of science, climate or NWP model are the “labs of the Earth system” – we use these models for forecasts, hindcasts, projections, data generation, sensitivity studies, ideal and real data cases, process understanding, etc.

- Water cycle is fundamental for the climate system, subsurface hydrodynamics incl. groundwater are relevant (L-A coupling, hydroclimatic extremes, applied water resources questions, etc.)
- Our TSMP RCSM: A coupled atmosphere-land-hydrology/subsurface model (land surface processes we saw yesterday). To capture water and energy cycles we need coupled models.
- How is the coupling implemented, what are considerations behind coupling compartments?
- Does it matter to consider GW? – Some examples from our work, human water use is important
- Current developments: going to coupled km-scale resolution simulations

Our tool for water cycle research:

The fully coupled model system TSMP for groundwater-to-atmosphere simulations of the closed terrestrial water cycle

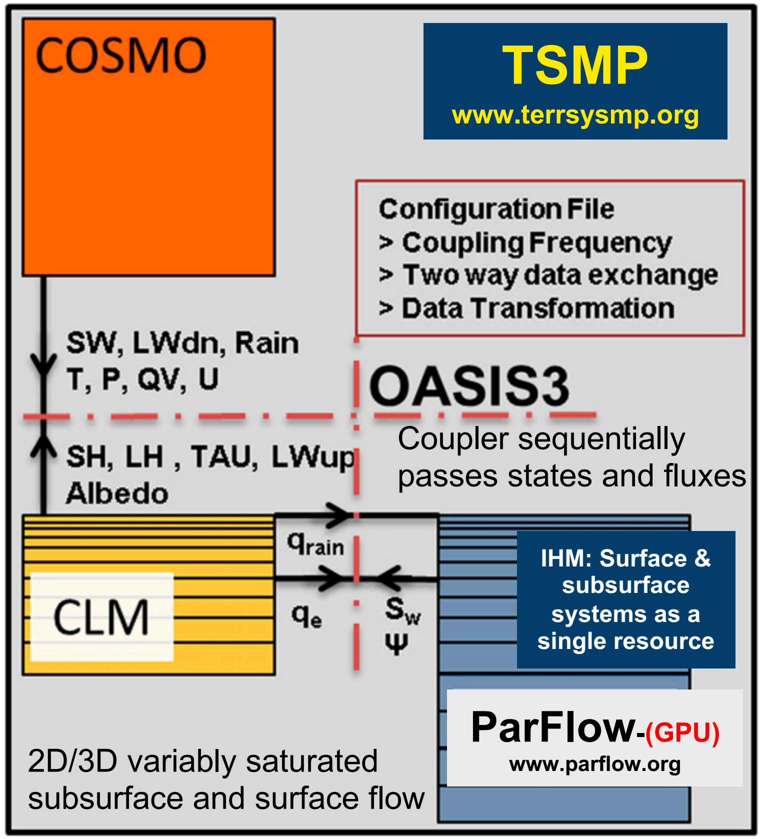
There is a need for integrated groundwater-to-atmosphere simulations – the coupled land surface/subsurface and atmospheric water and energy cycles are impacted

Terrestrial Systems Modelling Platform (TSMP) model system

Closure of the terrestrial water and energy cycle from groundwater-to-atmosphere (G2A)

- 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

→ Representation of complex interactions among the compartments in the geo-ecosystem

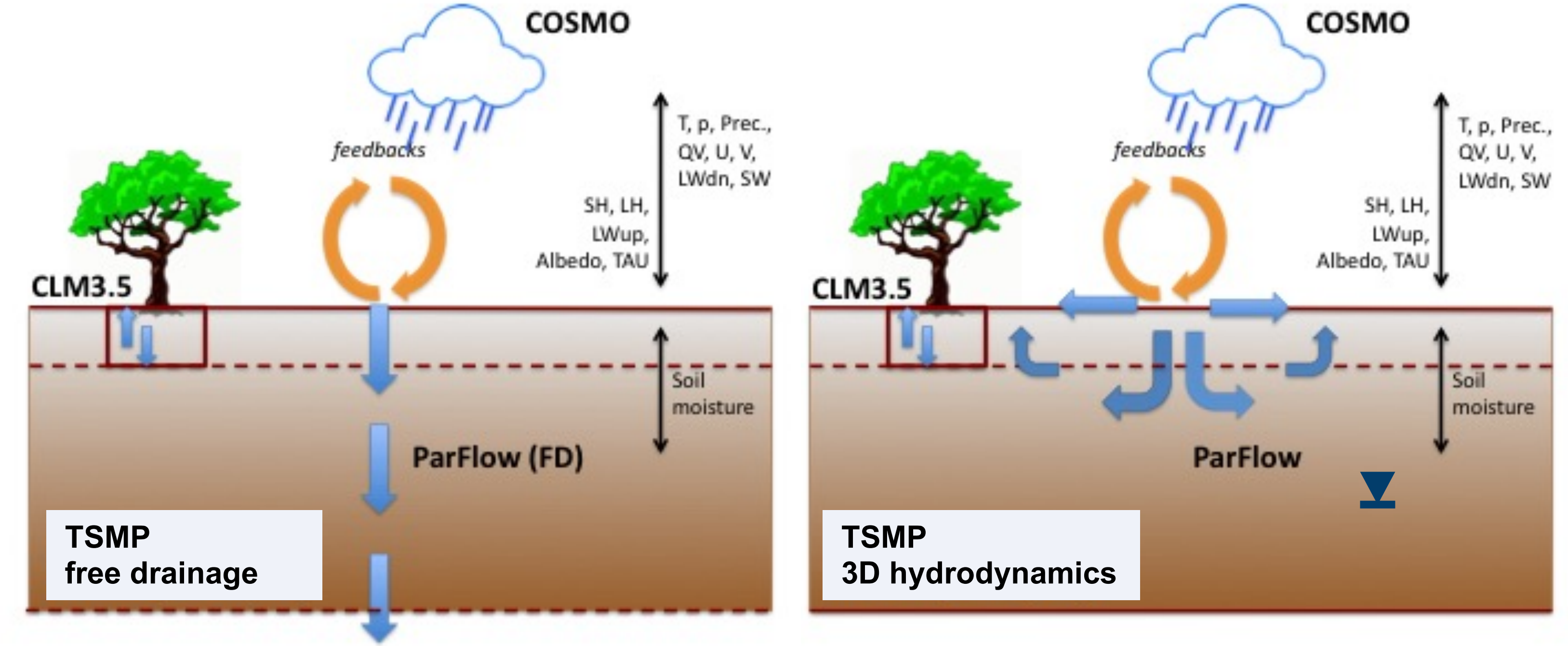


Shrestha et al. (2014, Mon Weather Rev); Kurtz et al. (2016, GMD); Hokkanen et al. (2021, Comput Geosc)

Integrated hydrological models in coupled RCSMs

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

TSMP: CCLM5-0-1-CLM3-5-0-ParFlow3-12-0 (OASIS3-MCT2)

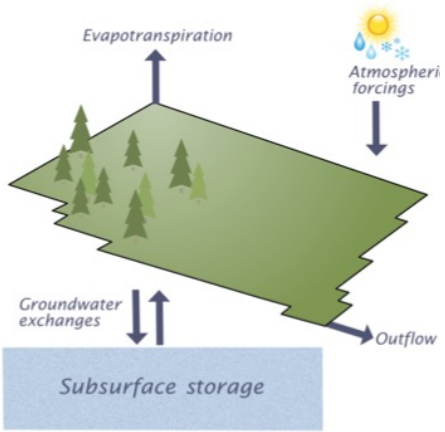


Keune et al. (2016, JGR)

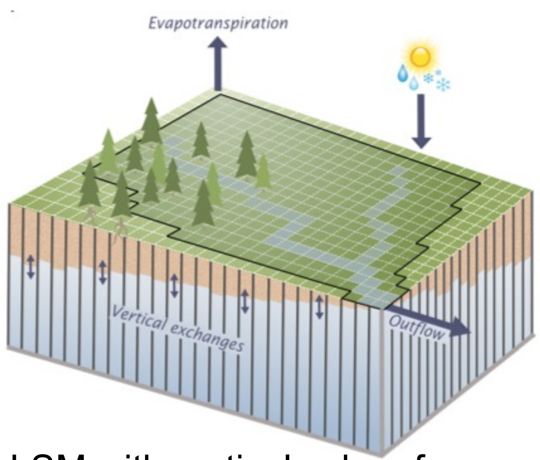
Integrated hydrological models in coupled RCSMs

Added value of 3D subsurface hydrodynamics

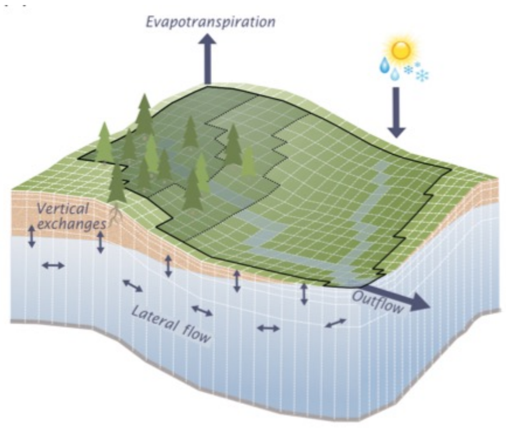
IHMs: resolve km-scale heterogenity, hill slopes, linked (sub-)surface hydrodynamics, variable source area hydrology



Lumped parameter HM



LSM with vertical subsurface exchanges



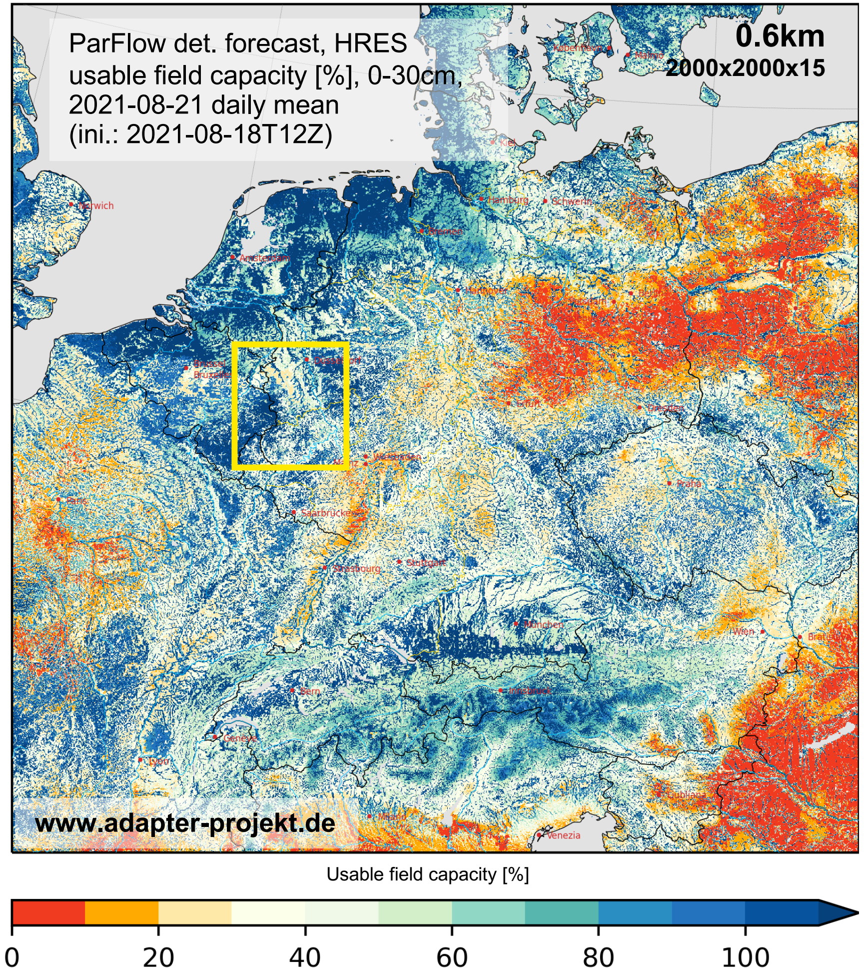
Integrated HM

Condon and Maxwell (2017, HESS)

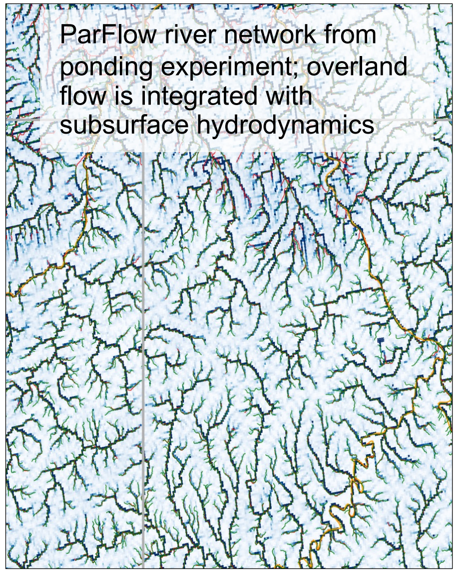
- Groundwater affects L-A coupling, land water balance, hydrometeorology in RCMs
  (e.g., Keune et al., 2016, JGR-A; Furusho-Percot et al., 2022, GRL; Poshyvailo et al., 2022, ESDD; Barlage et al., 2021, GRL)
- Closed terrestrial water cycle: water resource investigations, including human water use w/ water abstraction and irrigation
  (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 (Barlage et al., 2021, GRL)

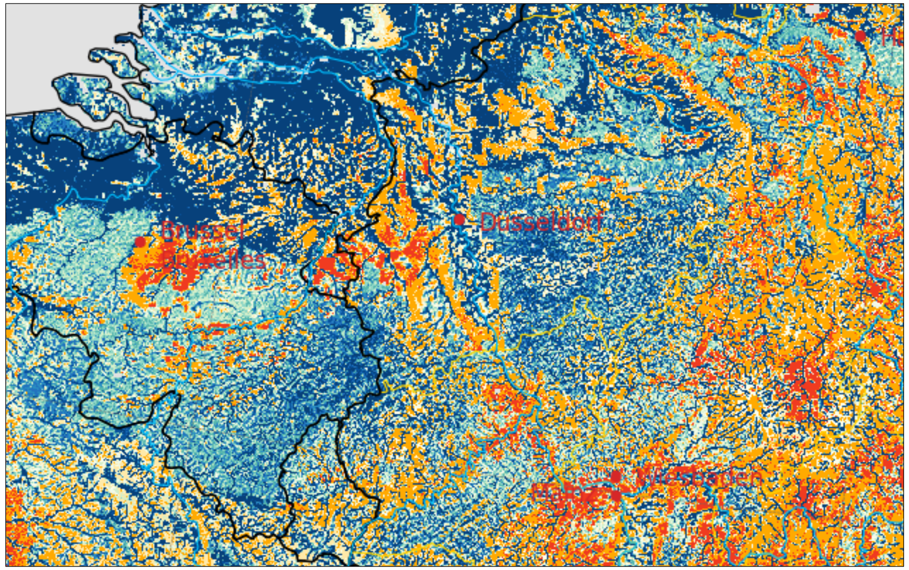
Integrated hydrologic model simulations at 611m example

Redistribution of water in continuum approach, river networks evolve in convergence zones


ParFlow det. forecast, HRES
usable field capacity [%], 0-30cm,
2021-08-21 daily mean
(ini.: 2021-08-18T12Z)

Belleflamme et al. (2023, Frontiers in Water)

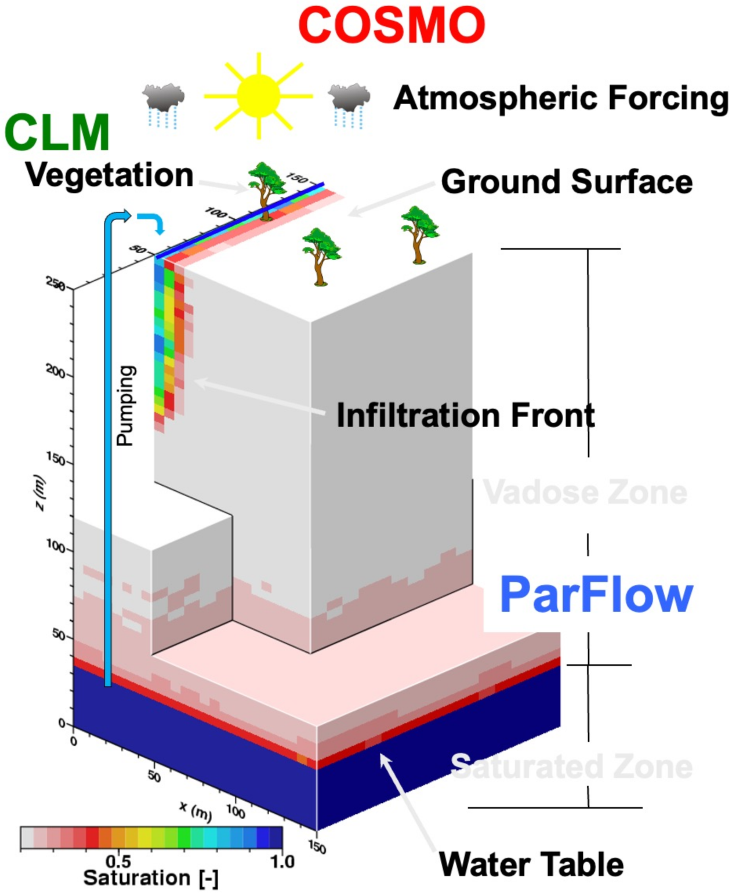

ParFlow river network from ponding experiment; overland flow is integrated with subsurface hydrodynamics



- River networks start to evolve, redistribution of surface and groundwater in continuum approach
- Small-scale surface heterogeneities, detailed catchment characteristics, improved process representation, stakeholder scale
- Physically consistent with atmospheric forcing

ParFlow integrated hydrological model in TSMP

- 3D Variably saturated subsurface flow including pumping and irrigation, and integrated overland flow (Jones & Woodward, 2001; Kollet & Maxwell, 2006; Maxwell, 2013)
- Integrated land surface and regional climate model (Shrestha et al., 2014)
- External coupling via OASIS3-MCT (Shrestha et al., 2014; Gasper et al., 2014)
- Parallel Data Assimilation Framework: TSMP-PDAF (Kurtz et al., 2016)
- Optimized for massively parallel supercomputers; excellent scaling out to 10^6 compute cores (Gasper et al., 2014, Burstedde et al., 2018)



Overland flow, 2D kinematic wave equation approximation

velocity vector [LT-1]

surface ponding depth [L]

$$\frac{\partial \psi_s}{\partial t} = \nabla(\boldsymbol{v}\psi_s) + q_s + q_e$$

source/sink term [T-1]

exchange rate with subsurface [T-1]

Variably saturated flow, Richards equation

specific storage coeff. [L-1]

relative saturation [-]

$$S_s S_w(p)\frac{\partial p}{\partial t} + \phi\frac{\partial (S_w(p))}{\partial t} = \nabla \boldsymbol{q} + q_s$$

pressure head [L-1]

porosity [-]

specific volumetric (Darcy) flux [LT-1]

saturated hydraulic conductivity [LT-1]

relative permeability [-]

depth below surface

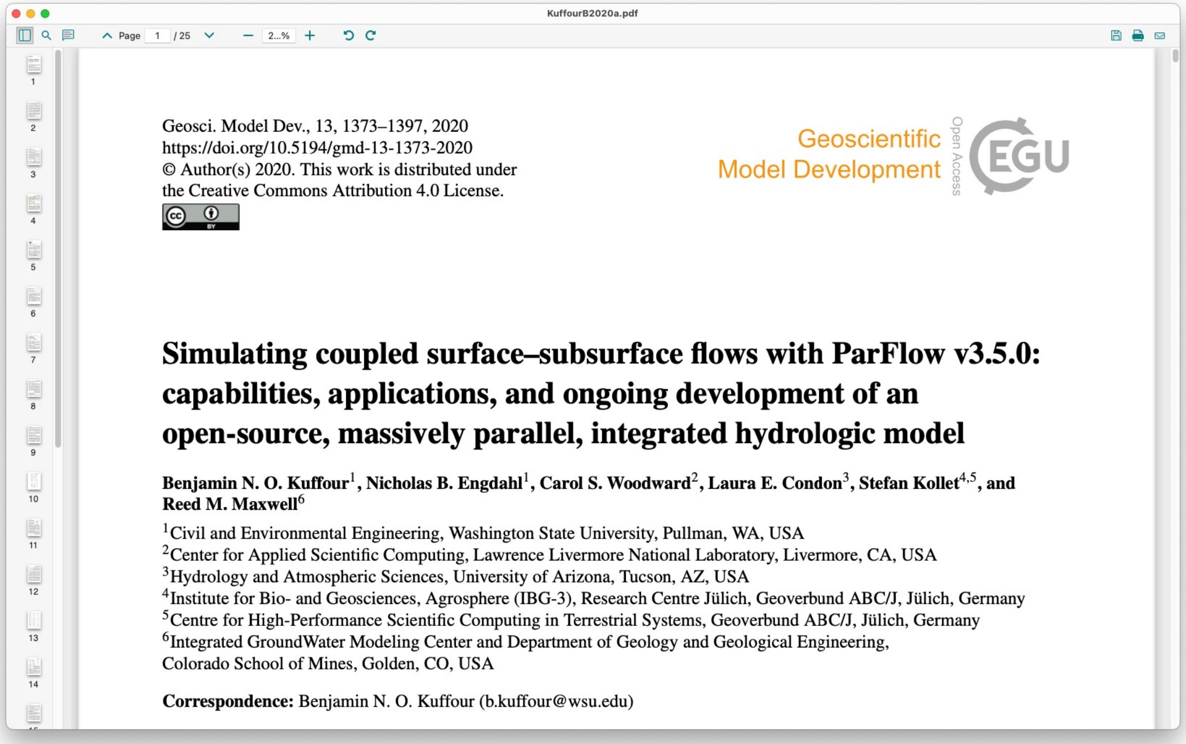
$$\boldsymbol{q} = -k_s k_r(p)\nabla(p - z)$$

Kuffour et al. (2020, GMD)

Getting started with ParFlow

Free, open source research code

Kuffour et al. (2020, GMD)



Geosci. Model Dev., 13, 1373–1397, 2020
https://doi.org/10.5194/gmd-13-1373-2020
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Simulating coupled surface–subsurface flows with ParFlow v3.5.0: capabilities, applications, and ongoing development of an open-source, massively parallel, integrated hydrologic model

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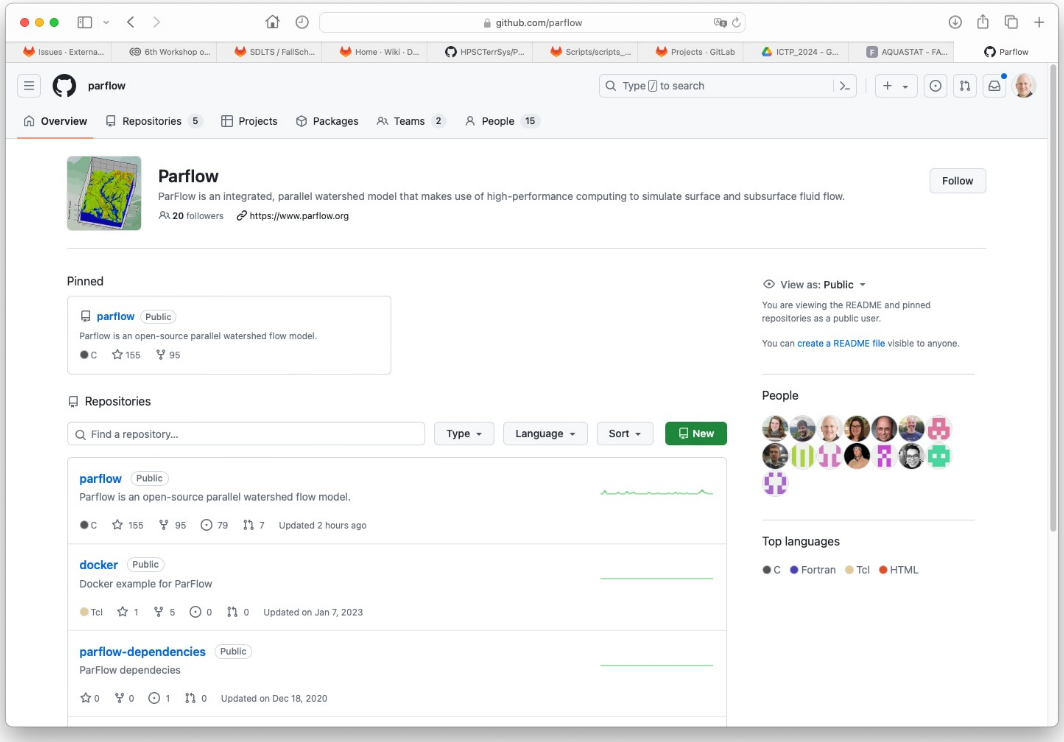
https://github.com/parflow



Parflow

ParFlow is an integrated, parallel watershed model that makes use of high-performance computing to simulate surface and subsurface fluid flow.

20 followers https://www.parflow.org

You are viewing the README and pinned repositories as a public user.

You can create a README file visible to anyone.

parflow Public
Parflow is an open-source parallel watershed flow model.
● C ☆ 155 95

parflow Public
Parflow is an open-source parallel watershed flow model.
● C ☆ 155 95 79 7 Updated 2 hours ago

docker Public
Docker example for ParFlow
● Tcl ☆ 1 5 0 0 Updated on Jan 7, 2023

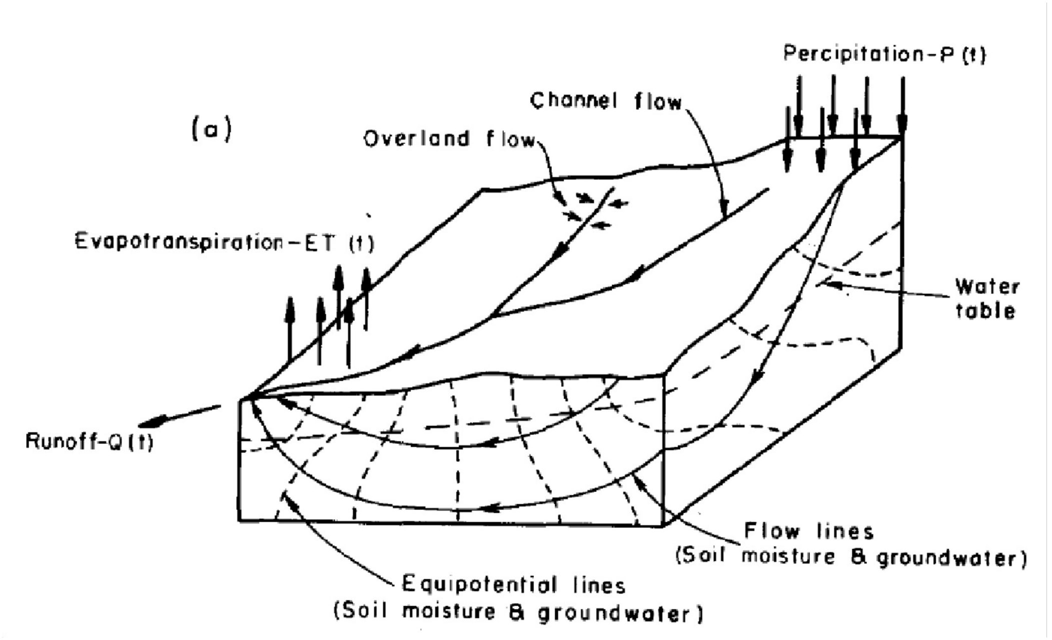
parflow-dependencies Public
ParFlow dependecies
☆ 0 0 1 0 Updated on Dec 18, 2020

Model coupling

Hydrologic Response Model

Freeze & Harlan's main message

- Hydrologic Response Model is feasible: composite boundary value problem (coupled PDEs)



Freeze and Harlan, 1969

top

Influence of meteorological phenomena (top boundary)

Coupling with atmosphere (top boundary)

Role of vegetation (top boundary).

Coupling with surface water (top boundary).

Continuity between groundwater flow and unsaturated flow (top boundary).

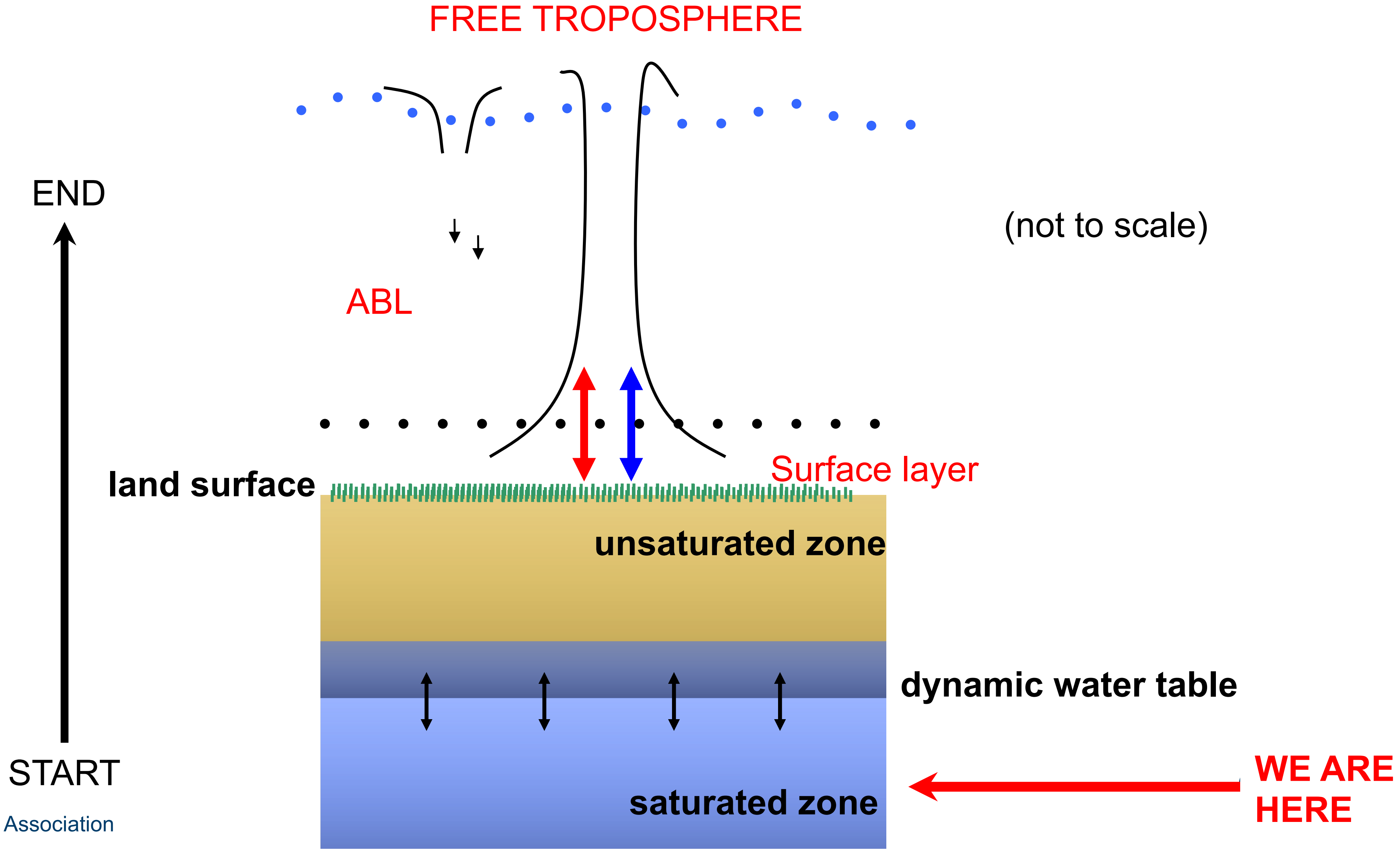
bottom

The problem of the top boundary is ubiquitous

Freeze, R. A., & Harlan, R. L. (1969). Blueprint for a physically-based, digitally-simulated hydrologic response model. *Journal of hydrology*, *9*(3), 237-258.

Groundwater to Atmosphere

Schematic: Starting point saturated zone



FREE TROPOSPHERE

END

(not to scale)

ABL

land surface

Surface layer

unsaturated zone

dynamic water table

START

saturated zone

WE ARE HERE

The Ingredients of Flow/Transport Modeling

Continuity equation and Darcy's law

1. Continuity equation

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}) + \rho \Gamma$$

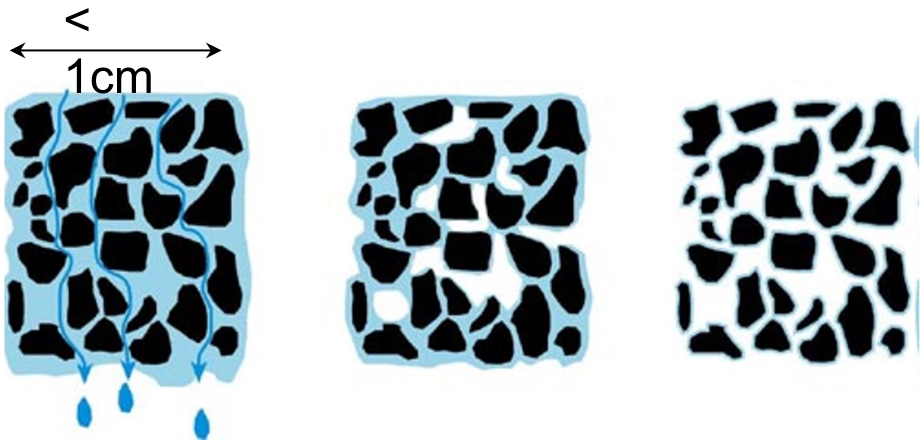
ρ: water density
$\mathbf{v}$: flow velocity
$\mathbf{\Gamma}$: general sink/source term

2. Movement equation

- at which scale (micro or macro)?
- Darcy's law

$$q = K\frac{\Delta h}{\Delta l} = \frac{dh}{dl}$$

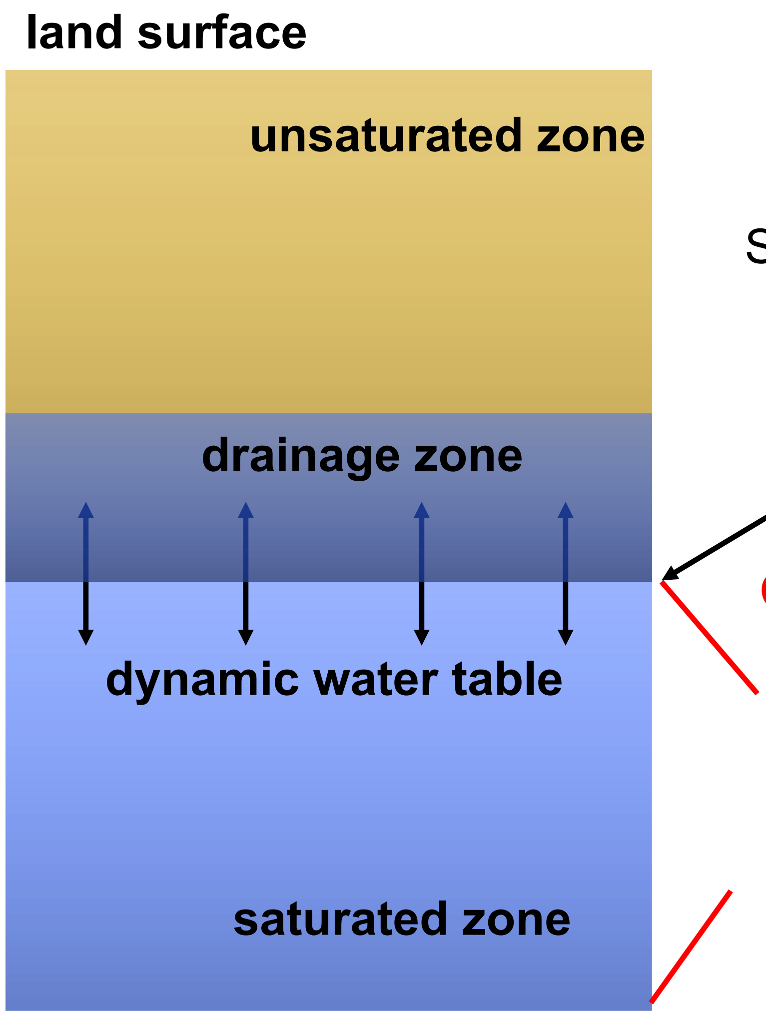
h: hydraulic head/potential
K: hydraulic conductivity



JÜLICH
Forschungszentrum

Groundwater Flow

Schematic: drainage zone



Solution at water tab $K_{zz}\frac{\partial h}{\partial z} = S_y \frac{\partial h}{\partial t}$

free surface BC

Continuity with unsaturated zone ???

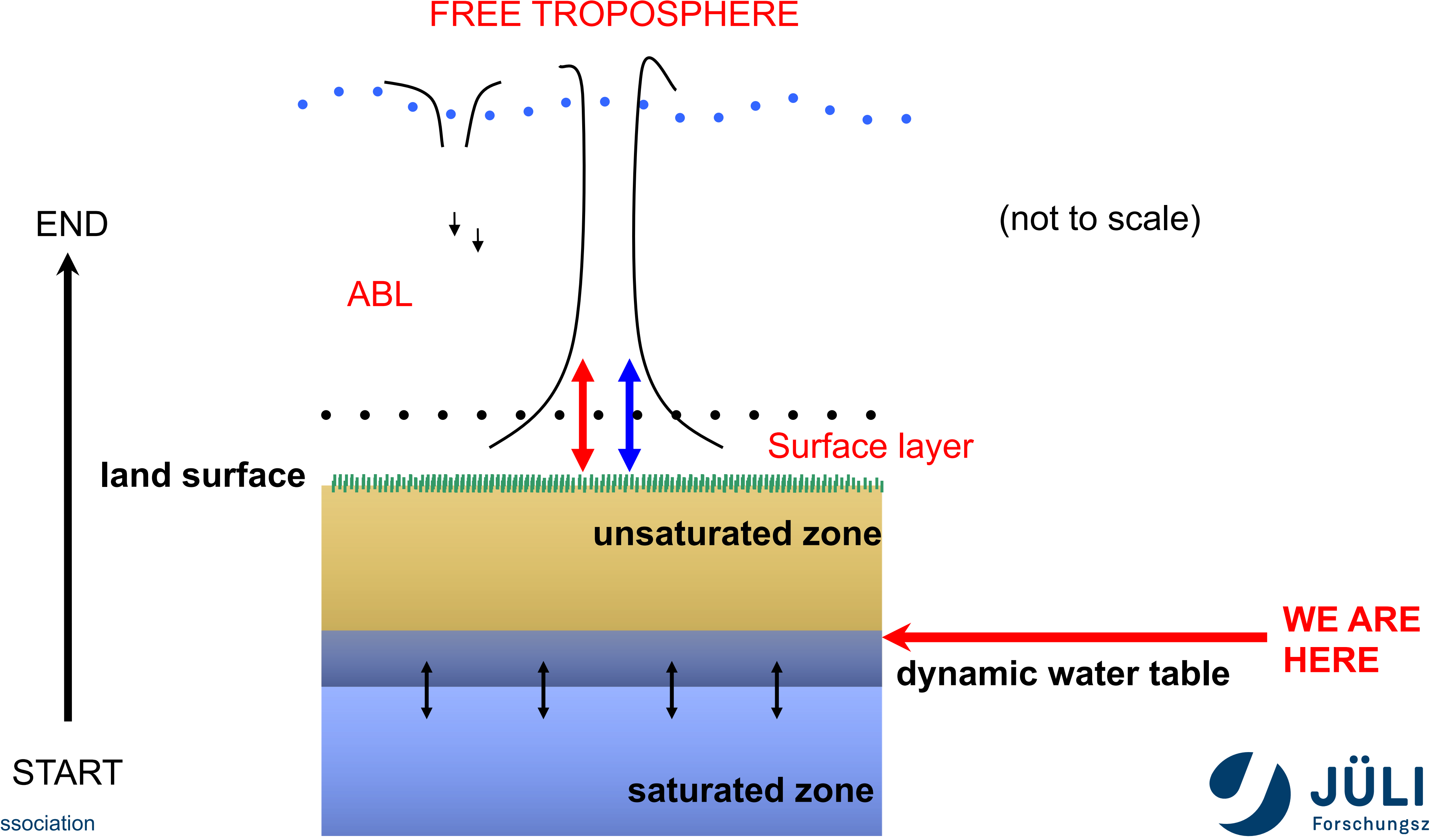
$$S_s \frac{\partial h}{\partial t} = \nabla \cdot \mathbf{q} + Q$$

$$\mathbf{q} = \mathbf{K}\nabla h \qquad h = p + z$$

Ss: specific storage coeffic
h: head potential
q: specific volumetric flux
K: hydraulic conductivity
Q: Source/sink term

Terrestrial Processes

Schematic: Dynamical water table



FREE TROPOSPHERE

END

(not to scale)

ABL

Surface layer

land surface

unsaturated zone

WE ARE HERE

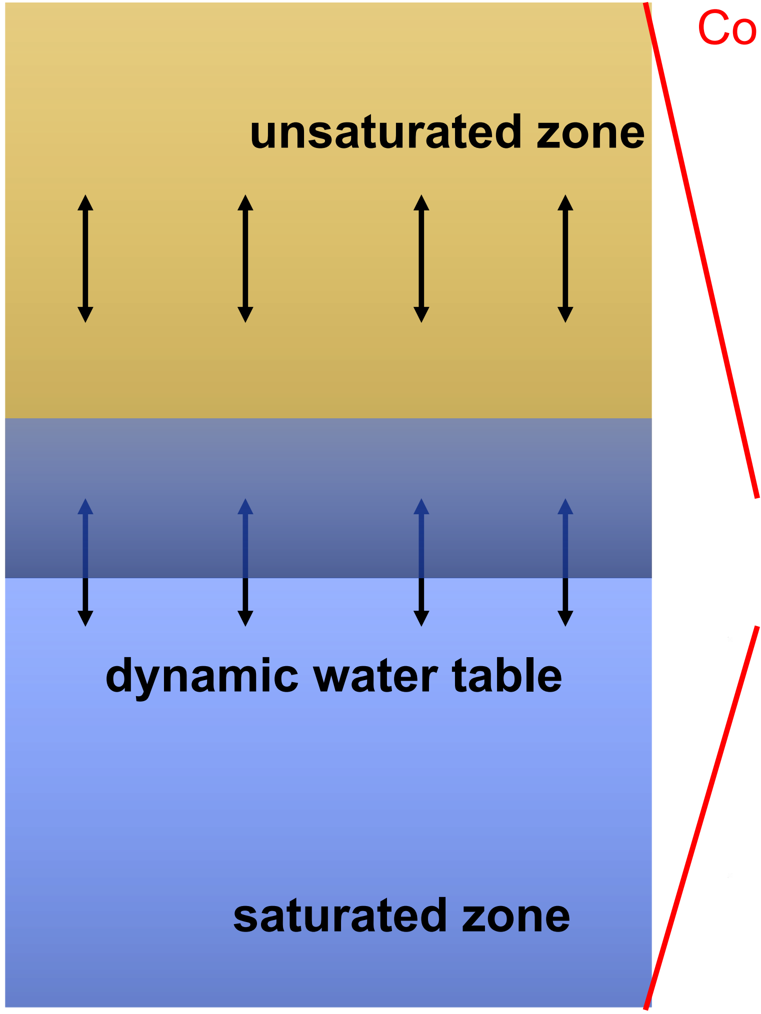
dynamic water table

saturated zone

START

Including the Variable Saturated Zone

Schematic: Soil moisture dynamics



land surface

unsaturated zone

dynamic water table

saturated zone

Continuity with land surface processes ???

$$q_{ls} = K_{zz} k_r(p) \frac{\partial (p+z)}{\partial z}$$

Application of simple flux boundary condition

No feedbacks with surface water, plants, atmosphere

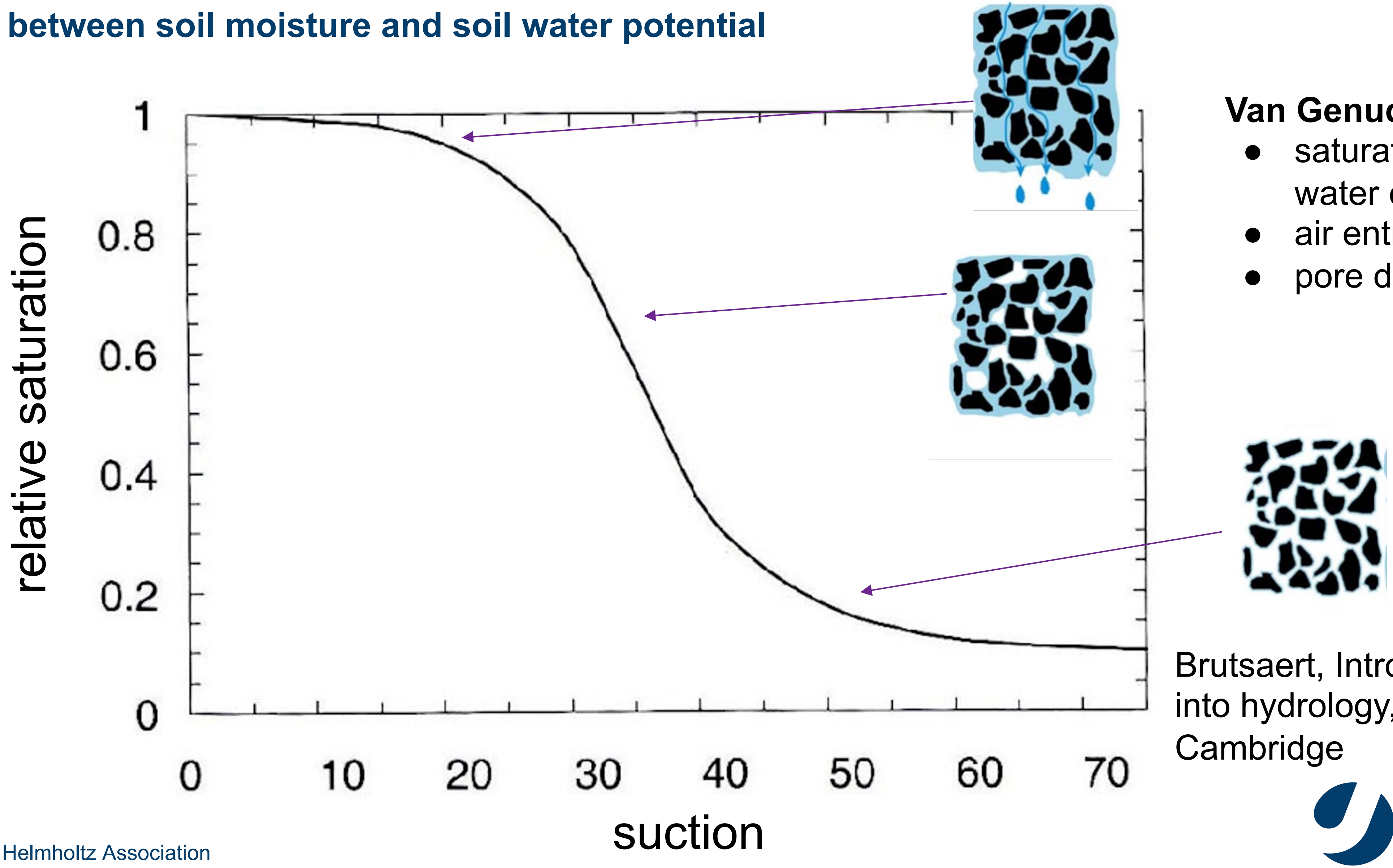
$$S_s \frac{\partial p}{\partial t} + \frac{\partial \theta(p)}{\partial t} = \nabla \cdot \mathbf{q} + q_s$$

$$\mathbf{q} = \mathbf{K} k_r(p) \nabla (p+z)$$

Ss: specific storage coefficient **q**: specific volumetric flux
p: pressure head of water **K**: hydraulic conductivity
kr: relative permeability

Soil Water Retention Curve

Relation between soil moisture and soil water potential



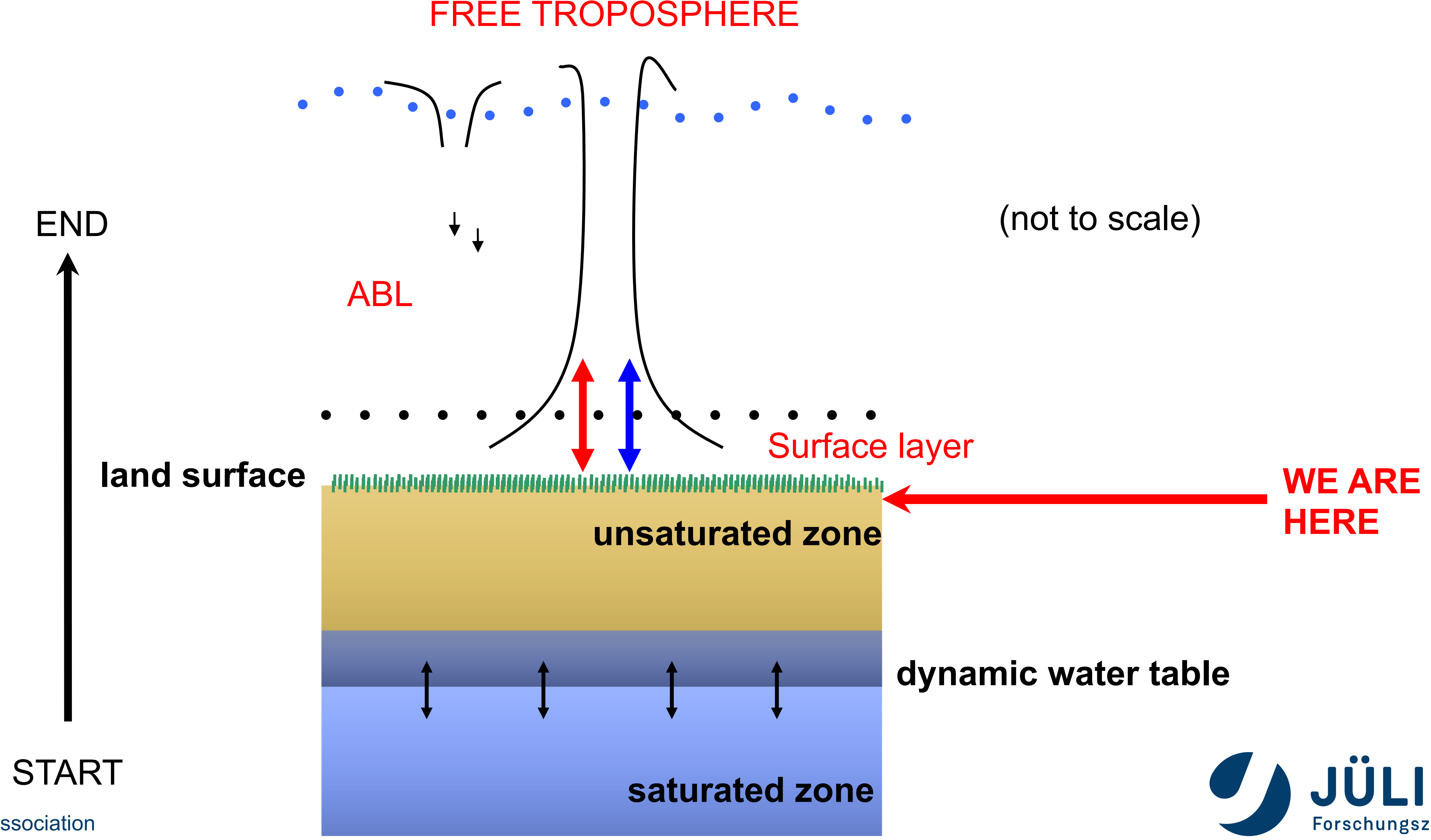
Van Genuchten

- saturated/ residual water content
- air entry suction
- pore distribution

Brutsaert, Introduction into hydrology, Cambridge

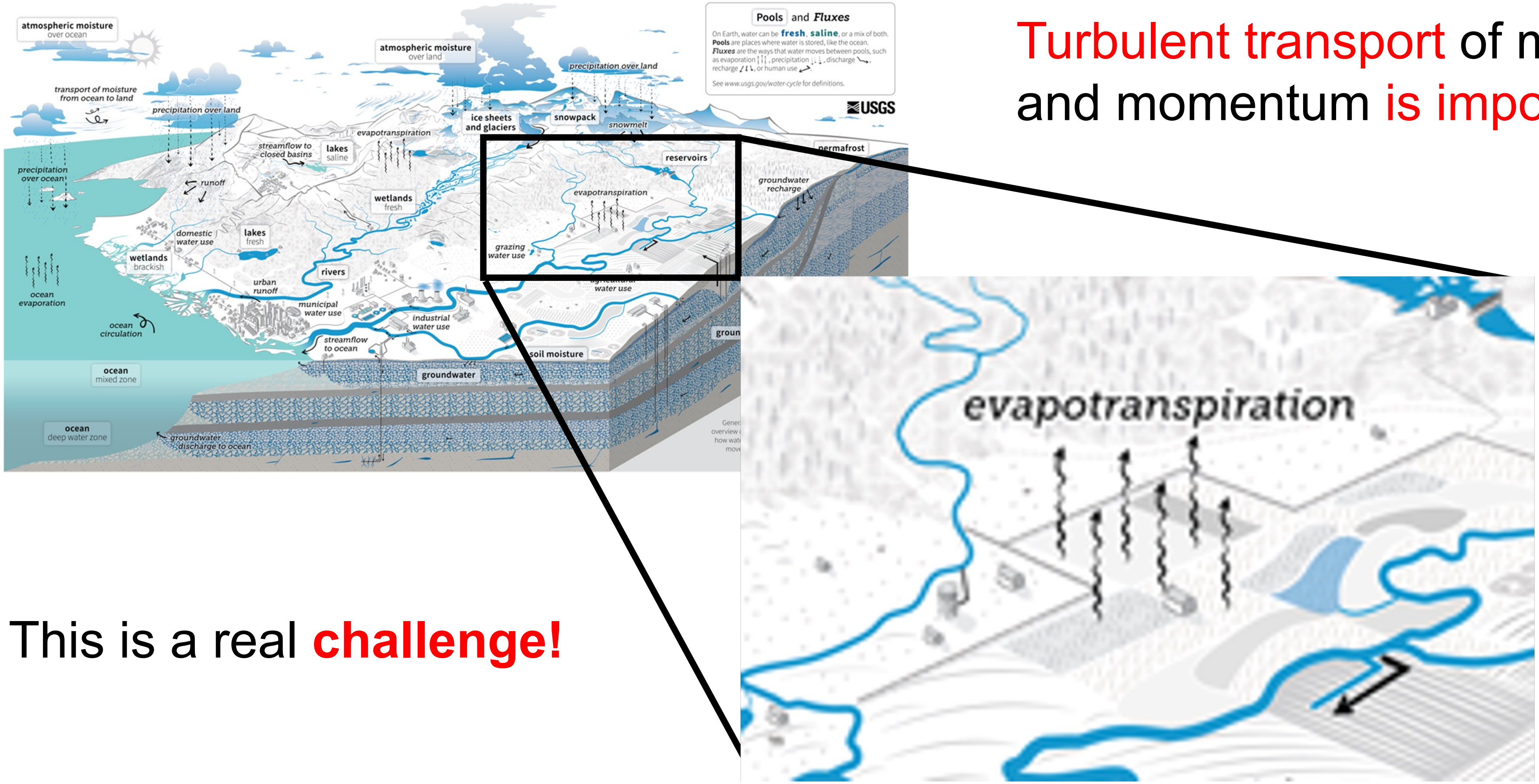
Land Surface Processes

Schematic: Land surface



Turbulent Transport

The real challenge!

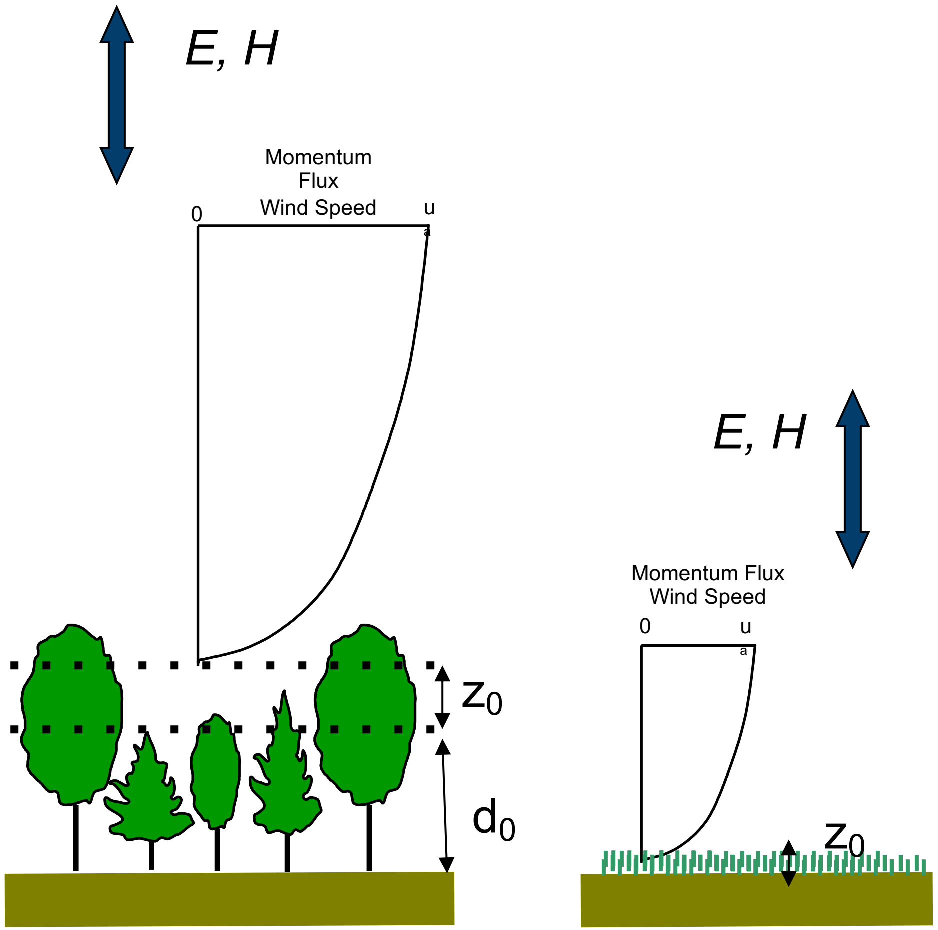


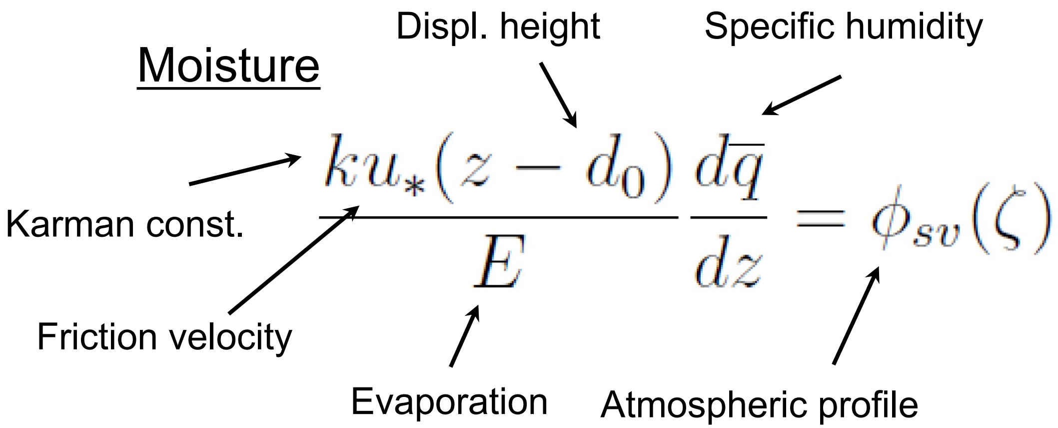
Turbulent transport of mass, energy, and momentum is important!

This is a real **challenge!**

Approximation of turbulent transport

Monin-Obukhov similarity theory (MOST)





Moisture

$$\frac{k u_*(z-d_0)}{E}\frac{d\bar{q}}{dz} = \phi_{sv}(\zeta)$$

Displ. height

Specific humidity

Karman const.

Friction velocity

Evaporation

Atmospheric profile

1D isolated columns; requires average lateral scale on the order of ~10^2m

A perhaps more intuitive expression

Resistance formulation

$$\frac{ku_*(z-d_0)}{E}\frac{d\overline{q}}{dz}=\phi_{sv}(\zeta)$$

$$\overline{q}_s-\overline{q}_a=\frac{E}{ku_*\rho}[ln(\frac{z-d_0}{z_0})-\Psi(\zeta)]$$

$$E=\frac{\rho}{r_{aw}}(\overline{q}_s-\overline{q}_a)$$

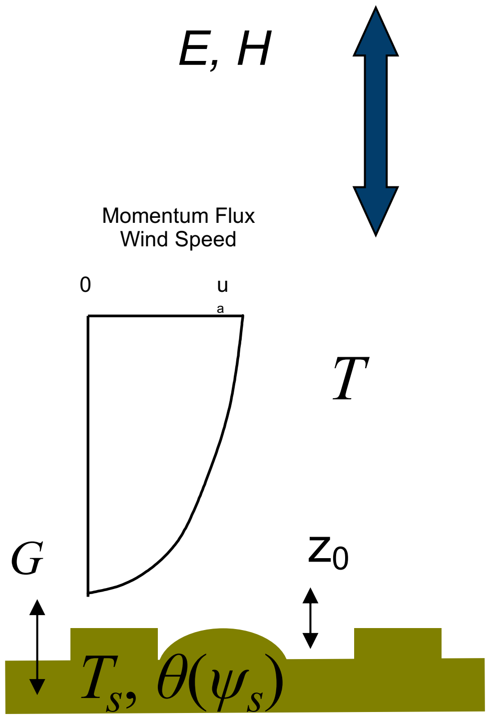
Conductance

***r_{aw}* depends on e.g.,**

- **surface (canopy vs. bare soil)**
- **stability of atmosphere**

Coupling with the Subsurface

Coupling subsurface with atmosphere



Since no vegetation, MOST is again applicable for r_{aw}

$$E_g = -\frac{\rho}{r_{aw}}(q_{atm} - q_g)$$

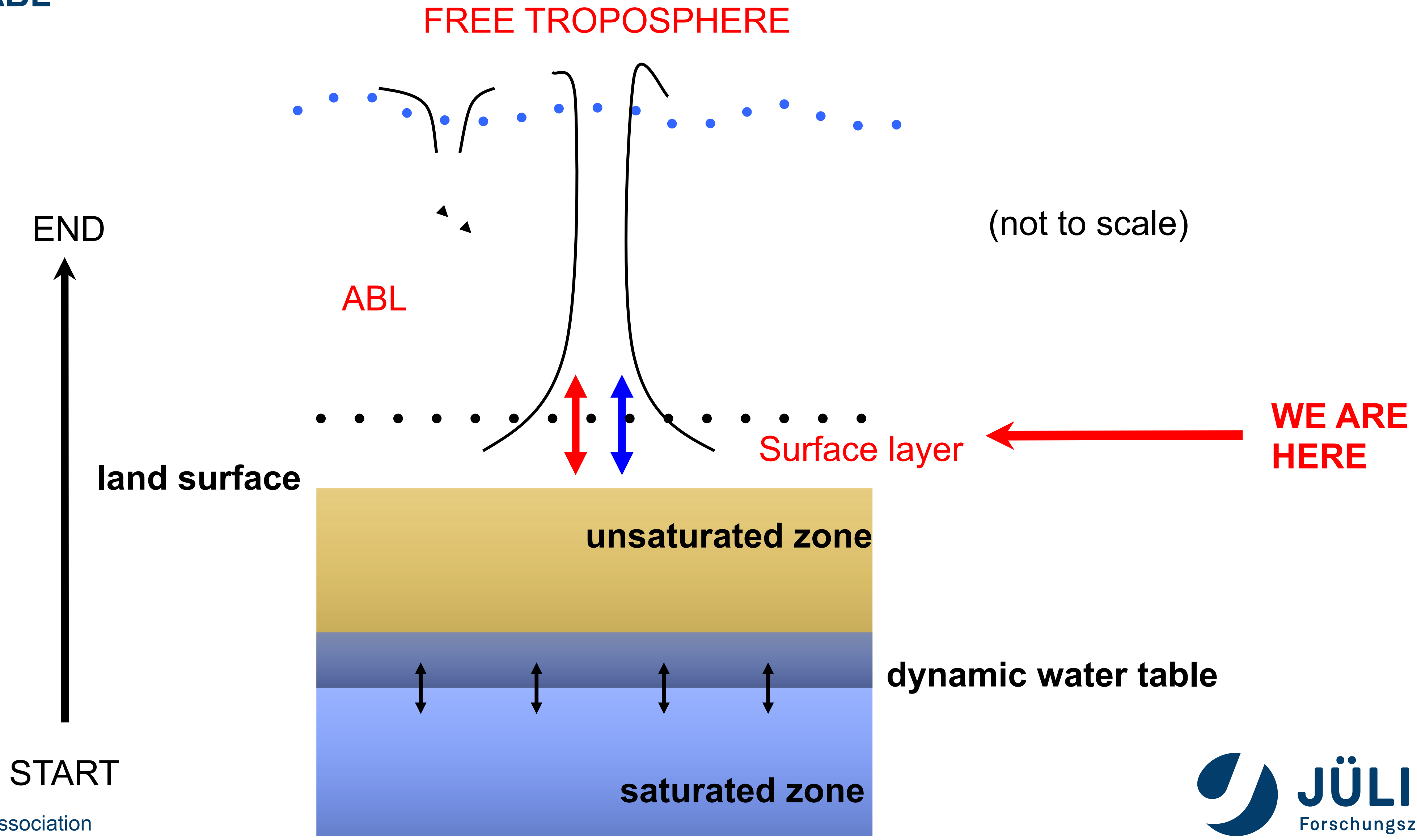
$$q_g = q_{sat} e^{\frac{pg}{cRT}}$$

p: soil pressure head/matric pot.
R: gas constant
g: grav. constant
T_g: ground temperature

Equation relates the soil pressure/matric potential p to humidity of soil air based on the assumption of thermodynamic equilibrium.

Transfer Layer

Coupling with ABL



LSM ATM MODEL COUPLING

Example approaches to couple the land surface with the atmosphere

Flux Inversion Approach

- Coupling via turbulent fluxes
- Determination of exchange coefficients
- Used for recalculation of surface fluxes

$$E = -\rho_{atm}\frac{(q_{atm} - q_s)}{r_{aw}}$$

Exchange Coefficients Approach

- Coupling via exchange coefficients and surface variables
- Determination of surface fluxes

COSMO; CLM3.5 ; ParFlow

Fixed Fluxes Approach

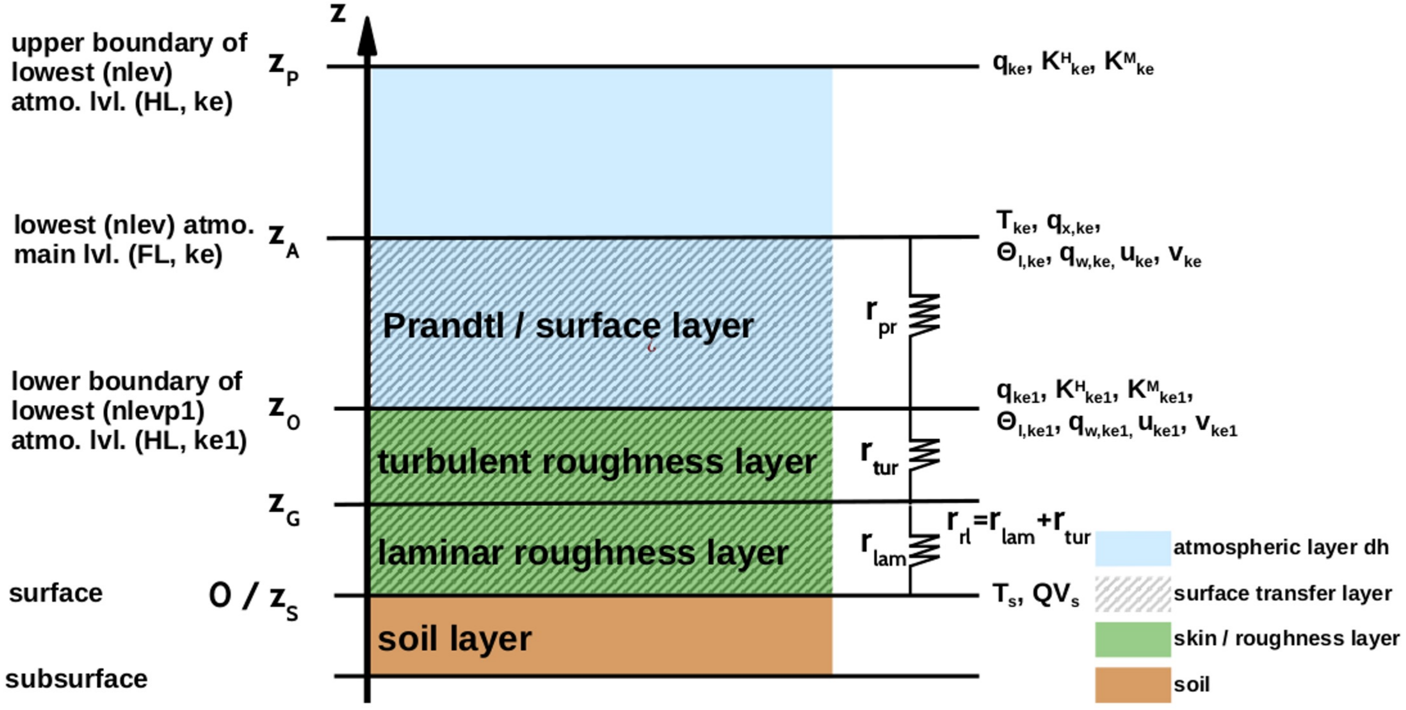
- Coupling via turbulent fluxes
- Direct usage of surface fluxes

ICON ; eCLM ; ParFlow

Transfer Layer (cont'd)

TKE based surface transfer scheme

Structure of Surface Transfer Layer



TKE at lowermost model layer

$$\frac{\partial q^2}{\partial t} = 2K^M\left[\left(\frac{\partial \bar{u}}{\partial z}\right)^2 + \left(\frac{\partial \bar{v}}{\partial z}\right)^2\right] - 2K^H\frac{g}{\bar{\theta}_v}\left(A_\theta\frac{\partial\bar{\theta}}{\partial z} + A_{q_w}\frac{\partial\overline{q_w}}{\partial z}\right) - 2\frac{q^3}{\alpha_{MM}\lambda}$$

Temperature at lowermost model layer

$$\frac{\partial \theta_l}{\partial z} = \frac{\theta_{l,ke} - \theta_{l,ke1}}{r^H_{pr}} \qquad \theta_{ke1} = (1 - tfh)\cdot\theta_{ke} + tfh\cdot\theta_s \qquad tfh = \frac{r^H_{pr}}{r^H_{tot}}$$

Resistances

$$r^{\varphi}_{XY} = \int_X^Y \frac{dz}{K^{\varphi}_{XY}(z)} \qquad K^{\varphi}_{XY}(z) = \lambda u^{\varphi}_x \qquad u^{\varphi}_h = q_h S^{\varphi}_h + \frac{k^{\varphi}}{\kappa z_h}$$

Sublayers

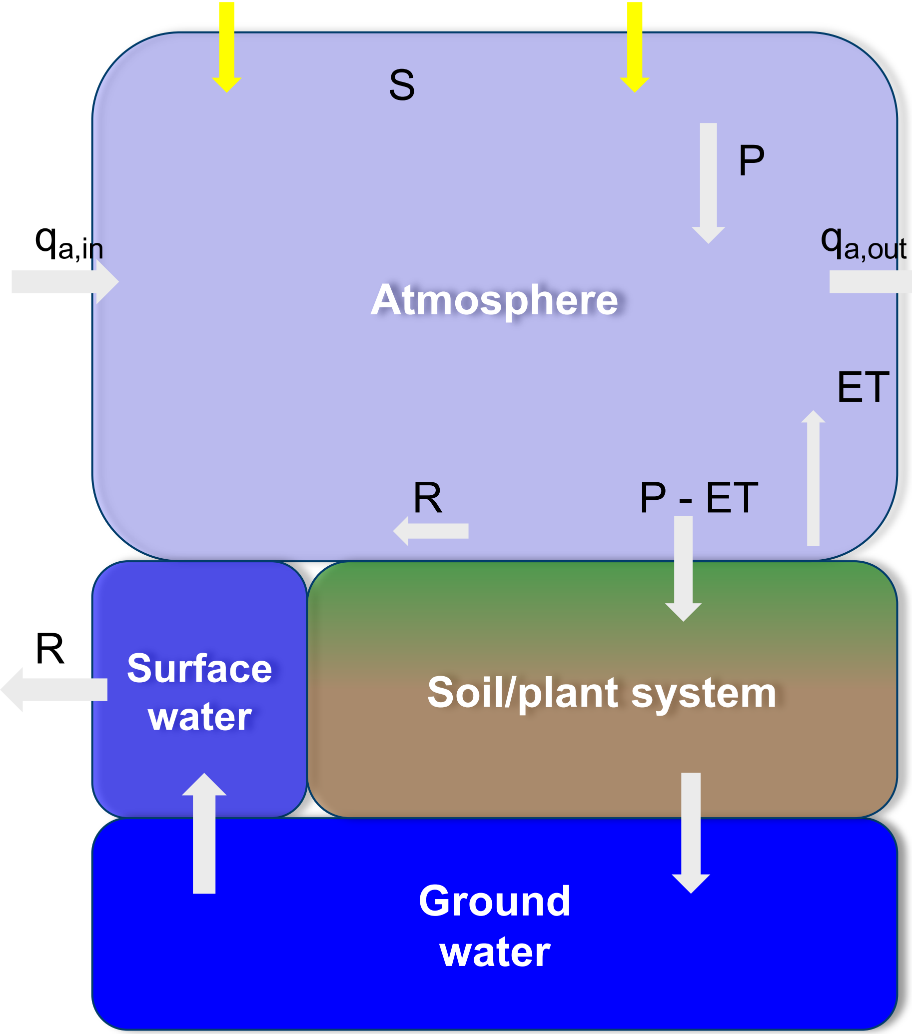
- Prandtl layer: Transport velocity scale u' is assumed to be linear with height
- Turbulent roughness layer: Transport velocity scale is assumed to be constant
- Laminar roughness layer: The velocity scale component of u' vanished

The mathematical model

ICON, COSMO

eCLM, CLM3.5

ParFlow



$$\frac{\partial T}{\partial t}+\mathbf{v}\cdot\nabla T=\frac{1}{\rho c_p}\left(\frac{\partial p'}{\partial t}+\dots\right)+\frac{Q}{c_p}$$

$$\frac{\partial q^k}{\partial t}+\mathbf{v}\cdot\nabla q^k=-\frac{1}{\rho}\left(\nabla\cdot\mathbf{J}^k+\dots\right)-\frac{1}{\rho}I^k$$

$$\left(\bar{q}_s-\bar{q}\right)=\frac{E}{k u_* \rho}\left[\ln\left(\frac{z-d_0}{z_0}\right)-\Psi_{sv}(\zeta)\right]$$

$$\frac{\partial \psi_s}{\partial t}=\nabla\vec{v}\psi_s-q_r(x)-q_e(x)$$

$$S_s S_w\frac{\partial \psi}{\partial t}+\phi\frac{\partial S_w(\psi)}{\partial t}=\nabla\cdot q$$

$$q=K_v k_r(\psi)\frac{\partial(\psi+z)}{\partial z}$$

Example applications on the impacts of considering subsurface hydrodynmics, options for new applications / research questions with RCMs

Added value of explicit groundwater treatment in RCMs

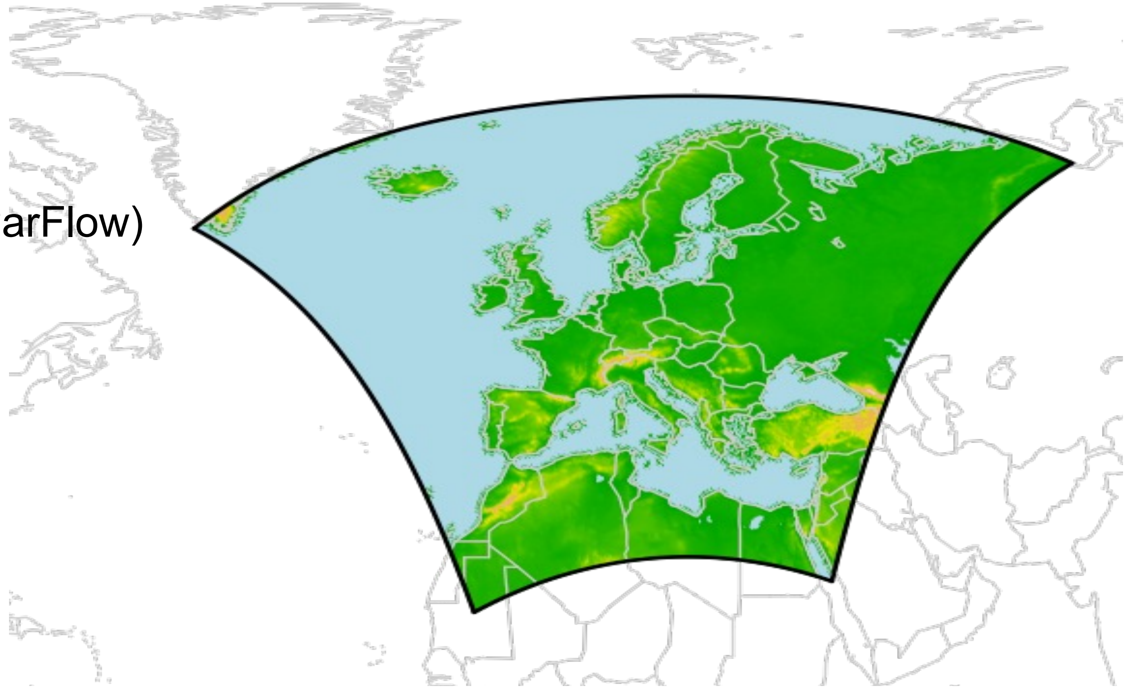
Recap

- 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)
- Closed terrestrial water cycle: water resource investigations, including human water use w/ water abstraction and irrigation
  (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)

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

Some examples, mainly 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)
- Selection of experiments used in examples
  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)
  4. **Regional climate change historical and projections, heatwaves** Poshyvailo-Strube et al. (2024, ESD)

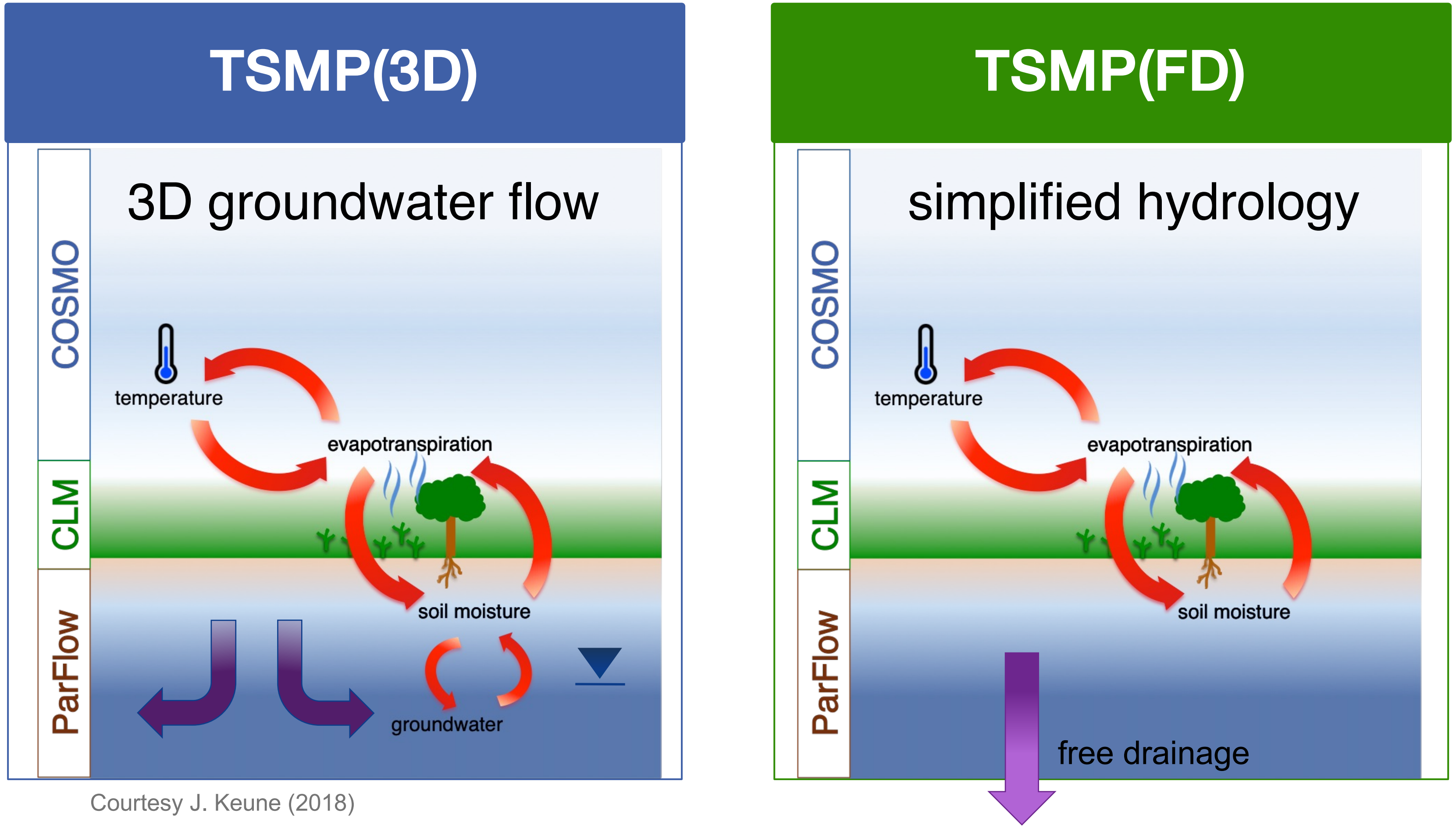
Example 1
Impact on coupling, heatwaves

Keune et al. (2016, JGR, https://dx.doi.org/10.1002/2016JD025426)
Furusho-Percot et al. (2022, GRL, https://doi.org/10.1029/2021GL096781)
Poshyvailo-Strube et al. (2024, ESD, https://doi.org/10.5194/esd-15-167-2024)

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

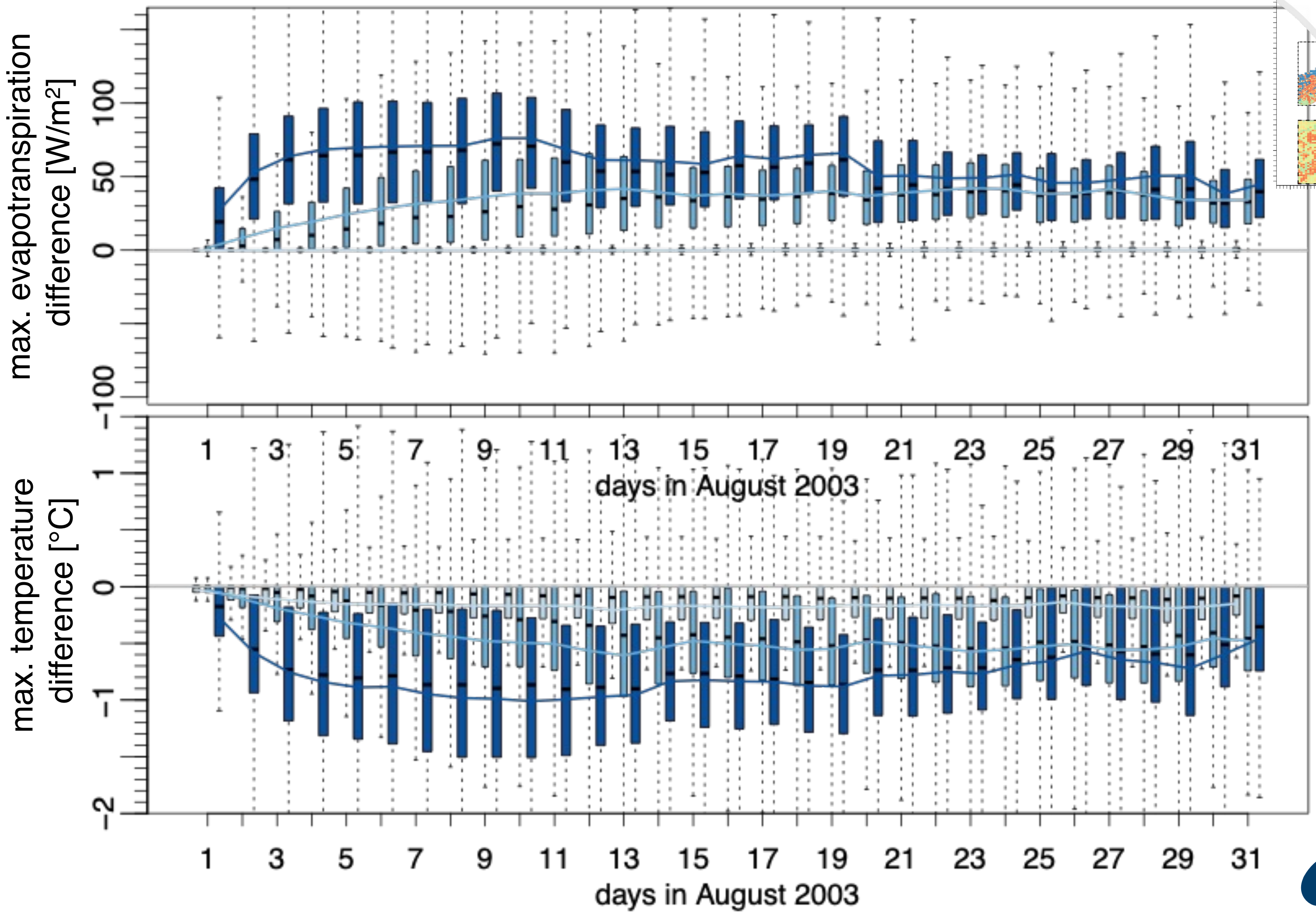


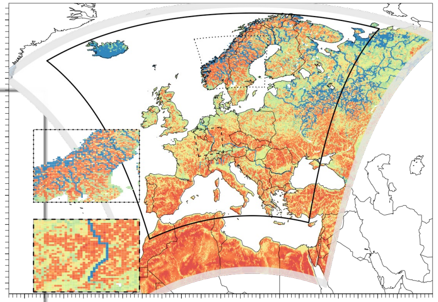
Courtesy J. Keune (2018)

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





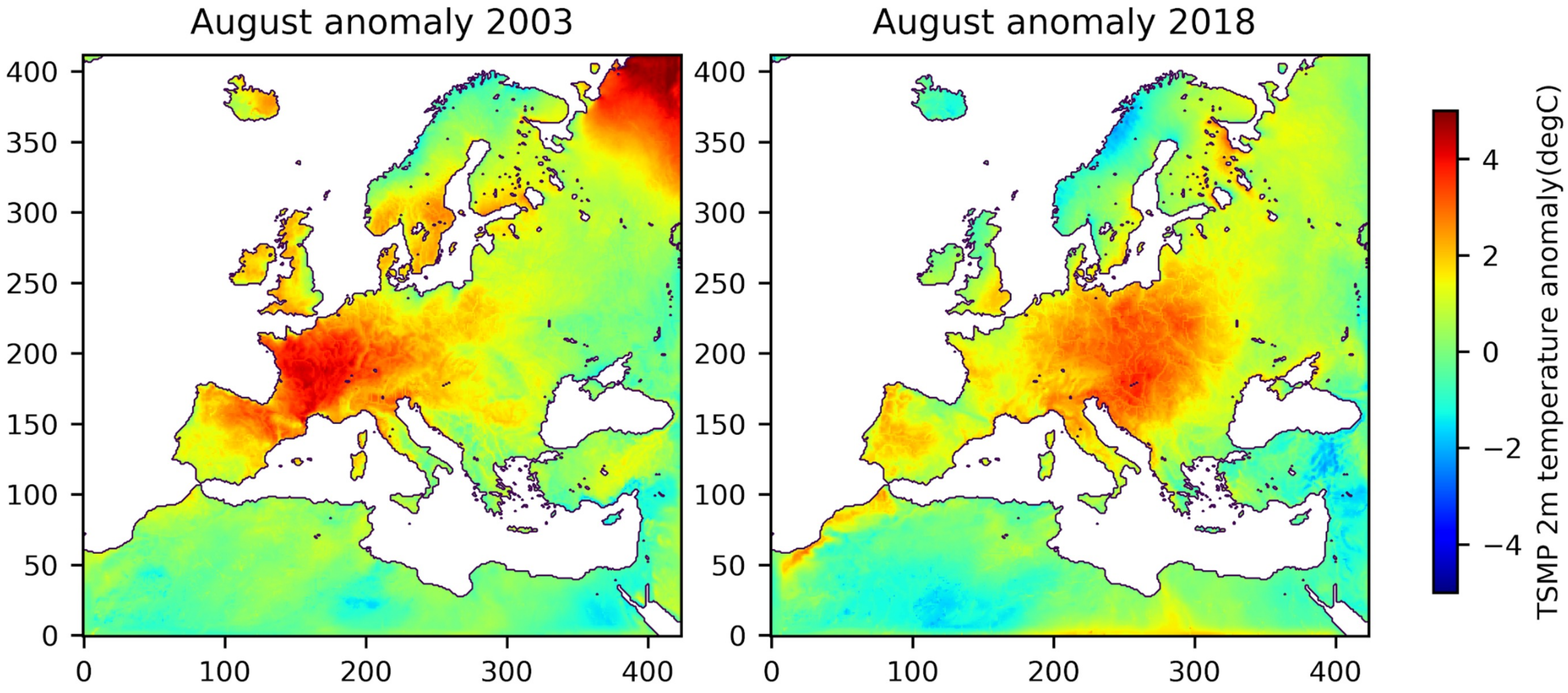
Complete focus domain

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

Keune et al. (2016, JGR)

Hydroclimatic extremes

August 2003 and 2018 2m air temperature monthly anomalies

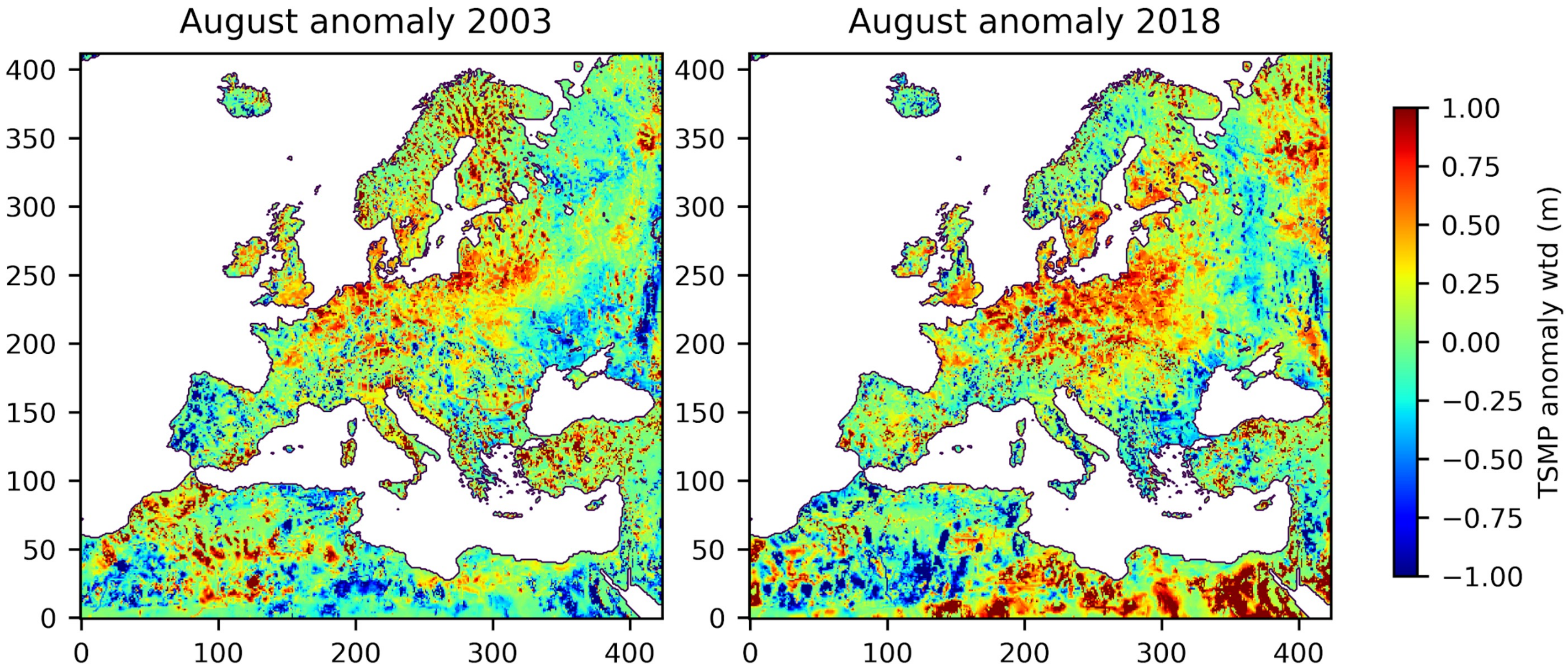


Courtesy: Furusho-Percot

Hydroclimatic extremes

August 2003 and 2018 water table depth monthly anomalies

Portugal: Positive precipitation anomaly in 2003



Lower ground-water table, deeper

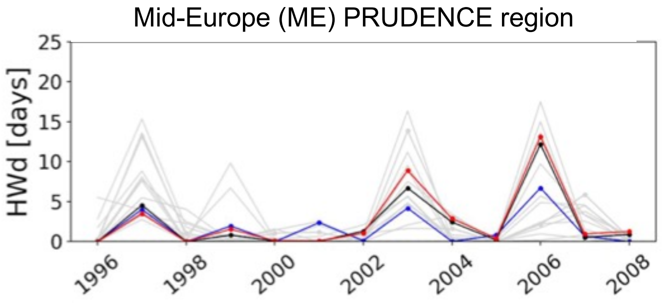
Higher ground-water table, more shallow

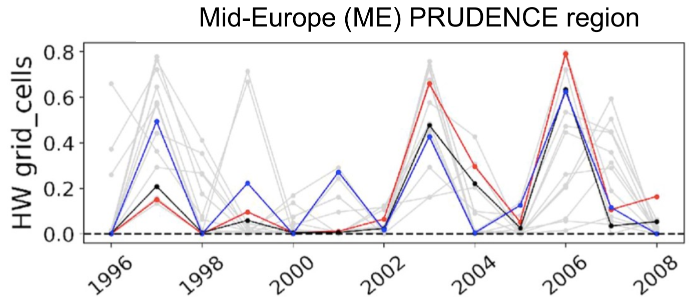
Courtesy: Furusho-Percot

Heat waves in ERA-Interim eval runs, 3D groundwater impacts

Comparison (1996-2008) of coupled COSMO-CLM-ParFlow, ERA-Land, 12 EURO-CORDEX RCMs w/ E-OBS

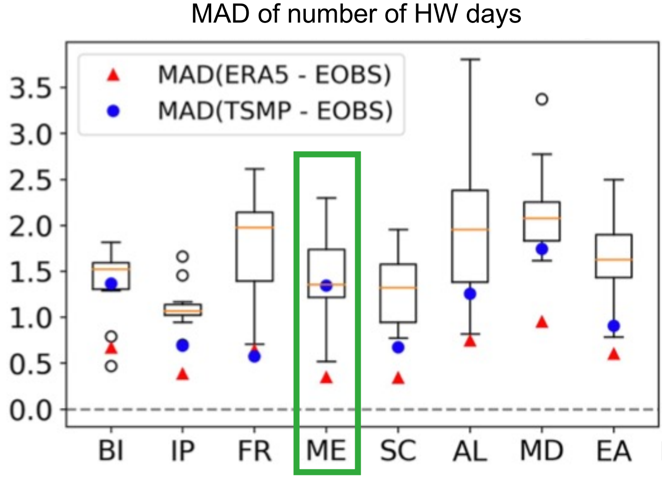
Annual number of heat wave days (HWd), accumulated days per JJA, spatial means

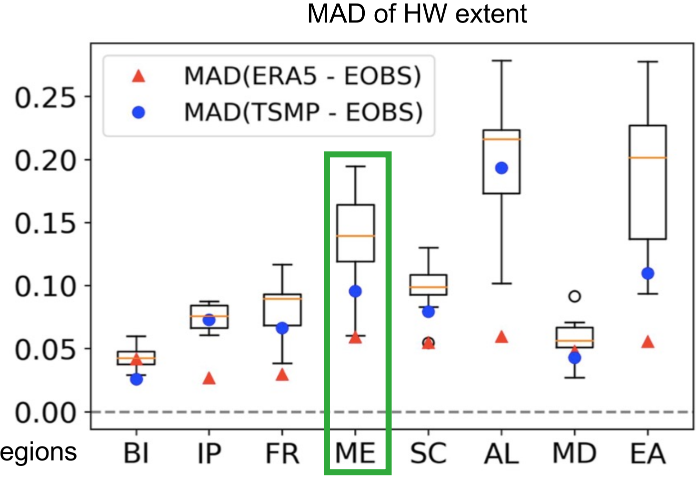




HW extent (ratio of land grid cells that experienced at least one HW per JJA and # of land grid cells per region)

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





Multi-annual mean absolute deviation (MAD) of HW grid_cells wr.r.t. E-OBS

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

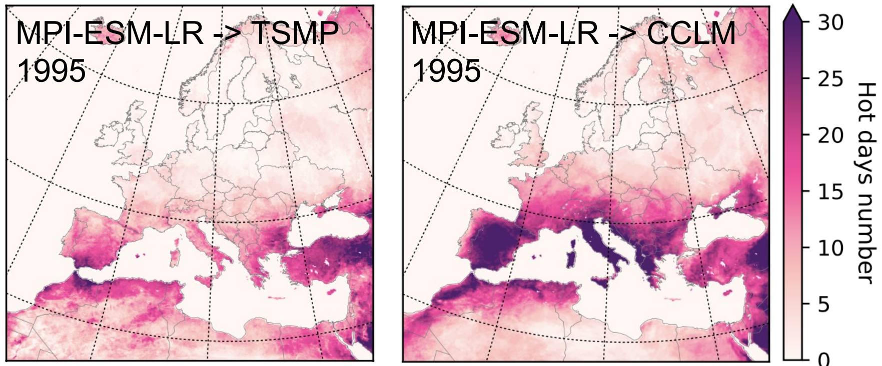
- Coupled TSMP has tendency towards reduced deviations of HW metrics from E-OBS
- Redistribution of soil water leads to lower bias of TSMP in an ET comparison with GLEAM

Furusho-Percot et al. (2022, GRL)

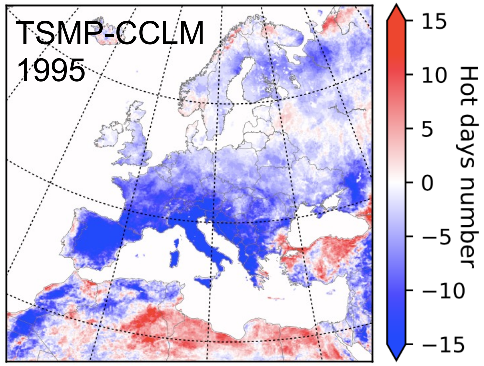
Heat waves in historical EURO-CORDEX runs

Comparison (1976-2005) of COSMO-CLM-ParFlow (MPI-ESM-LR r1i1p1) with 8 EURO-CORDEX RCMs

Cummulative number of hot days
(TG90P index; based on tas, wrt 1961-90)



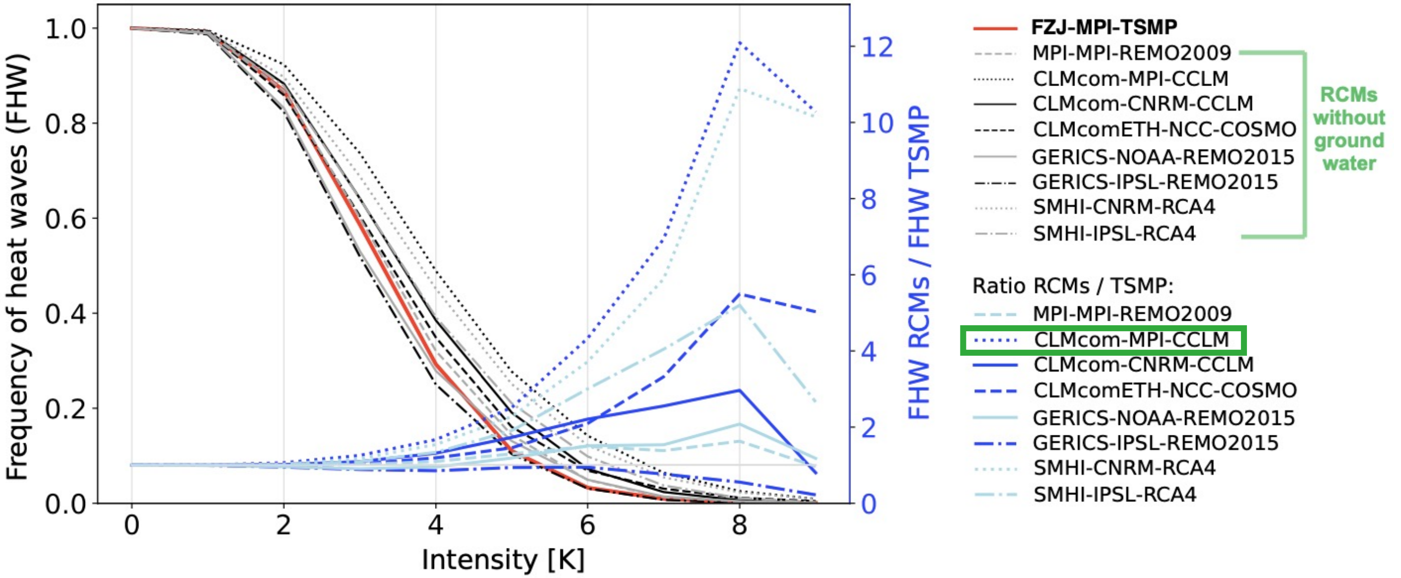
Large spatio-temporal variability of GW impacts, with similar RCM



Heat event:
daily mean tas >
61-90 JJA P90 tas
Heat wave: heat
events ≥ 6
consecutive days

Poshyvailo-Strube et al. (2024, ESD)

JJA **HW frequency vs intensity** (max tas during HW wrt 61-90 JJA P90 tas), EUR-11



- Decrease of frequency of severe heat waves (intensity > 4K), x1.5-12
- Decrease mean number of long heat events (> 6d) (x1.5-6.5)
- Increase of short heat events (< 3d); decrease heat events (> 3d)

Example 2
Water resources, gw memory effects

Hartick et al. (2021, WRR, https://doi.org/10.1029/2020WR027828)

A “pristine” groundwater climatology, no human impacts

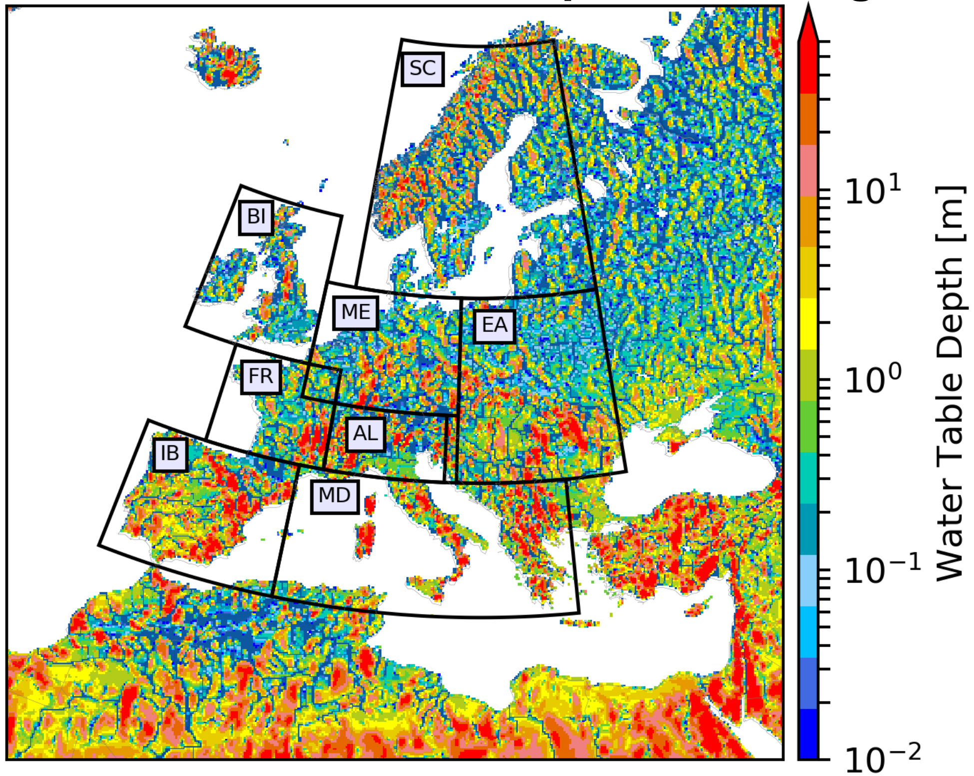
Simulated water table depth (WTD) with fully coupled TSMP (3D ParFlow)

- 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

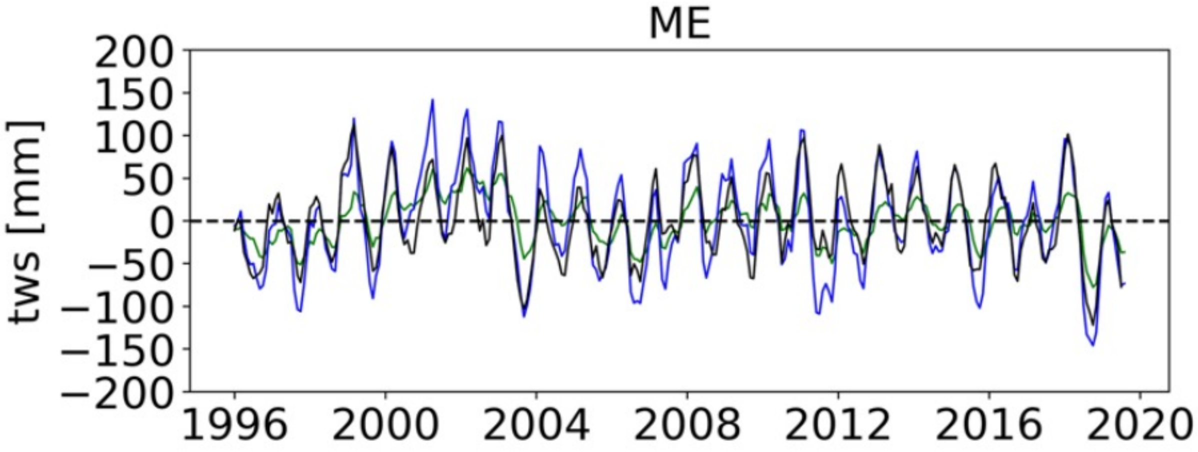
TSMP mean WTD, 1996/Sep to 2018/Aug

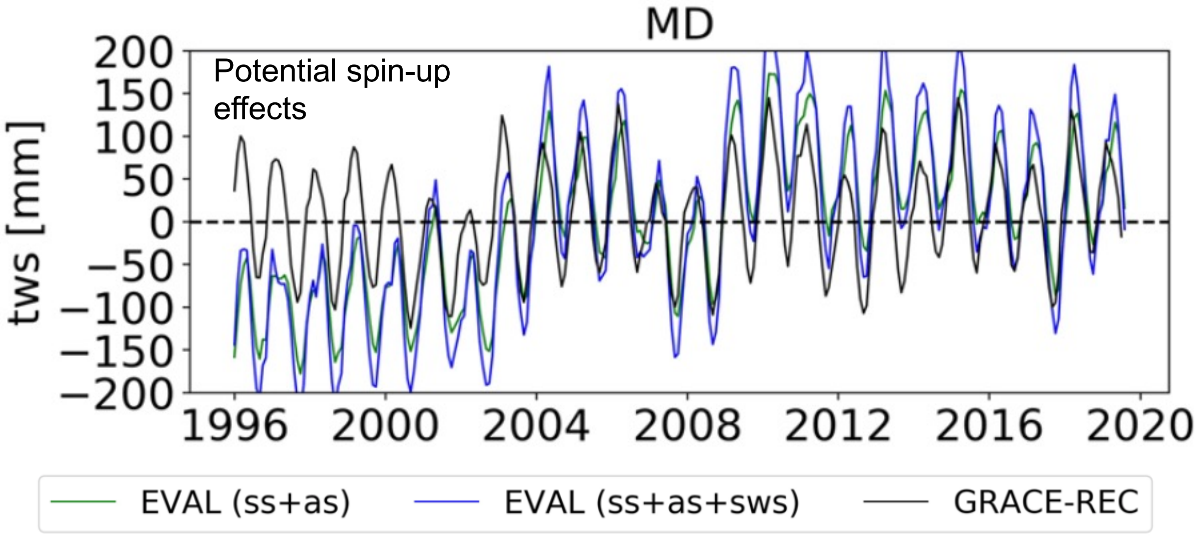


Furusho-Percot et al. (2019, Sc Data)

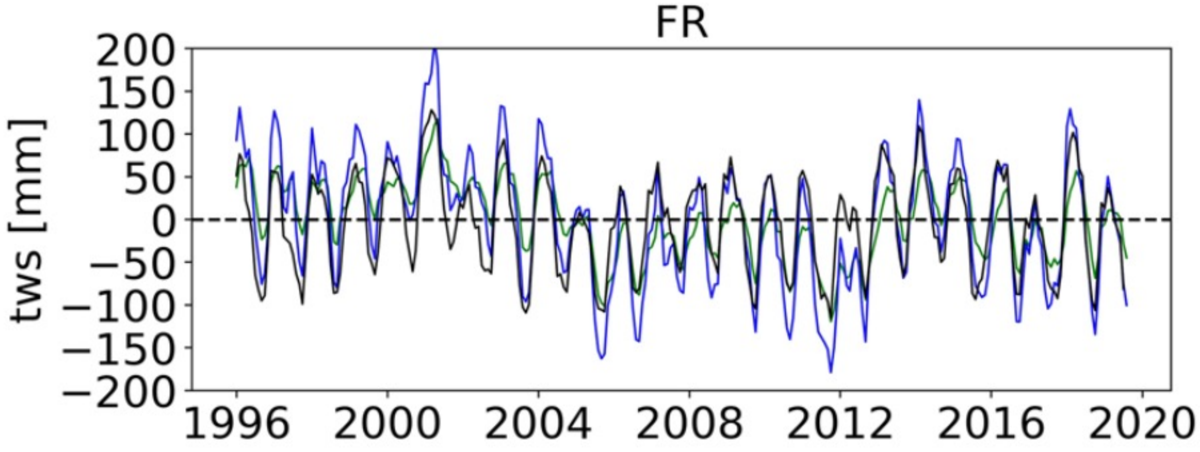
Water storage variability over Prudence regions reproduced

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





Potential spin-up effects



soil storage, aquifer storage, surface water storage

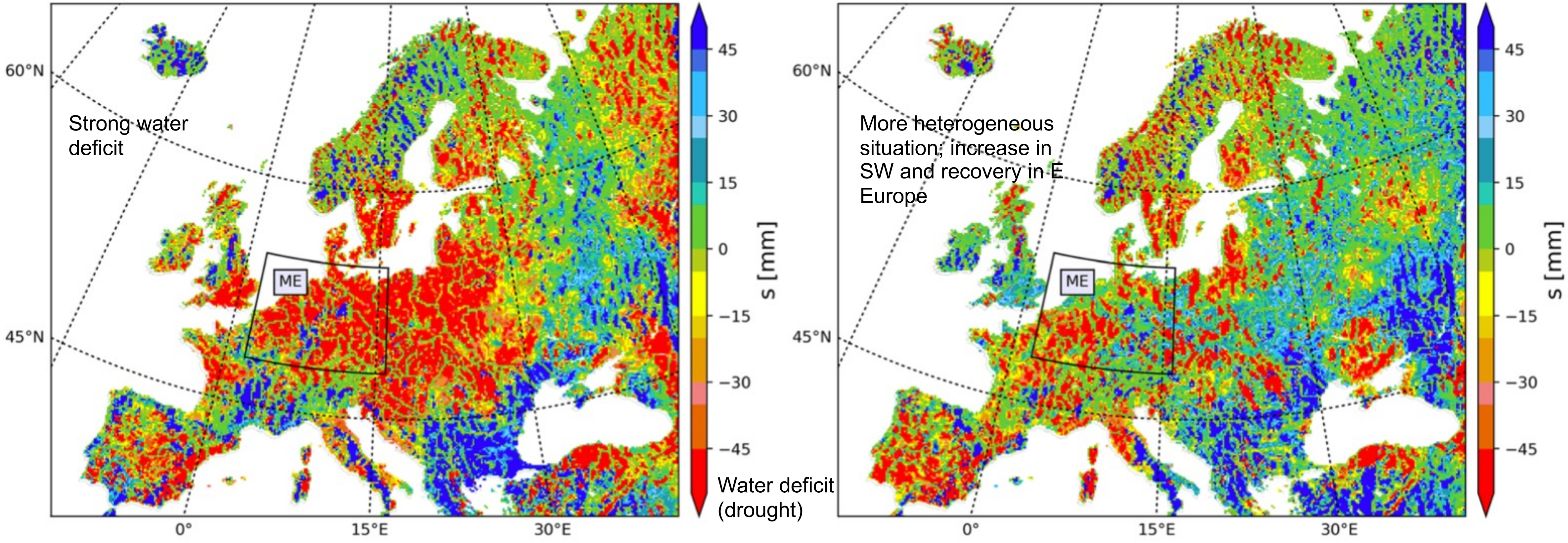
$$s_{i,j} = \sum_{k}^{nz} sat_{i,j,k} \, por_{i,j,k} \, dz \, k$$

Hartick et al. (2021, WRR)

Hydroclimatic extremes

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

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



Strong water deficit

Water deficit (drought)

More heterogeneous situation; increase in SW and recovery in E Europe

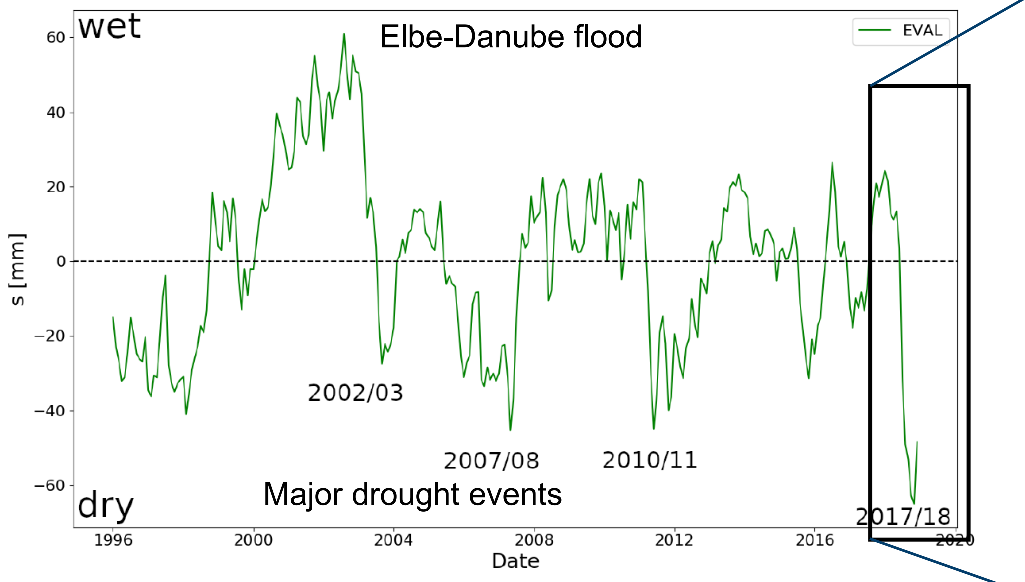
August 2018

August 2019

Hartick et al. (2021, WRR)

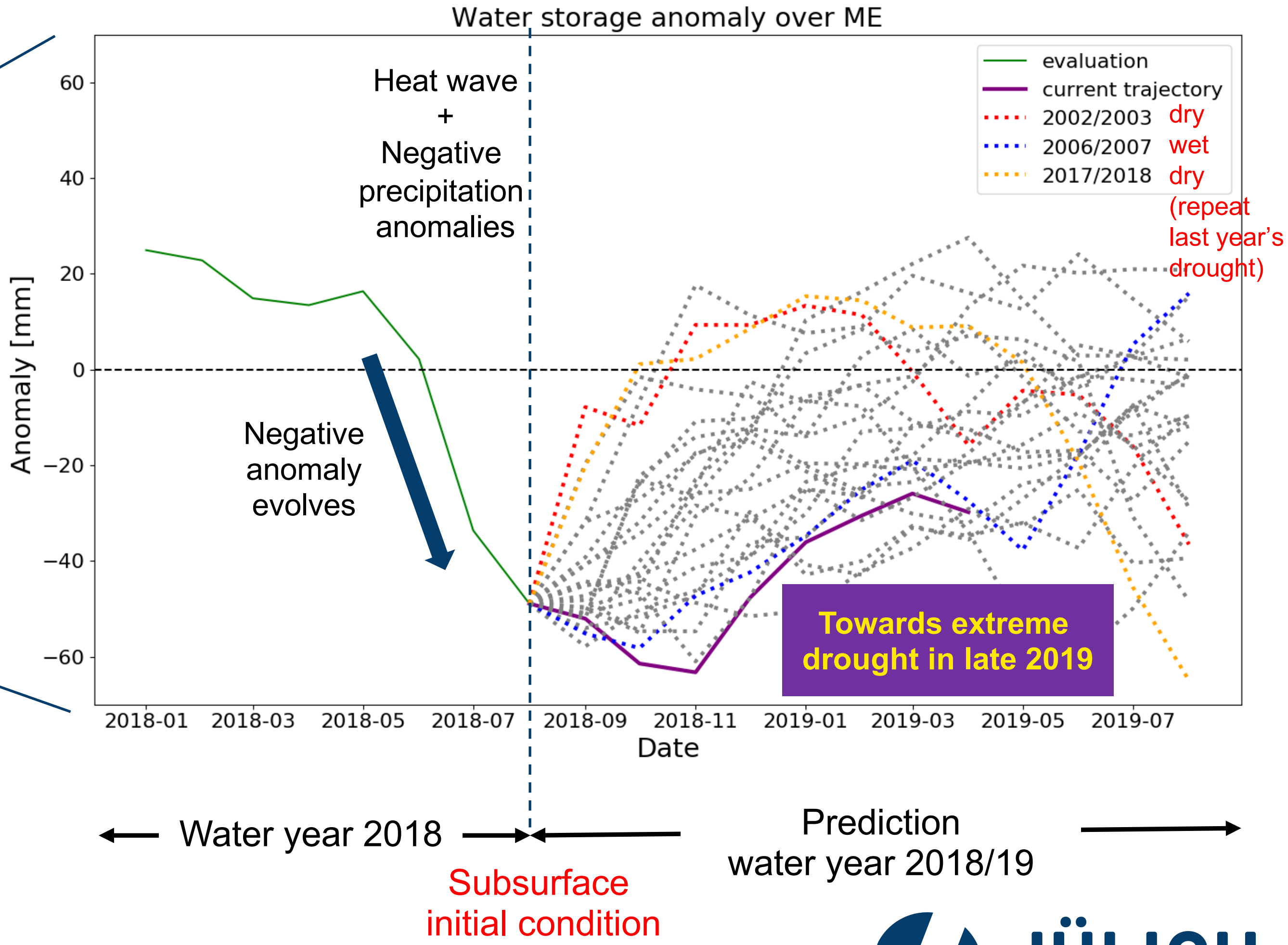
Hindsight assessment of water year 2018/Sep-2019/Aug, ME

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



TSMP water storage anomalies, ME

Hartick et al. (2021, WRR)



Example 3
Land use land cover change

Zipper et al. (2019, ERL, https://doi.org/10.1088%2F1748-9326%2Fab0db3)

Example results from 12km TSMP ERA-Interim simulations

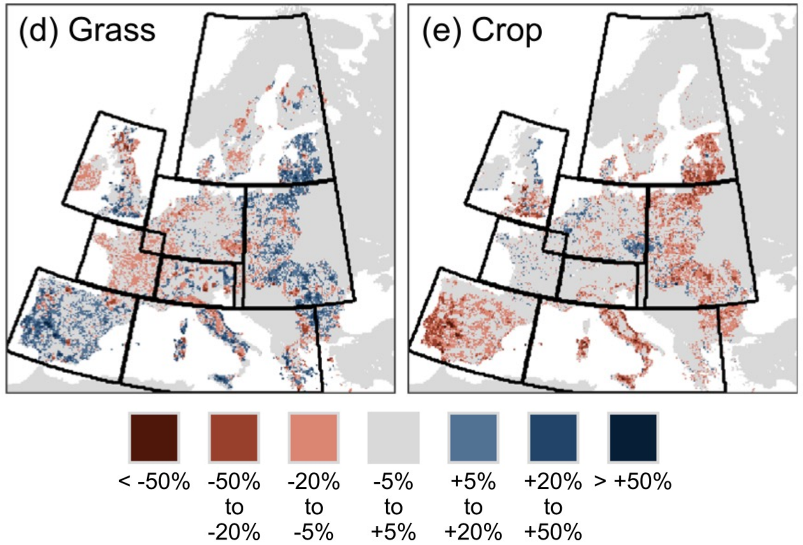
Impacts of LULCC on heat (and drought) in Europe (Zipper et al., 2019, ERL)

TSMP
w/ spectral nudging

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

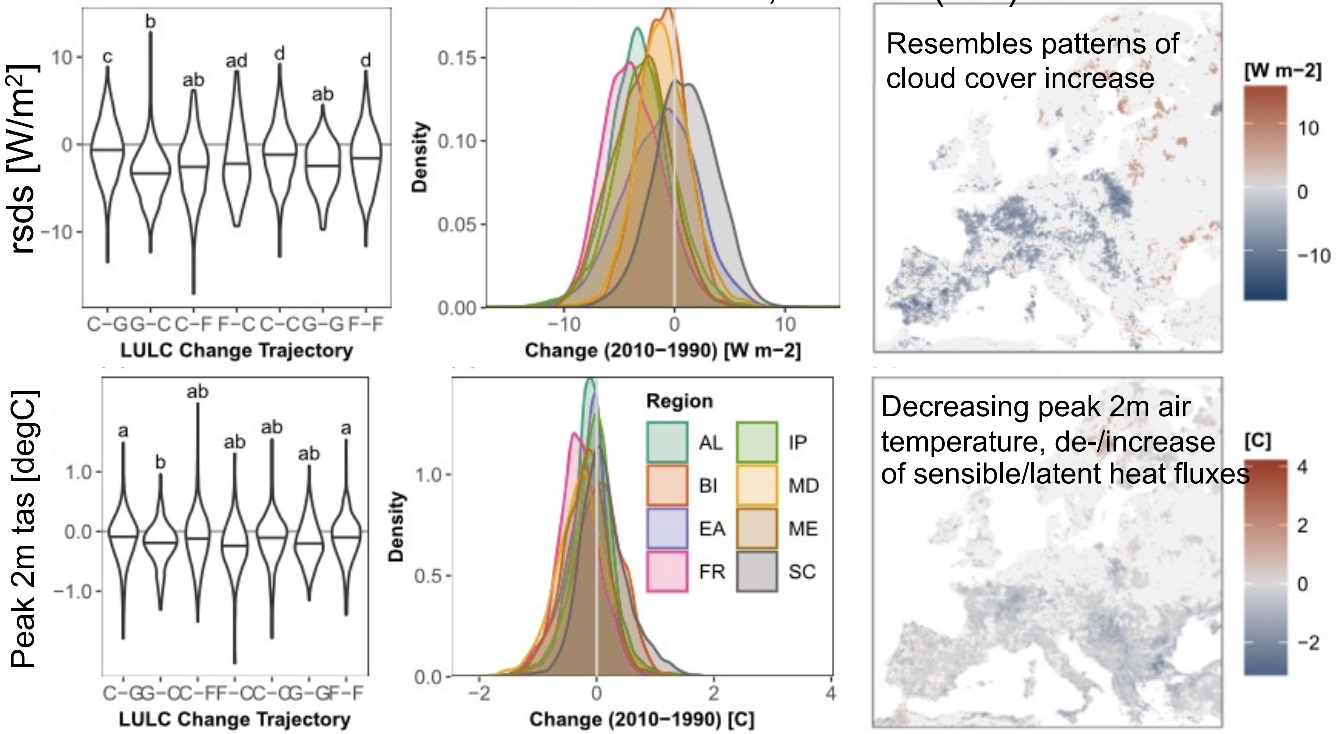
LULCC ensemble:
- 2 land cover datasets 1990 and 2010,
- 3 vegetation parametrisations each

Analyses for 2003 JJA



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

Differences LULC2010-LULC1990, summer (JJA)



Resembles patterns of cloud cover increase

Decreasing peak 2m air temperature, de-/increase of sensible/latent heat fluxes

(Remote) L-A feedbacks due to LULCC lead to widespread changes of energy and water balances, e.g., through substantial increases in cloud cover; shallow groundwater mitigates those heterogeneous impacts; local and non-local LULCC effects are altered by gw-to-atmosphere coupling (not shown)

Example 4
Human water use

Keune et al. (2018, GRL, https://doi.org/10.1029/2018gl077621)

Consideration of human water use (HWU) in TSMP simulations

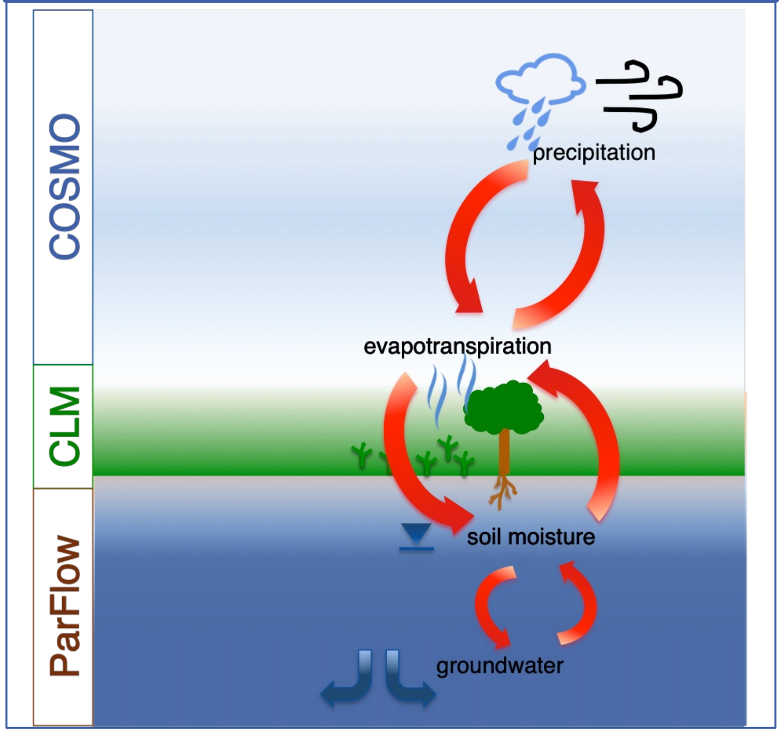
How does human water use affect atmospheric processes, how do these affect water resources?

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?

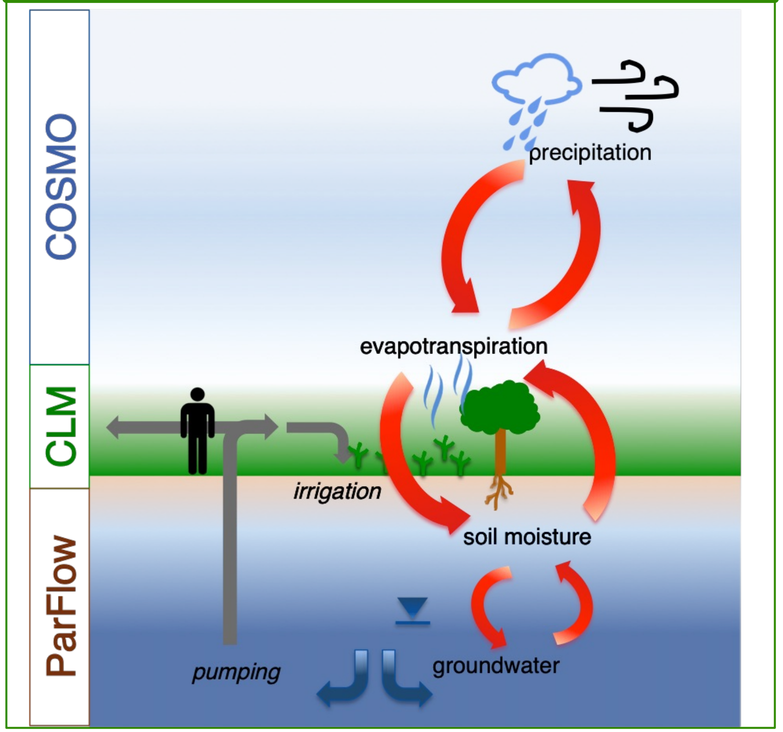
<u>Five simulations for 2003:</u>

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

Natural hydrological cycle



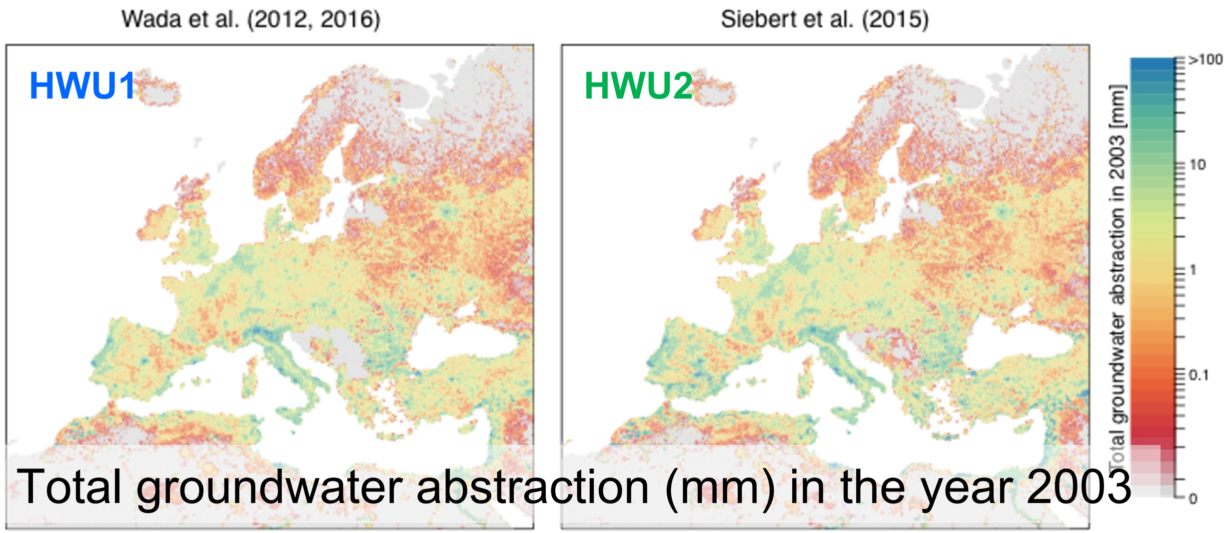
Incorporation of water use



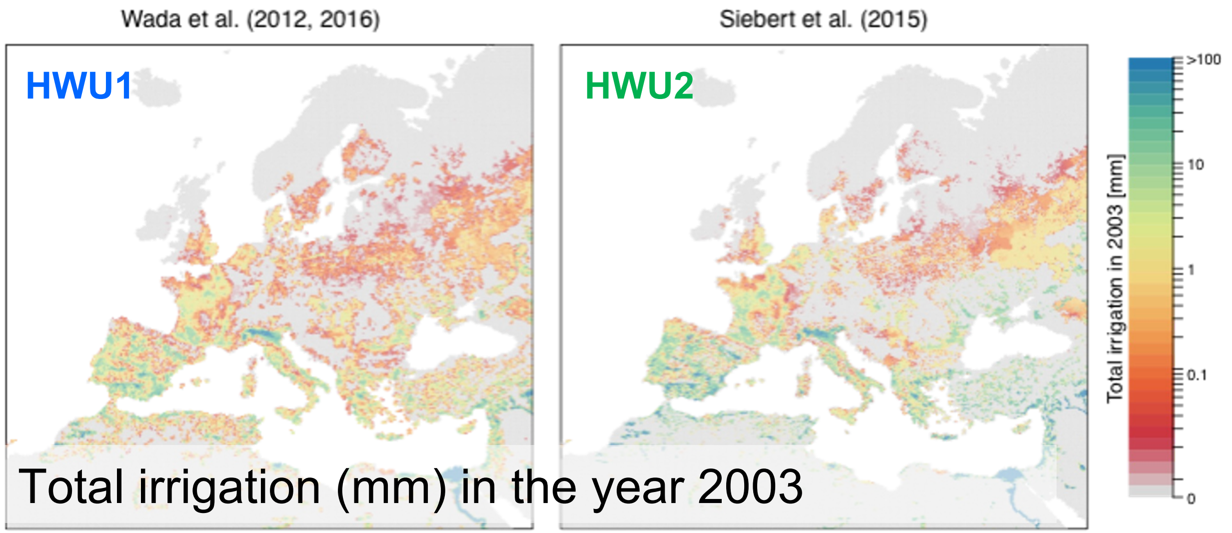
Courtesy J. Keune (2018)

Spatial distribution of groundwater abstraction and irrigation

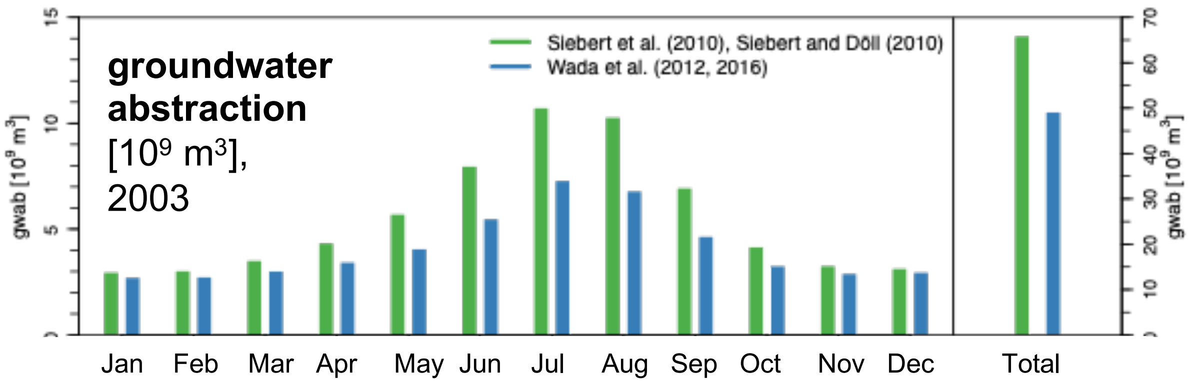
Daily estimates, large uncertainties, Wada et al. (2016) (HWU1) and Siebert et al. (2010) (HWU2) datasets



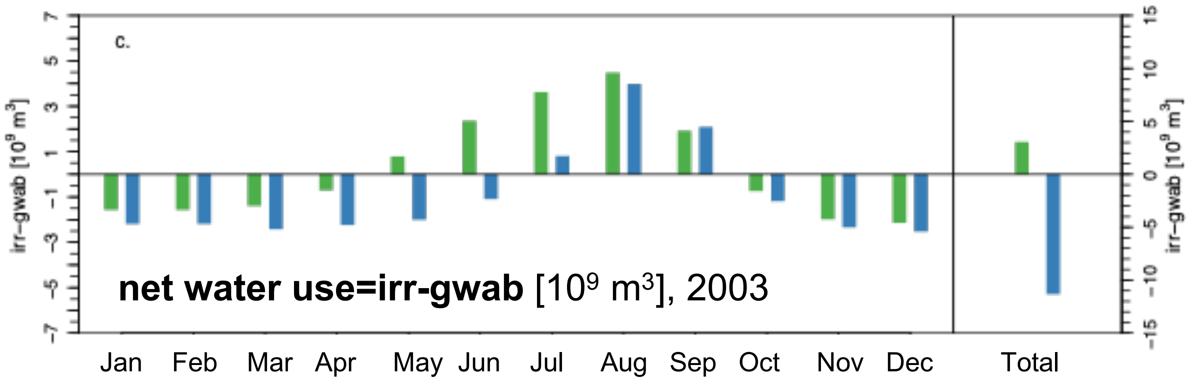
Total groundwater abstraction (mm) in the year 2003



Total irrigation (mm) in the year 2003



groundwater abstraction [10^9 m^3], 2003



net water use=irr-gwab [10^9 m^3], 2003

Keune et al. (2018, GRL)

Example results from 12km TSMP ERA-Interim simulations

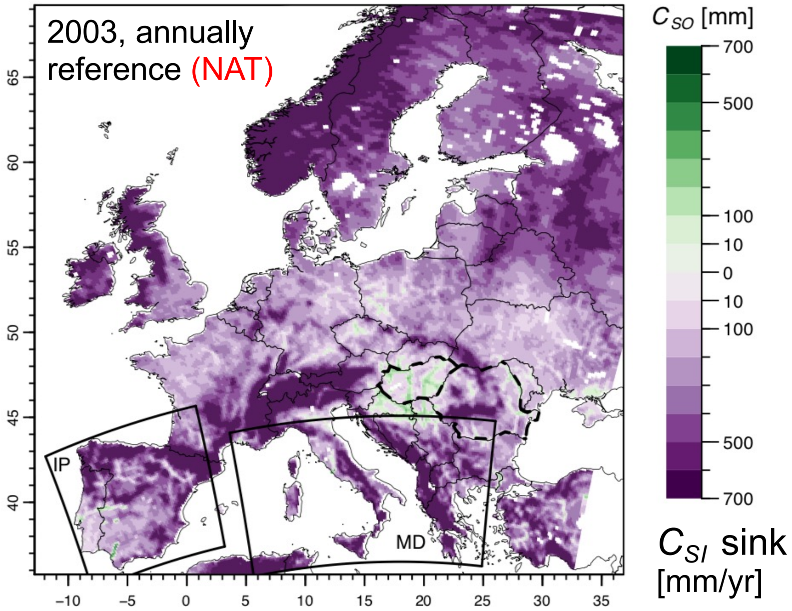
HWU impact on atmospheric water budget and terrestrial water resources (Keune et al., 2018, GRL)

TSMP
w/ spectral nudging

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

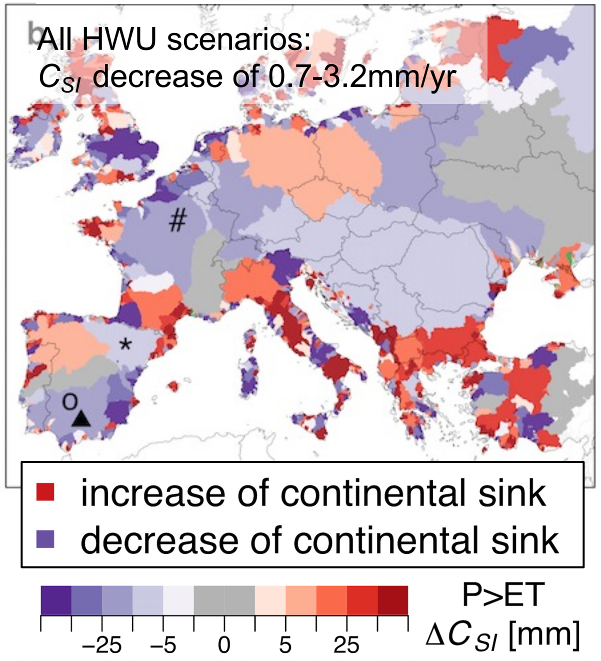
Shown scenario: Wada et al.; for EUR-11 domain: gw abstraction≈ $50*10^9 m^3/yr$ irrigation≈ $38*10^9 m^3/yr$

Atm. water budget, div(Q) = ET-P



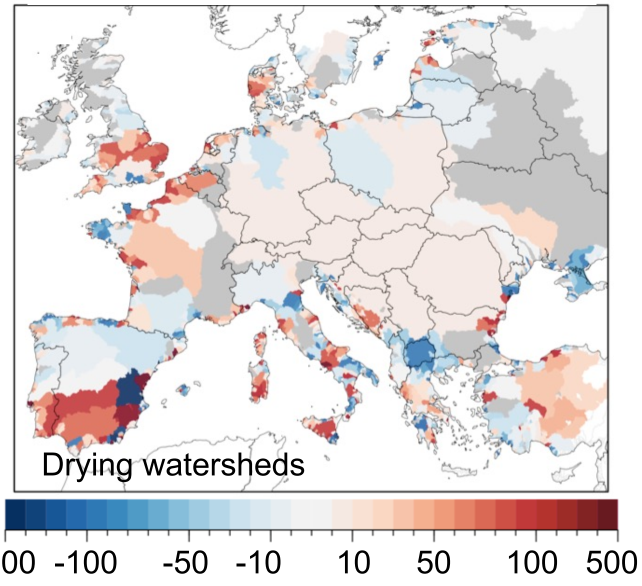
Continental sink C_{SI}: P > ET (net import)
Source C_{SO}=div(Q)=ET-P: ET> P (summer)

HWU1-n - NAT, 2003, example



HWU-induced C_{SI} alteration

NAT - HWU1-n, 2003, example



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

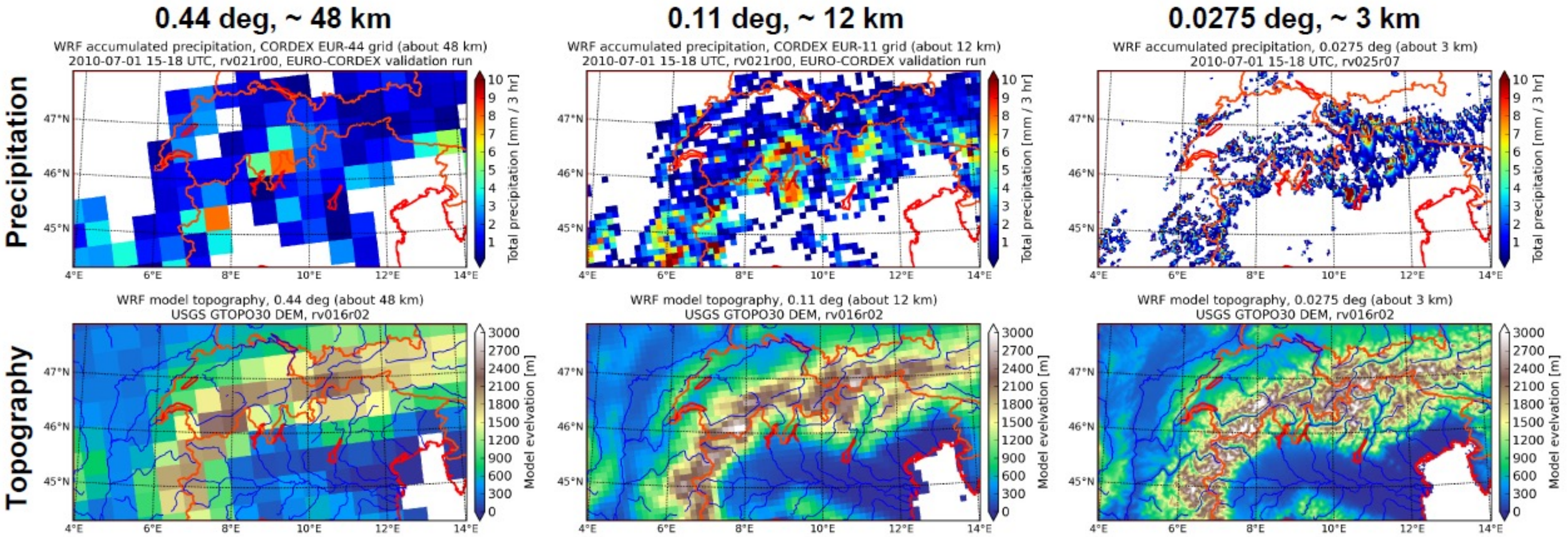
Consistent with HWU: Systematic C_{SI}-changes (weakening in arid watersheds, ET increase); through atmospheric feedbacks and redistributions: (non-local) impacts on subsurface water storage, especially southern Europe (with water management sustainability implications)

Towards km-scale resolution with coupled model systems

At km-scale RCM resolution, surface hydrology and subsurface hydrodynamics seem to become even more important

Added value of convection-permitting RCM simulations

Main RCM commuity experiment so far: CORDEX Flagship Pilot Study on CP climate modelling



- Better capture of small-scale land surface heterogeneities (soils, orography, land cover, etc.)
- More realistic representation of dynamical processes
- Error-prone convection parameterisation is off
- Better reproduction of precipitation intensities, timing, spatial distribution

CORDEX-FPSCONV (first-of-its-kind km-scale RCM ensemble) (Coppola et al., 2020, Clim Dynam)

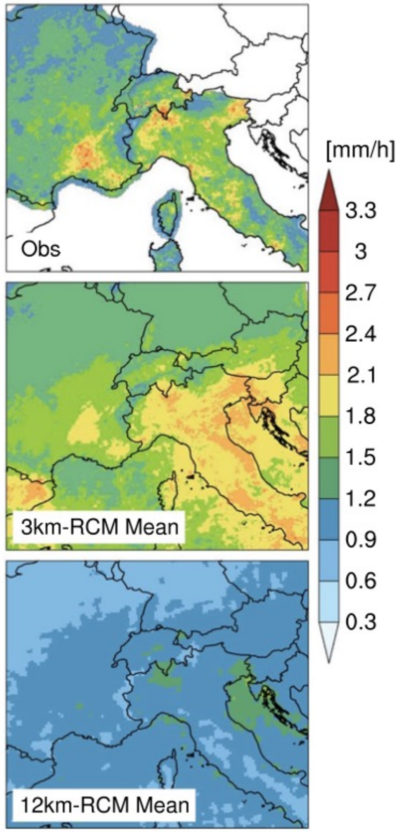
“Flagship Pilot Studies“ address specific key scientific challenges; subcontinental, targeted regions

Added value in km-scale or convection permitting RCMs simulate in model detail (deep-convection parametrisation is off) (e.g., Lucas-Picher et al., 2021, WIREs; Prein et al., 2015 Rev Geophys; Schär et al., 2020, BAMS):

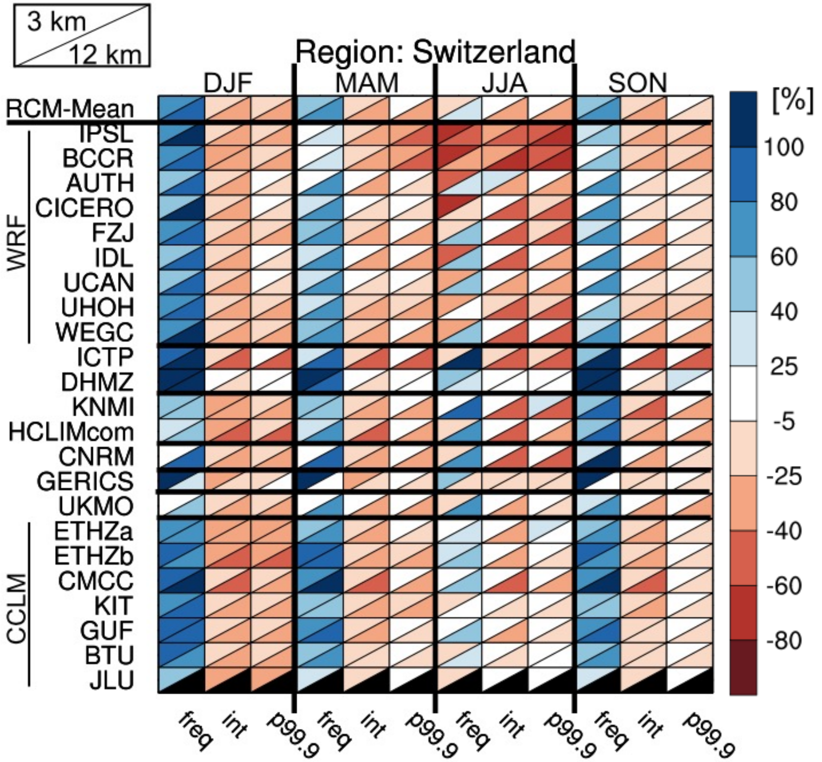
- Small-scale atmospheric processes
- Surface heterogeneities
- Mesoscale dynamical processes

-> Improved precipitation characteristics, MCSs, local wind systems, cload cover, radiation, orographically induced phenomena

-> But heat waves, e.g., over-estimated (Sangelantoni et al., 2023, Clim Dynam)



Ensemble (20 member) mean of JJA hourly precipitation intensity.



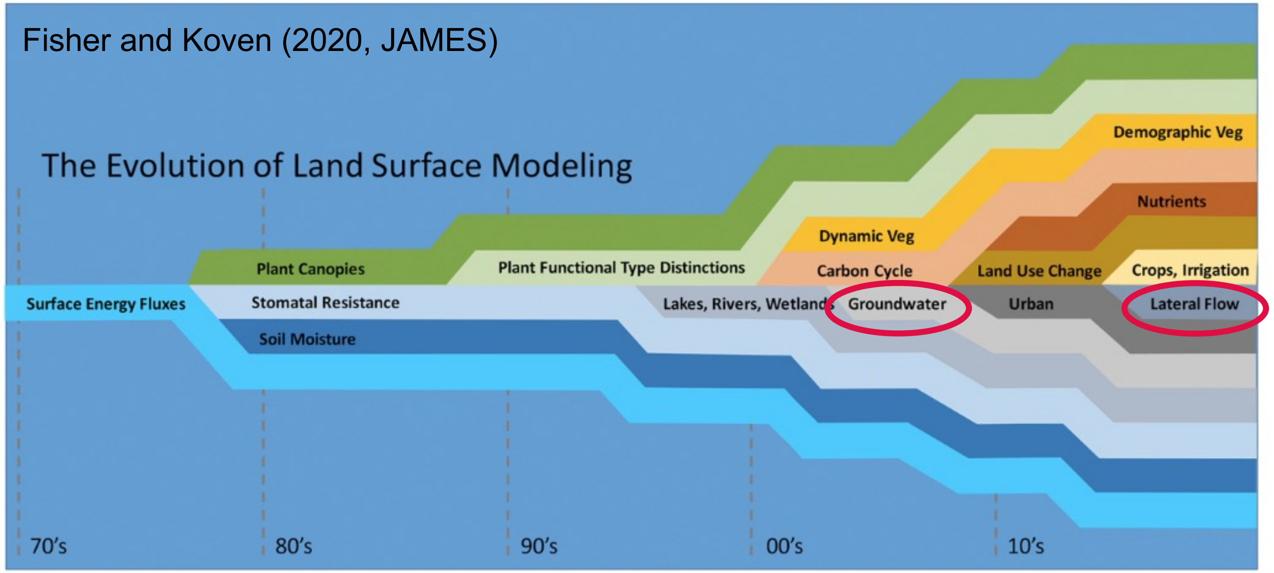
Relative bias, hourly precipitation wrt EURO4M-APGD. Boxes: domain mean bias for 3 km/12. Evaluation runs.

high resolution

Ban et al. (2021, Clim Dynam)

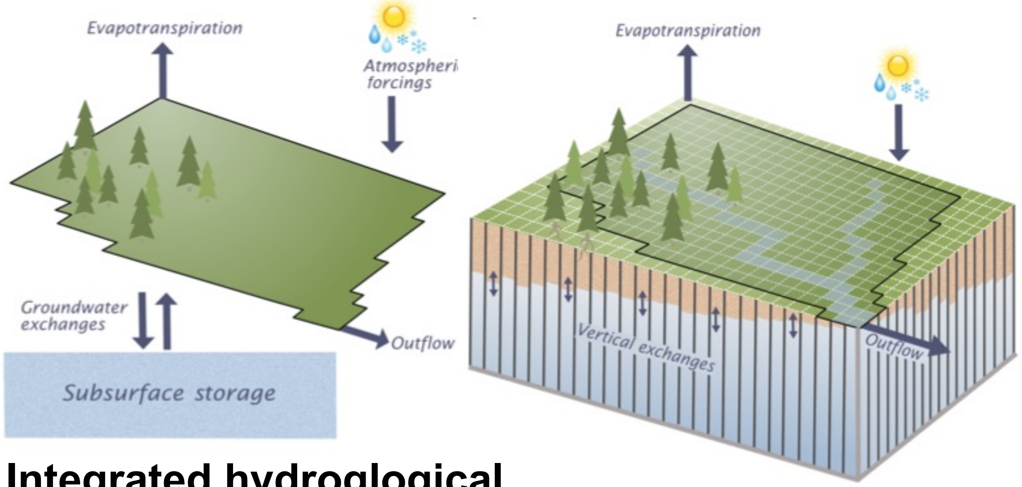
Part of LSM evolution km-scale res. needs explicit hydrology

Surface and sub-surface hydrology is currently under improvement with many model systems

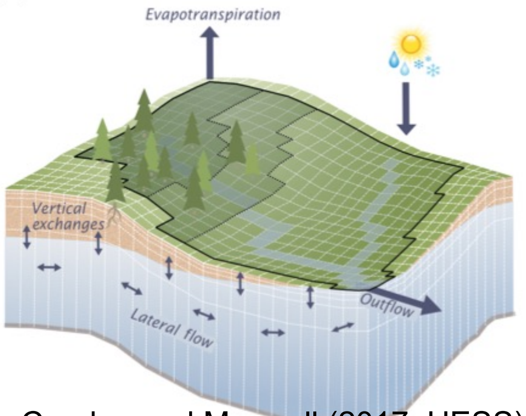

Fisher and Koven (2020, JAMES)

Some conclusions form J. Polcher and M. Best:

- At **km-scale** role of **flowing water** becomes more **important**
- **Surface gradients** need to be explicitely represented, strong gradients between moisture convergence and divergence
- **Transfer** of **surface and subsurface** water needs consideration
- **Feedbacks** with the **atmosphere** (very differentiated ET)
- Better suitability for **climate services**



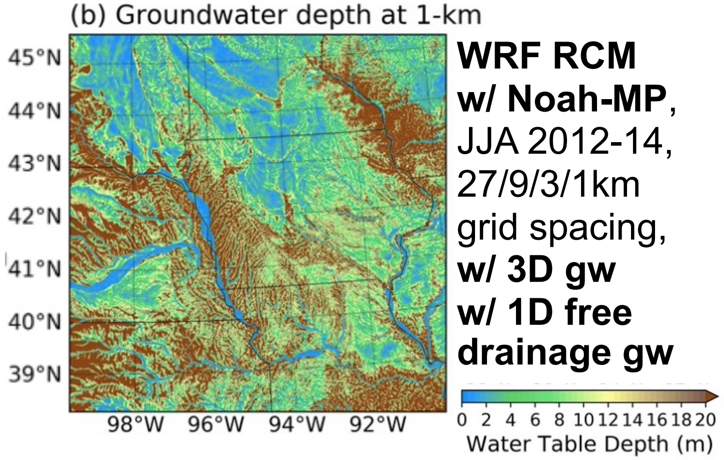
- **Integrated hydroglogical models (IHMs)**
- Resembling heterogenity at km-scale
- Hill slopes are resolved: 3D redistribution of water
- Important for surface-aquifer interactions and streamflow



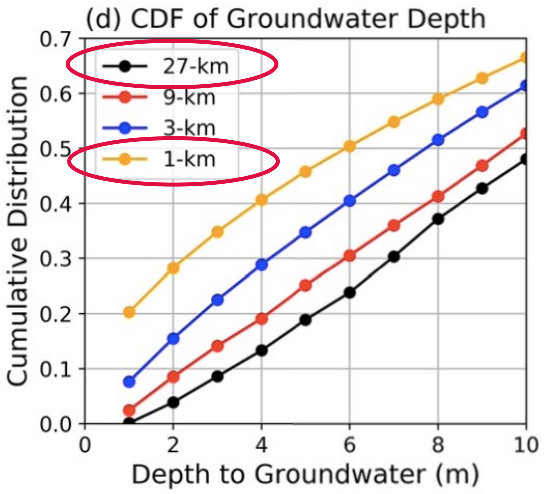
Condon and Maxwell (2017, HESS)

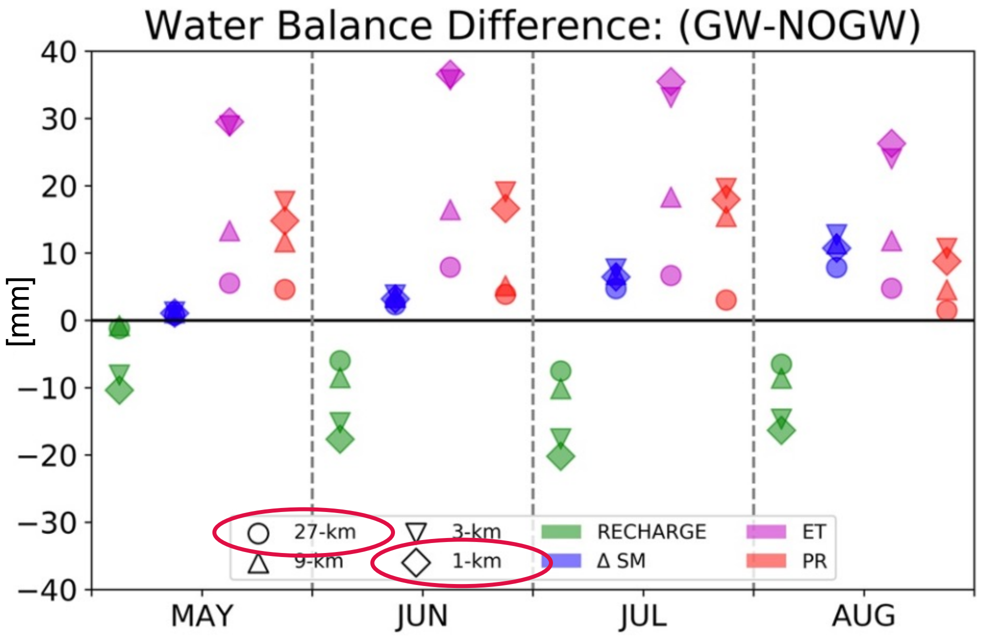
Km-scale added-value in RCMs: need for explicit hydrology

Resolution-dependence: GW processes modify land-surface water balance (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**





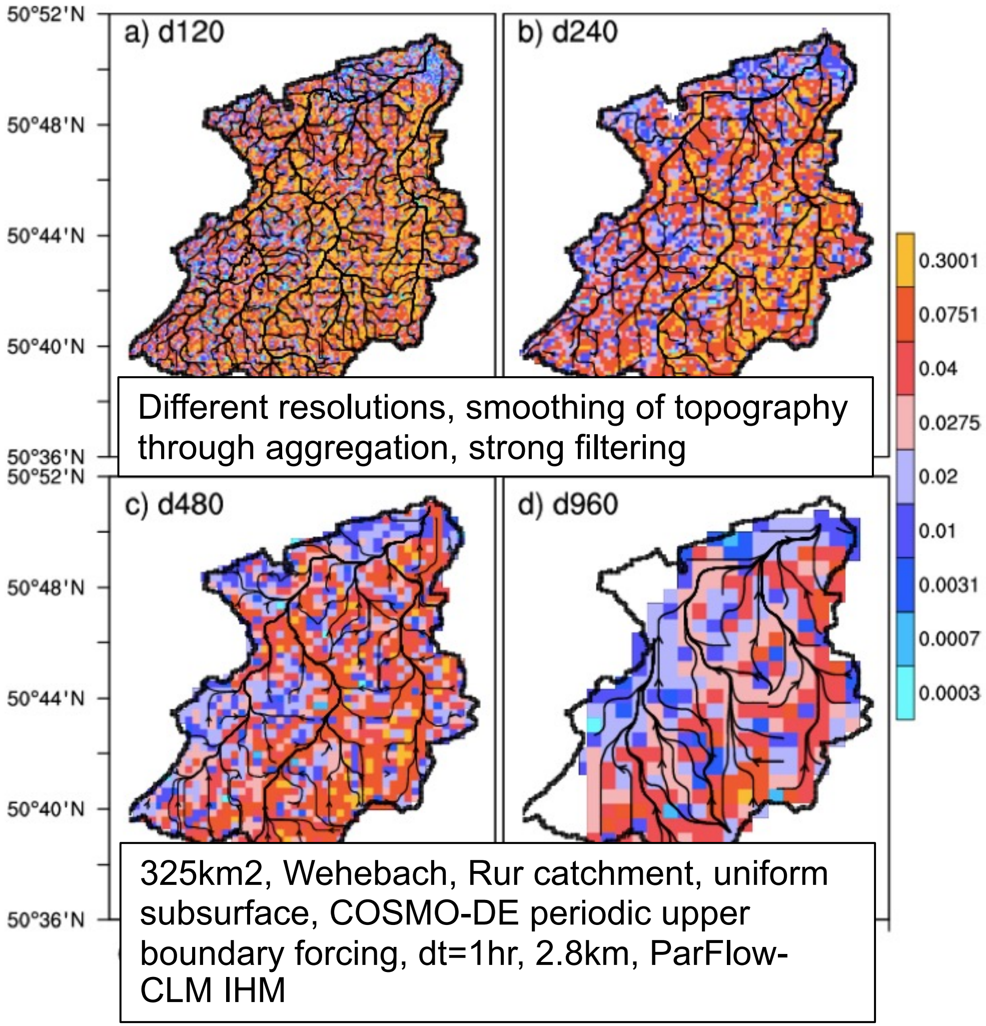
- At km-scale role of flowing water becomes more important
- Surface gradients need to be represented, strong gradients between moisture convergence and divergence
- Transfer of surface and subsurface water needs consideration

Explicit groundwater physics leads, e.g., to:

- Realistic water table pattern (depending drainage, convergence, etc.)
- At 3km or less: Realistic gw processes (shallow water tables in convergence zones with alluvia) and water redistribution in complex terrain
- Feedbacks with the atmosphere: Higher evaporative fractions, lowering of tas biases

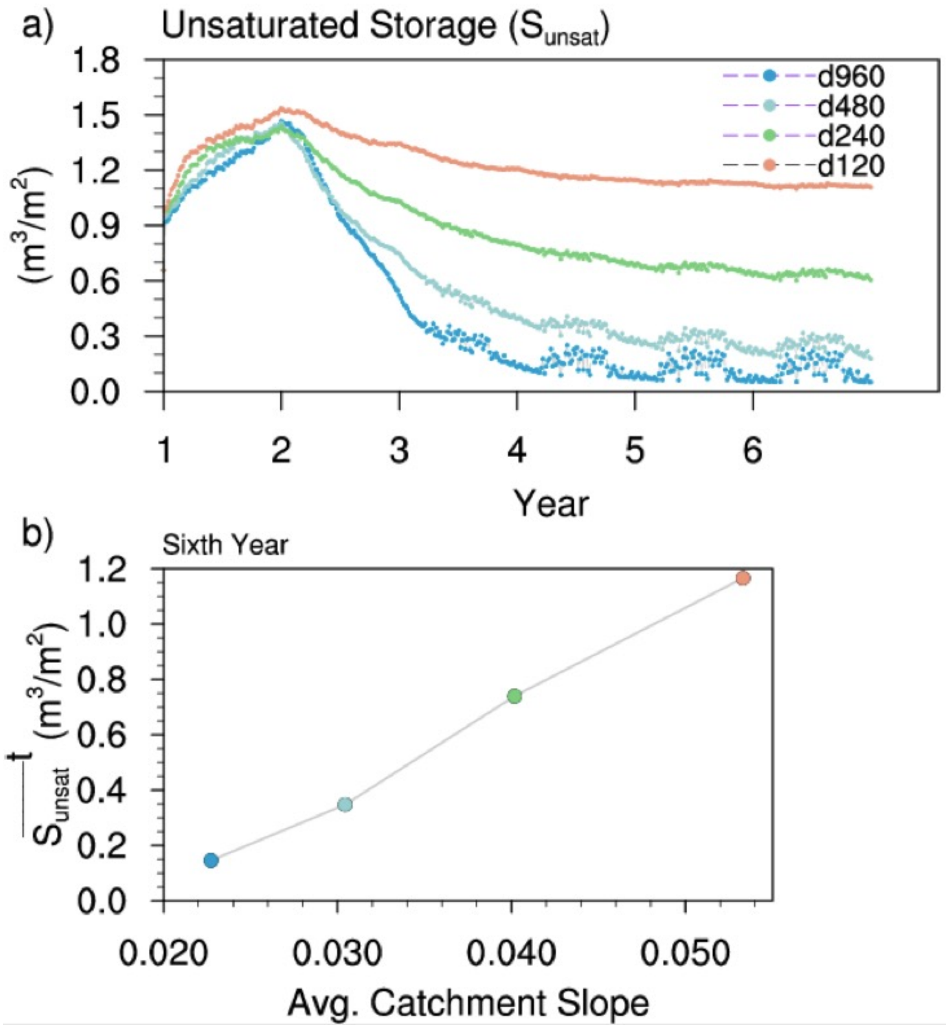
Resolution-dependence of hydrological processes

Surface gradients are becoming more important



Different resolutions, smoothing of topography through aggregation, strong filtering

325km2, Wehebach, Rur catchment, uniform subsurface, COSMO-DE periodic upper boundary forcing, dt=1hr, 2.8km, ParFlow-CLM IHM

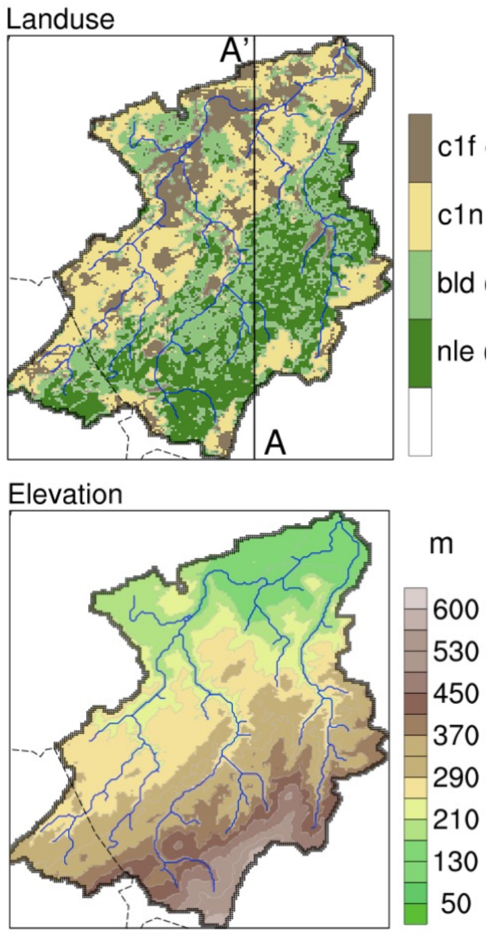


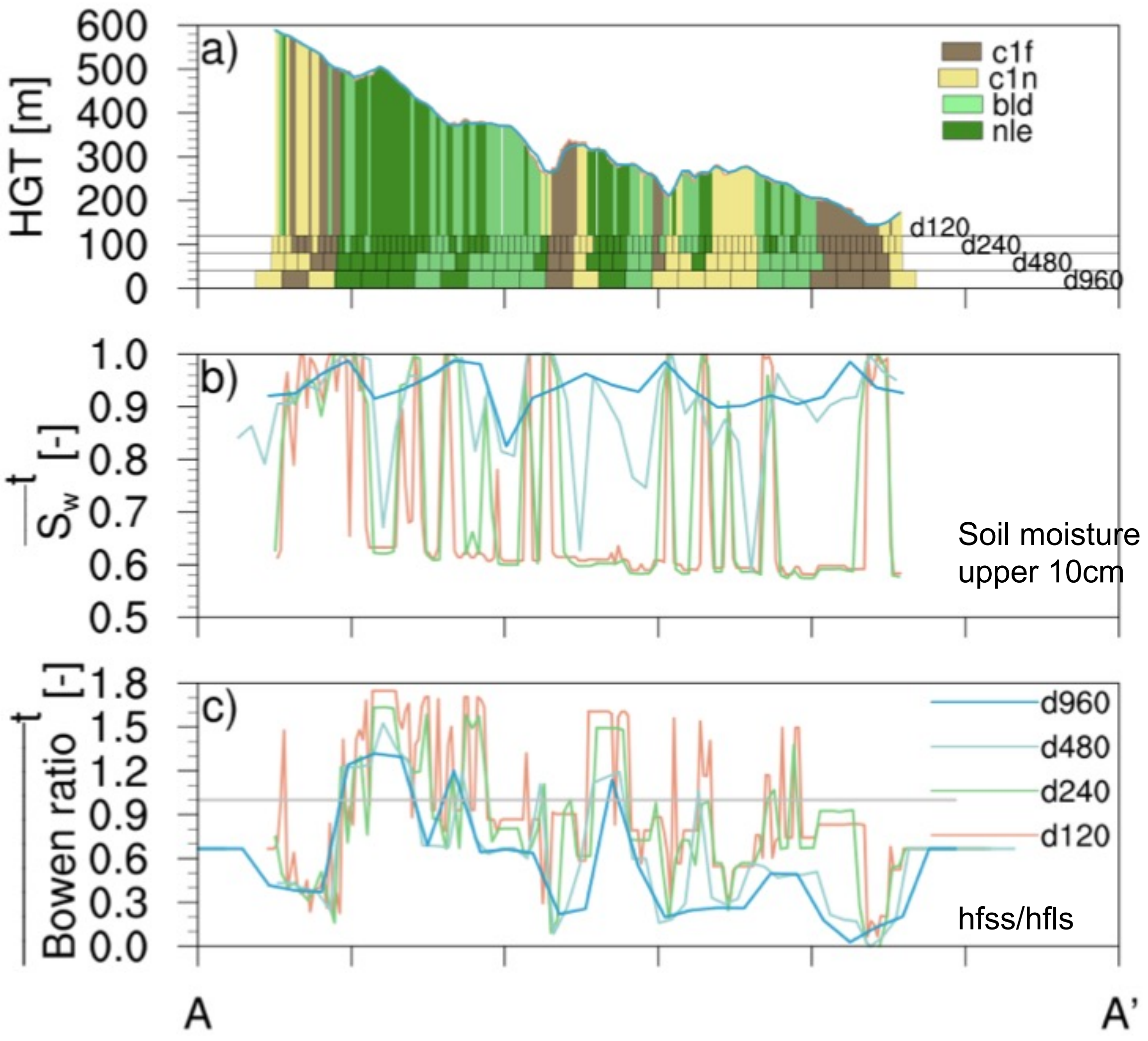
ParFlow+CLM; small-scale surface heterogeneities and properties significantly affect surface run-off and infiltration and subsurface redistribution leading to different coupling regimes

Shrestha et al. (2015, HESS)

Resolution-dependence of surface energy fluxes

Modulated through heterogeneity and redistribution of surface water





- Non-local controls of soil mois. patterns 100-1000m grid resolutions
- Strong modulation of soil temp. and surface fluxes by local PFTs
- Non-linear scaling behaviour of energy balance with respect to grid resolution

Shrestha et al. (2015, HESS)

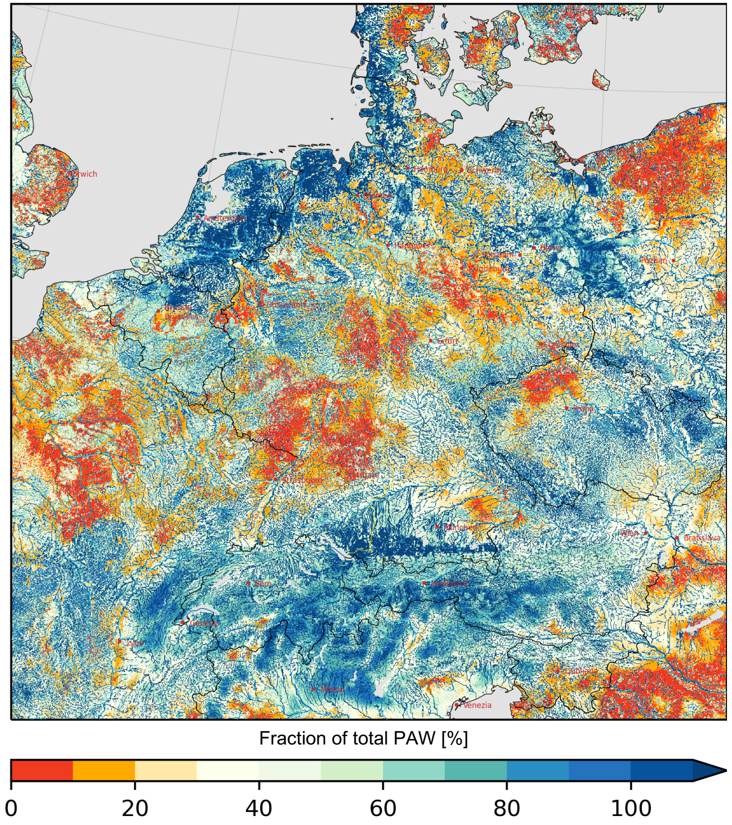
Example 5
ParFlow km-scale hydrological forecasts

Belleflamme et al. (2023, ERL, https://doi.org/10.3389/frwa.2023.1183642)

Example use of high resolution hydrol. model runs

ParFlow forecasts, provided daily on a product platform (www.adapter-projekt.de)

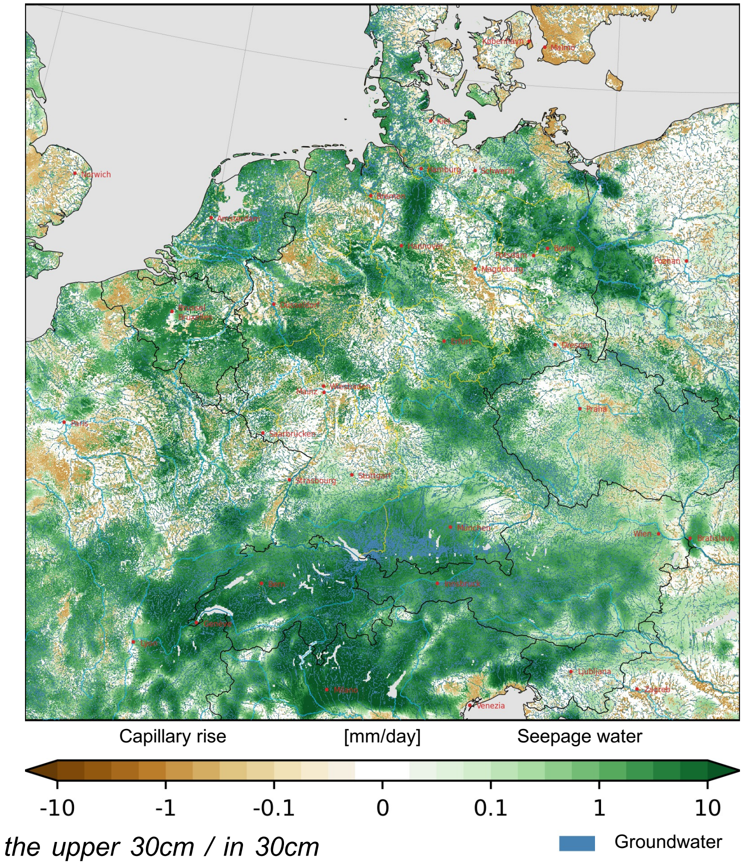
- Water stress



Plant available water

2022-09-08 daily mean, 0-30cm depth

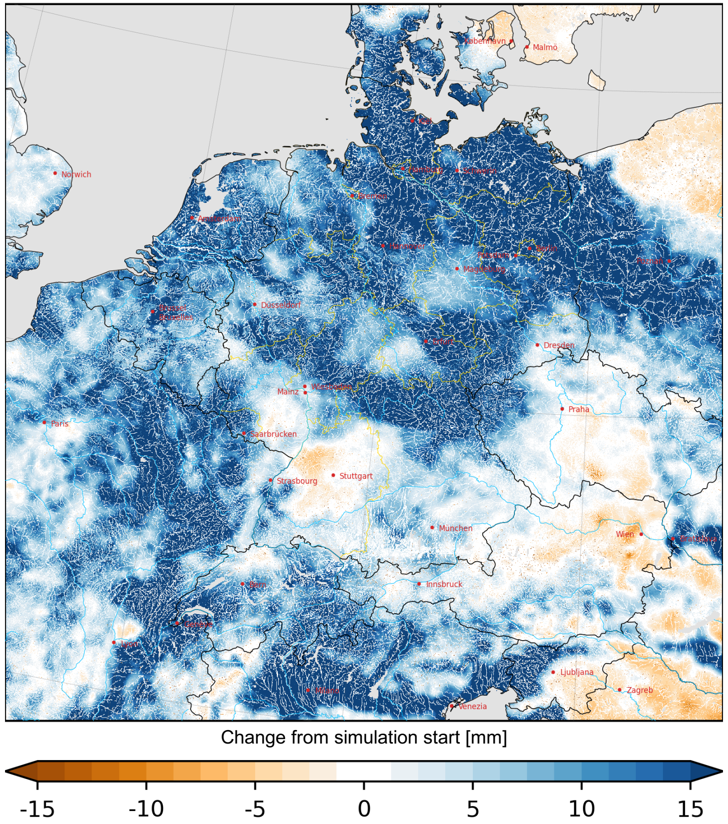
- Leakage of nutrients



Seepage water / capillary rise

2022-09-08 daily sum, 30cm depth

- Irrigation / water resources



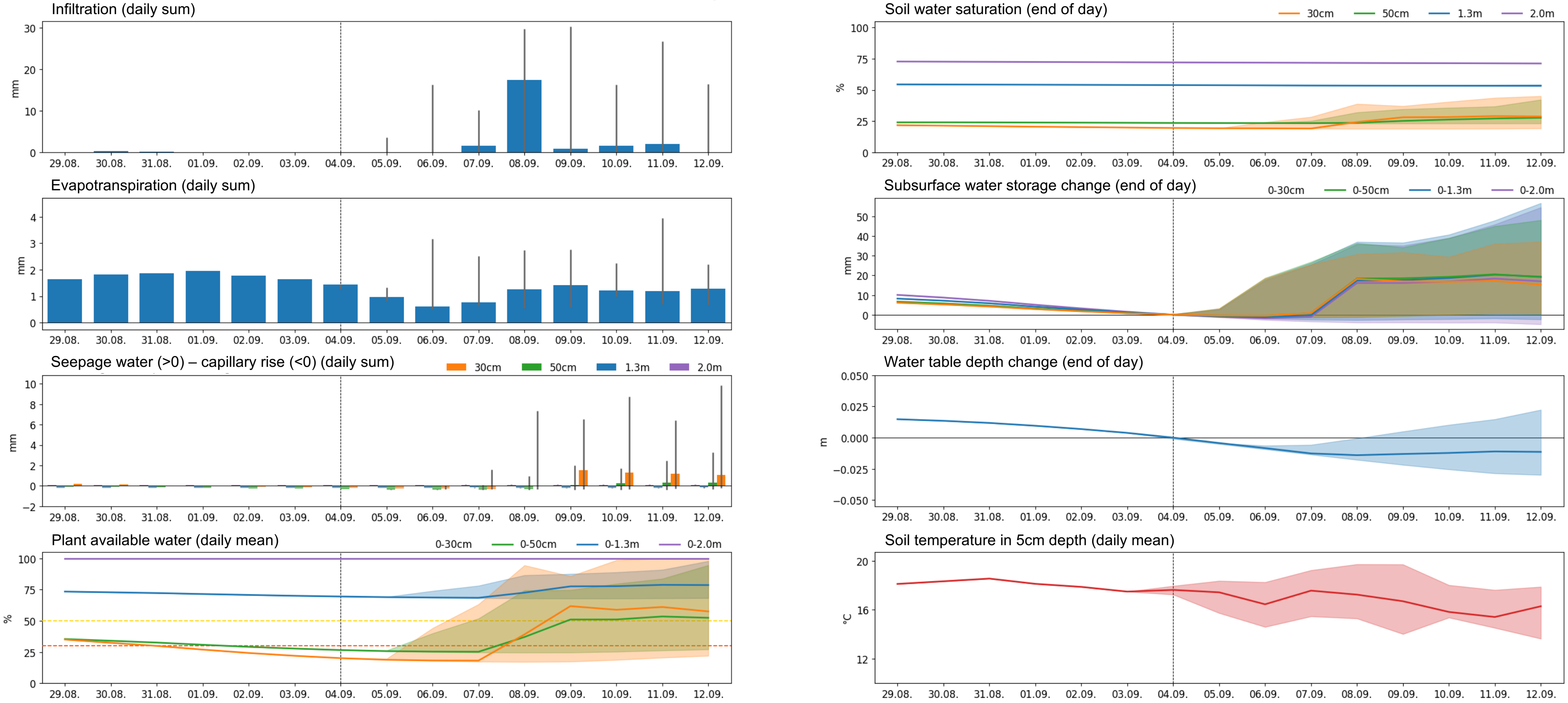
Change in subsurface water storage

2022-09-08 end of day, 0-30cm depth

Examples of diagnostics based on the deterministic forecast for the upper 30cm / in 30cm depth. Forecast for the 8th of September 2022 from the run initialized at 2022-09-04T12:00Z.

Uncertainty is communicated to users

For four (root-)depths, aggregated on a 3x3km² grid



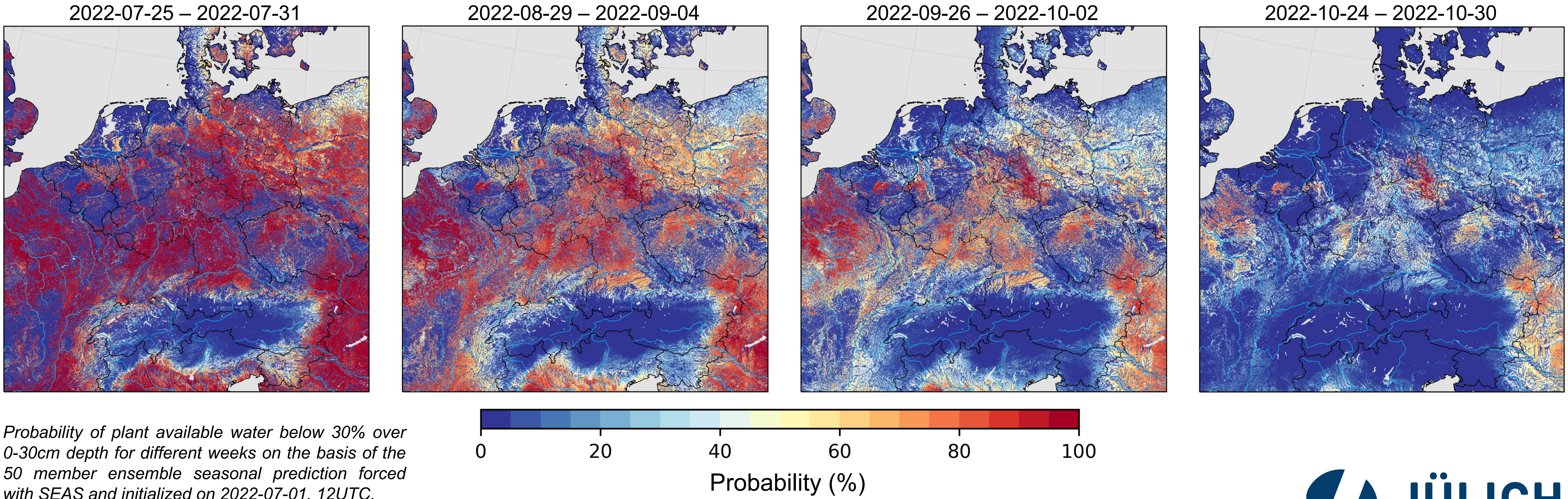
Time series for 51.9502°N 13.6564°E (Brandenburg, south of Berlin) hindcast + forecast initialized on 2022-09-04T12:00Z.

Seasonal ensemble predictions allow risk estimations

Through indices highlighting e.g. the probability of water stress occurrence

This can help stakeholders to

- Manage their water resources for the coming months
- Adapt their activities to mitigate the risk of yield loss through water stress

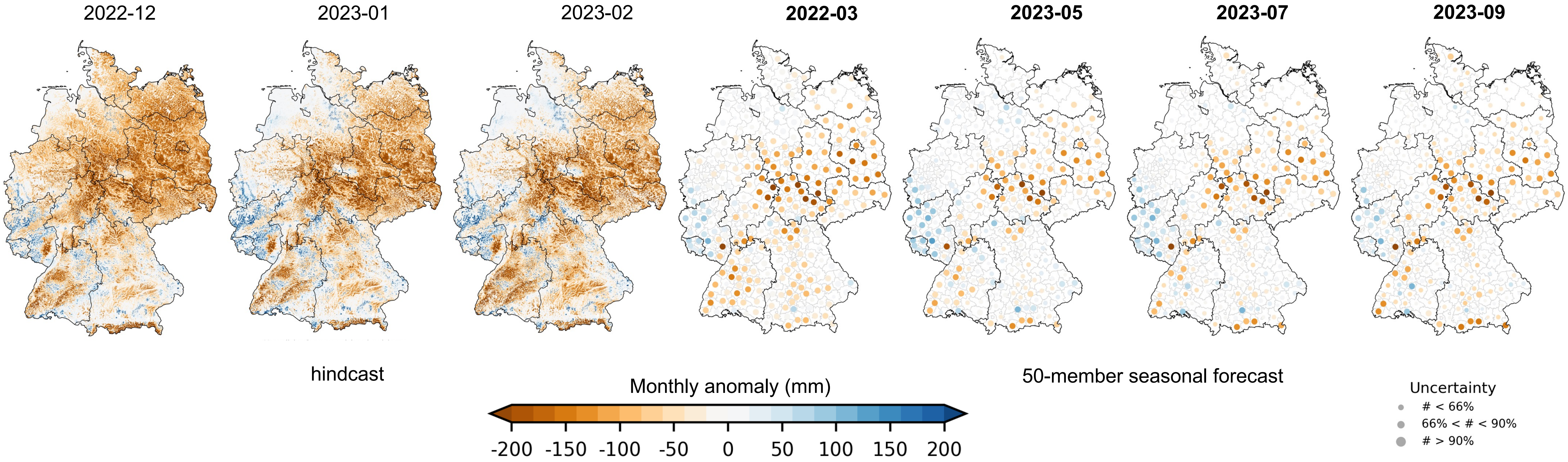


Probability of plant available water below 30% over 0-30cm depth for different weeks on the basis of the 50 member ensemble seasonal prediction forced with SEAS and initialized on 2022-07-01, 12UTC.

Information for water resources management

Beyond the agricultural sector (FZJ Water Resources Bulletin for Germany, www.adapter-projekt.de/bulletin)

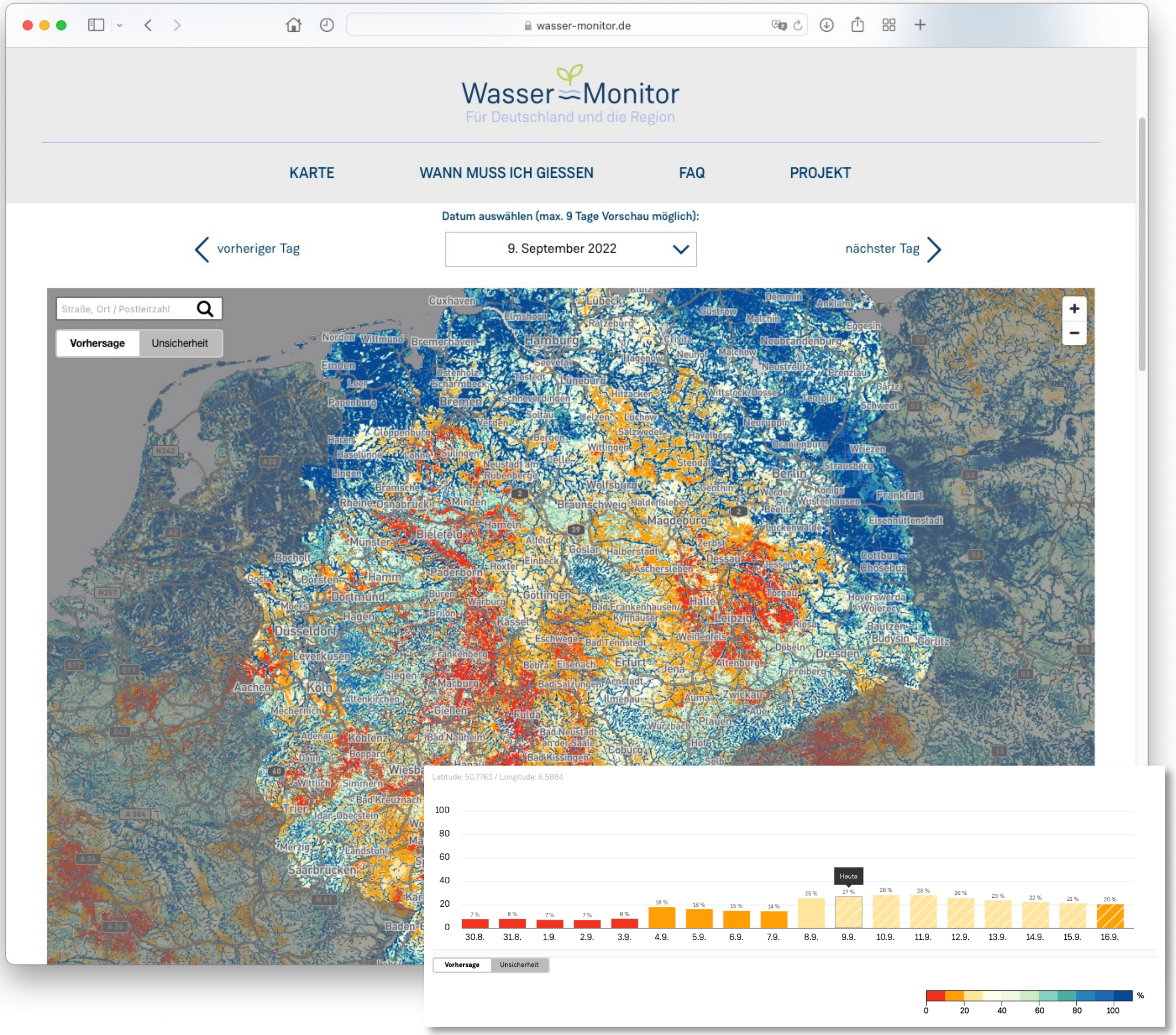
- Show current situation and forecast in the context of the past decade
- Example: monthly anomalies of total subsurface water storage [mm]



Monthly anomalies of total subsurface water storage with respect to 2011-2021, in mm. Hindcast (Winter 2022/23) is forced with HRES (deterministic run). Seasonal forecast (Spring and Summer 2023) is shown as 50-member ensemble mean forced with the SEAS 50 ensemble members and initialized on 2023-03-01, 12UTC. The ensemble mean is averaged at the NUTS3 level (Kreise). The size of the circles reflects the number of members showing the same sign for the anomaly.

www.wasser-monitor.de – dissemination for general public

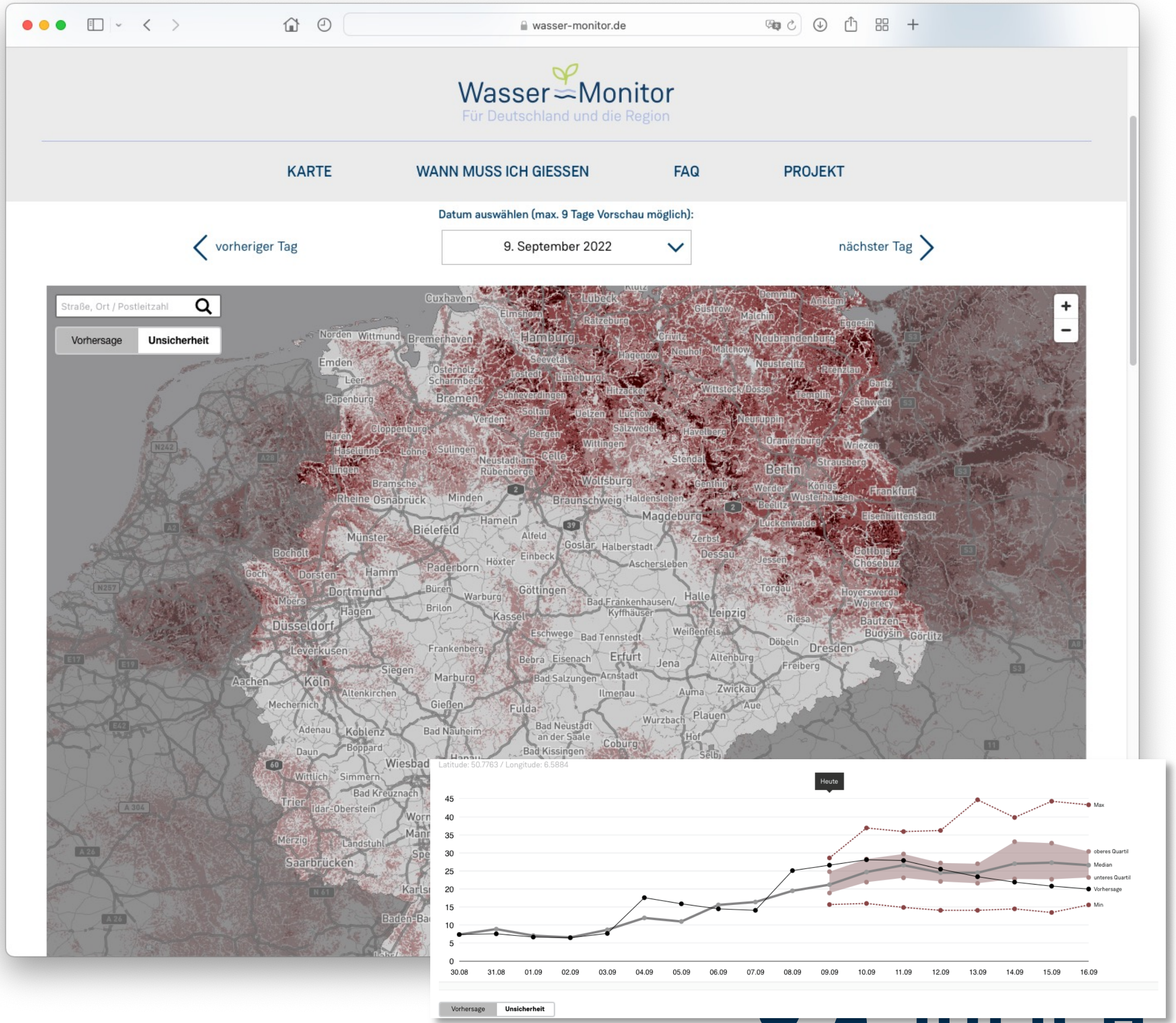
PAW forecasts (+9d); ParFlow/CLM; 2022-09-09 daily mean, 0-0.3m, sub-km (611x611m^2)



Datum auswählen (max. 9 Tage Vorschau möglich):

9. September 2022

Latitude: 50.7763 / Longitude: 6.5884



Datum auswählen (max. 9 Tage Vorschau möglich):

9. September 2022

Latitude: 50.7763 / Longitude: 6.5884

Example 6
New frontier simulations, fully coupled km-scale pan-European

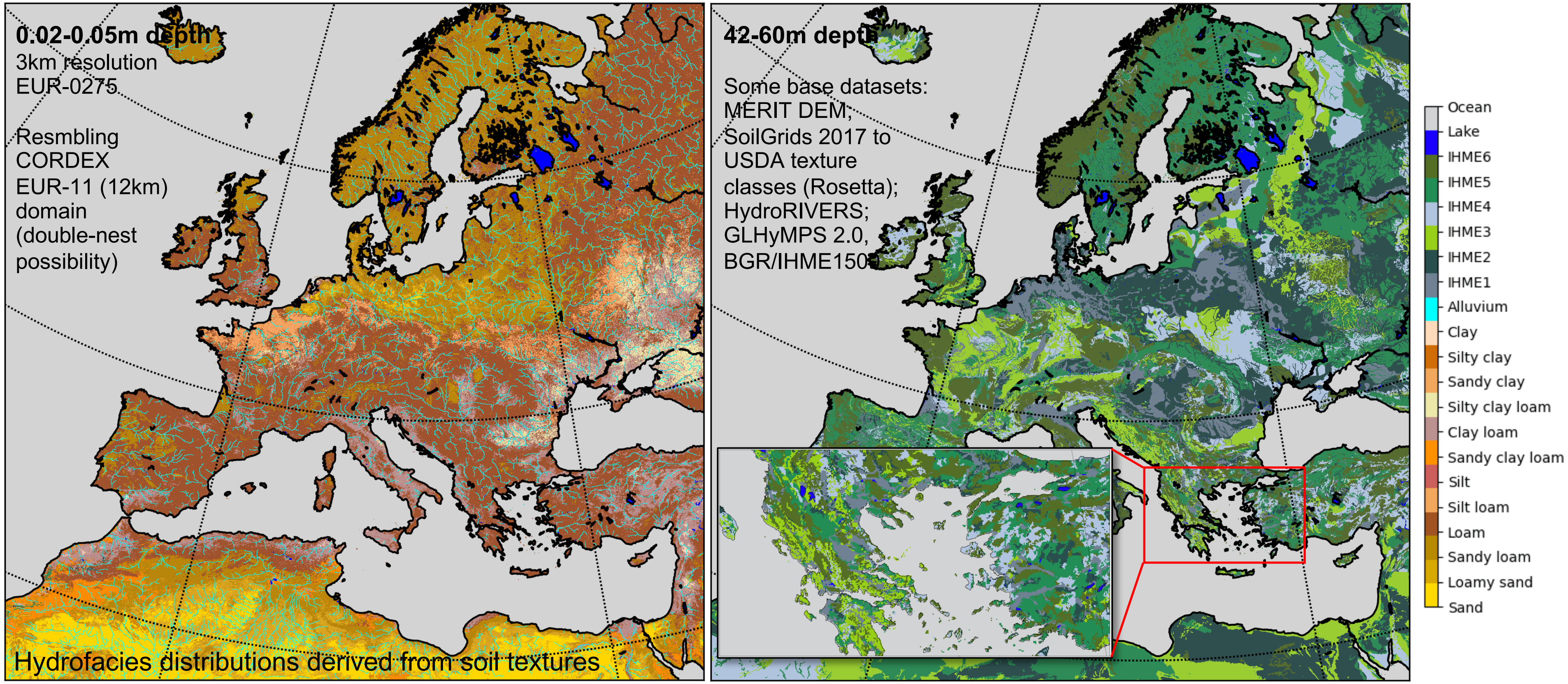
Setting up a new pan-EU km-scale coupled TSMP

Frontier simulation with TSMP RCSM: COSMO v5.01 + CLM v3.5 + ParFlow v3.x + OASIS3-MCT2

- **Coupled G2A TSMP**
- **Continental** (1600x1552x50/15)
- **Km-scale**: 3km (12km)
- **Climate mode**
- w/ HWU, LULCC (SSPs)
- ERA5, CMIP6 downsc.
- Large domain benefits, e.g.: remote feedbacks, EU socio-econmic assessments

Challanges:

- Computing (hetero-geneous, modular HPCs, big data analytics)
- Spinup of subsurface
- (Sub-)surface settings



0.02-0.05m depth
3km resolution
EUR-0275

Resmbling CORDEX EUR-11 (12km) domain (double-nest possibility)

Hydrofacies distributions derived from soil textures

42-60m depth

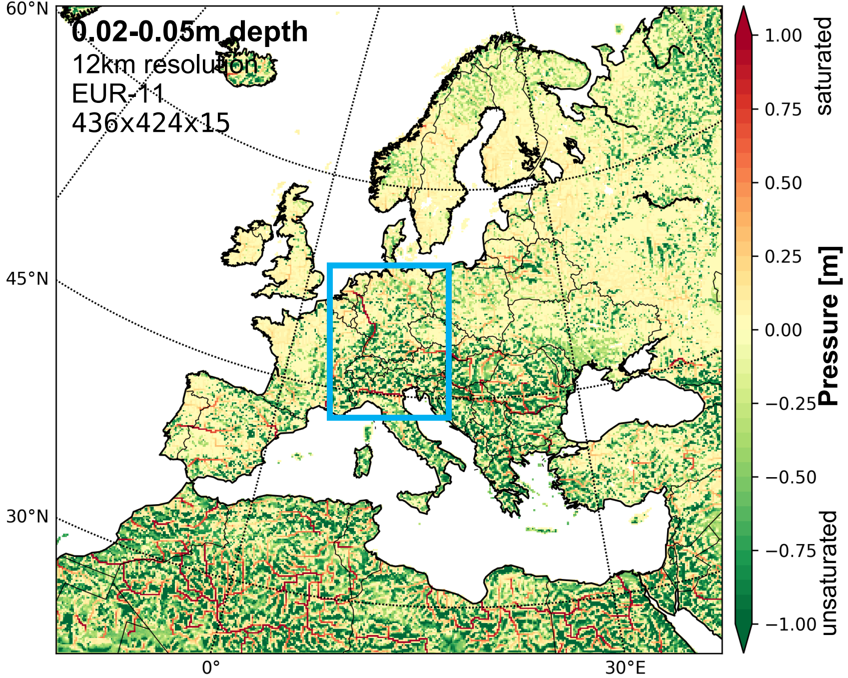
Some base datasets: MERIT DEM; SoilGrids 2017 to USDA texture classes (Rosetta); HydroRIVERS; GLHyMPS 2.0, BGR/IHME1500

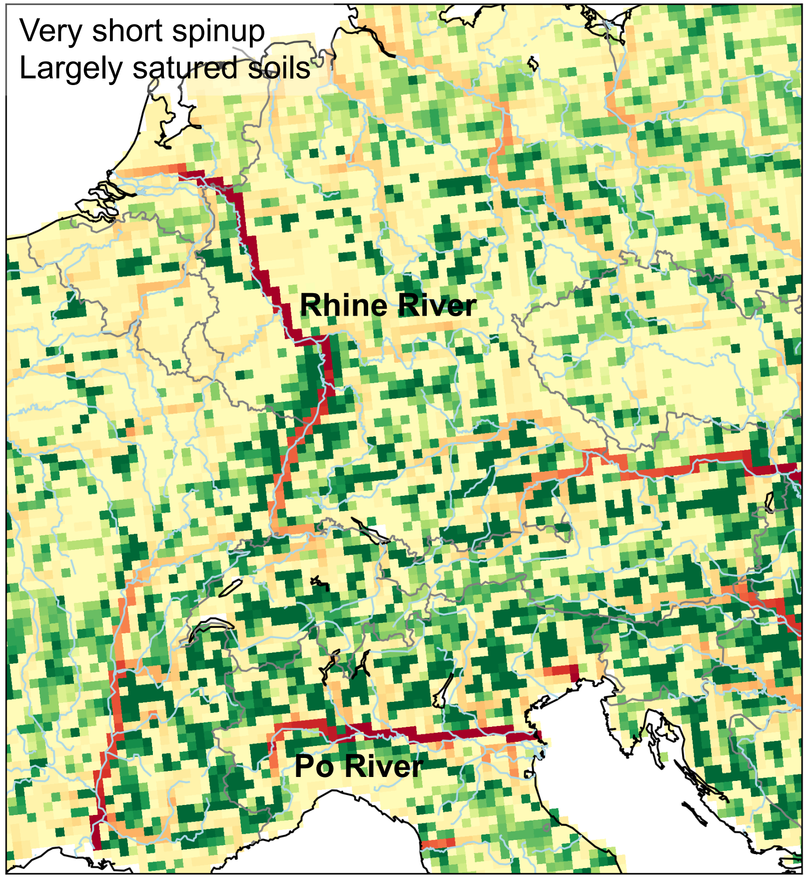
ParFlow indicators for soil hydraulic properties (permeability, specific storage, porosity, van Genuchten parameters)

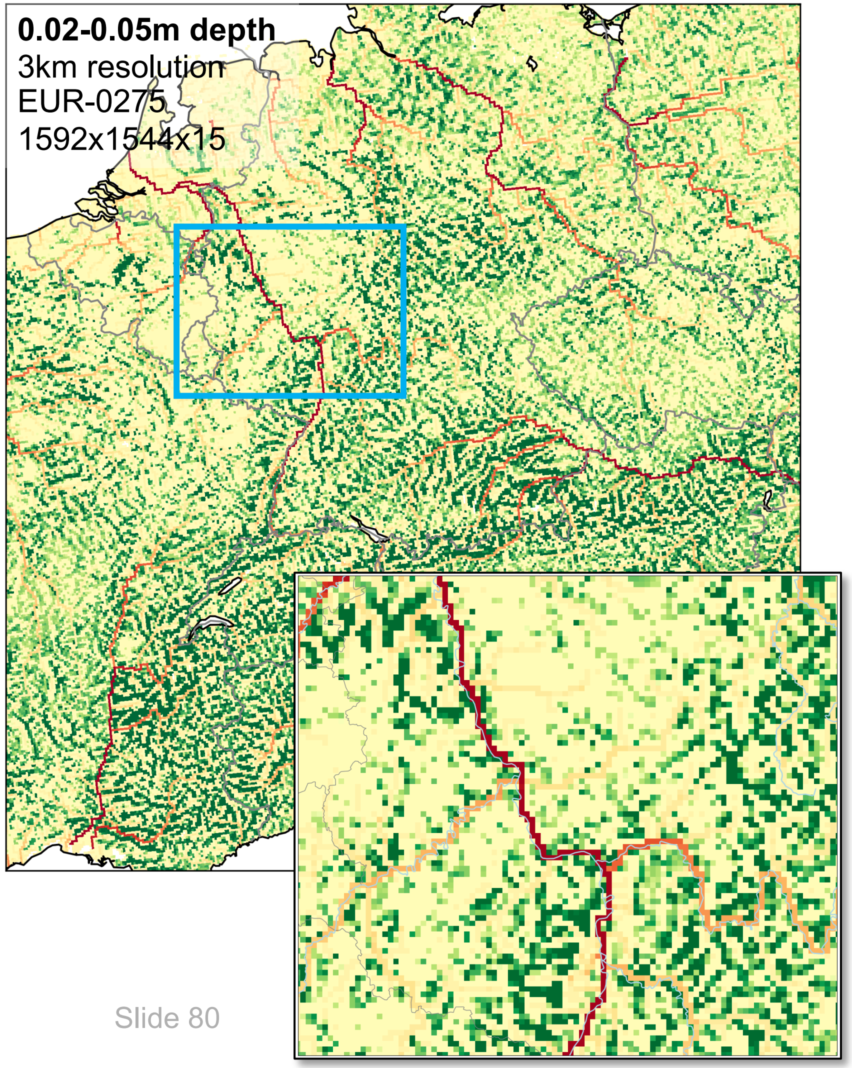
Setting up a new pan-EU km-scale coupled TSMP

High initial soil moisture exp., river networks start to evolve, redistribution of surface and groundwater

TSMP / ParFlow, 2020-01-23, 23 UTC







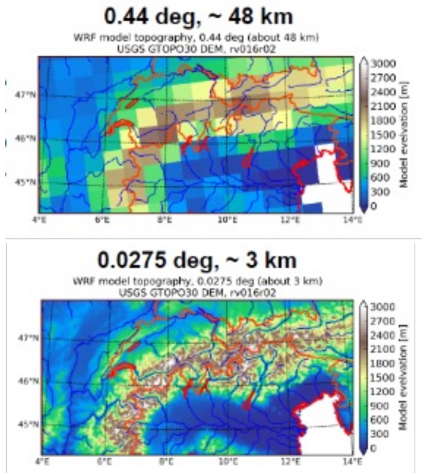
Ponding and flowing water in convergence zones; aquifer-streamflow interactions; strong heterogenity in surface states and fluxes will alter L-A feedbacks

Conclusions

Summary of ongoing developments with RCMs

Increasing next generation, modular HPC capacities: Challenge but enables more advanced simulations

Convection permitting, “hyper” resolution (added value), short output intervals, big data volumes



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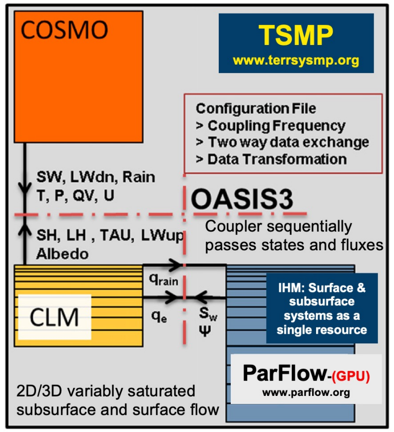
Multiphysics, **fully coupled** (regional) model systems (“Earth system simulator”)


COSMO

TSMP
www.terrsysmp.org

Configuration File
> Coupling Frequency
> Two way data exchange
> Data Transformation

SW, LWdn, Rain
T, P, QV, U

OASIS3
Coupler sequentially passes states and fluxes

SH, LH, TAU, LWup
Albedo

CLM

q_{rain}

q_e

S_w
ψ

IHM: Surface & subsurface systems as a single resource

ParFlow-(GPU)
www.parflow.org

2D/3D variably saturated subsurface and surface flow

Shrestha et al. (2014, Mon Weather Rev)

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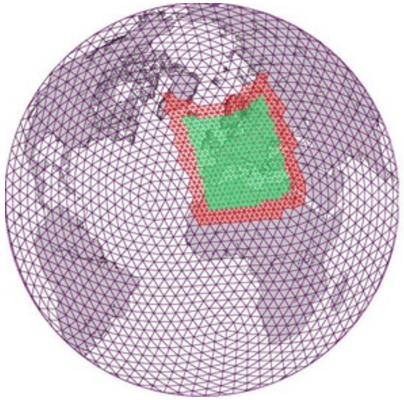
Increasing domains (multi-scale processes, AMR), **data synthesis**, new data types



https://www.earthsystemcog.org

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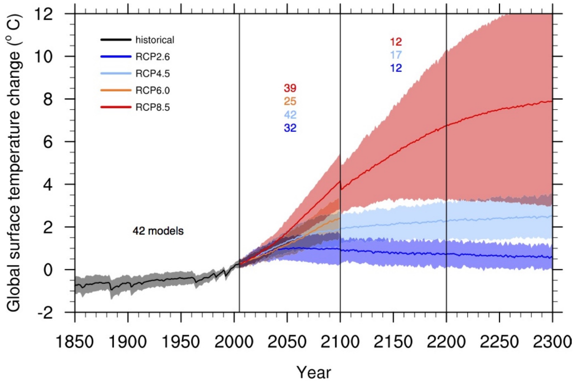
Data assimilation (uncertainties), **long integration times**, increasing **ensemble sizes**



Collins et al. (2013, IPCC WG1 AR5)

- ***Towards* extreme scaling**, global 1km resolution, fully coupled, 1 SYPD (e.g., EVE, DestinE)
- **Hardware** / HPC developments (e.g., GPUs, schedulers); **algorithms** (e.g., solver libraries, memory usage); new **software** / development paradigms (“separation of concerns” via DSLs, in-situ, compression, etc.)
- Contribution to a more **integrated Earth system science** approach (e.g., NatESM, WW)

Summary and conclusions

Coupled models bridge gap between hydrology and meteorology; potential to explore new feedbacks

Example 1

- Shallow water tables simulated with a physics-based GW model can alleviate temperature extremes by 1°C
- Groundwater processes play a crucial role for climate and the evolution of heatwaves and droughts
- The groundwater treatment in TSMP attenuates hot events and heat wave extremes, w.r.t. RCM ensemble
- Multiannual heat wave statistics in RCMs and TSMP are consistent w/ observations; reduced deviations w/ GW
- Explicit groundwater treatment is important for heat wave with implications for regional climate projections

Example 2

- “Natural” groundwater climatology consistent with the atmospheric forcing generated by TSMP for Europe
- Good representation of spatio-temporal variability of interannual anomalies w.r.t. 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

Summary and conclusions, cont'd

Coupled models bridge gap between hydrology and meteorology; potential to explore new feedbacks

Example 3

- (Remote) land use / land cover changes can have impacts on heat and can be mitigated through shallow groundwater

Example 4

- Human water use can be integrated and induces systematic atmospheric feedbacks (changing the strength of the continental atm. water sink, impacts on terrestrial water storage, potentially aggravating the drying of arid watersheds)

Take-home message:

- Coupled **TSMP** with ParFlow IHM **allows to simulate all states and fluxes of the terrestrial water and energy cycles**, **G2A**, incl. interactions between catchments; at km-scale 3D (sub-)surface hydrodynamics become even more important
- **Added value in water cycle processes simulation** (flux partitioning, water resources, hydro-climatic extremes)
- **Groundwater processes** and **human water** use impact the terrestrial system at the continental scale
- **Consistent G2A simulations** are useful information for **climate change impact assessments** for many sectors
- Integrated simulations as tools to **develop adaptation strategies**, **securing freshwater availability**

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Lab session overview

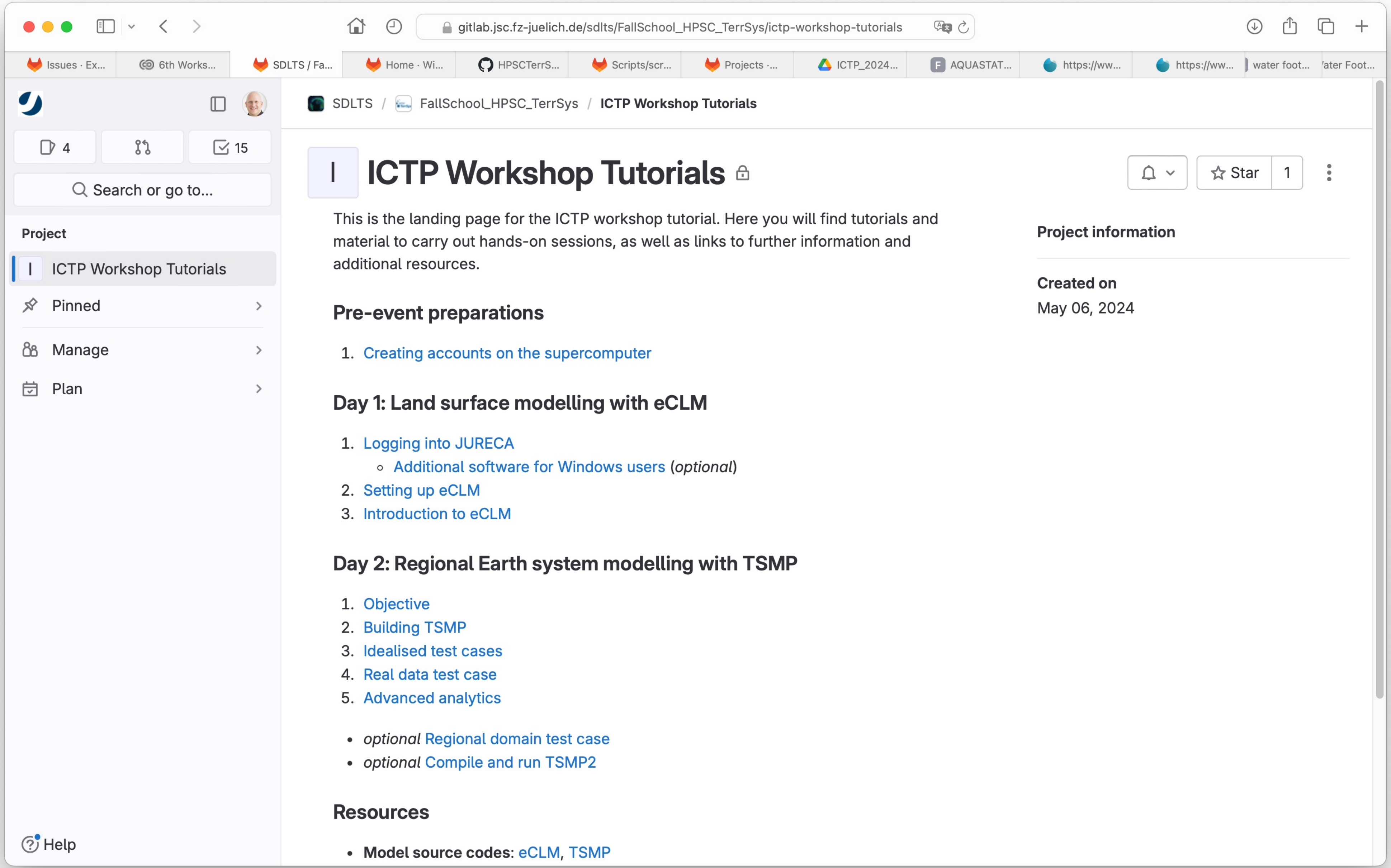
TSMP lab sessions

2024-05-28, 10:30-12:30, 14:00-16:00, 16:30-18:00, Adriatico Guest House - Informatics Lab

Landing page: **https://gitlab.jsc.fz-juelich.de/sdlts/FallSchool_HPSC_TerrSys/ictp-workshop-tutorials**

(use your login and password for the JSC JUDOOR and JSC gitlab – not ssh passphrase for the HPC)

- **Getting started with TSMP1, building TSMP, first experiments on land-atmosphere coupling**
  - Login to JSC, use same computer, use ssh-keyfile from yesterday, (maybe from clause needs updating)
  - (Today's TSMP work coexists with eCLM work from yesterday, no need to copy / safe anything)
  - Get TSMP components installed
  - Run idealized experiment, it is an ensemble experiment, **use the paper sheets with the configuration!**
- **TSMP1 pan-European fully coupled real data case**
  - Run 12h of a real EUR-11 12km test case
  - Work with analysis
- **TSMP1 pan-European fully coupled real data case cont'd or optional work as in the tutorial**



ICTP Workshop Tutorials

This is the landing page for the ICTP workshop tutorial. Here you will find tutorials and material to carry out hands-on sessions, as well as links to further information and additional resources.

Project information

Created on
May 06, 2024

Pre-event preparations

1. Creating accounts on the supercomputer

Day 1: Land surface modelling with eCLM

1. Logging into JURECA
    - Additional software for Windows users (*optional*)
2. Setting up eCLM
3. Introduction to eCLM

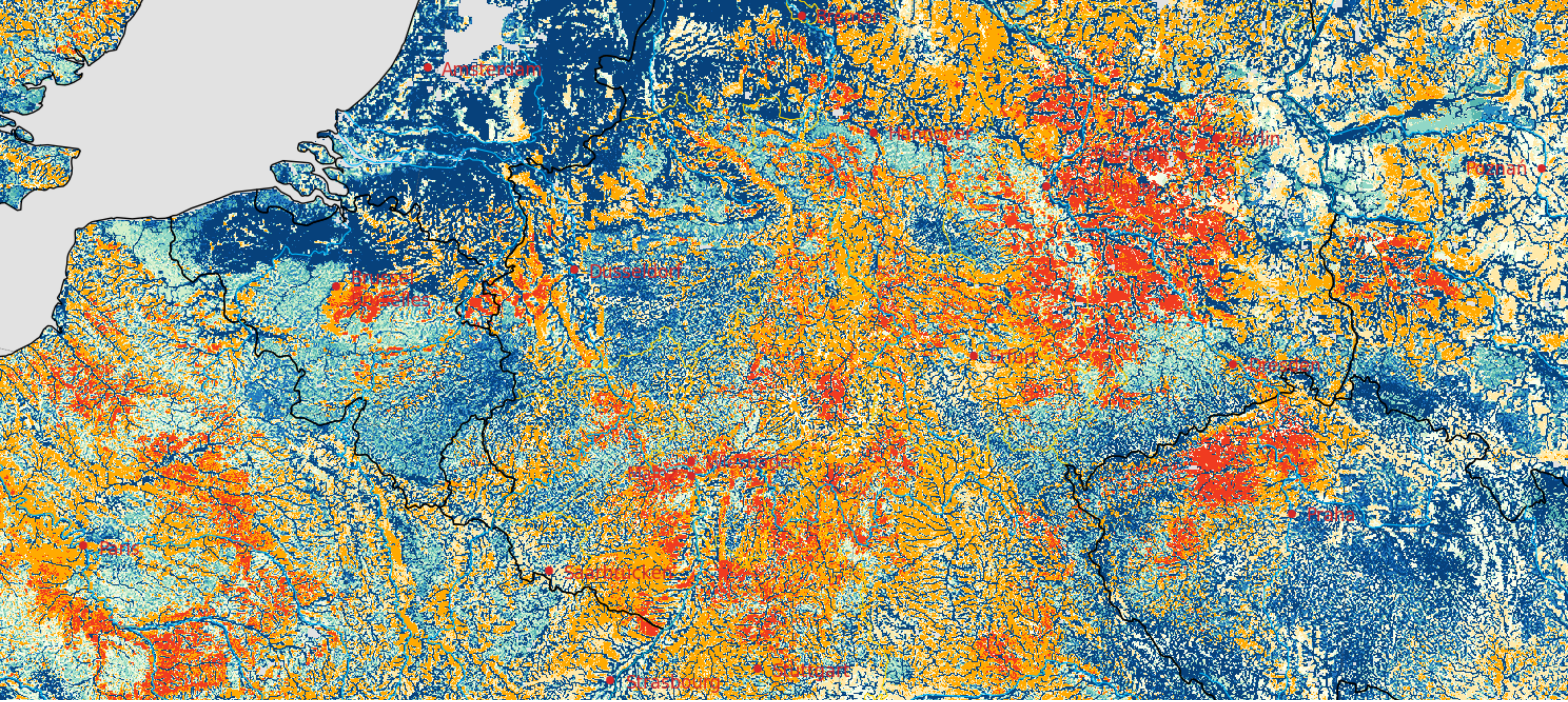
Day 2: Regional Earth system modelling with TSMP

1. Objective
2. Building TSMP
3. Idealised test cases
4. Real data test case
5. Advanced analytics

- *optional* Regional domain test case
- *optional* Compile and run TSMP2

Resources

- **Model source codes:** eCLM, TSMP



Plant-available water; ParFlow/CLM forecast (+9d); daily mean, 0-0.3m, sub-km ($611x611m^2$); simulation on JSC GPU booster

Daily forecasts (Germany and surrounds): www.adapter-projekt.de and www.wasser-monitor.de