Coupled data assimilation for atmosphere-land surface-subsurface models

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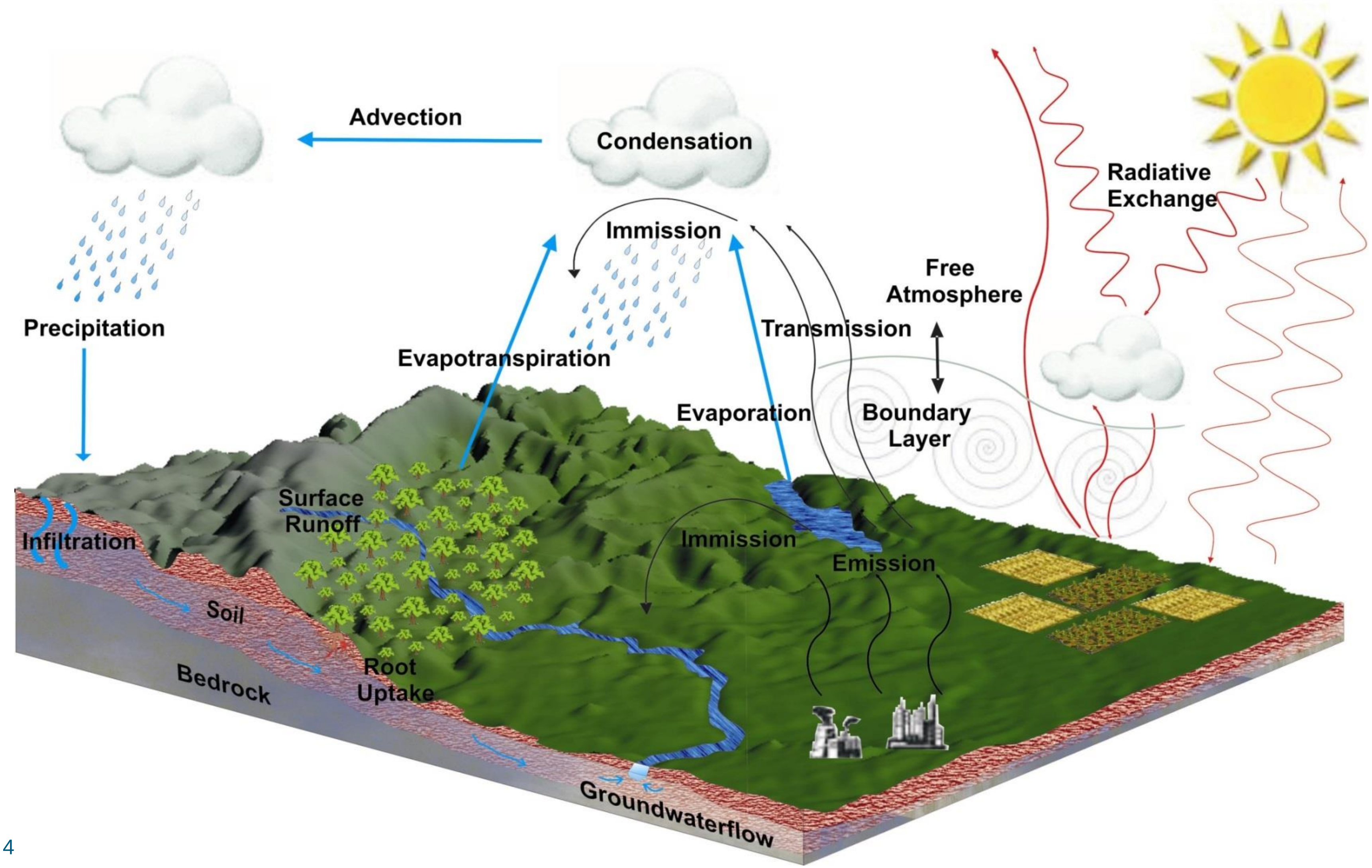
Overview

- Introduction on coupled data assimilation.
- Coupled atmosphere-land surface- subsurface model TerrSysMP.
- Data assimilation framework TerrSysMP-PDAF.
- Example synthetic and real-world studies.
- Conclusions and outlook.

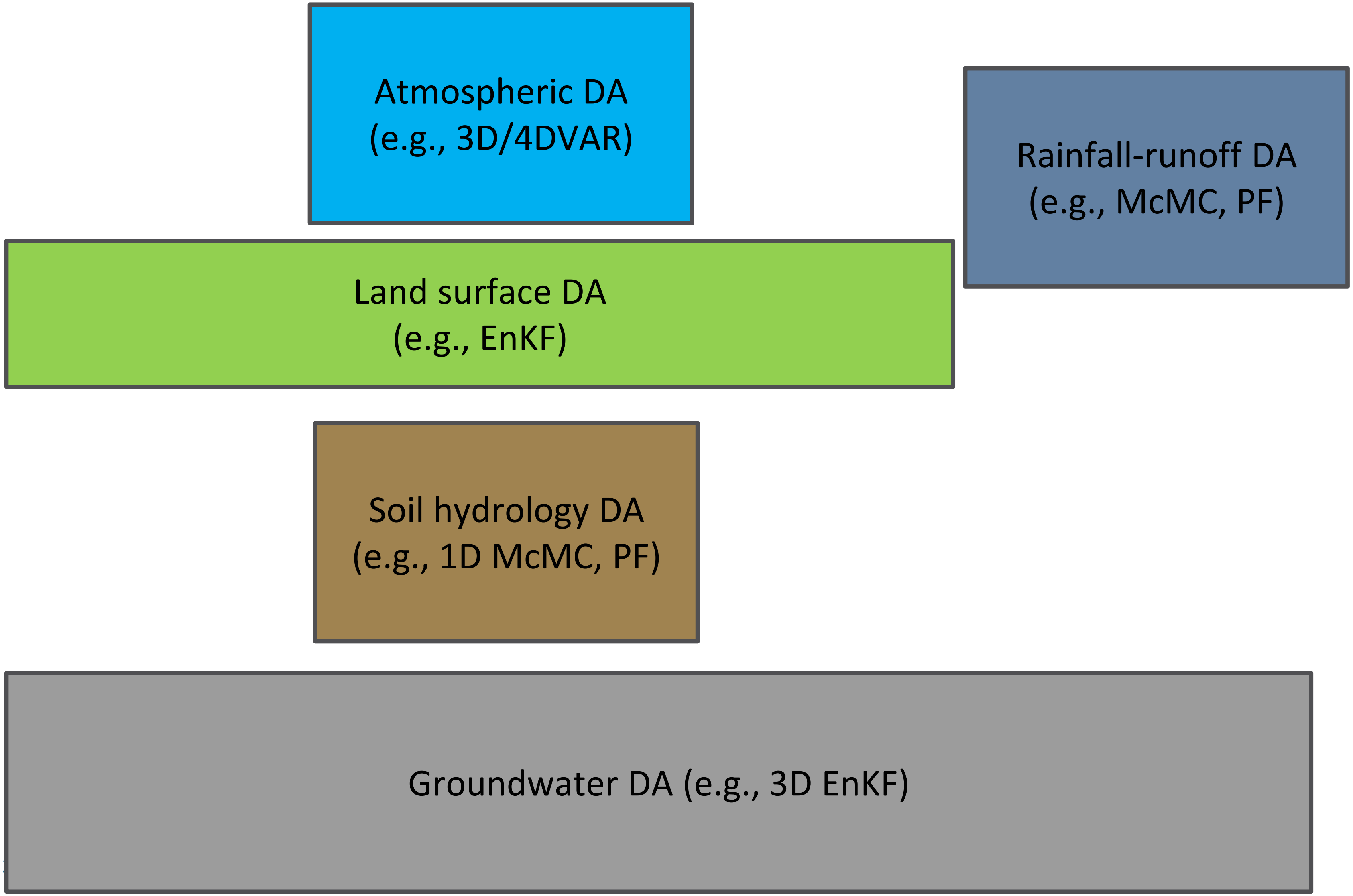
Non-coupled DA

- Non-coupled DA of hydrological cycle.



Non-coupled DA

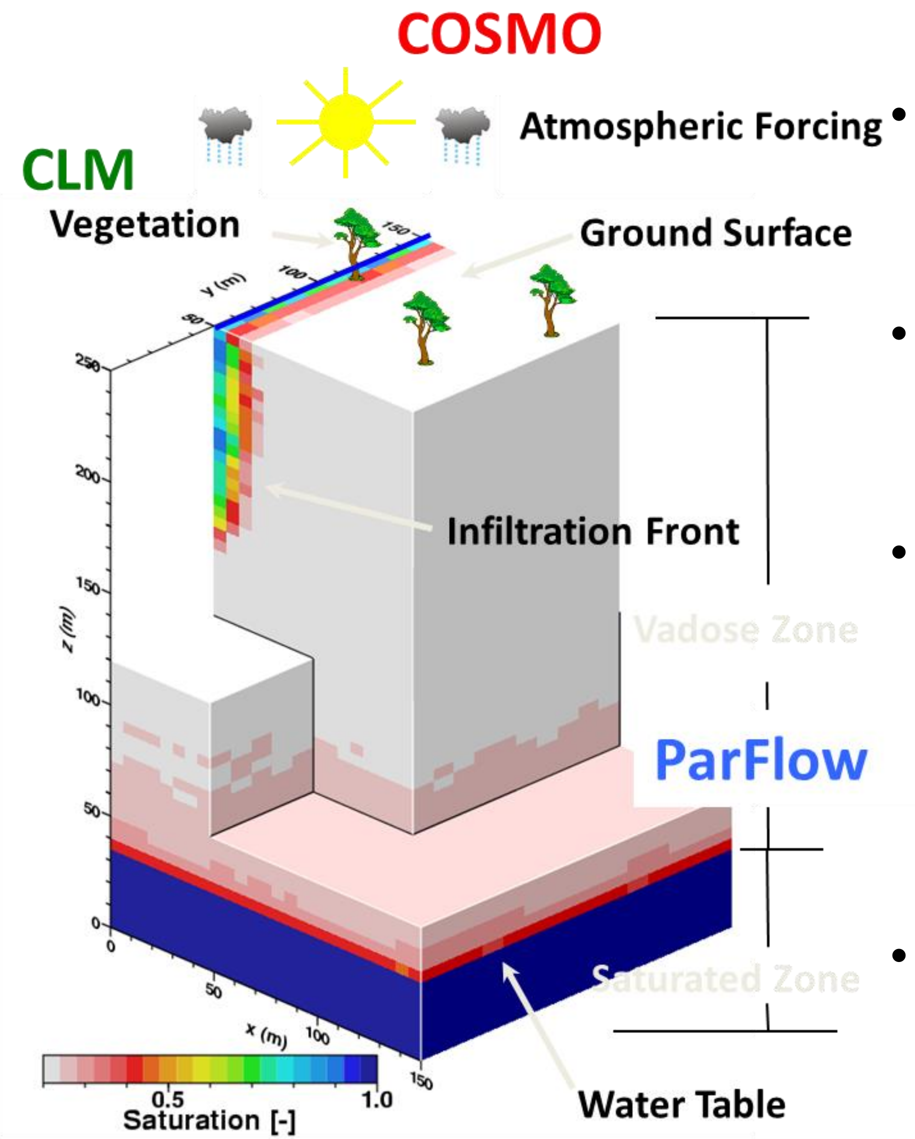
- Non-coupled DA of hydrological cycle.



Coupled DA

- *Weakly coupled DA*
  - DA for individual compartments of terrestrial system.
  - Covariances between states of different compartments not calculated.
  - Updates for single compartments propagated through coupled model equations
- *Fully coupled DA*
  - DA for multiple compartments of terrestrial system.
  - Covariances between states of different compartments calculated.
  - States of multiple compartments are directly updated by DA.

TerrSysMP



- 3D Variably saturated subsurface flow and energy transport (Jones & Woodward, 2001; Kollet et al., 2009)
- Integrated overland flow, terrain following grid (Kollet & Maxwell, 2006; Maxwell, 2013)
- Integrated land surface and regional climate model (Shrestha et al., 2014)

External coupling via OASIS3: Multiple Program Multiple Data Execution Model (Shrestha et al., 2014)

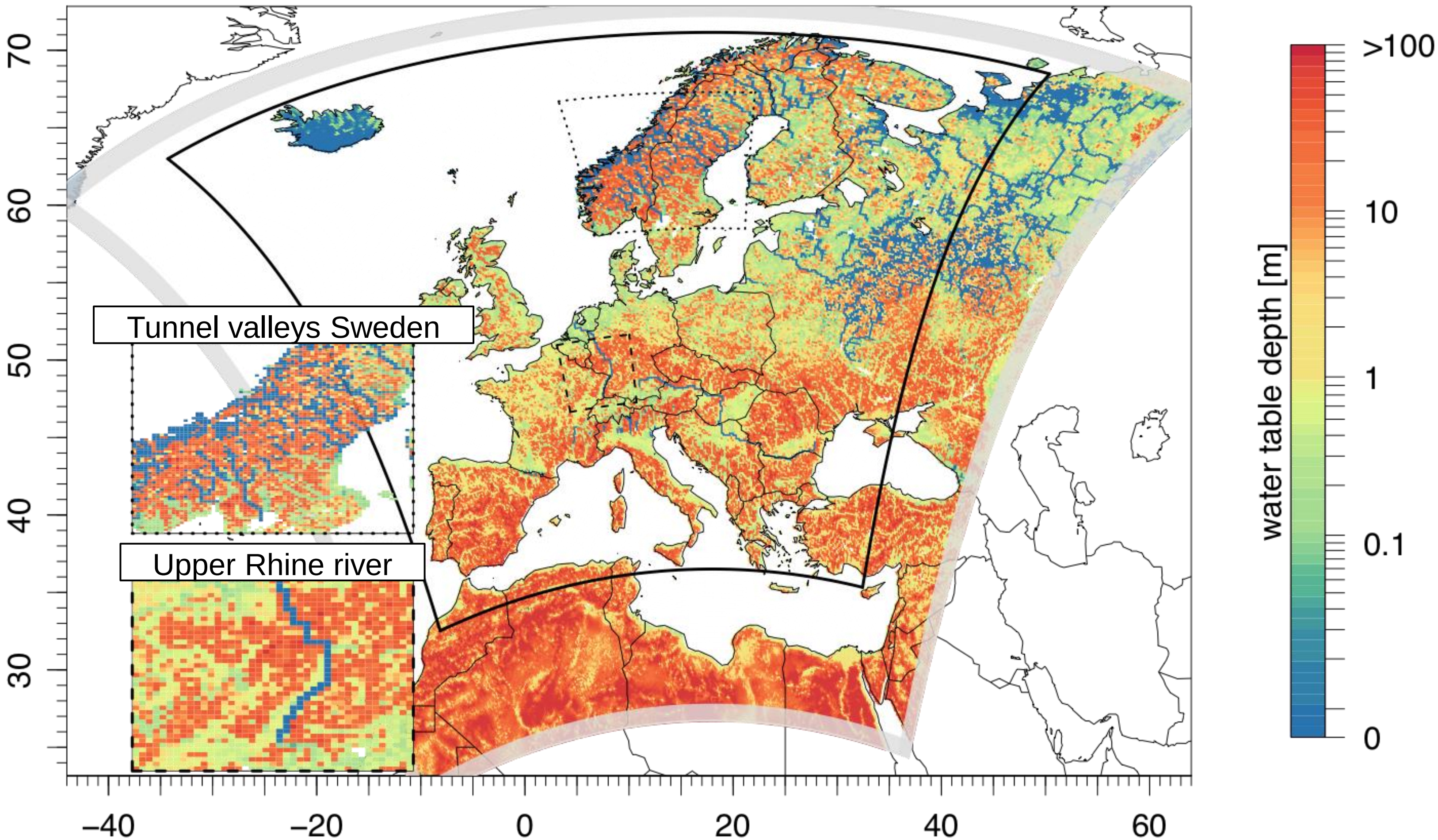
- Atmospheric downscaling algorithm (Schomburg et al., 2010)

TerrSysMP

- Lateral subsurface transport of water and energy via groundwater
- PDE-based description of two-way interactions between groundwater, vadose zone, surface water, vegetation and atmosphere
- Land surface (CLM3.5) component still has large potential to be improved (e.g., beta-function for drought stress, photosynthesis types, plant traits)
- Overland flow process very non-linear → very high spatial resolution needed
- In general, many unknown parameters, initial states and forcings → data assimilation

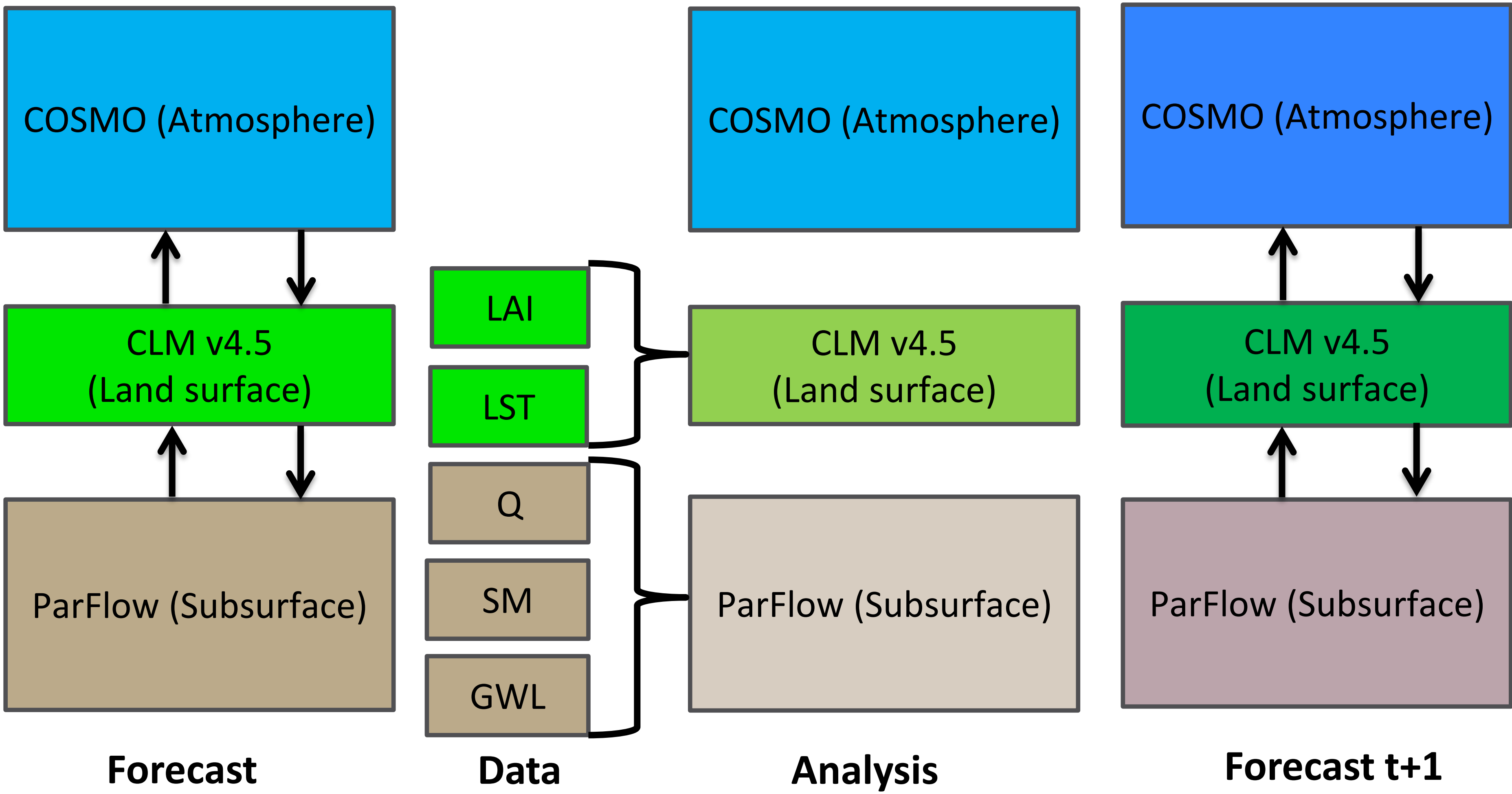
Simulations up to continental scale

- Groundwater depth calculated over Europe
- Problem: long spin-ups needed related to slow groundwater dynamics.



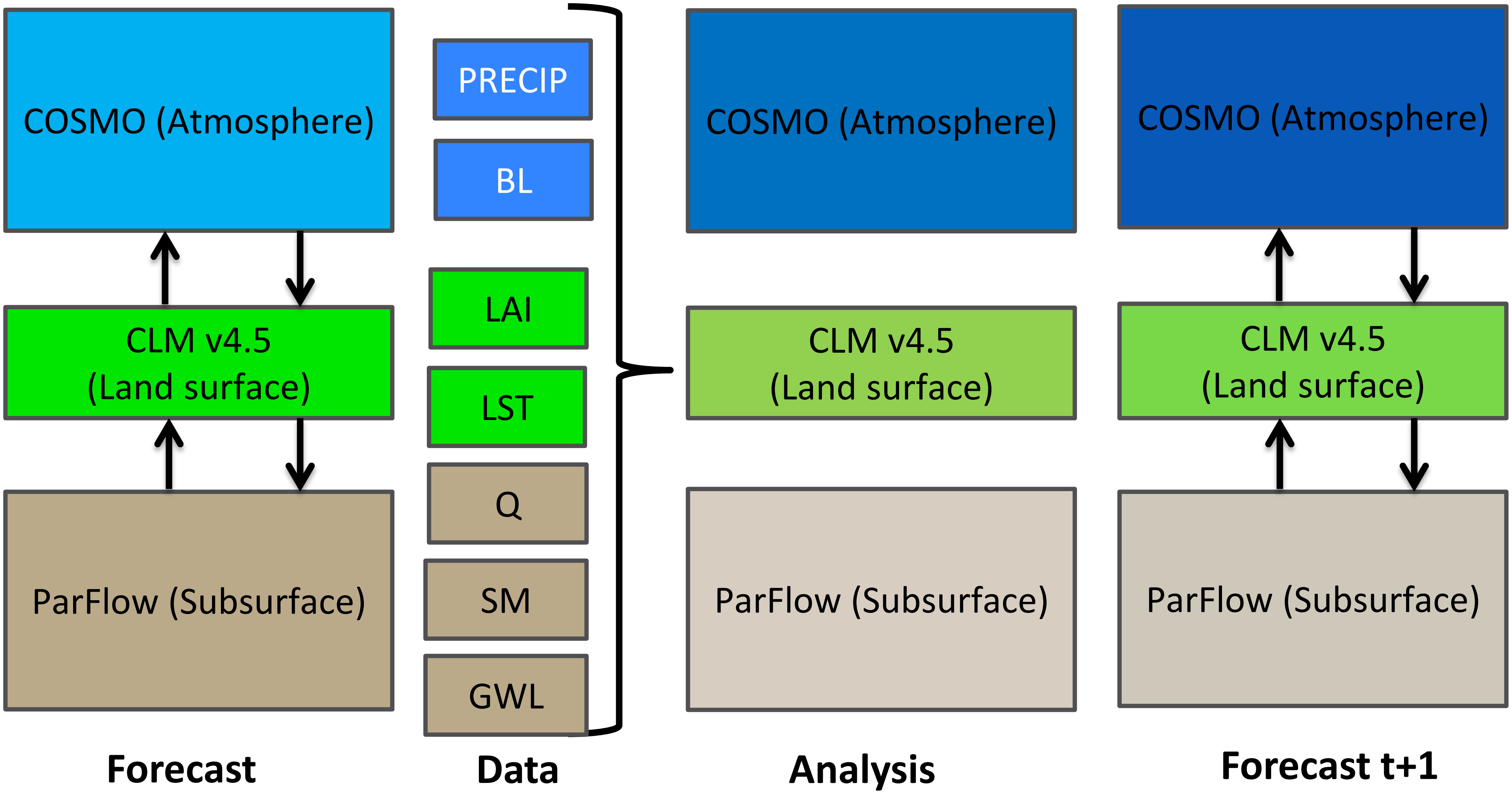
Keune et al., 2016

Current work: weakly coupled DA



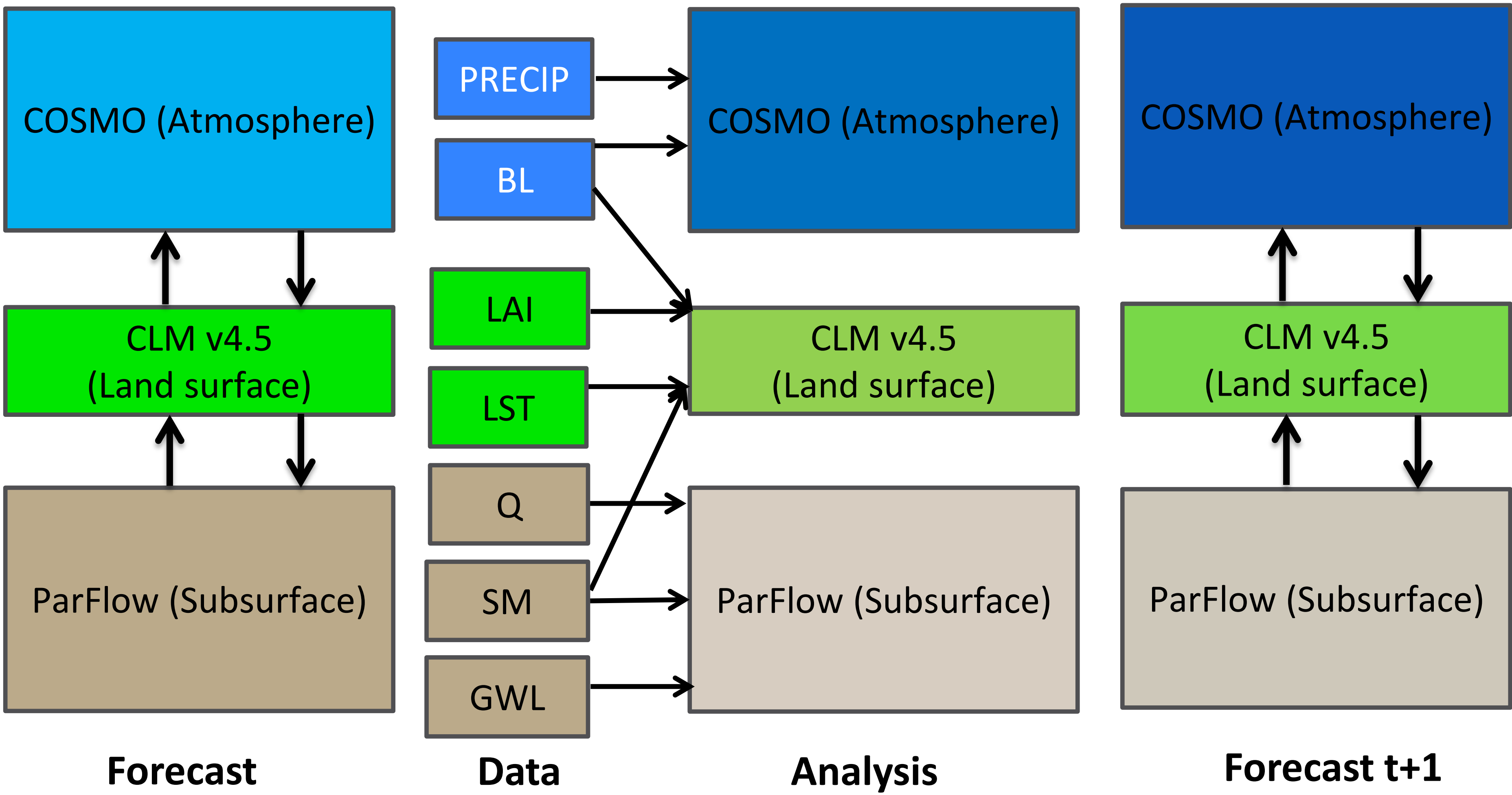
Example: Assimilation of land surface and subsurface data, which only update own compartments and later other compartments.

Towards fully coupled DA?



Example: Assimilation of atmospheric, land surface and subsurface data; all of them can update all compartments.

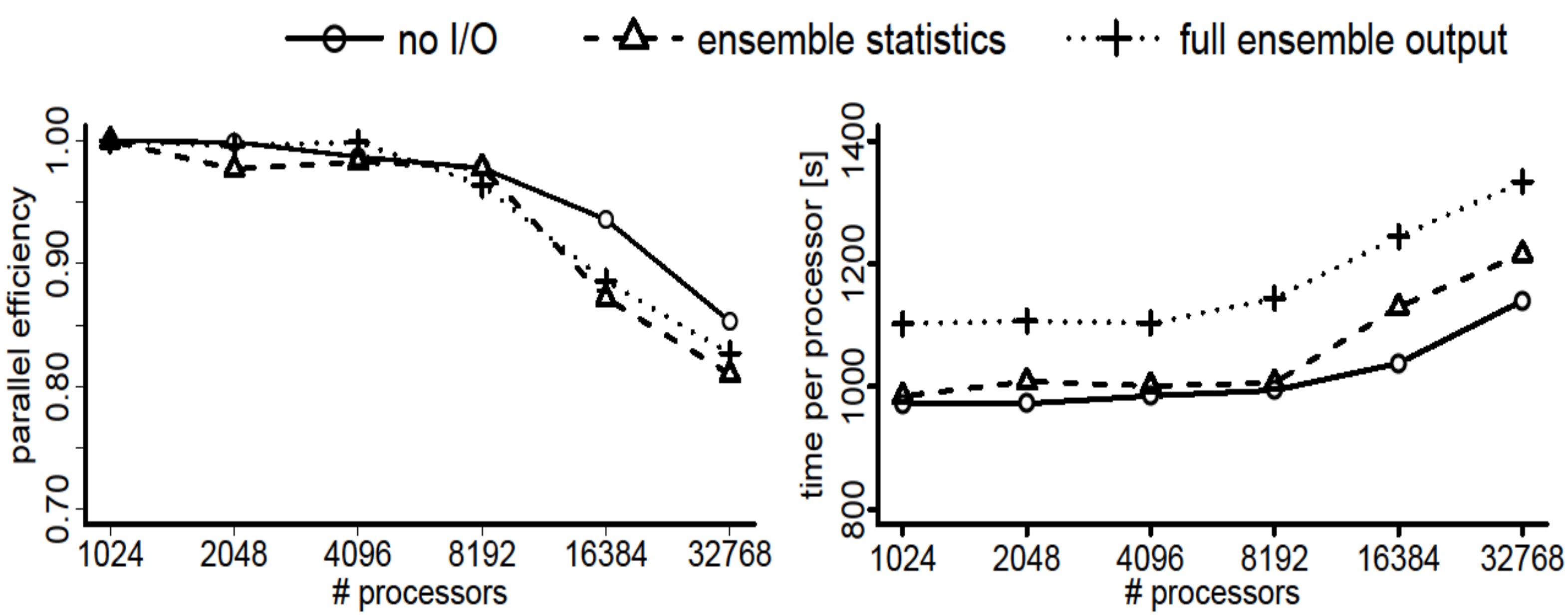
Between weakly and fully coupled DA?



Example: Only some of the measurement data are used to update (sensitive) states in other compartments

TerrSysMP-PDAF

- PDAF (Nerger and Hiller, 2013) was coupled to TerrSysMP
- COSMO, CLM and ParFlow are parallel, DA in addition also parallel
- DA system is fully integrated (no I/O, no model reinitializations)
- Good scalability through effective use of domain decomposition
- Different DA-algorithms activated (EnKF, local EnKF, LETKF)
- Multiscale SM, GW levels and river water levels can be assimilated



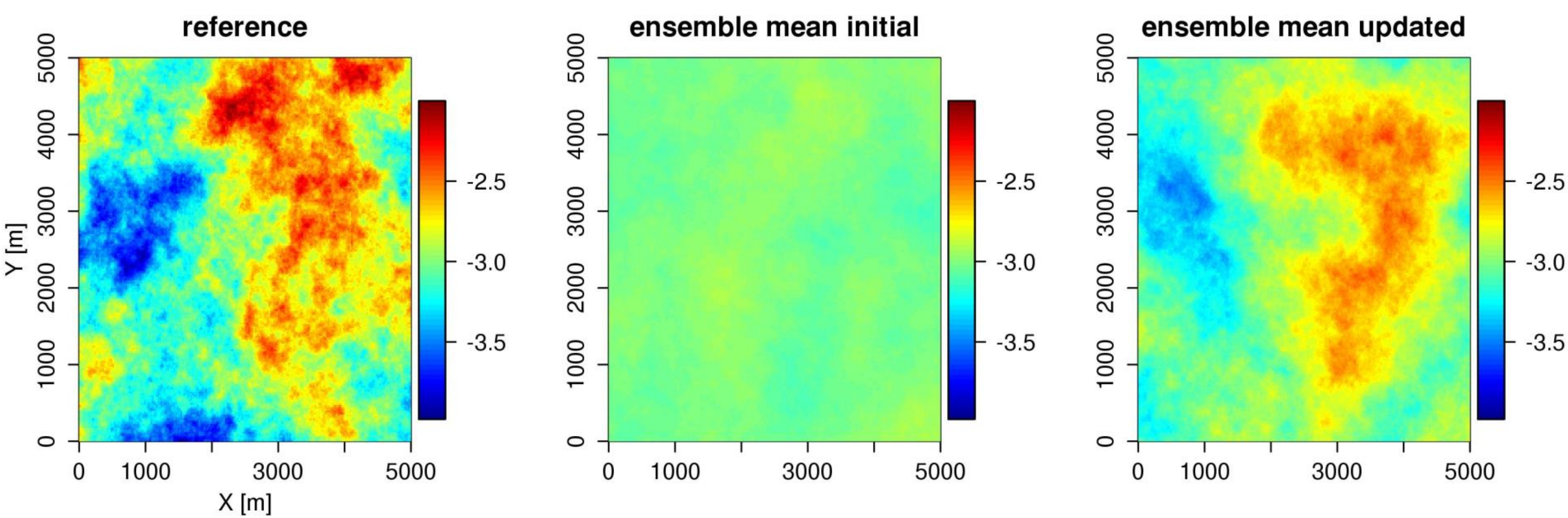
Kurtz et al. (2016), GMD

Results feasibility test (synthetic)

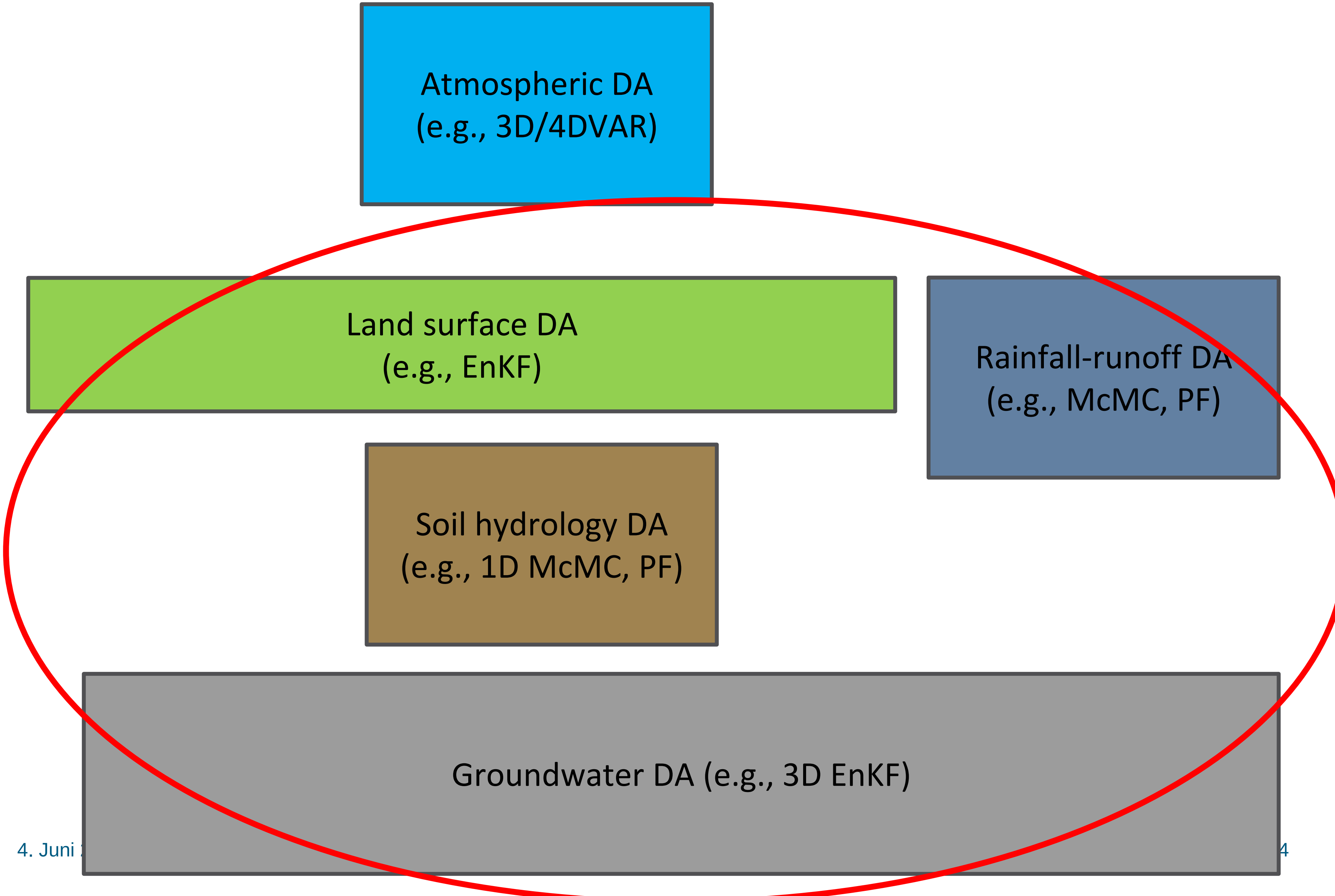
In total 2×10^7 states and 2×10^7 parameters are updated with EnKF

(Kurtz et al., 2016, GMD)

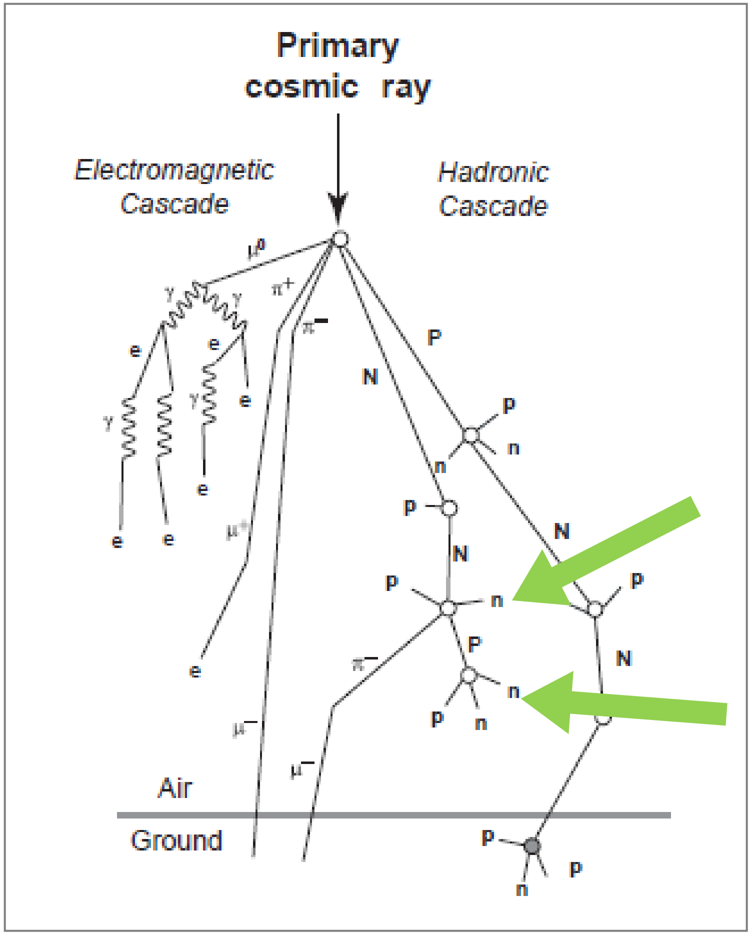
REFERENCE K **INITIAL K** **FINAL K**



1st Example: Weakly coupled DA



Cosmic ray probe data



Cosmic ray scattering
(HydroInnova, 2007)

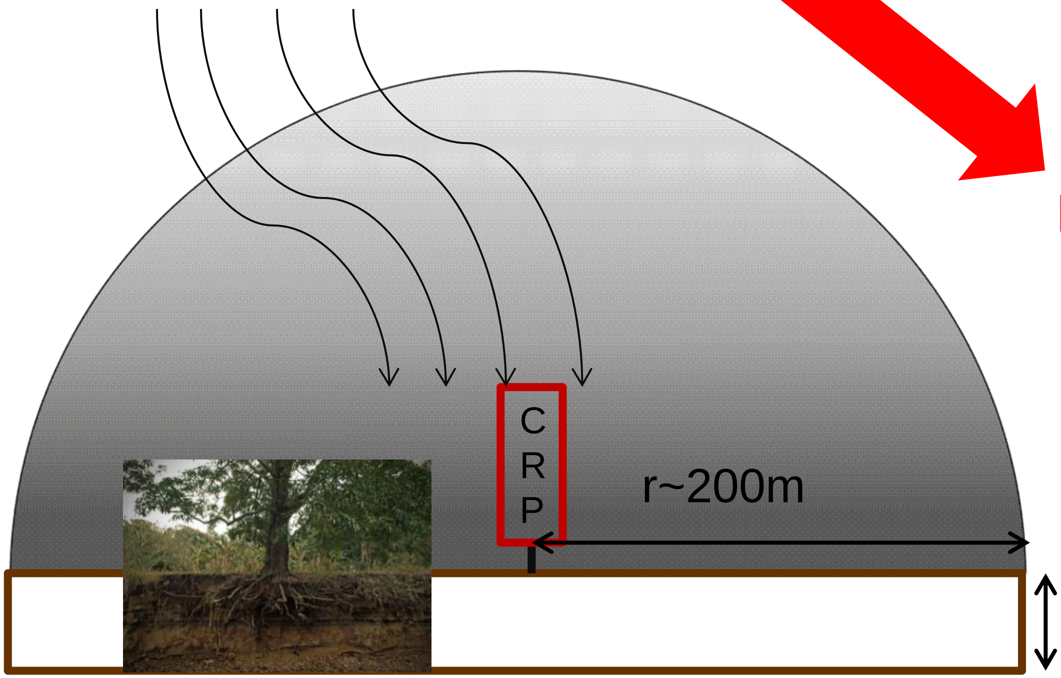
- Primary cosmic rays collide with atomic nuclei
- Creation of secondary cosmic rays with lower energy
- Hydrogen is the most effective neutron absorber

Cosmic ray probe data: local effects

Neutron counts to be corrected for:
- incoming cosmic-ray intensity
- air pressure
- atmospheric humidity

Hydrogen pools include:
- soil water content
- lattice water
- aboveground biomass

Non-linear measurement operator

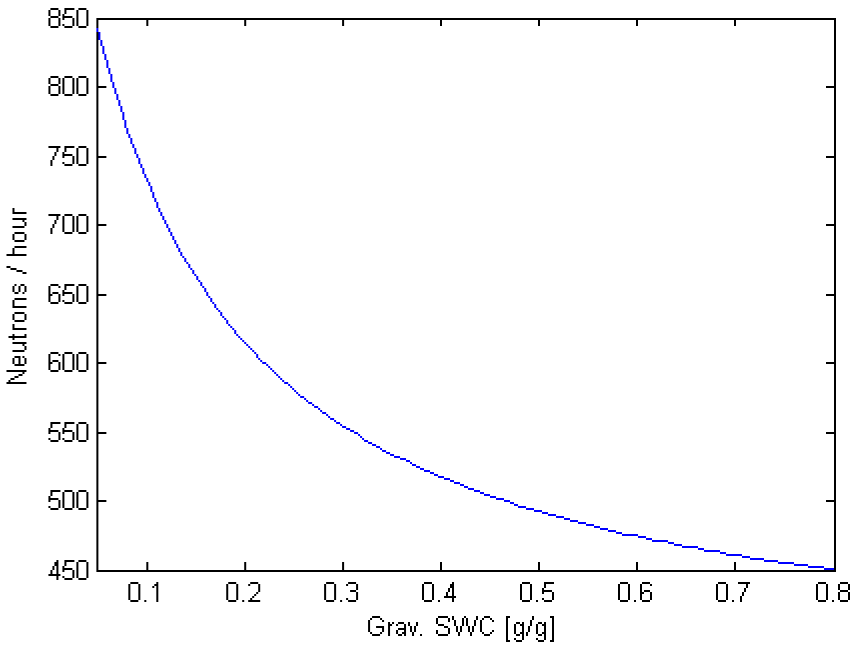


r - effective radius$_{air}$ … up to 200 m
z* - effective depth$_{soil}$ … up to 0.7 m

Cosmic ray probe data: function

Equation to calculate soil moisture from cosmic ray counts:

$$\theta_{grav} = \frac{a_0}{\left(N_{corr} / N_0\right) - a_1} - a_2$$

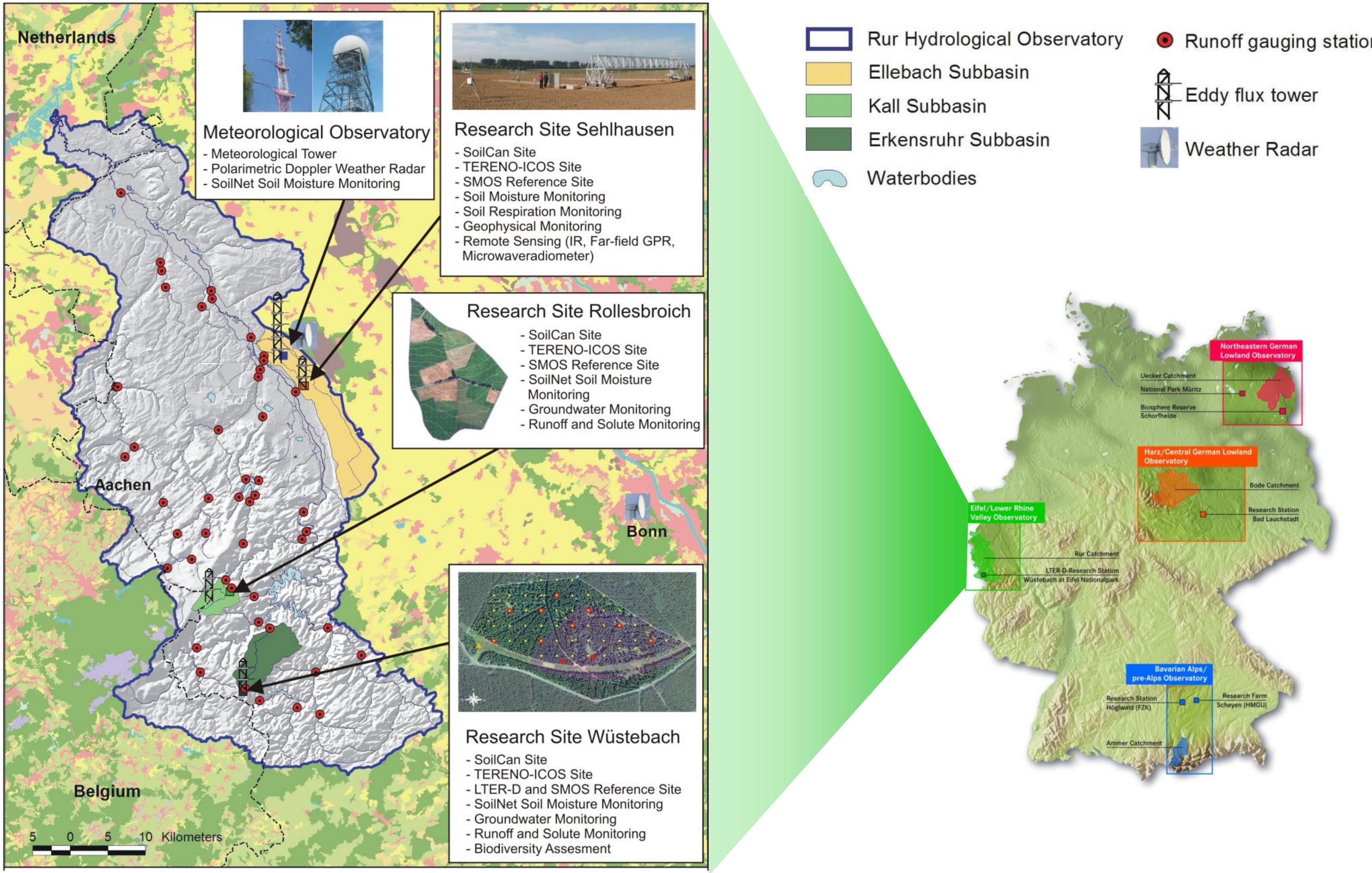


Θ_{grav} – soil water content [g/g]
a_0, a_1, a_2 – constants
N_{corr} – Measured neutrons / hour
N_0 – Neutron counts under dry soil conditions

Fitting curve with a_0, a_1, a_2
$a_0 = 0.0808$
$a_1 = 0.372$
$a_2 = 0.115$
and
$N_0 = 1107$

Ref.: Desilets et al. (2010). Nature's neutron probe: Land surface hydrology at an elusive scale with cosmic rays. Water Resources Research.

TERENO observatory Rur catchment



Cosmic Ray Probe Network Rur catchment

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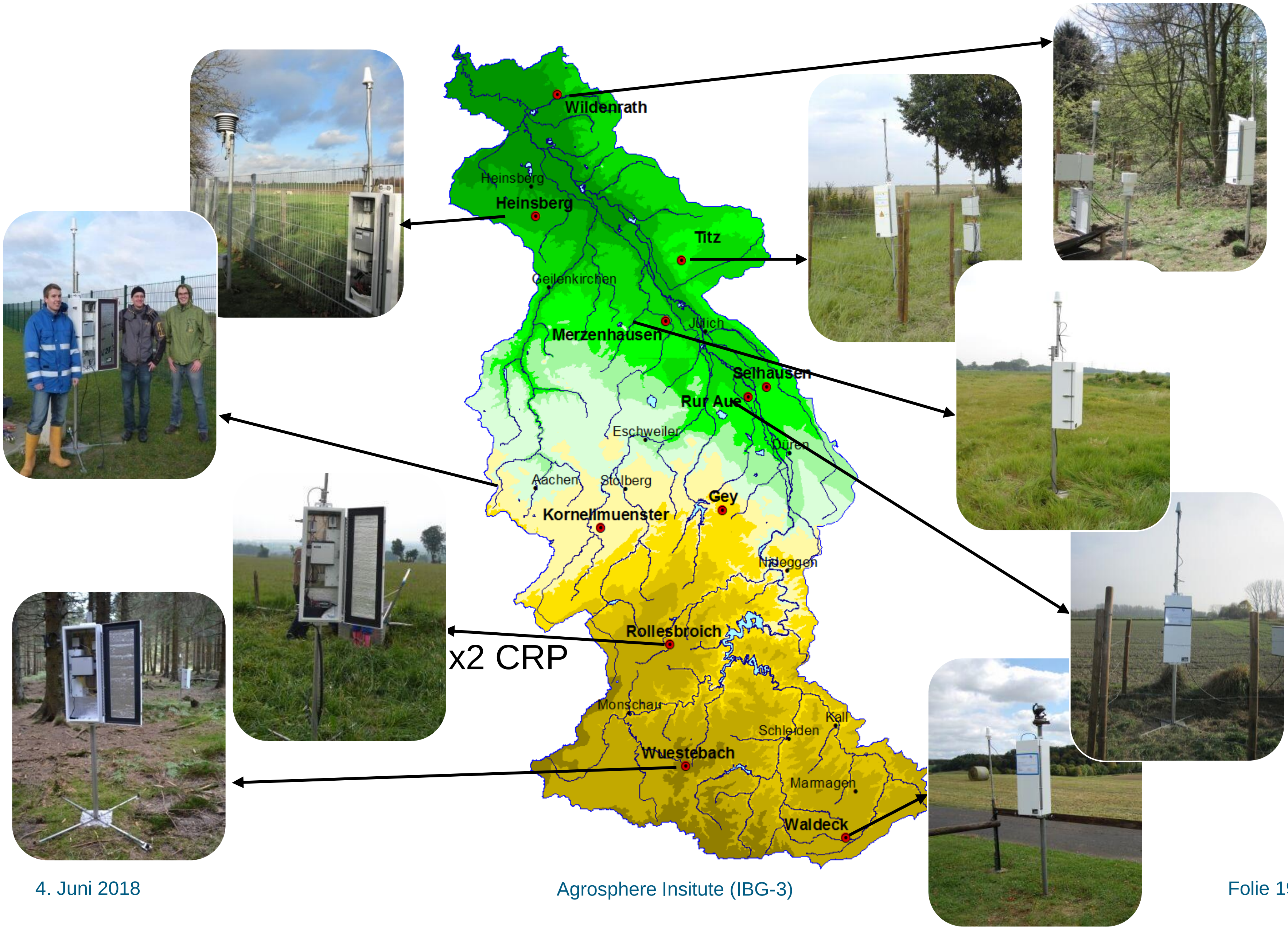


Weakly coupled DA Land Surface-Subsurface

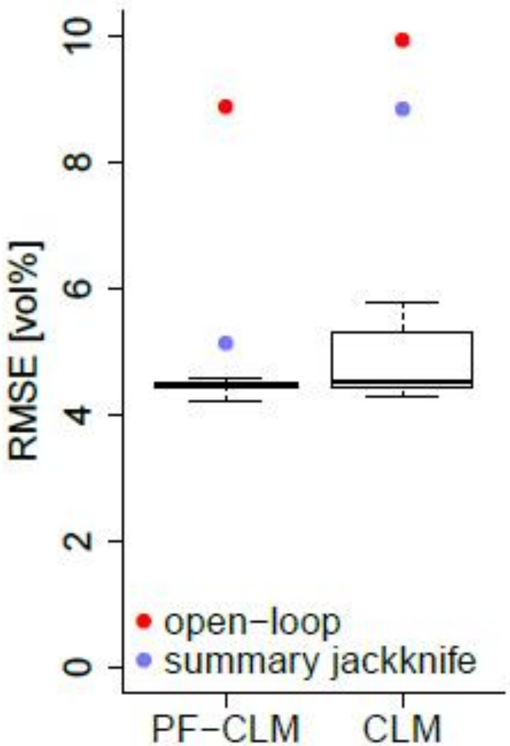
- Test value of cosmic ray probe data measured by cosmic ray probe
- Horizontal model resolution: 500 m (100x162 cells)
- Vertical resolution: 2cm-136 cm, 30 layers (30 m total thickness)
- Vegetation classification from MODIS
- Model forcings from COSMO-DE reanalysis
- Subsurface properties from European Soil data base

Set up DA-experiments

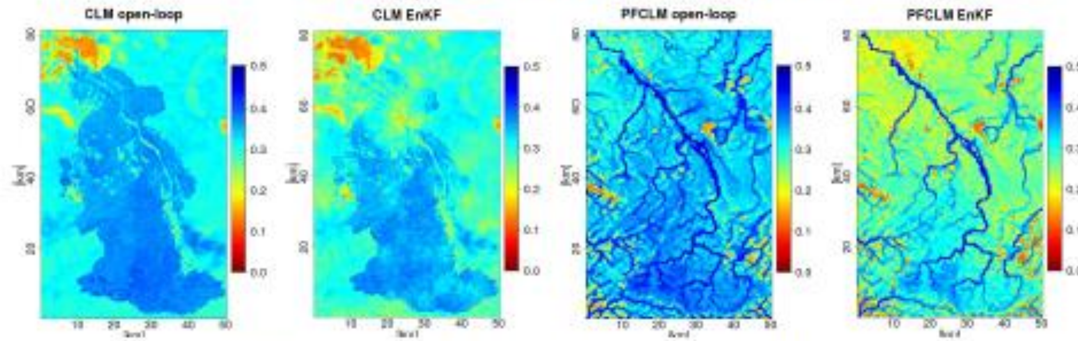
- 128 ensemble members, perturbation of precipitation, incoming short wave and long wave radiation, air temperature and porosity and log(K_{sat}).
- Assimilation period April – September 2013.
- Assimilation of soil moisture from 8 cosmic ray probes with EnKF.
- Probe left out in assimilation used for verification (jackknife).
- Repeated 9 times (all probes once left out).
- CLM versus ParFlow-CLM assimilation.

RMSE soil moisture

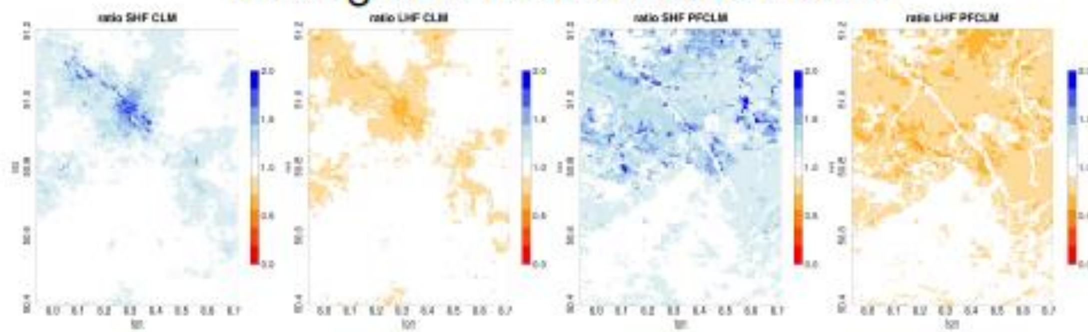
Error statistics



Changes in soil moisture

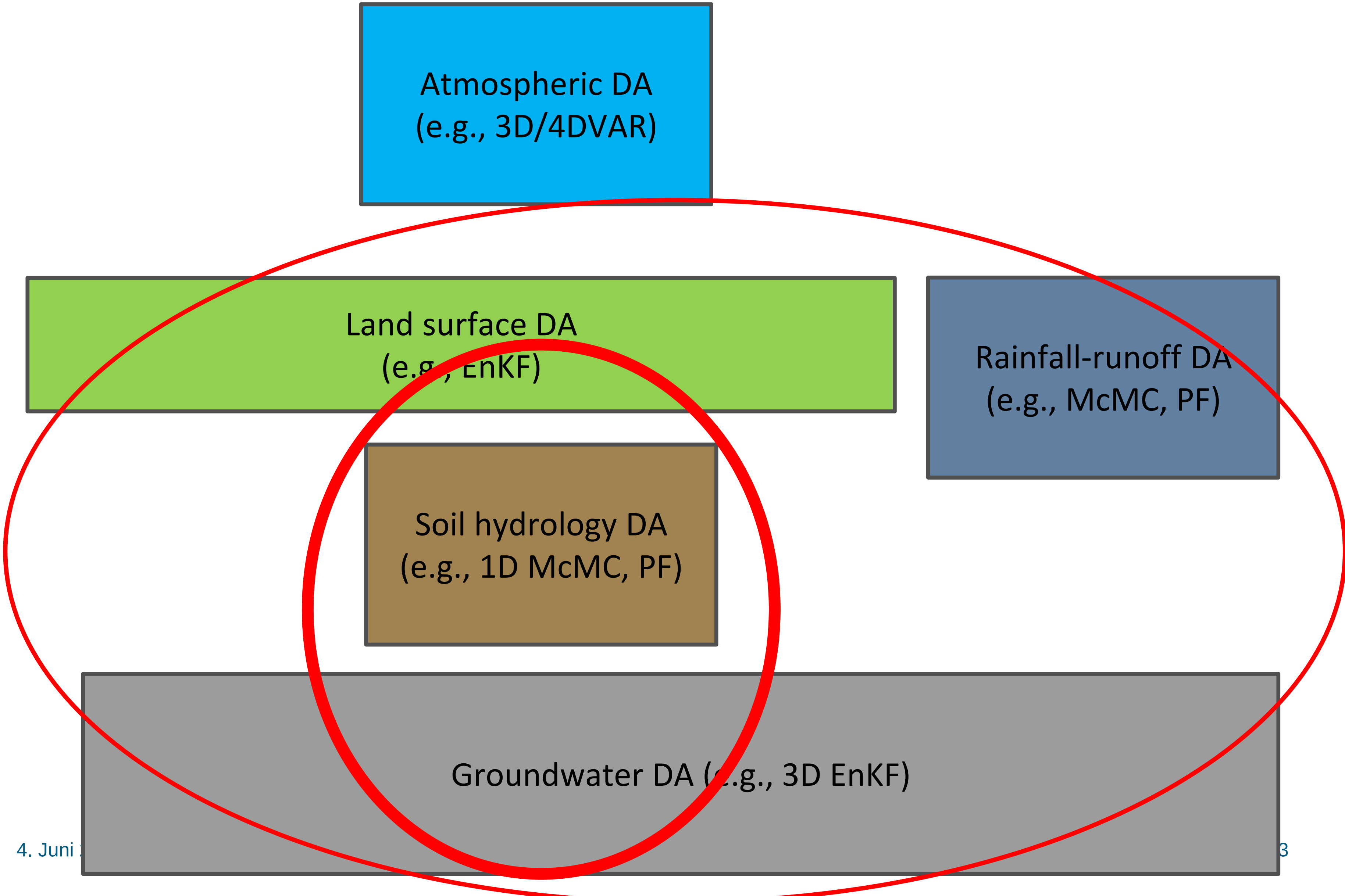


Changes in land surface fluxes



- Assimilation of soil moisture data from cosmic-ray probe network is effective for catchment wide soil moisture characterization
- Subsurface conceptualization affects update of soil moisture data

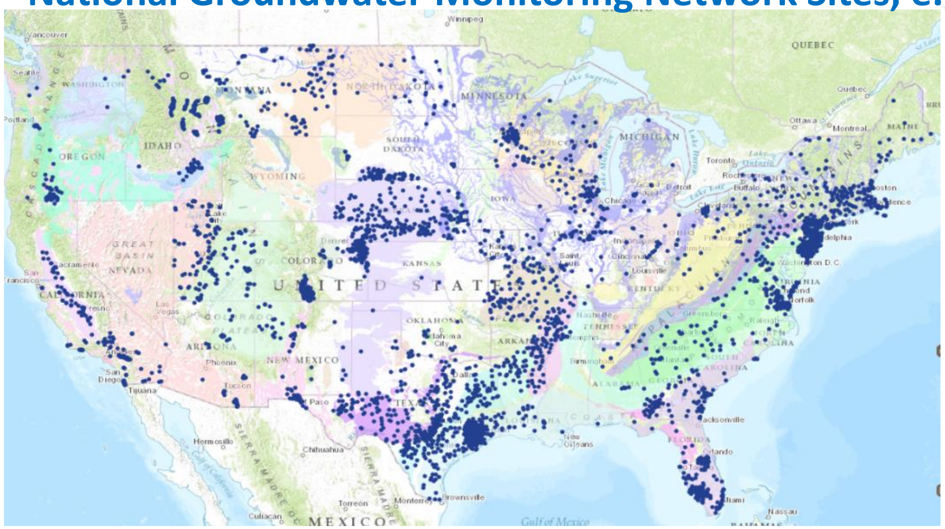
2nd Example: Strongly coupled DA



2nd example: GW-level assimilation

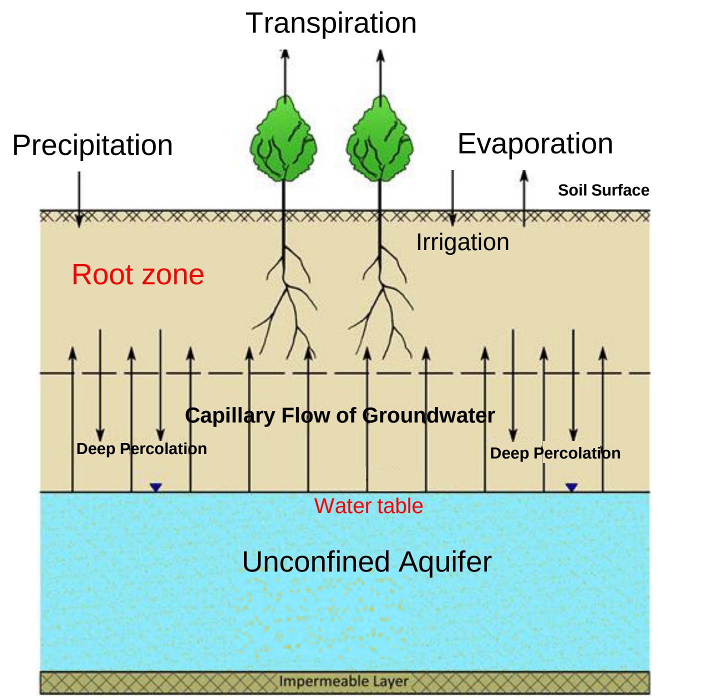
- Soil moisture from satellite: indirect, coarse scale, only upper cm, not reliable over dense vegetation

National Groundwater Monitoring Network Sites, e.g. USA



Good data source:

- low cost
- high accuracy
- widely available



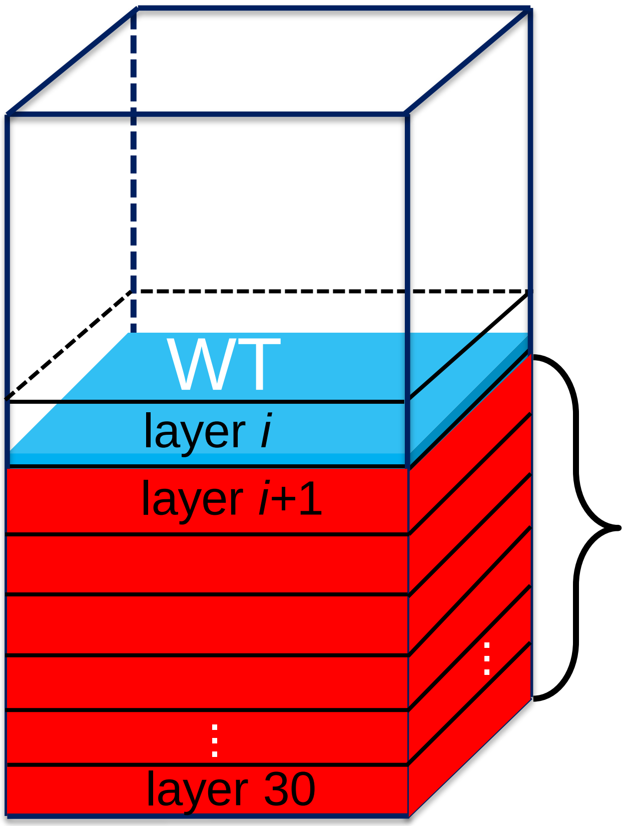
(Source: Modified from Smedema and Rycroft, 1983)

May contain valuable information about root zone soil moisture:

- Statistical correlations
- Physically related

How to assimilate GWL-data?

Soil Column



Water Table (WT) is in the i^{th} layer

State variable: pressure head.

Assimilation of GWL could be done in terms of soil moisture or pressure head:

observation

- pressure head (**P**): pressures in saturated zone (hydrostatic)
- soil moisture (**SM**): porosity in saturated zone

Five different DA-strategies

Method	Observation vector	State vector	Updated domain
P	P	P	strongly coupled
P_log	$\log_{10}(100\text{-p})$	$\log_{10}(100\text{-p})$	strongly coupled
P_mask	P	P	weakly coupled
SWC	SWC (=porosity)	SWC (=porosity)	strongly coupled
Mix	P	P (saturated) SWC (unsaturated)	strongly coupled

- strongly coupled = updating both saturated and unsaturated zone.
- weakly coupled = groundwater level data do not update unsaturated zone directly

Test case

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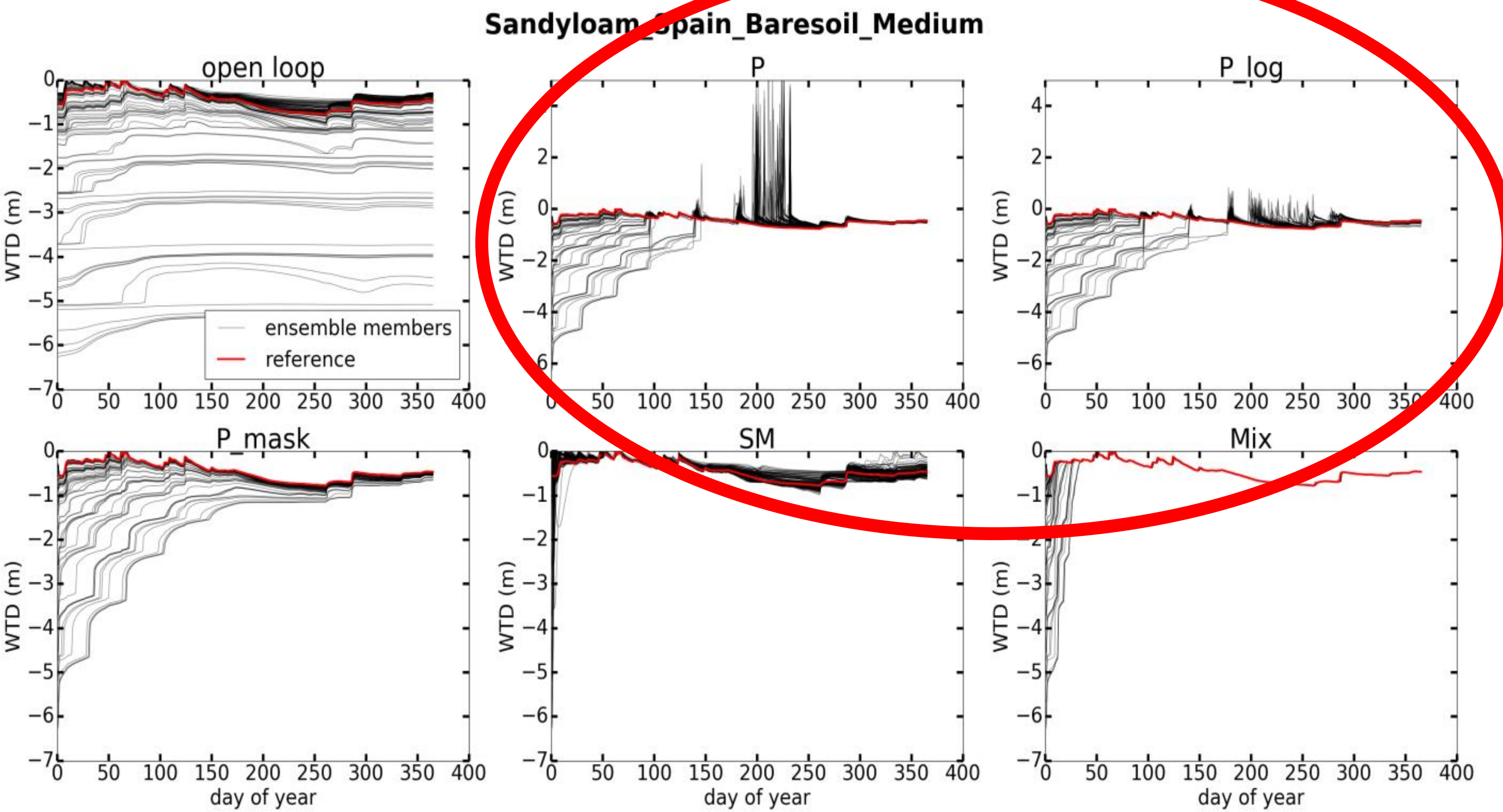
- 2 x 2 grid cells (and 30 layers). Slope 1%.
- Spatially homogeneous parameters.
- Only log(K_{sat}) uncertain ~ N(0,1); 128 ensemble members.
- 100 years spin-up, 1 year assimilation.
- Daily assimilation of GWL (measurement error 0.01m).

Example results

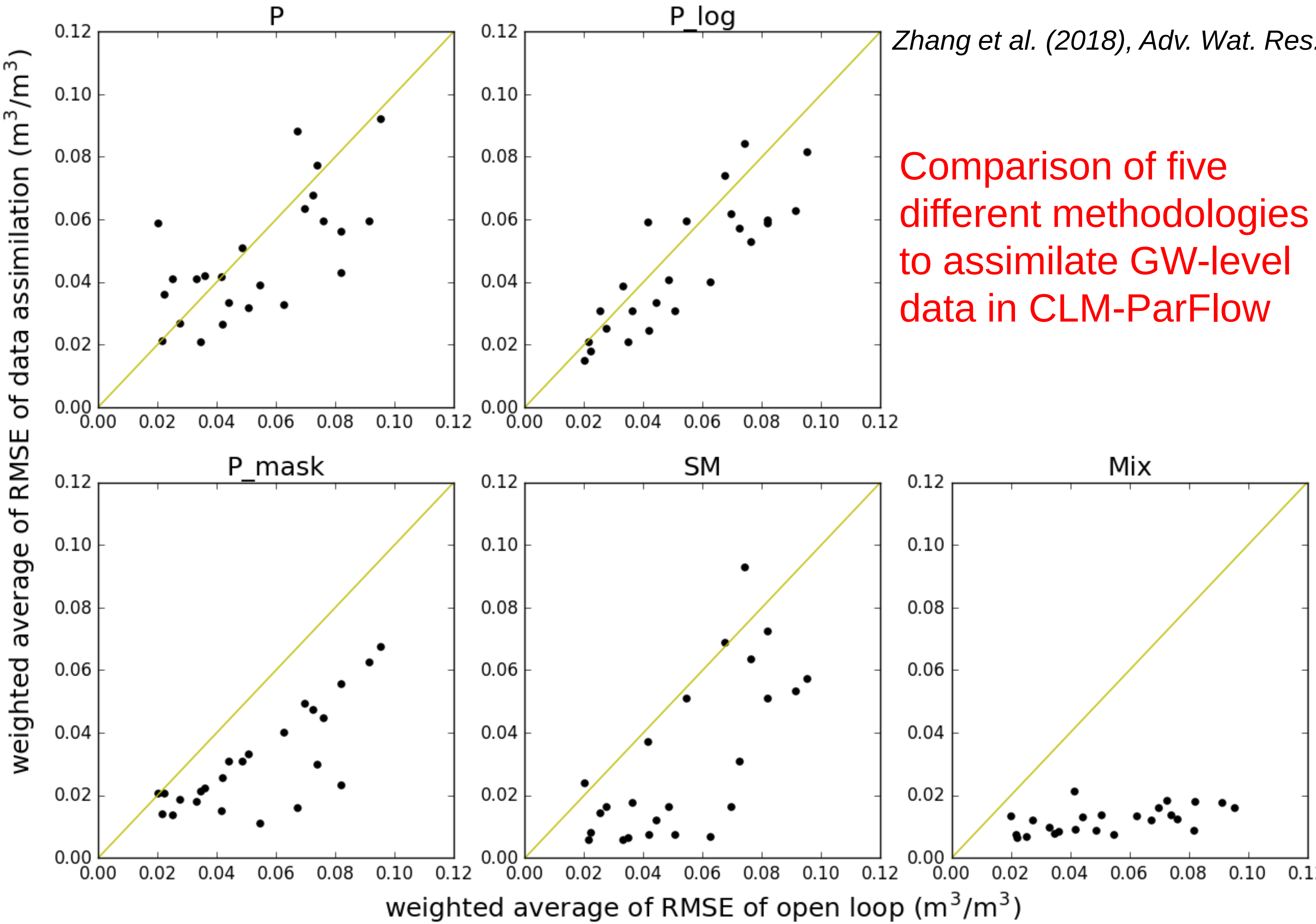
Strongly skewed (non-Gaussian) local pdf´s during dry conditions cause problems.



Methodology to incorporate GW-levels

Zhang et al. (2018), Adv. Wat. Res.

Comparison of five different methodologies to assimilate GW-level data in CLM-ParFlow



Value of GWL for RZSM-characterization

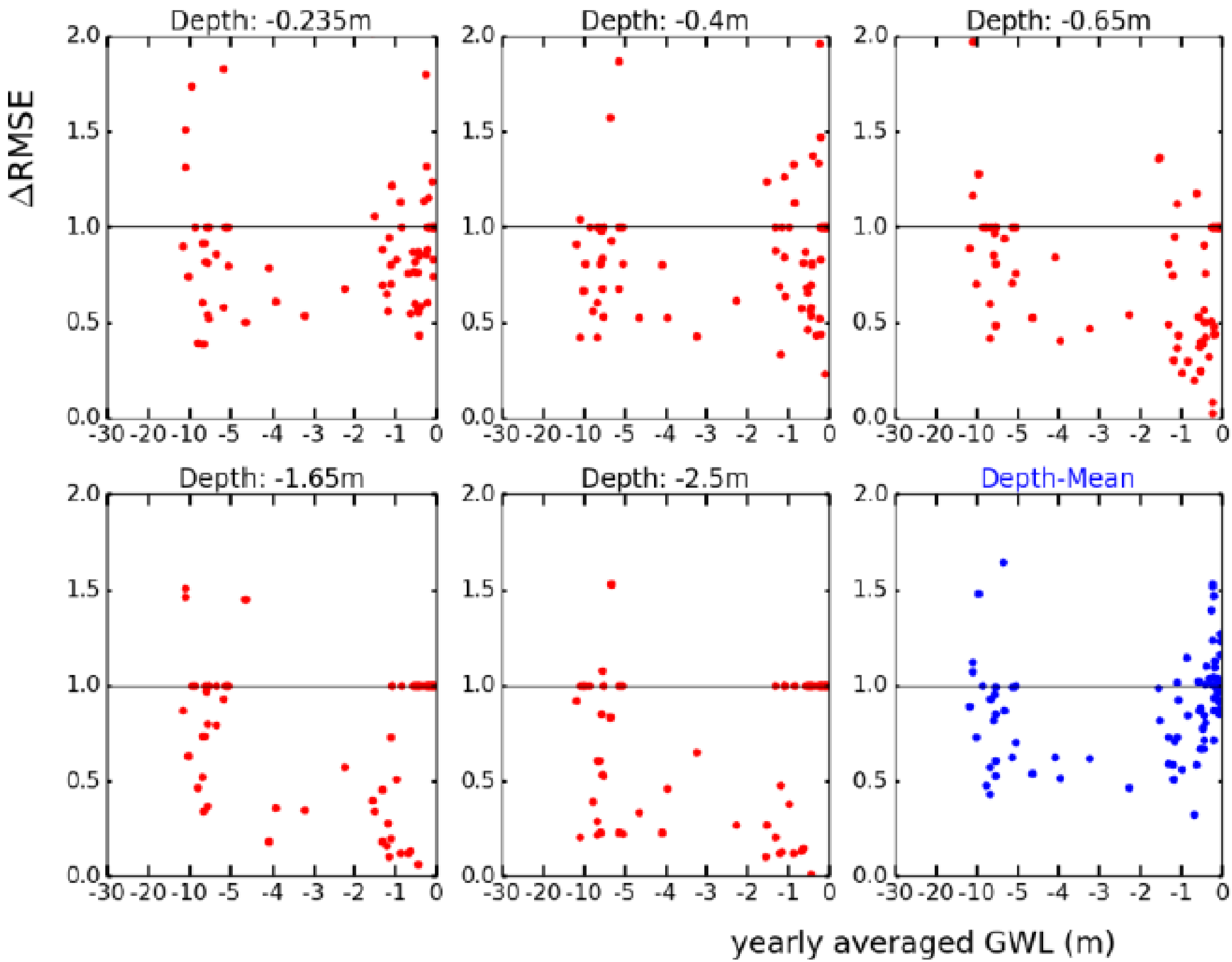
- Vertically heterogeneous K_{sat}, α and n parameters.

- K_{sat}, α and n uncertain and sampled from multi-normal distribution (transformed parameters).

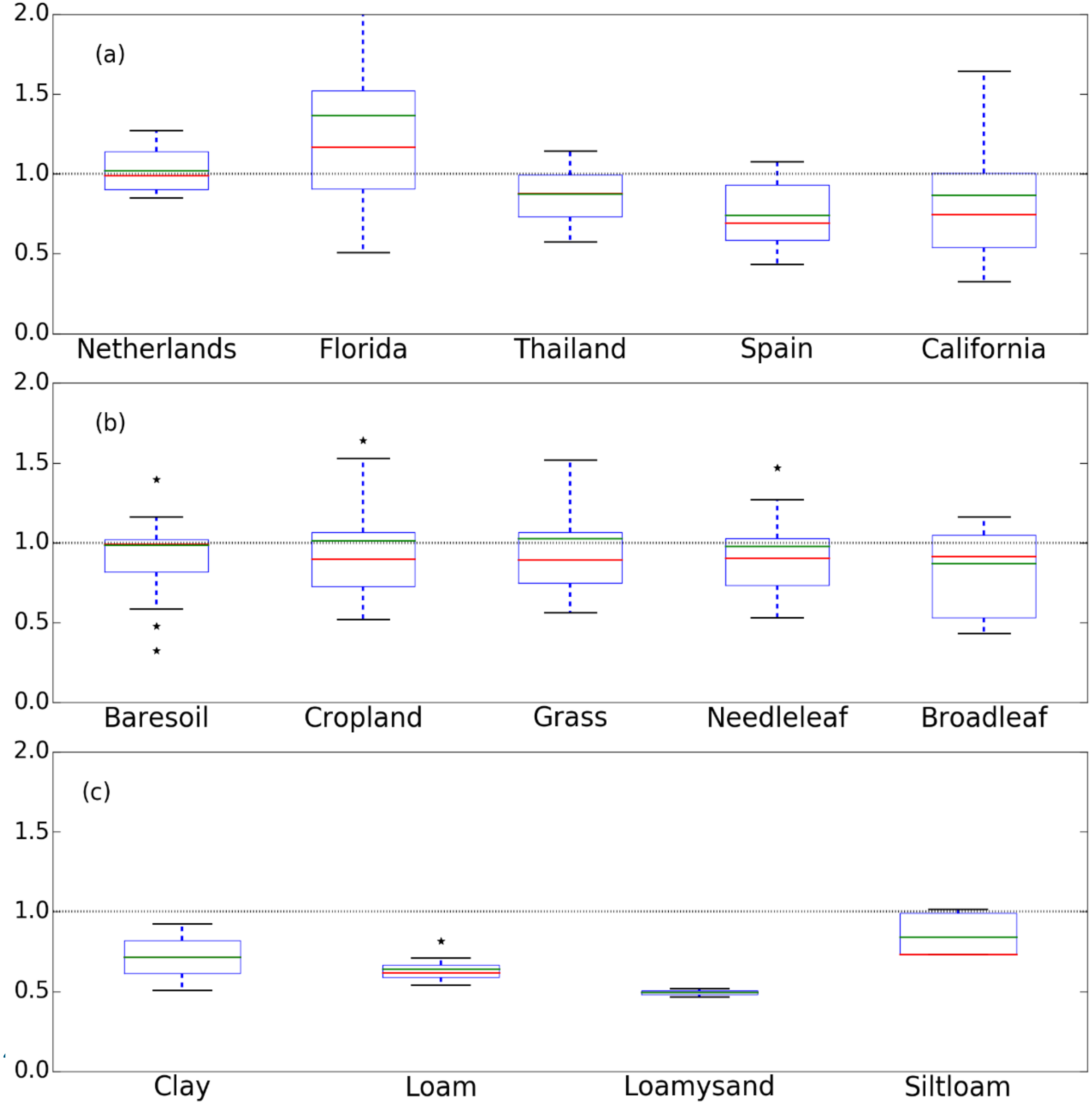
- Precipitation uncertain: perturbed with multiplicative noise U[0.5, 1.5].

- Performance evaluated for large number of synthetic experiments (100 cases: 4 soil types x 5 PFT´s x 5 climate types).

RMSE Reduction vs. GWL



RMSE Reduction vs. Climate/PFT/Soil



green: mean

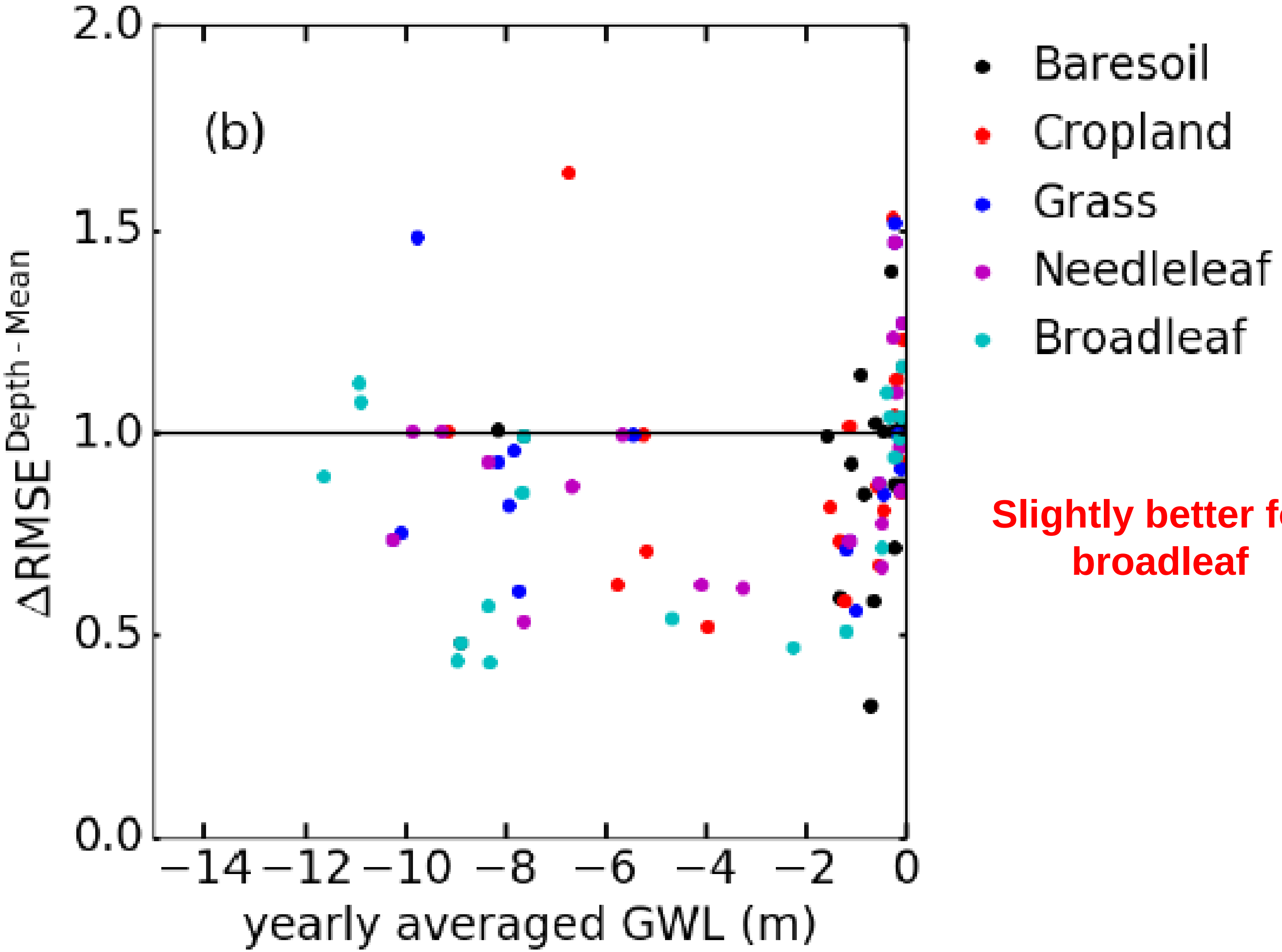
red: median

If GW-level is not very shallow or very deep, assimilation shows clear benefit

Better results for loam soils.

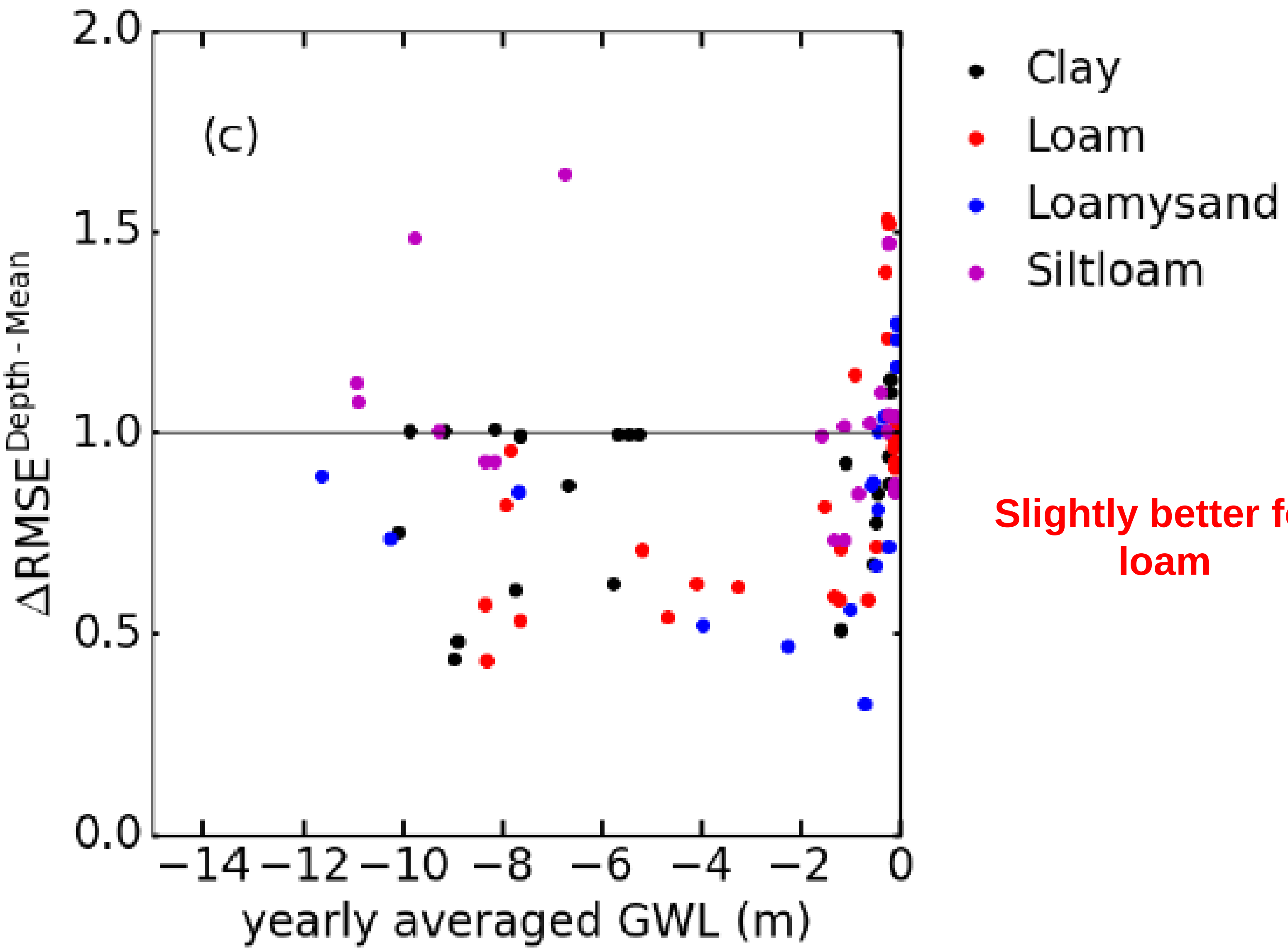
Better results for broadleaf trees.

RMSE Reduction vs. GWL (PFT´s)



Slightly better for broadleaf

RMSE Reduction vs. GWL (soil types)



Slightly better for loam

3rd example: atmosphere-land surface DA

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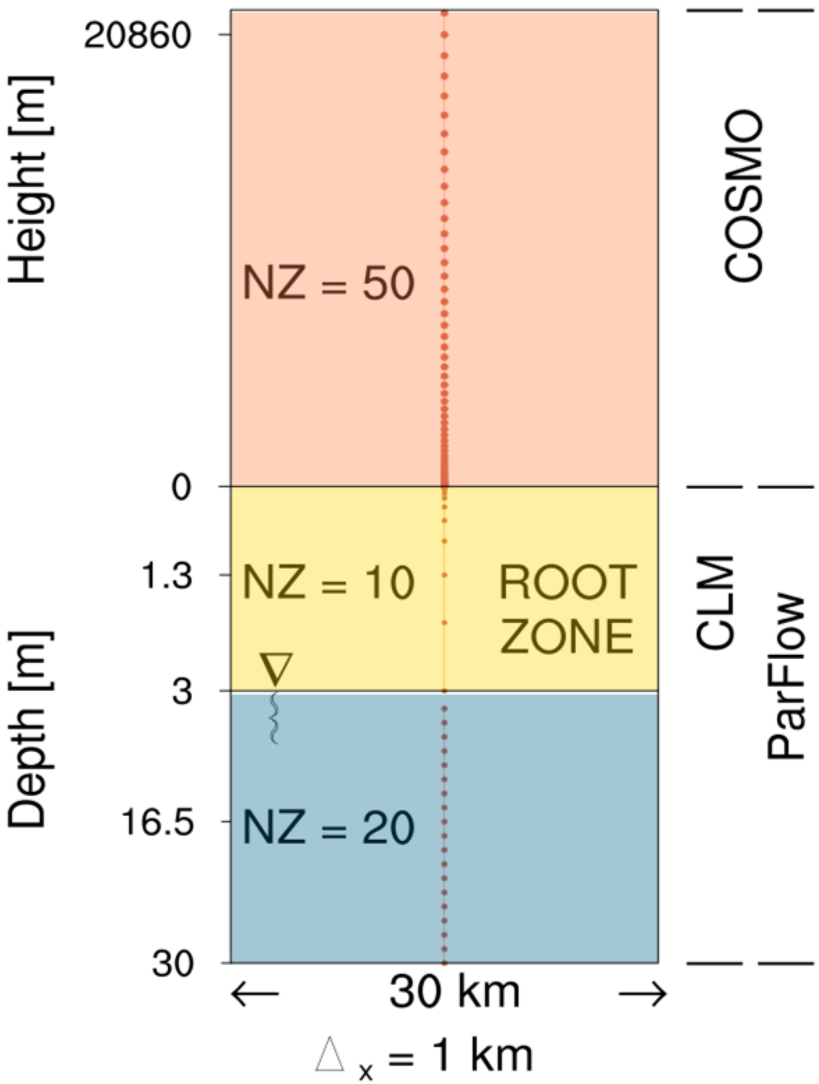


- Homogeneous land surface & subsurface.
- 30 x 20 km^2 and resolution of 1km.
- Atmosphere has 50 vertical layers, with 20m resolution near surface.
- Subsurface has 30 vertical layers stretching until 30m.
- Periodic lateral BCS /impermeable lower BCS,

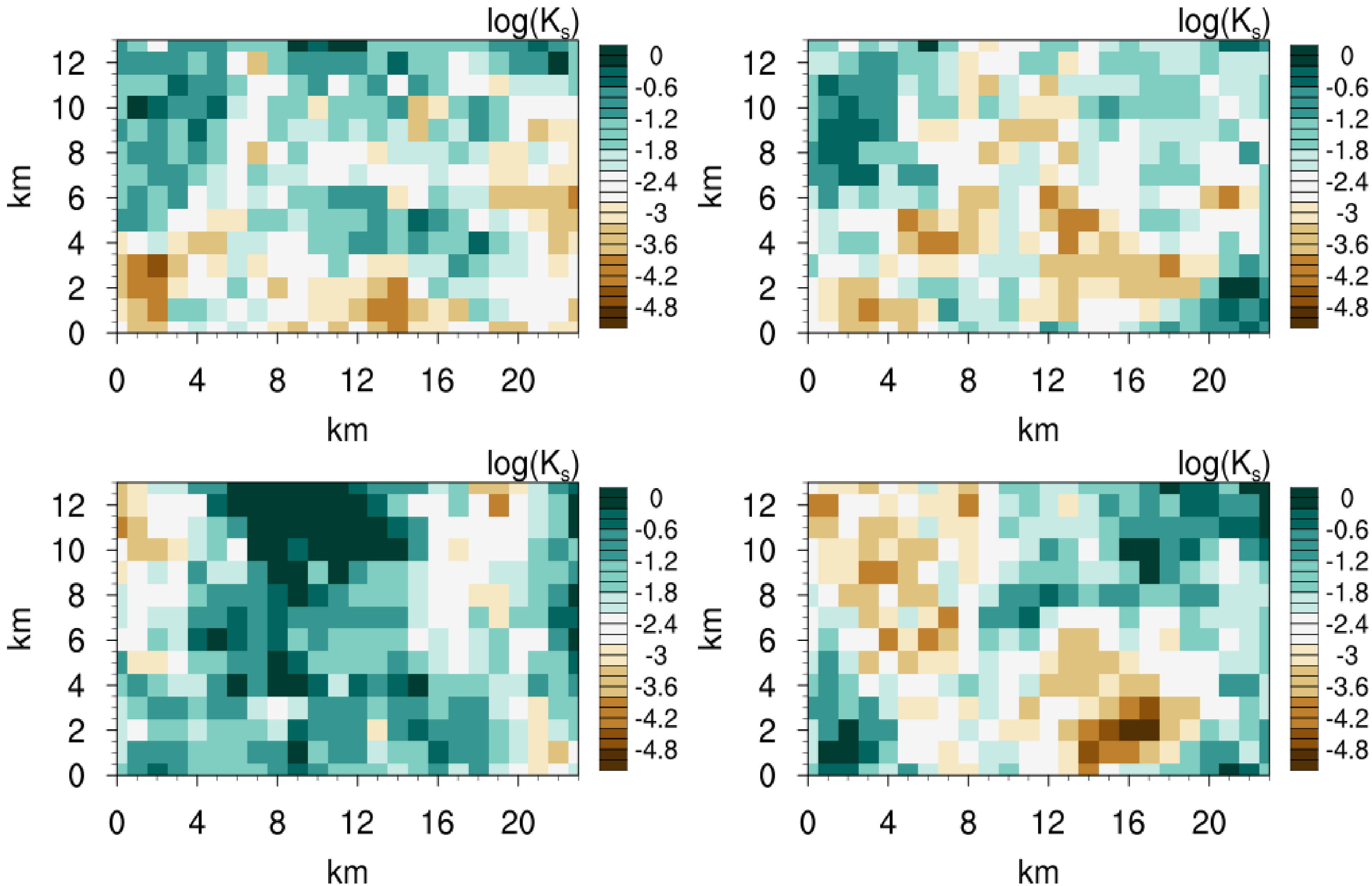
Spin-up

- 100 days of spin-up (Feb 1- May 7, 2008).
- Initial ground and vegetation temperature 283 K.
- Initial groundwater table depth 3m, hydrostatic profile.
- External forcing by COSMO-DE reanalysis data.
- Other parameters deterministic.

Ensemble generation

- 48 ensemble members.
- Spatially variable fields of saturated hydraulic conductivity.
- LAI, soil color, clay percentage, leaf carbon-nitrogen ratio randomly perturbed (but spatially constant).
- Turbulent mixing scale parameter.
- Other parameters deterministic.

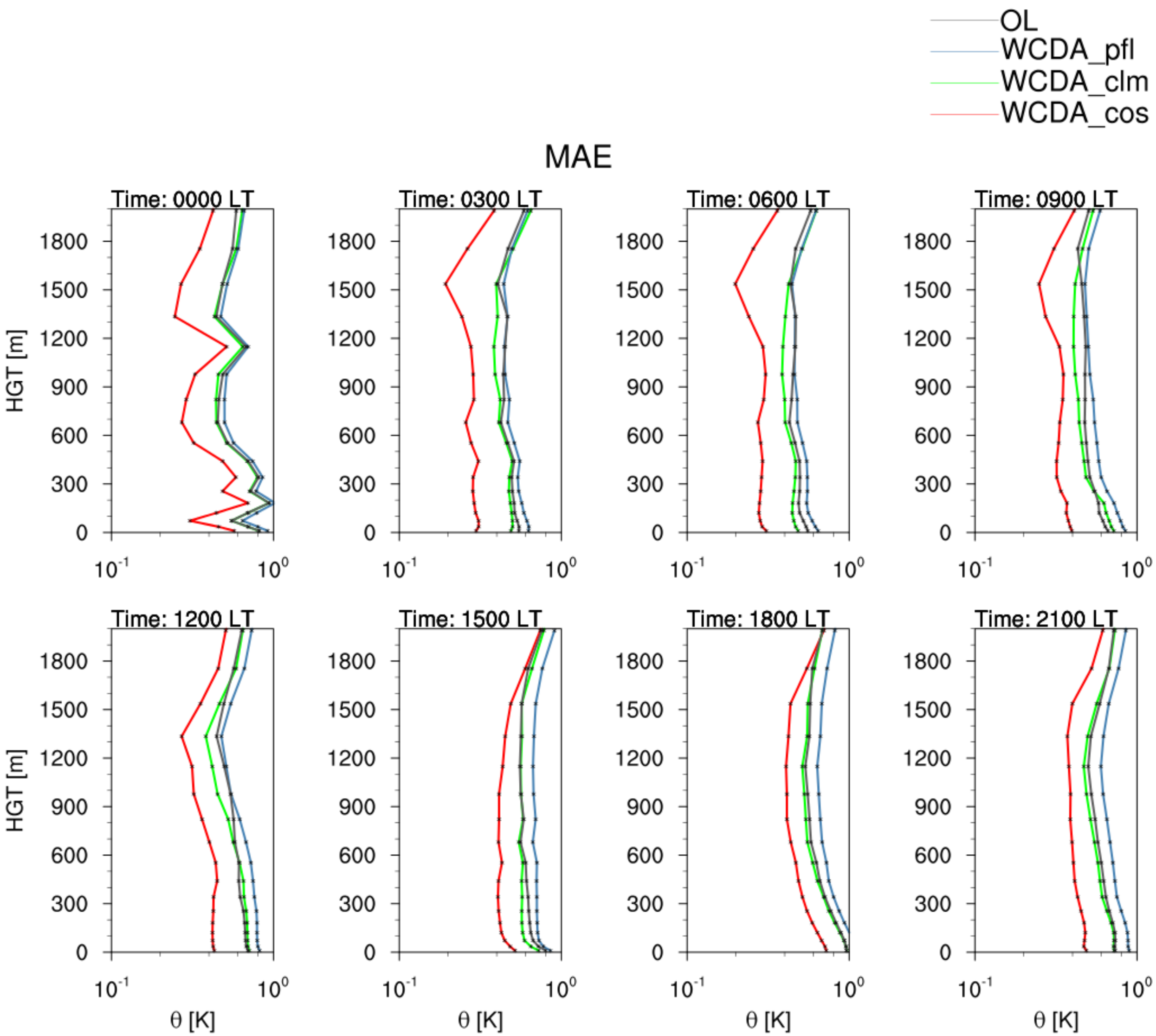
Spatially variable hydraulic conductivity



DA experiments

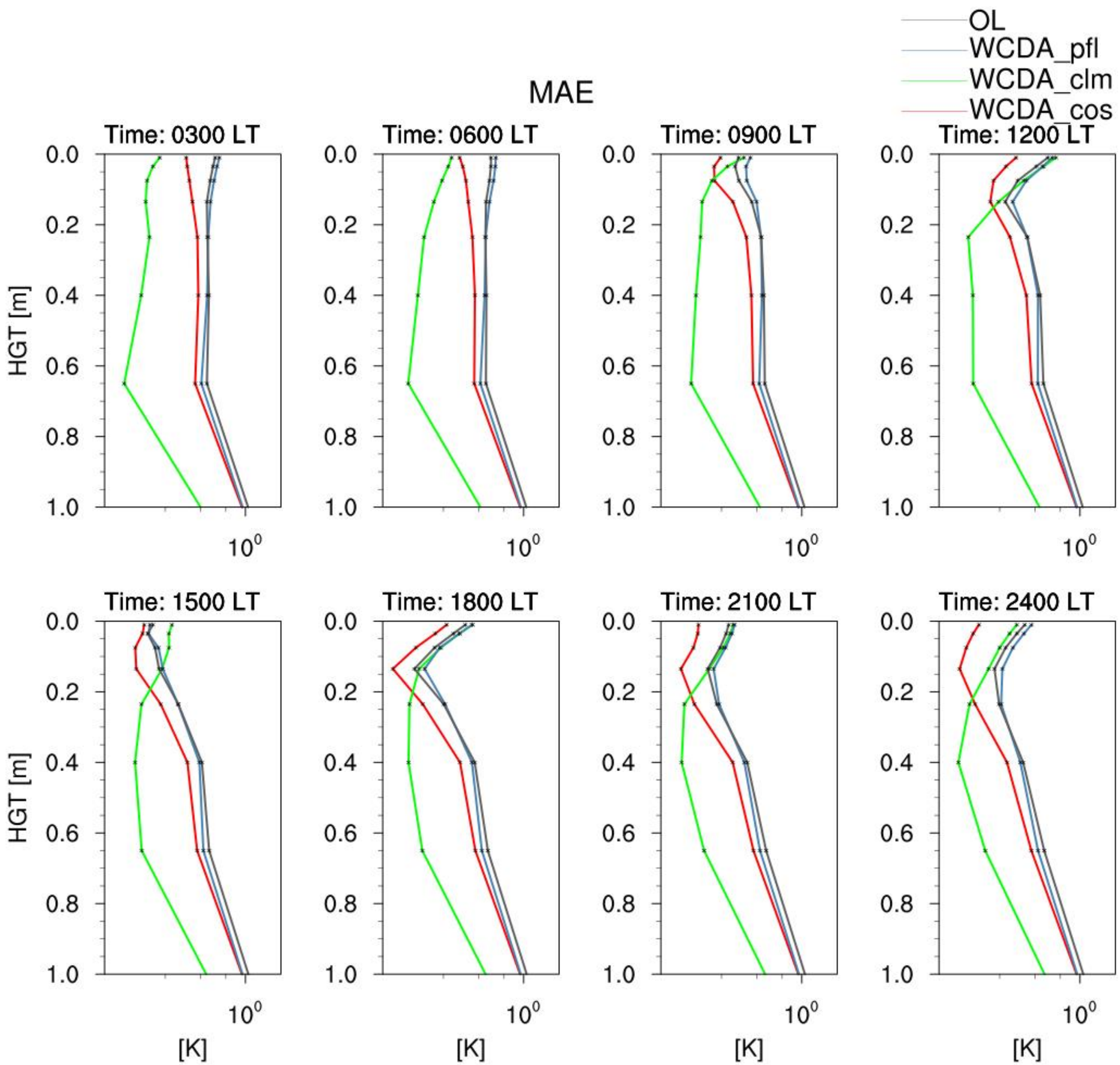
- Atmospheric DA: Atmospheric temperature at 10, 100, 200, 500, 1000, 3000 and 5000m.
- Land surface DA: Soil temperature at 2, 6, 10, 20, 30, 50, 80 cm depth.
- Subsurface DA: Soil moisture at 2, 6, 10, 20, 30, 50 and 80 cm depth.
- Observation variances: 0.60 K^2, 0.10 K^2 and 0.005.
- Daily assimilation for 10 locations in space.

Characterization atmospheric states



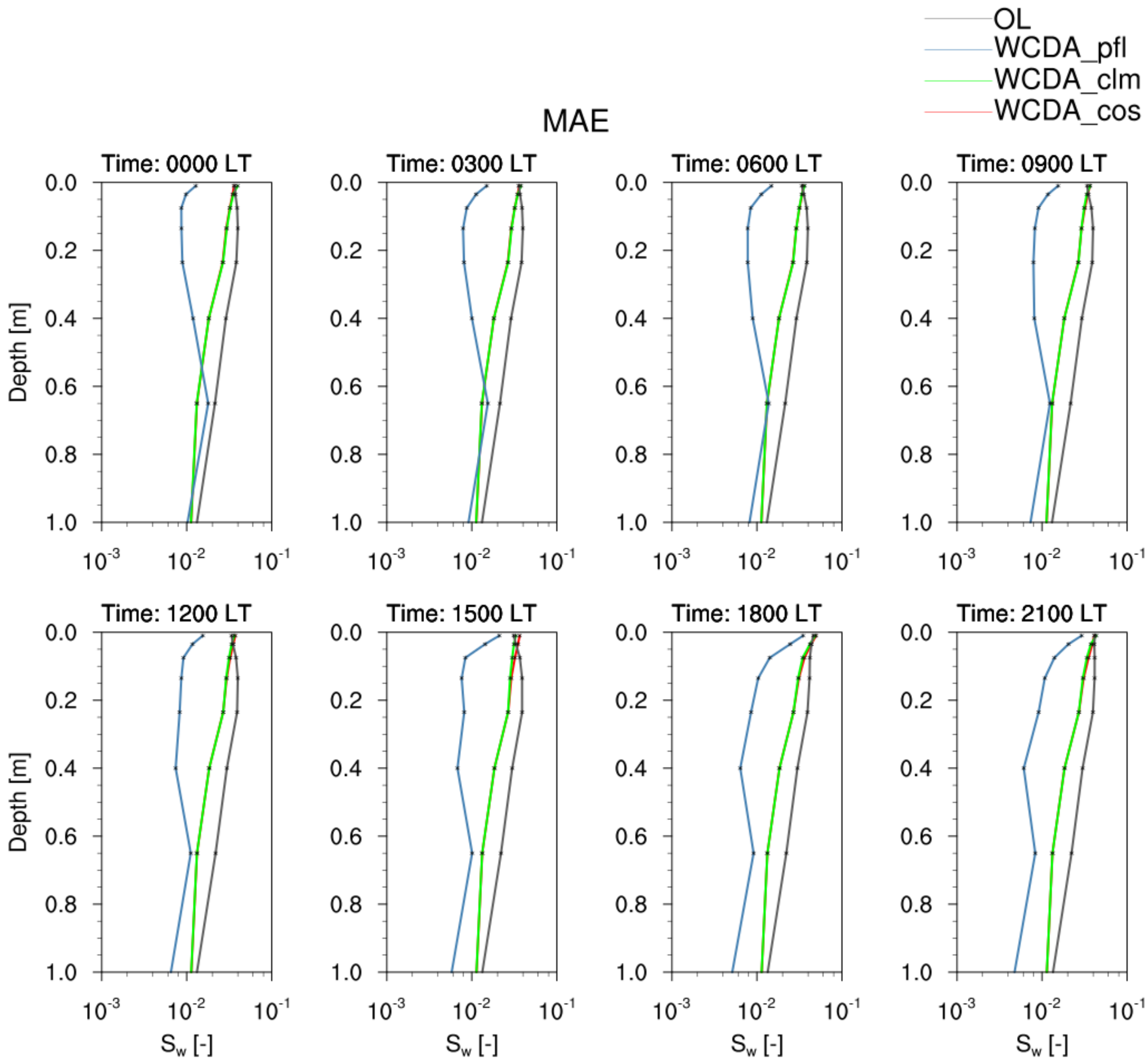
- Only atmospheric DA improves characterization of boundary layer potential temperature.

Characterization soil temperature



- Assimilation of soil temperature improves soil temperature, but less for upper 20 cm.
- Assimilation of atmosperic temperature improves soil temperature for upper layers.

Characterization soil moisture



- Assimilation of soil moisture improves soil moisture.
- Assimilation of soil temperature has also an impact on improving soil moisture characterization.

Conclusions and outlook

- TerrSysMP-PDAF: DA-framework optimally suited for HPC.
- Cosmic ray probe data very promising for land surface DA.
- GW-level data have high potential to improve root zone soil moisture characterization (under certain conditions) using fully coupled DA.
- Weakly coupled atmospheric-land surface- subsurface DA tested with different impacts of different observations. New test for drier conditions.
- DA with fully coupled model does not allow for compute intensive alternative DA-methods ((iterative) smoothers, PF).
- Current work: extension of coupled DA. See also poster by Natascha Brandhorst.

Thanks for your attention!