Development and application of a coupled atmospheric-hydrological model system, suitable for regional spatial and climate relevant temporal scales

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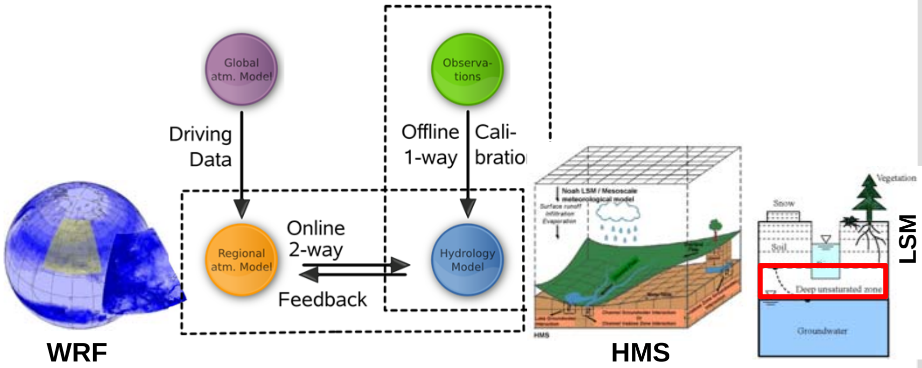
Objectives

- All components of hydrological cycle are affected by climate and landuse changes
- Joint landuse- & climate change impact analysis on regional water cycle requires

  Investigations on Feedback mechanisms between the atmosphere, land surface & subsurface conditions

- The quantification of such feedback mechanisms calls for coupled modelling systems that consist of a
  - regional atmospheric- &
  - distributed hydrological model
  - sharing compatible water & energy flux formulations

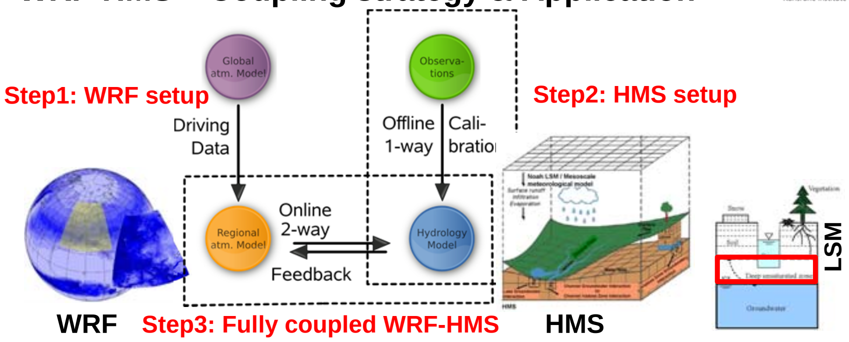
Overview Model Approach



- Both models use the same land surface model (Noah-LSM)
- Both models communicate at the same scale

- Allows long-term simulations at regional spatial and climate relevant temporal scales

WRF-HMS – Coupling strategy & Application



- Implementation of HMS model in the WRF code structure (hydrology driver routine) allowing flexible time step application
- Serial HMS code was adapted to support MPI parallel execution

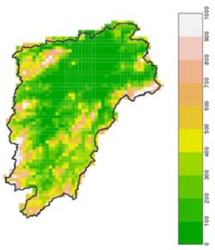
→ HPC capacity of coupled modelling system

→ Prerequisite for long-term simulations !!!

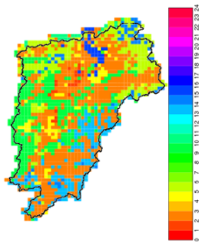
Research area: Poyang Lake Basin, China

- Basin size: 160 000 km² (lake up to 4000 km²)
- Tributary of Yangtze River
- Humid subtropical climate:
  - mean annual temperature: 17.6°C
  - mean annual precipitation: 1500 mm

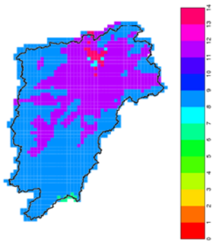
DEM:



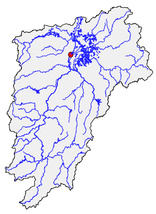
LU map:



Soil map:

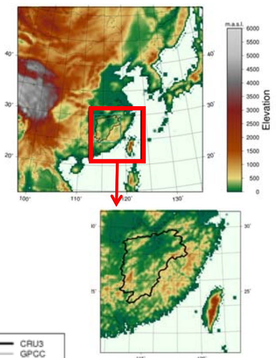


River network:

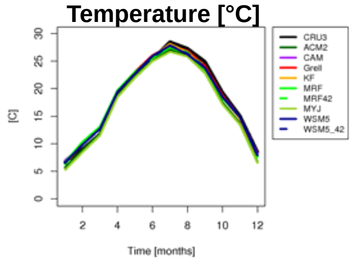


Step1: WRF setup

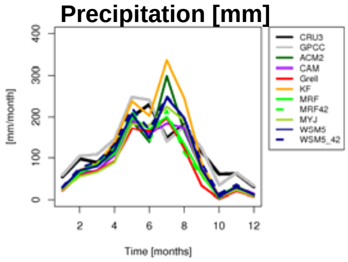
- Double nesting approach: D01 (30km), D02(10km)
- Several configurations of WRF with respect to model physics and vertical resolution
- Reanalysis simulations to find appropriate setup using ERA interim (2003-2005)
- Validation data: CRU3, GPCC, APHRODITE



Temperature [°C]



Precipitation [mm]



- MP: WSM5
- Radiation: RRTM
- PBL: Yonsei Univ.
- Cumulus: Betts-Miller-Janjic

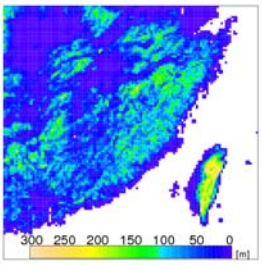
Wagner et al (2013)

Step2: NOAH-LSM – HMS simulations

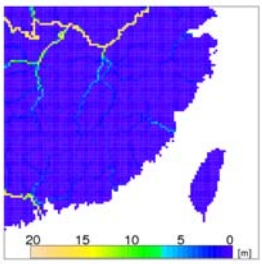
- Meteorological forcing: interpolated station data
- use implemented HMS model in the WRF code
  - same modules & input data (except met. forcing)

Step 2: NoahLSM-HMS – PREPROCESSING: Additional hydrological input parameters

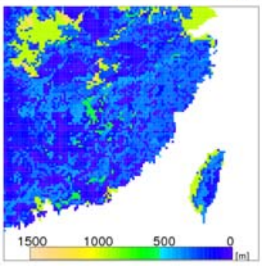
DEM (sd): USGS HYDRO1K (GTOPO30)



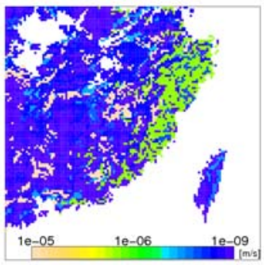
Streambed depth: USGS HYDRO1K



Aquifer thickness: Chinese Geological data set

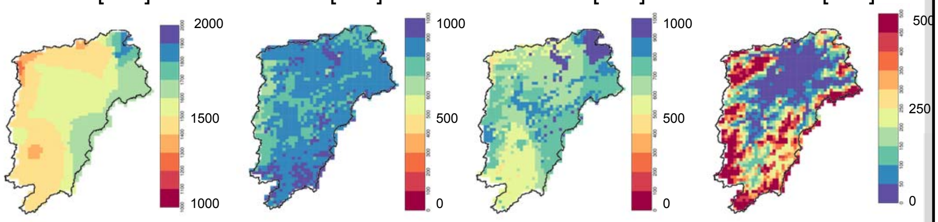


Hydraulic conductivity: Chinese Geological data set

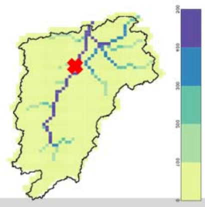


Step2: NOAH-LSM – HMS simulations

➢ Simulation results for 1978 - 1986:



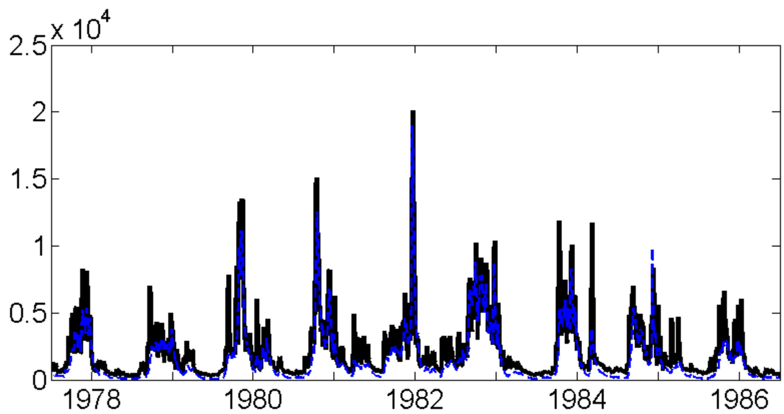
DISCHARGE [m³/s]:



Waizhou

Step2: NOAH-LSM – HMS simulations

➢ VALIDATION: simulated discharge [m3/s] @ Waizhou for 1978 – 1986:

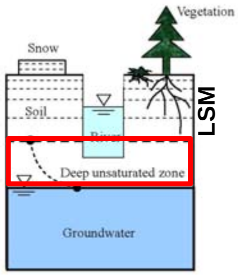


Step2: NOAH-LSM – HMS with GW-feedback

Methods for allowing feedbacks between LSM and saturated zone

- Coupling of saturated to unsaturated zone
- Two way interaction & fluxes (e.g. capillary rise vs. gravity fluxes) between saturated and unsaturated zone

- **Richard's equation with *fixed-head boundary condition*** based on Zeng et al. (2009), De Rooij (2010)
- ***Darcy flux boundary condition***
  based on Bogaart et al. (2008)

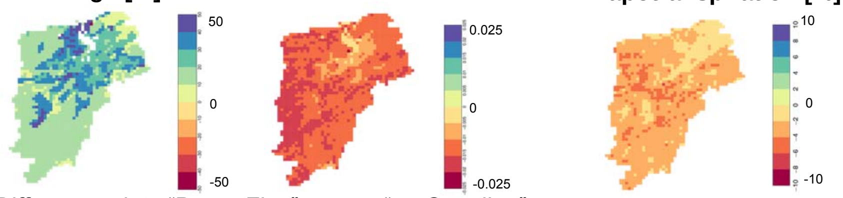


Step2: NOAH-LSM – HMS with GW-feedback

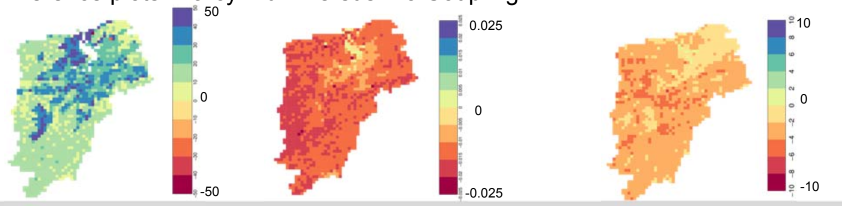
Impact of feedback between LSM and saturated zone on simulation results

- Difference plots “Fixed head” versus “no Coupling”

Recharge [%] **Soil moisture 0–10 cm** **Evapotranspiration [%]**

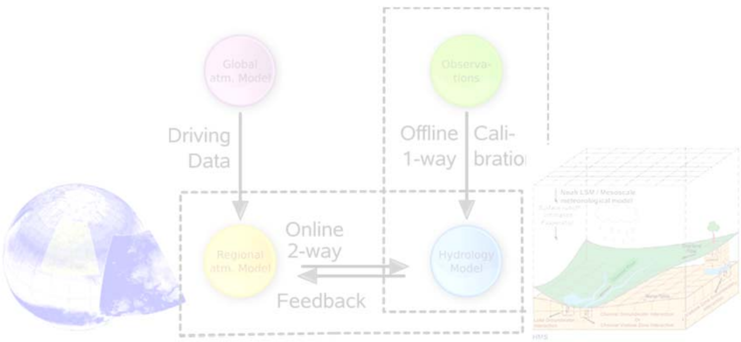


- Difference plots “Darcy-Flux” versus “no Coupling”



Step3: WRF – NOAH-LSM – HMS simulations

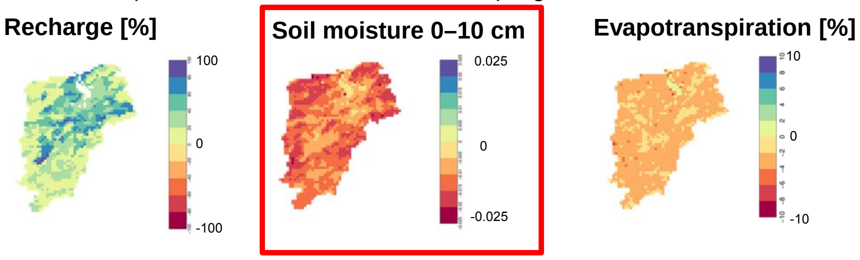
- Use the identified optimal stand-alone WRF and HMS setup
- Allows investigations of hydrological land surface – atmosphere feedback



Step3: WRF – NOAH-LSM – HMS simulations

Fully coupled simulation results with GW feedback

- Difference plots “Fixed head” versus “no Coupling”

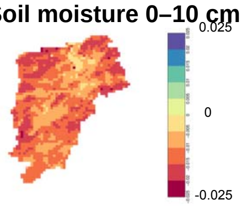


Step3: WRF – NOAH-LSM – HMS simulations

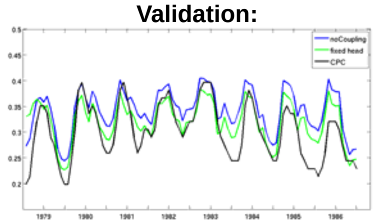
Fully coupled simulation results with GW feedback

- Difference plots
  “Fixed head” versus “no Coupling”

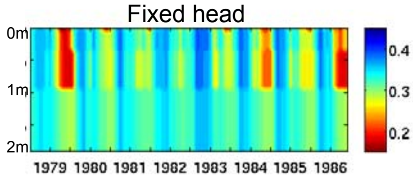
Soil moisture 0–10 cm



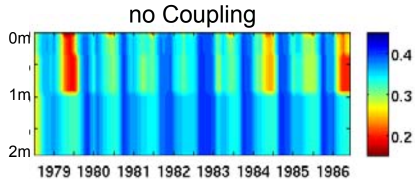
Validation:



Fixed head



no Coupling

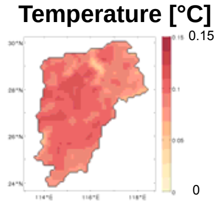


Step3: WRF – NOAH-LSM – HMS simulations

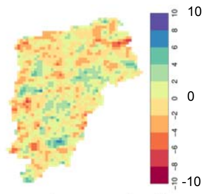
Fully coupled simulation results with GW feedback

- Difference plots “Fixed head” versus “no Coupling”

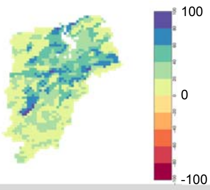
Temperature [°C]



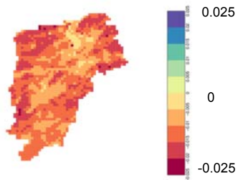
Precipitation [%]



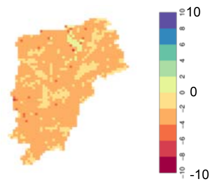
Recharge [%]



Soil moisture 0–10 cm



Evapotranspiration [%]



Summary

Objective: Investigations on Feedback mechanisms between the atmosphere, land surface & subsurface conditions

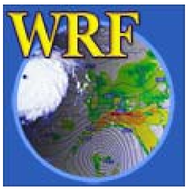
Fully coupled modelling system:
- Integration of HMS preprocessors & code in WRF model structure
- Integration of GW feedback mechanisms in coupled model system

Poyang Lake Basin:
- Performance & potential of fully coupled simulations incl. GW-feedback
- GW-feedback impact conditions in LSM, land surface & lower atmosphere

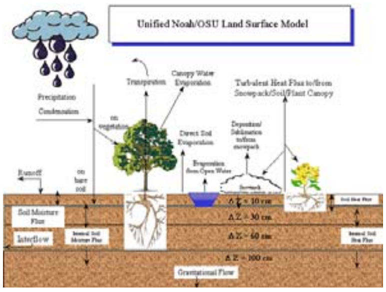
Thank you for your attention

This work is financially supported by the German Research Foundation (DFG) and National Natural Science Foundation of China (NSFC)

Model Components: WRF & Noah-LSM



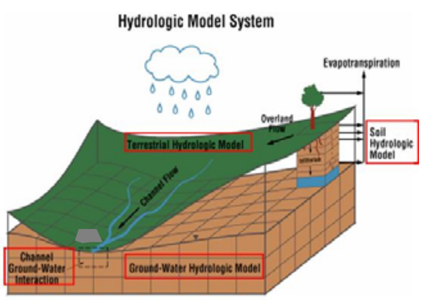
- Non-hydrostatic, Δx≈1km-50km, Δt ≈ tens of seconds
- Based on conservation laws
- Subgridscale processes: parameterized
- Nested approach: lateral boundary from GCM

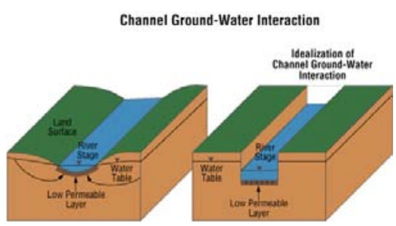


- "Lower boundary of WRF"
- Δt ≈ tens of minutes
- 4 soil layers
- Vertical water and energy fluxes

→ Important for feedbacks between near surface soil, boundary layer & atmosphere

Model Components: HMS (*Yu et al, 2006*)





- Spatially distributed
- Suitable for large- scale applications , Δx≈ up to a few tens of km: 10 km here
- streamflow routing - 2D diffusive wave, Δt ≈ tens of minutes
- Interaction of channel & vadose zone or channel & groundwater flux
- Unsaturated soil moisture profile is assumed to be in equlibrium
- 2D horizontal groundwater flow: one layer aquifer, simple bedrock, Δt ≈ 1 day

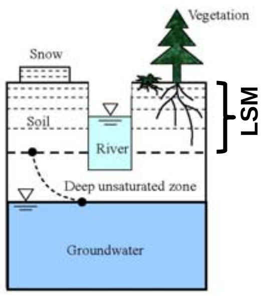
Step2: NOAH-LSM – HMS simulations

- Meteorological forcing: interpolated station data
- use implemented HMS model in the WRF code
  - same modules & input data (except met. forcing)
- Calibration of HMS:
  - Noah LSM parameters:
    FXEXP, REFKDT, …
  - HMS parameters:
    Manning, conductivities, …

Feedback between LSM and saturated zone

Approach 1: Richard's equation with *fixed-head boundary condition*
Based on *Zeng et al. (2009), De Rooij (2010)*

- **Free drainage boundary condition of LSM is replaced by a fixed-head bottom boundary condition** which assumes an equilibrium soil moisture distribution
- Hydraulic head & soil moisture at the lower boundary of LSM is derived from **distance between groundwater level and bottom of LSM** conserving the energy and mass of water
- New boundary condition realized with **additional layer** at bottom of Noah-LSM
- Label: **Fixed-Head**



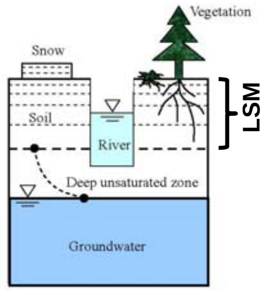
Distinction of 3 cases: new layer is un-, partially- or fully saturated, e.g.

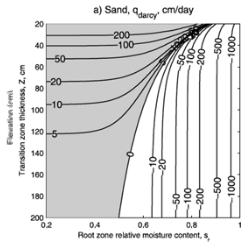
$$\overline{\theta}_i = \frac{\int_{z_{i-1/2}}^{z_{i+1/2}} \theta_E(z)\,dz}{z_{i+1/2} - z_{i-1/2}} = \frac{\theta_{sat}\psi_{sat}}{(z_{i+1/2} - z_{i-1/2})\left(\frac{1}{B} - 1\right)} \times \left[\left(\frac{\psi_{sat}}{z_p - z_{i+1/2}}\right)^{1/B-1} - \left(\frac{\psi_{sat}}{z_p - z_{i-1/2}}\right)^{1/B-1}\right].$$

Feedback between LSM and saturated zone

Approach 2: *Darcy flux boundary condition*
Based on *Bogaart et al. (2008)*

- Assumes a quasi steady-state moisture profile between groundwater head and lowest soil layer of the LSM.
- ***Darcy* equation** is used to describe flow through this transition zone depending on relative saturation at bottom of LSM
- **Parameterization** that approximates net Darcy flux q_{darcy} for different thicknesses of transition zone and different values of saturation for lowest LSM soil layer
- Label: **Darcy-Flux**

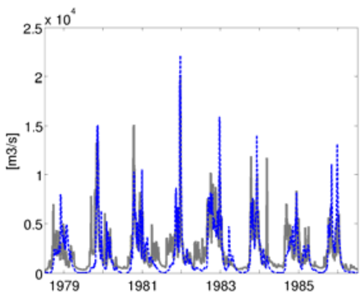




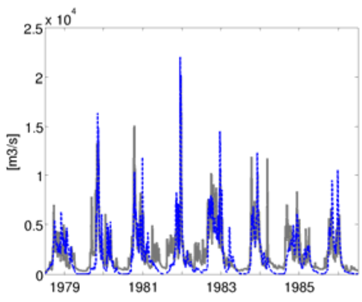
Step3: WRF – NOAH-LSM – HMS simulations

➢VALIDATION: simulated discharge [m3/s] @ Waizhou for 1978 – 1986 of fully coupled model system

“no GW-Coupling”



“Fixed-Head GW-Coupling”



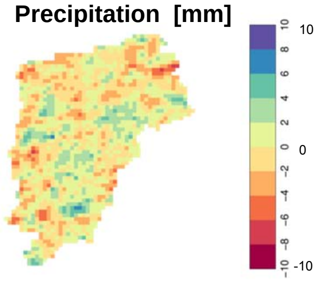
Step3: WRF – NOAH-LSM – HMS simulations

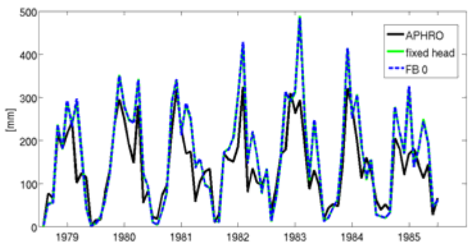
Fully coupled simulation results with GW feedback

- In fully coupled mode: in addition impact on atmospheric variables
- e.g. **Precipitation**

- Difference plots "Fixed head" versus "no Coupling"

Precipitation [mm]



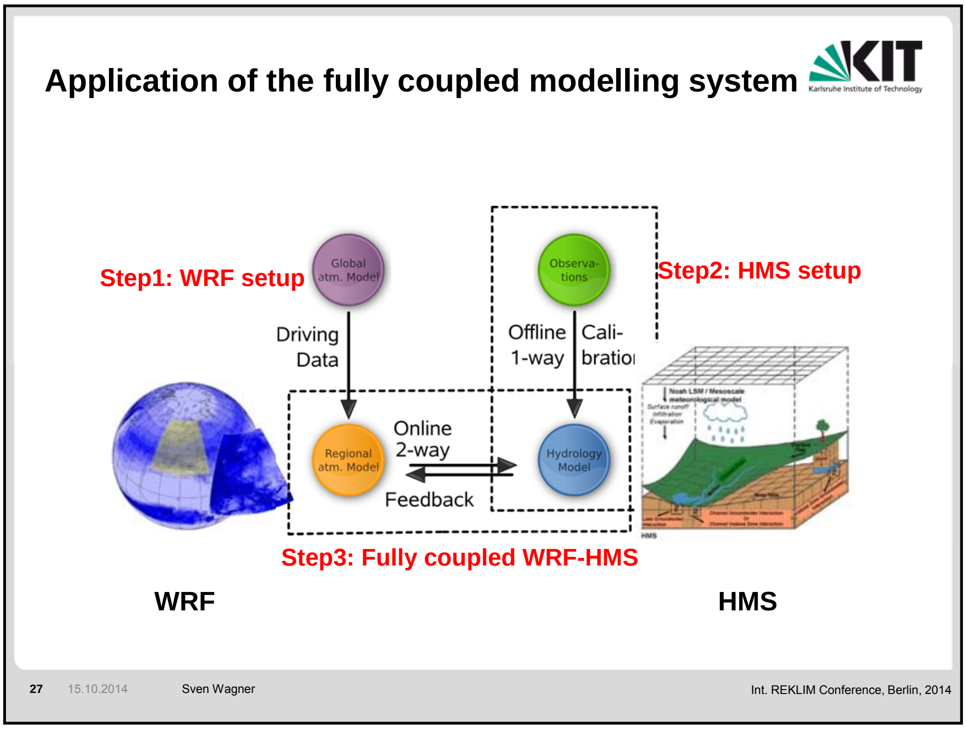


WRF-NoahLSM-HMS – Coupling strategy:

- Implementation of HMS model in the WRF code structure (hydrology driver routine) allowing flexible time step application
- Integration of preprocessors (static surface and sub-surface hydrological parameters)
- NetCDF compliance (IO)
- Serial HMS code was adapted to support MPI parallel execution

→ HPC capacity of coupled modelling system

→ Prerequisite for long-term simulations !!!


Application of the fully coupled modelling system
Karlsruhe Institute of Technology
Step1: WRF setup
Global atm. Model
Driving Data
Observa-tions
Step2: HMS setup
Offline 1-way
Cali-bratio
Regional atm. Model
Online 2-way
Feedback
Hydrology Model
Step3: Fully coupled WRF-HMS
WRF
HMS
27
15.10.2014
Sven Wagner
Int. REKLIM Conference, Berlin, 2014