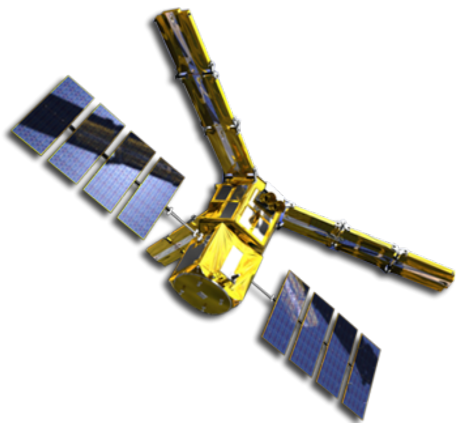
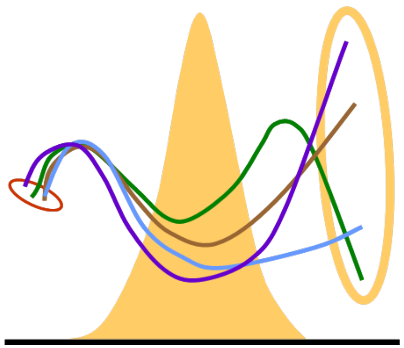
Land Surface Data Assimilation with TERRA





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In a Nutshell

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An ensemble data assimilation system for TERRA is implemented

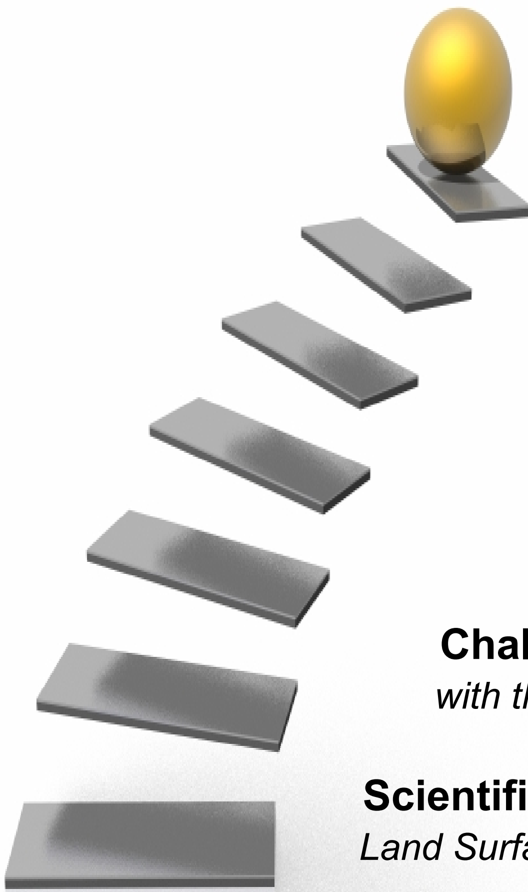
Estimation of the complete soil state from surface observations

Upper soil: weather

Deep soil: medium-range climate

First results & issues
Planned extensions

Steps



First results & outlook

Implemenation with **TERRA**
Experimental setup

Idealized tests
Conclusions

Challenges
with the deep soil...

Scientific questions
Land Surface / DA / Climate

Work embedded in MiKliP

Data Assimilation (DA) and Climate?

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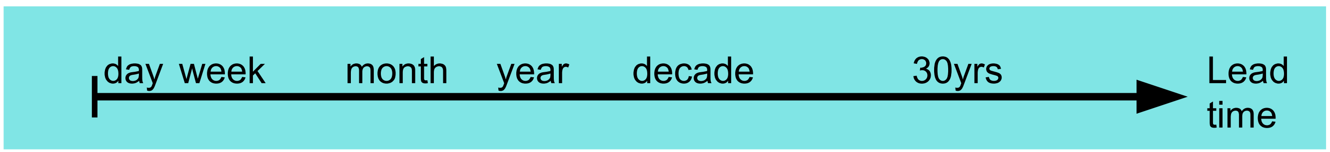
Data assimilation (DA) estimates ...

- Initial conditions
- Model parameters



Weather forecasts: initial value problem

DA essential

Medium Range

Climate prediction: boundary value problem

Medium-Range Climate Predictability

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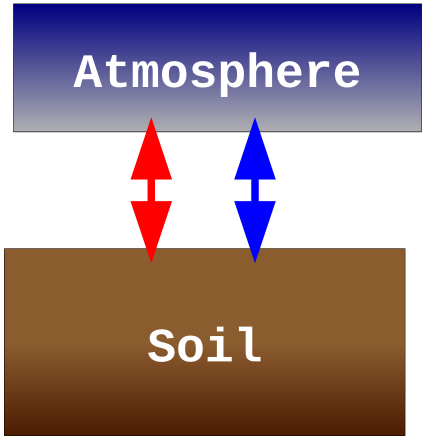
Carried by slowly-varying components of the earth system

- long-term memory of initial state → long-term feedback to fast subsystems

Land surface temperature & moisture

- Exchange of water & energy fluxes with atmosphere
- Strongly impacts screen level variables



Upper soil → weather

- Direct interaction with atmosphere → **fast** process

Deep soil → climate

- **Slow & delayed variability**
- Giant reservoir of energy & water
  → ***Initial amount long available***
- Influences first years in climate simulations

Typical Soil Temperature Behaviour

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$$T(z,t) = A(0)\exp\left(-\frac{z}{D}\right)\sin\left(\omega t - \frac{z}{D}\right) \quad , \quad D = \sqrt{\frac{2\lambda}{c_v\omega}}$$

With increasing depth...

- **Damping** of amplitude (storage)
- **Phase shift** of signal (delayed conduction)

D depends on soil type

- Capacity c_v
- Conductivity λ

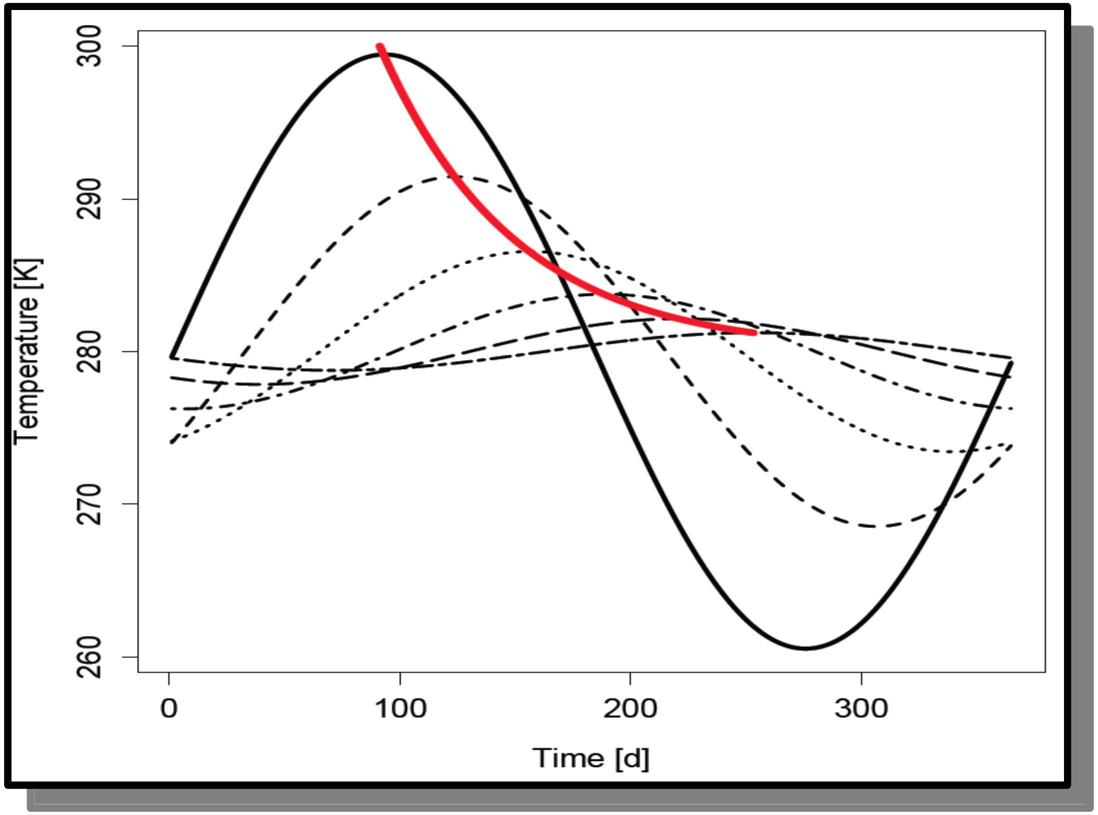
D(climate) ~ 4m

z=0...10m

- High-frequency signals (*weather*) are damped faster

D(weather) ~ 0.2m

z=0...0.5m



Potential Predictability in the Soil → How to Gain the Initial State?

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Spin-up

Run coupled system over long period

→ Soil state is expected to adjust to atmospheric forcing

Soil Data Assimilation

Model + Soil-related observations → Optimal estimate of the system's initial state

Spin-up		Soil Data Assimilation
✗	Considers uncertainties	✓
✗	Objectiveness / Diagnostics	✓
✗	Fast convergence	✓
✗	Parameter optimization	✓
✓	Simple implementation	✗

Challenge in Land Surface DA: Approach

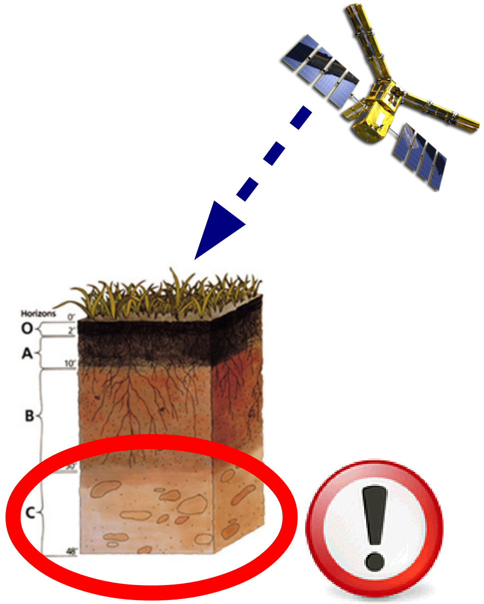
Land surface model

- Soil temperature & moisture to depth ~ 10m
- Aim: estimate the *full* state (→ climate)

Observations

- Only for first cm of soil
- Sparse temporal density
- Errors (measurement, retrieval)

→ Information transfer to the deep soil necessary



„Can a slow subsystem be estimated reliably with DA, using observations in a coupled fast process?"

Simplified Experiments

DA with TERRA (offline)

Ensemble Data Assimilation (EnDA)

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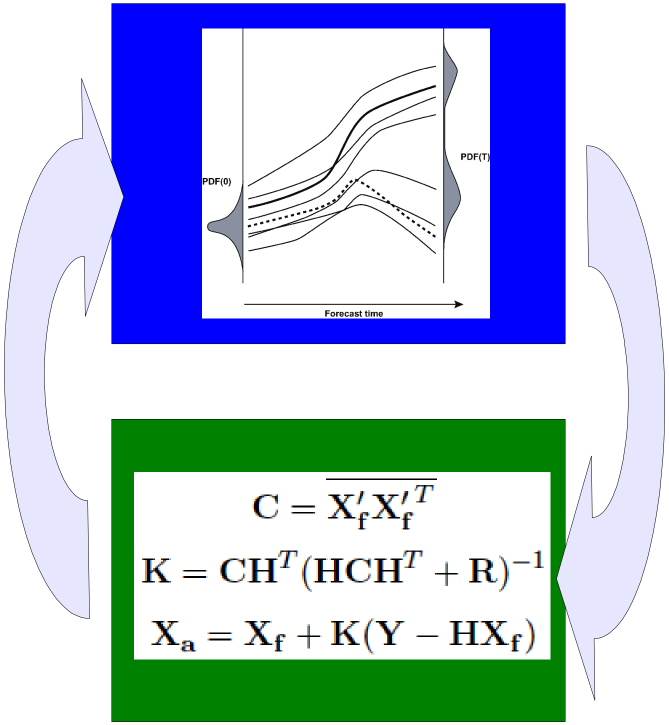
Sequential data assimilation through time window



$$\mathbf{C} = \overline{\mathbf{X}_f' \mathbf{X}_f'^T}$$

$$\mathbf{K} = \mathbf{C}\mathbf{H}^T(\mathbf{H}\mathbf{C}\mathbf{H}^T + \mathbf{R})^{-1}$$

$$\mathbf{X}_a = \mathbf{X}_f + \mathbf{K}(\mathbf{Y} - \mathbf{H}\mathbf{X}_f)$$

Forecast step

- Ensemble integration (full model)
- Implicitly integrates covariance matrix

Analysis Step at observation times

- Kalman Filter update for each member (EnKF)
- Covariance matrix determines increments

Advantages of EnDA

- Model integration & analysis algorithm separated
  → No tangent linear / adjoint code, no minimization algorithm
- Respects non-linearity, update step implicitly Gaussian
- Allows parameter estimation by state augmentation

Method for DA Experiments

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Observing System Simulation Experiments (OSSE)

1. Generate a true trajectory with the model
2. Generate observations by perturbing the true states
3. Perform a DA cycle with the model & these observations
4. Compare with reference:

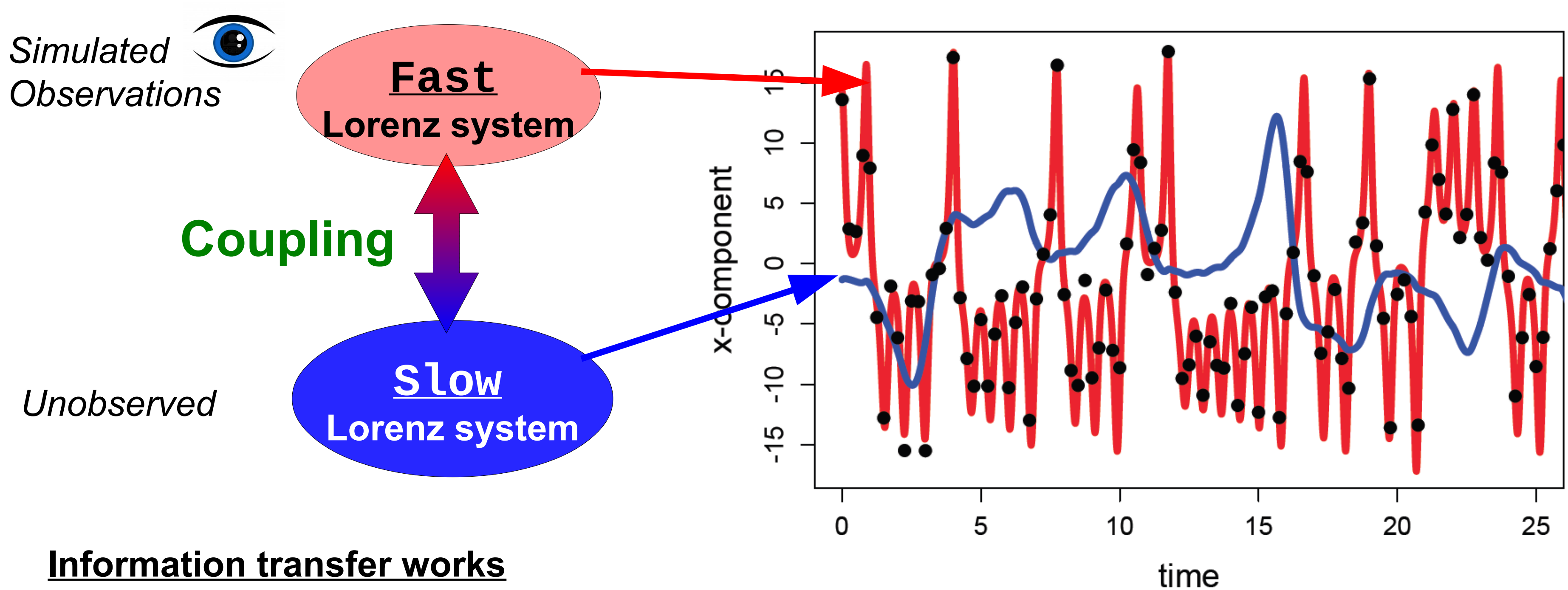
➔ **Can the filter reconstruct the truth?**

➔ **Derive conditions, sensitivies, time scales, ….**

➔ **Prepares use of „real observations“**

Experiment with a Strongly-Nonlinear Toy Model

Coupling of two Lorenz(63) models with different time scales



<u>Information transfer works</u>

Analysis in the hidden slow system successfull, depends on

- Coupling strength
- Observation error

Coupling in soil: { Conductivity, Capacity }

Soil Temperature Experiments

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Isolation of the heat conduction equation

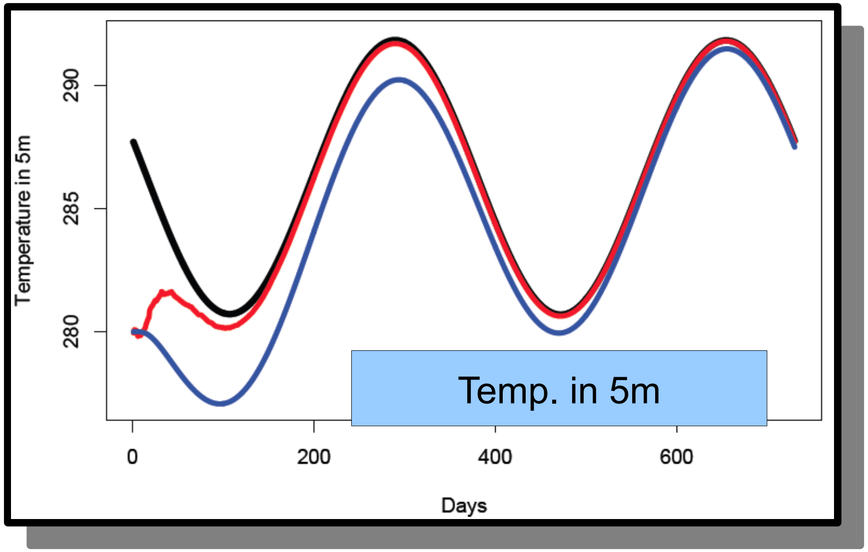
$$c_v \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right)$$

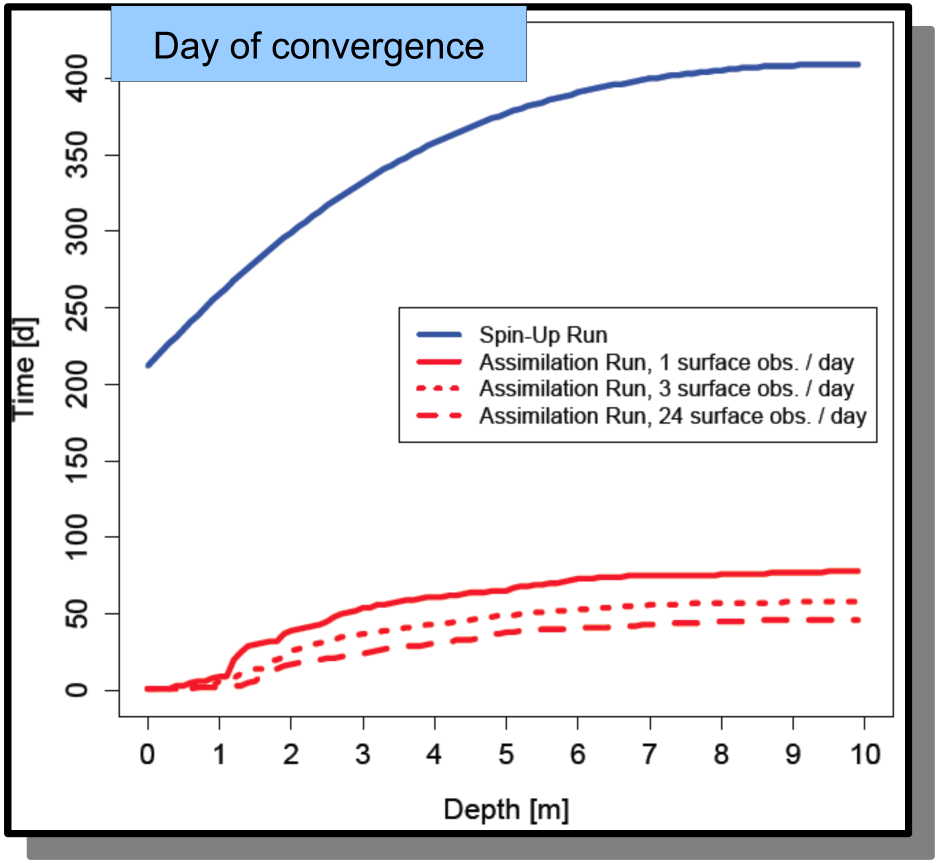
- As used in TERRA
- Observations: only for first layer

Comparison of analysis & spinup

- Starting from a *wrong* initial guess

DA converges much faster in deep soil





(*)Convergence: Relative error versus amplitude < 10%

The Land Surface Scheme TERRA-ML

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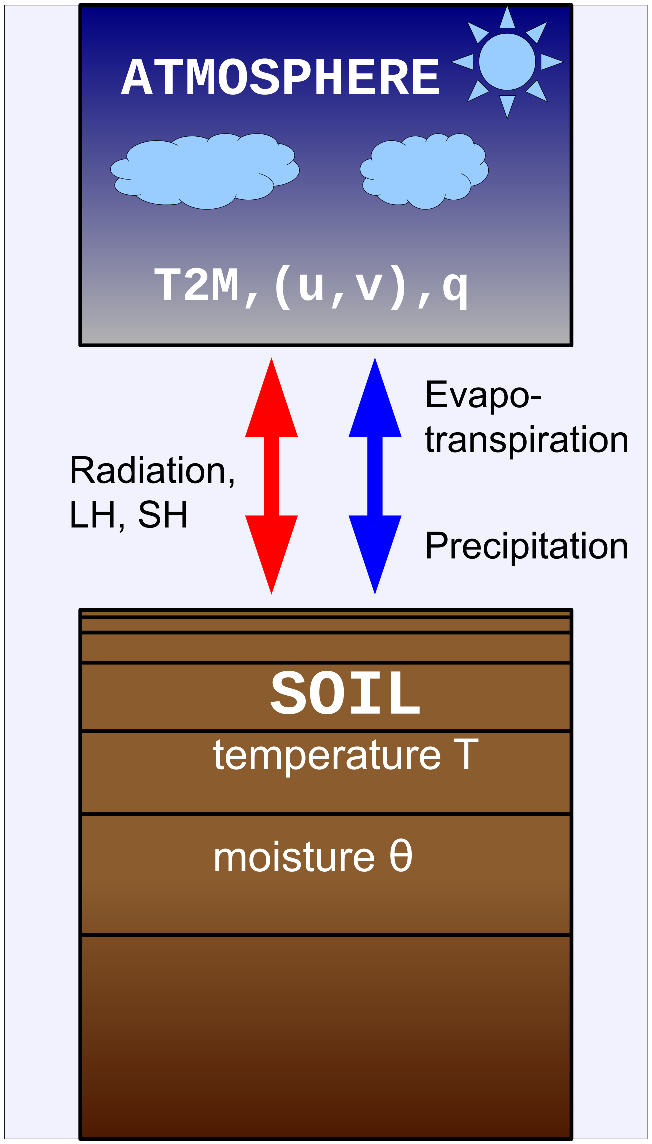

Included in COSMO & CLM

- provides lower atmospheric boundary condition

Exchange of fluxes

- Energy
- Moisture

Offline version

- Forced by atmospheric values
- Application on grid-point scale (Lindenberg,...)

  → Combined with EnKF algorithm

~ 10 vertical layers with increasing thickness

- Thermal: prognostic soil temperature
- Hydrological: prognostic soil moisture

  → *intermediate dimensionality of state vector (>10)*

EnDA with TERRA: Experimental Setup

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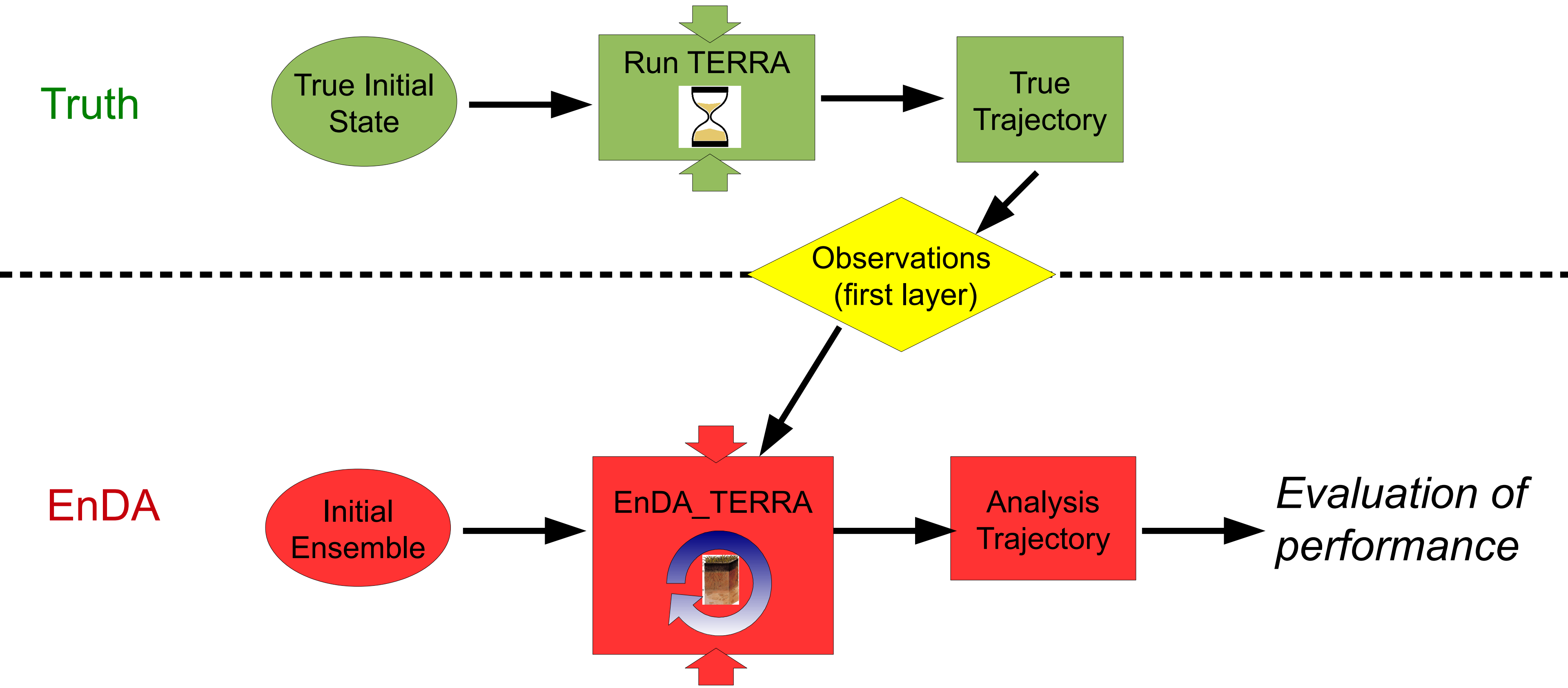
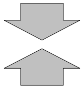
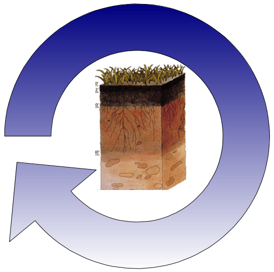


Same system can be used for real-world observations.



Comparison with „Soil Moisture Analysis“ (SMA)



Operational SMA

- Soil moisture adjusted so that simulated T2M fits to observed

  → *Acts as „auxilary variable“ to compensate model errors for T2M*
- Bound to atmospheric model: needs fully-coupled model runs

- Similar, but + RH2M
- Satellite data are monitored

EnDA for TERRA

- Assimilation of any soil-related observation

  → Soil moisture & temperature
- Requires offline soil model → cheap
- Accounts for atmospheric uncertainty
- Capable of reconstructing all layers
- Allows parameter estimation
- Fits to the LETKF framework

First TERRA Results: Weather - Top Soil

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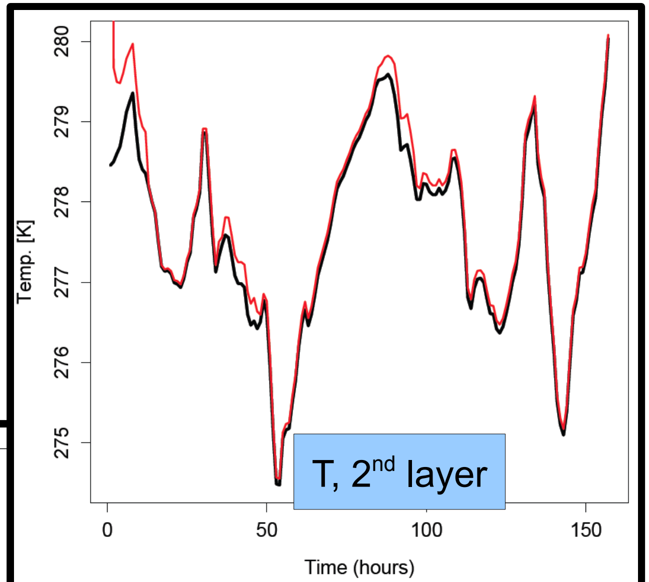
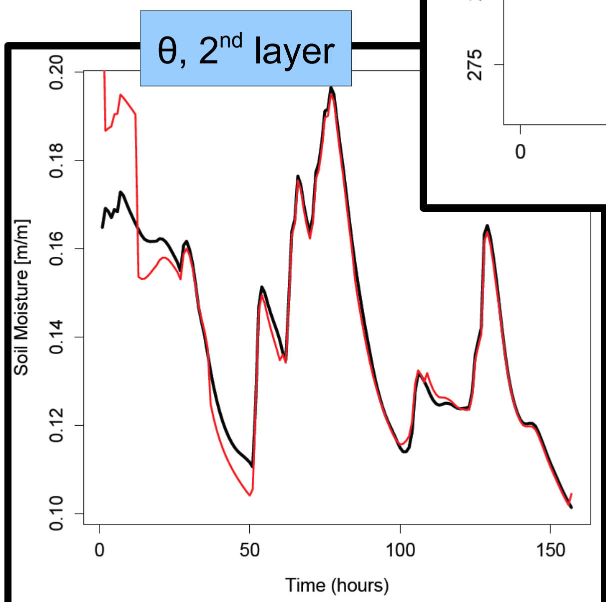
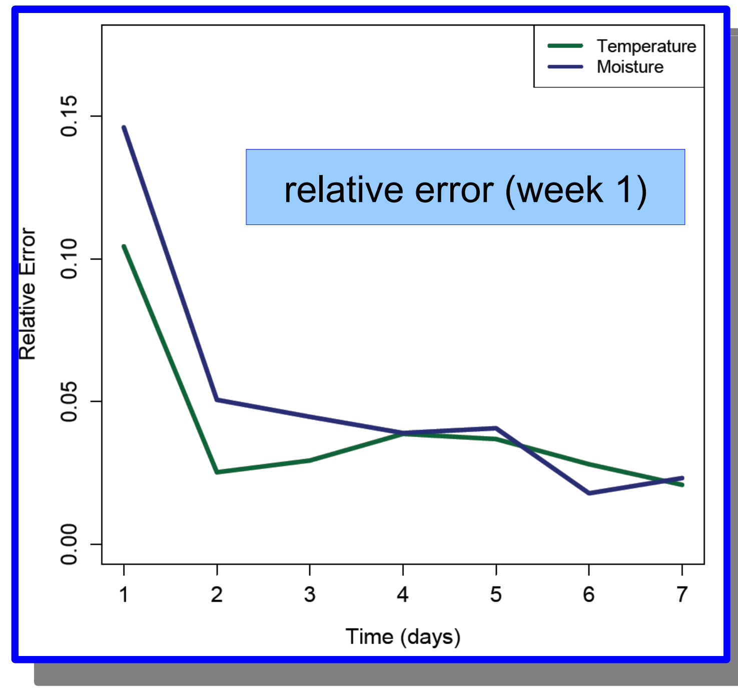
Quick adjustment due to the observations (1/day only)

→ Assimilation of soil observations useful to initialize the soil for weather forecasts

Timeseries







First TERRA Results: Climate - Deep Soil

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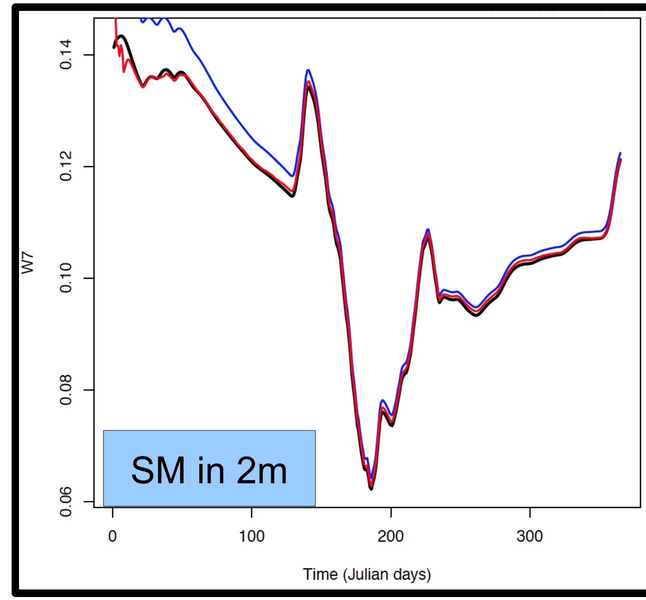
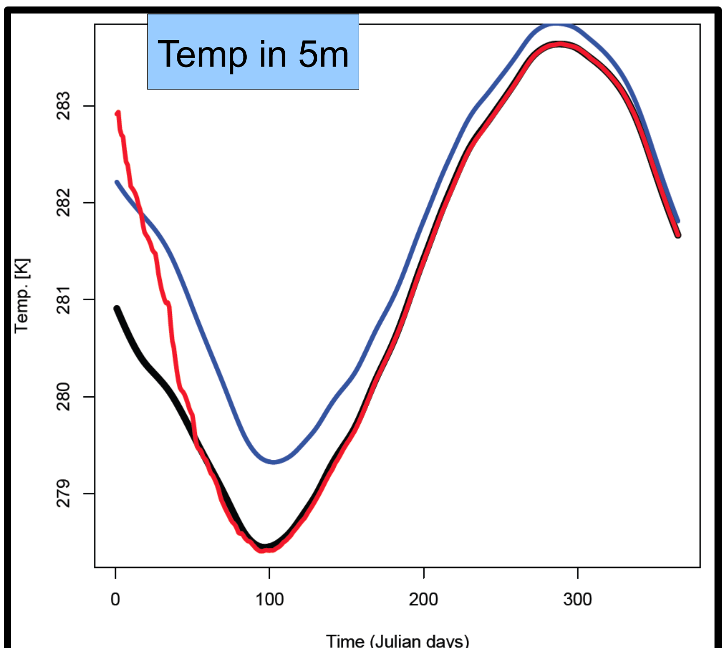
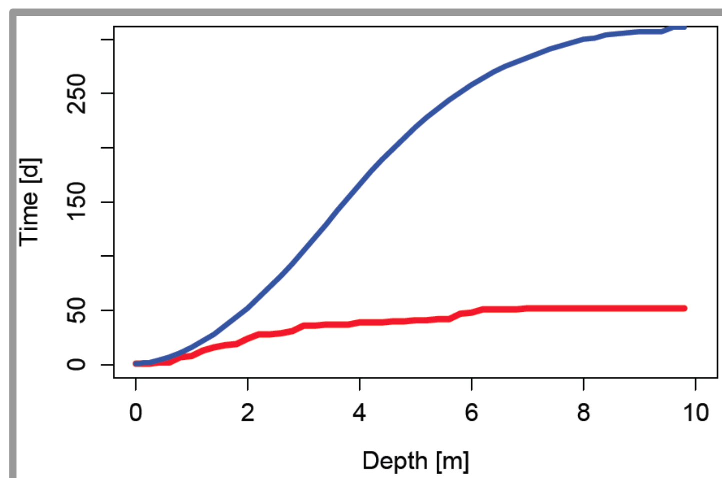
- Analysis converges due to observations (1/day)
  → Information is transferred, but delayed
- Analysis outperforms spinup
- More problems with moisture → model physics?







Days to convergence (Temp)

Outlook and Planned Extensions

Extensions
- Parameter estimation
- Optimize analysis algorithm
- Application to area
- EnKS

Boundary conditions
- Uncertainty → Ensembles
- Type of lower BC

Misc
- Model physics
- Localization
- ...

Observations
- Sensitivity to error
- Real observations (in situ / satellite)

Summary

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EnDA environment for TERRA with surface-only observations

First results promising, extensions coming

Upper soil: Good analysis

Deep Soil:
More challening, but feasible

Deep soil initialization can contribute to medium range climate