Can we monitor **groundwater head** variation from space?

Using **ERS spaceborne soil moisture** observations **to predict** groundwater heads **in space and time**

Edwin H. Sutanudjaja
Steven M. de Jong, Frans C. van Geer and Marc F. P. Bierkens

Department of Physical Geography
Faculty of Geosciences
Utrecht University – The Netherlands

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NWO
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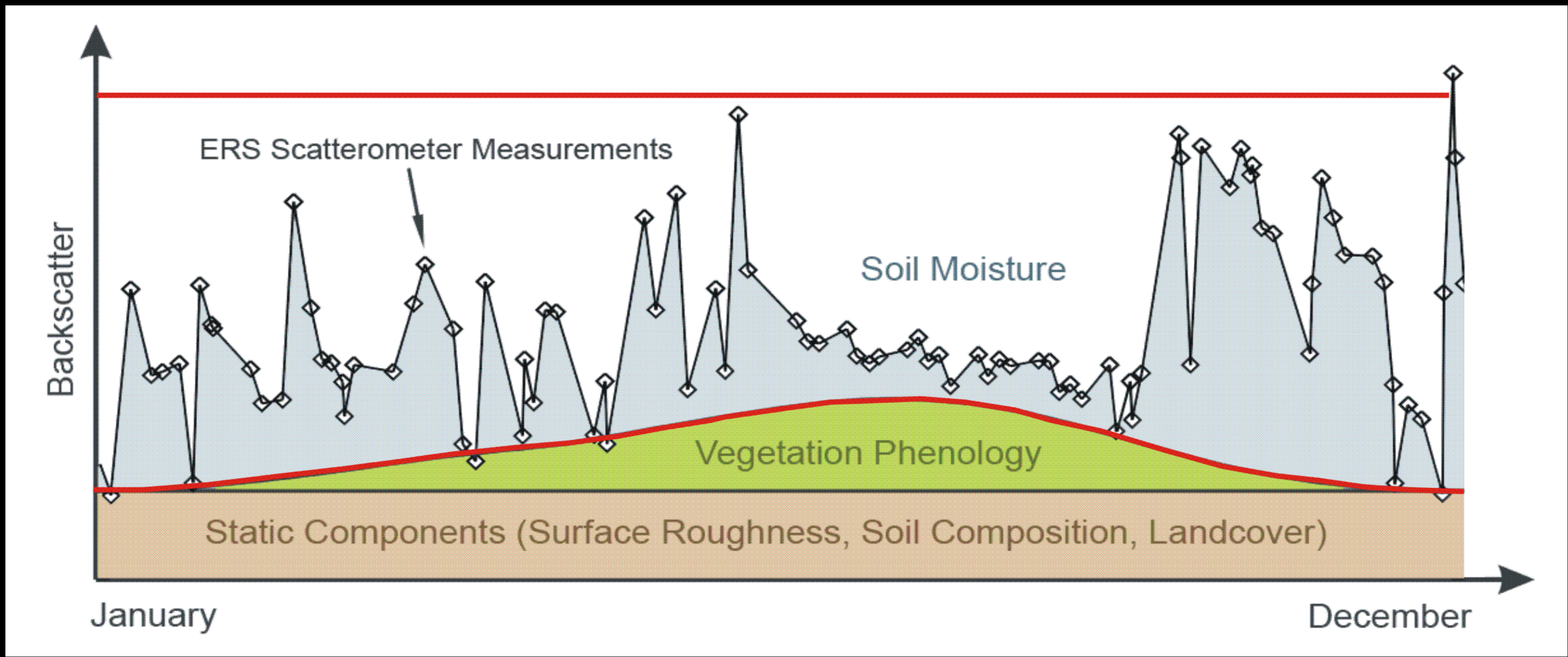
ERS Soil Water Index (SWI):

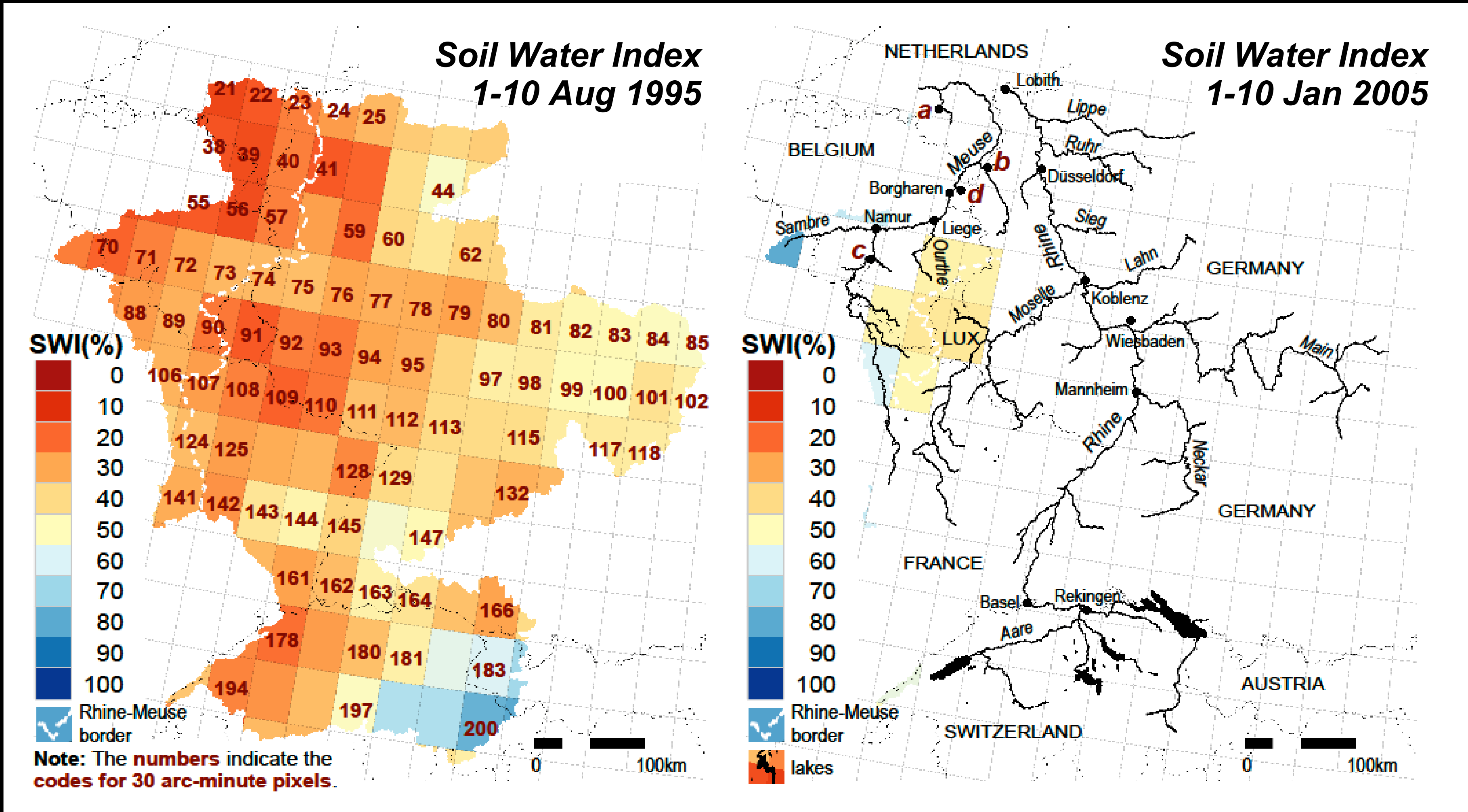
→ *profile soil moisture content (1st meter)*

- SWI time series are derived from SSM (surface soil moisture ~ 1-5cm)
- SSM time series are derived from backscatter signals.

- An exponential filter is used to convert from SSM to SWI.

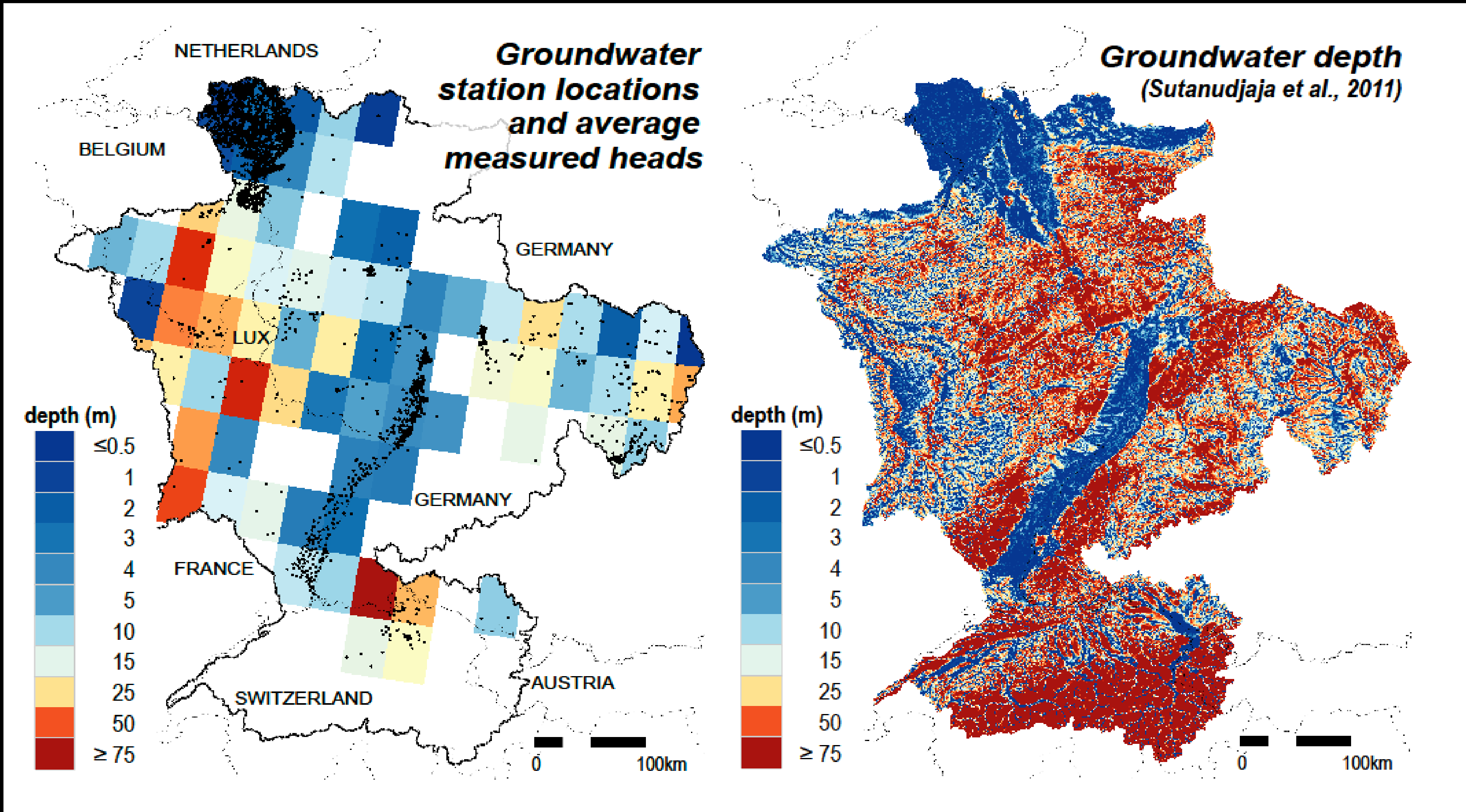


Study area: Rhine-Meuse basin



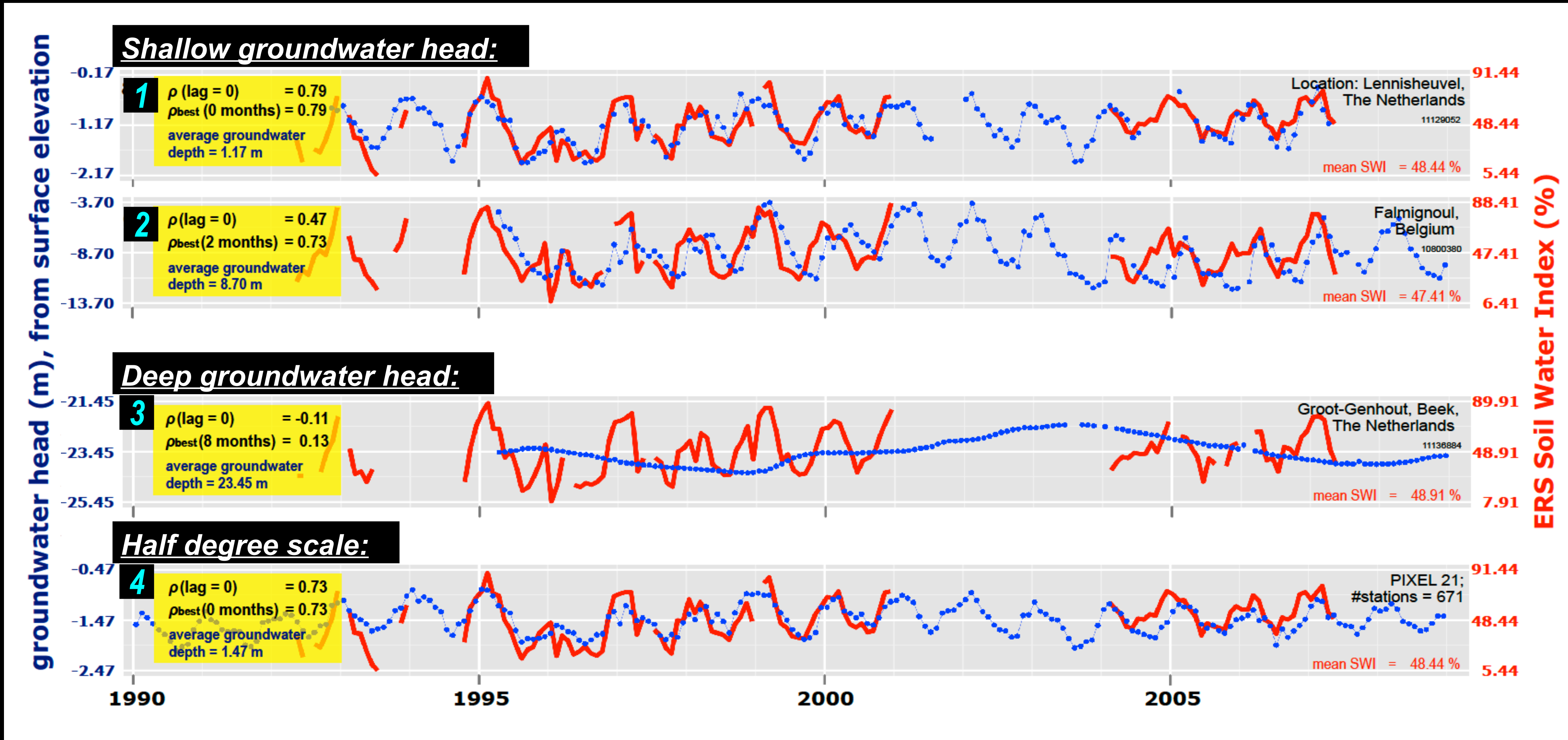
- SWI resolution used: half arc-degree and monthly

Study area: Rhine-Meuse basin



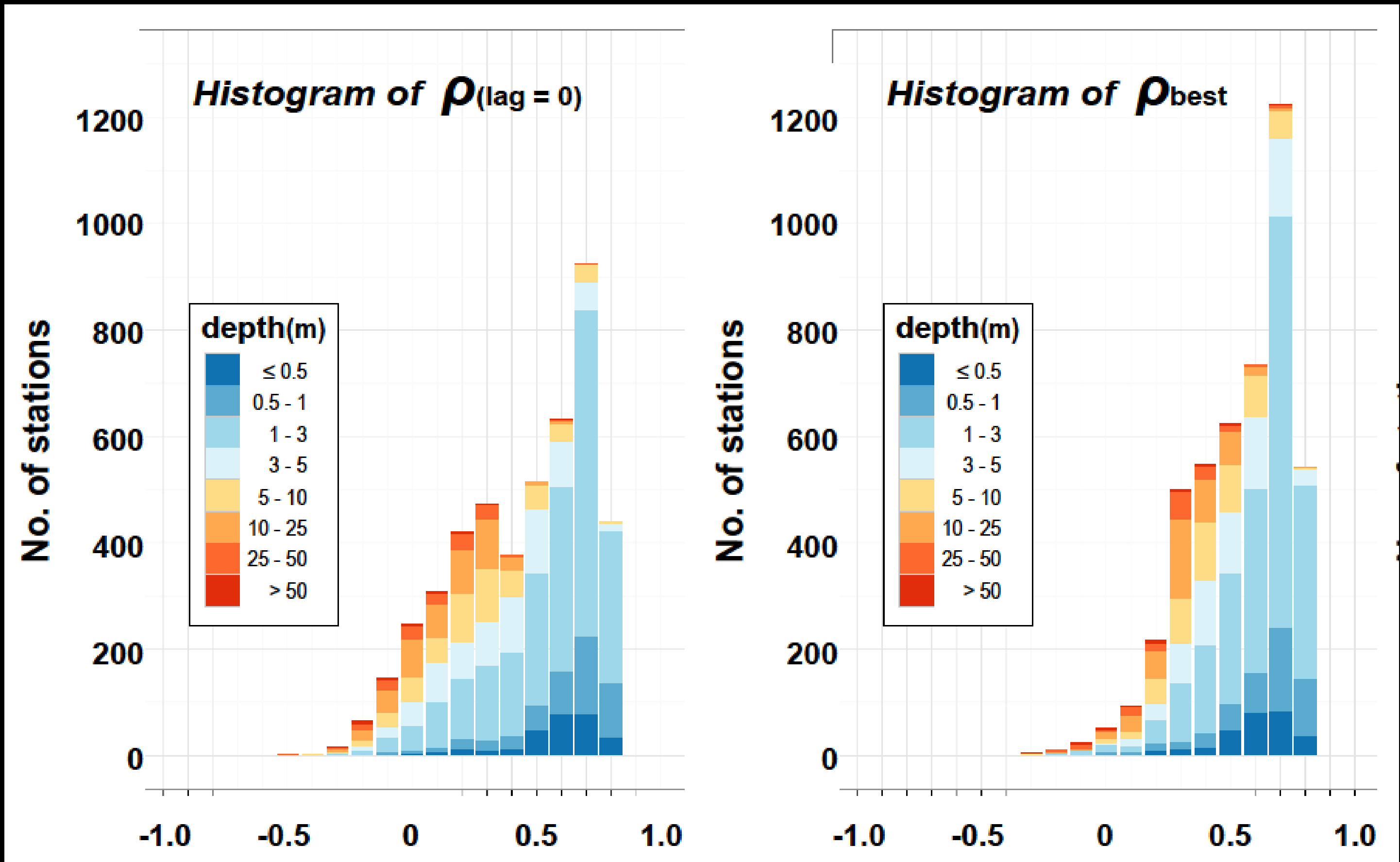
- > 5000 point-scale groundwater head time series are used.

Correlation SWI & head time series:



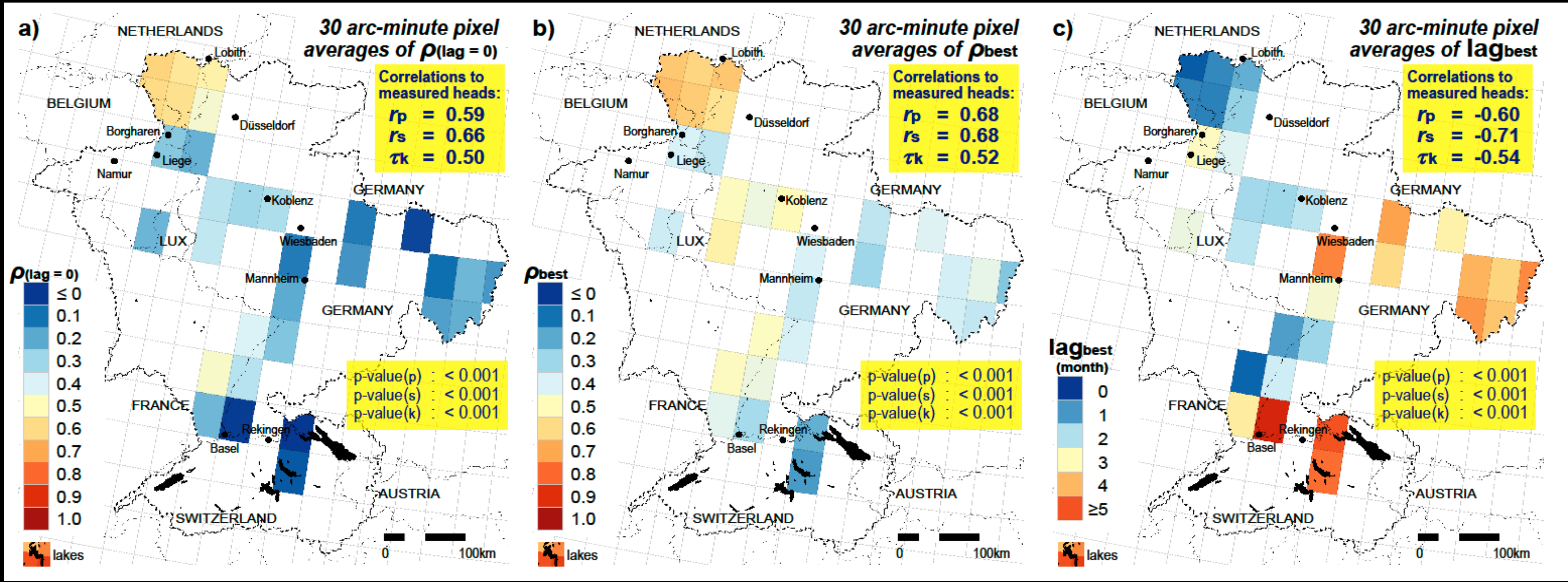
- In some areas, there are **time lags** between SWI and head time series.
- **Stronger** correlations are in **shallower** groundwater heads.

Histogram of correlation coefficients



- $\rho_{(lag = 0)}$: cross correlation coefficients without lags (lag = 0)
- ρ_{best} : highest ρ (from CCF), with lags = **lagbest**

Maps of correlation coefficients & lags:



- $\rho_{(lag = 0)}$: cross correlation coefficients without lags (lag = 0)
- ρ_{best} : highest ρ (from CCF), with lags = **lagbest**

- Stronger correlations & shorter lags are in shallower groundwater.

Can we use SWI to predict heads?
Transfer function noise (TFN) models:

TFN model:

$$h_t = h_t^* + n_t \quad (1)$$

$$h_t^* = \sum_{i=1}^{r} \delta_i h_{t-i}^* + \sum_{j=0}^{s} \omega_j \mathrm{SWI}_{t-j-b} \quad (2)$$

$$(n_t - c) = \sum_{k=1}^{p} \phi_k (n_{t-k} - c) + a_t + \sum_{l=1}^{q} \theta_l a_{t-l} \quad (3)$$

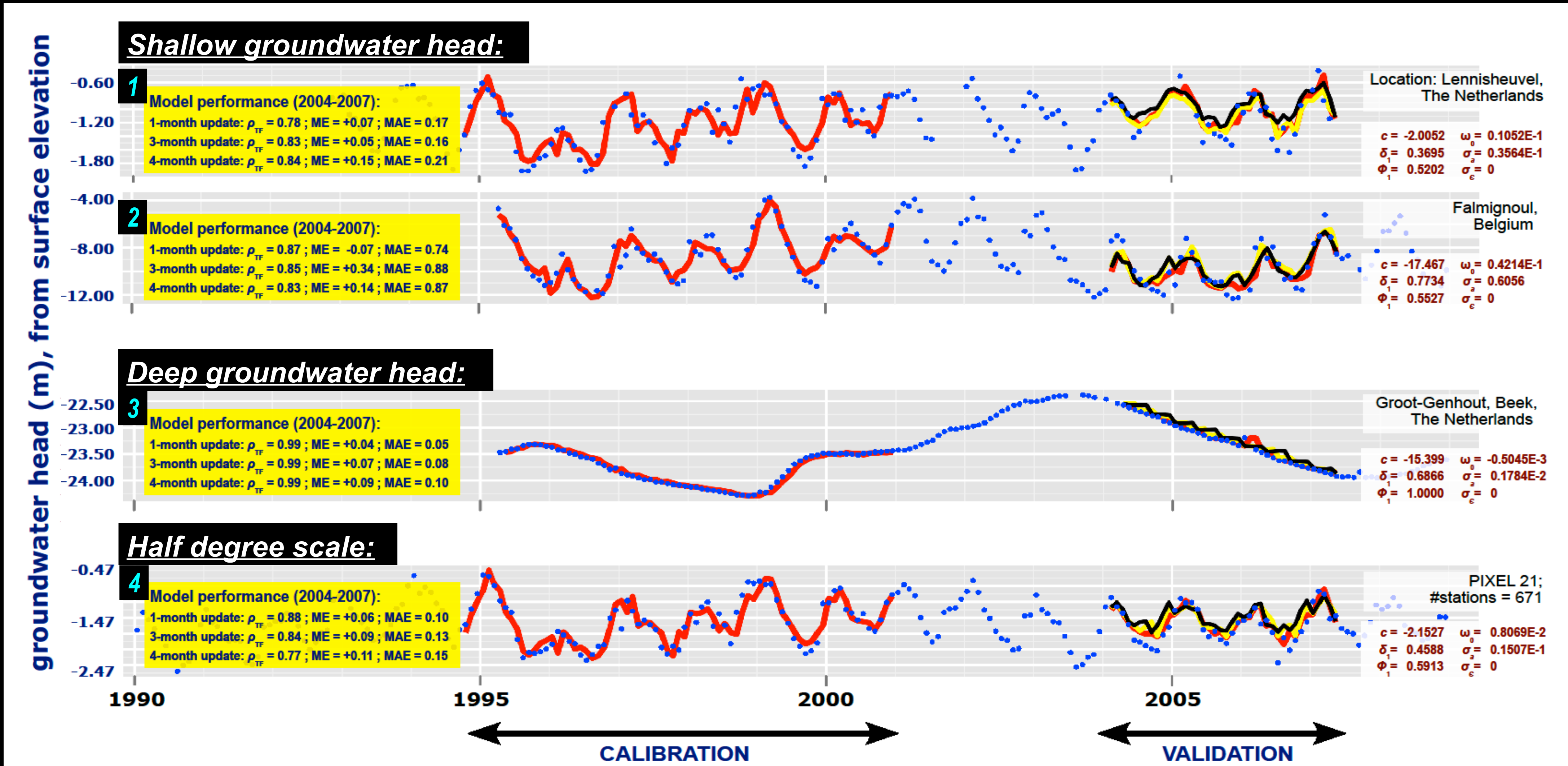
Using a simple TFN model:

- deterministic parameters : δ_1 , ω_0 and reference/base level c
- stochastic/noise parameters : ϕ_1 and variance σ_a

Parameter estimation:

- Embedding the TFN model in a Kalman Filter algorithm.
- Objective function: log-**likelihood**

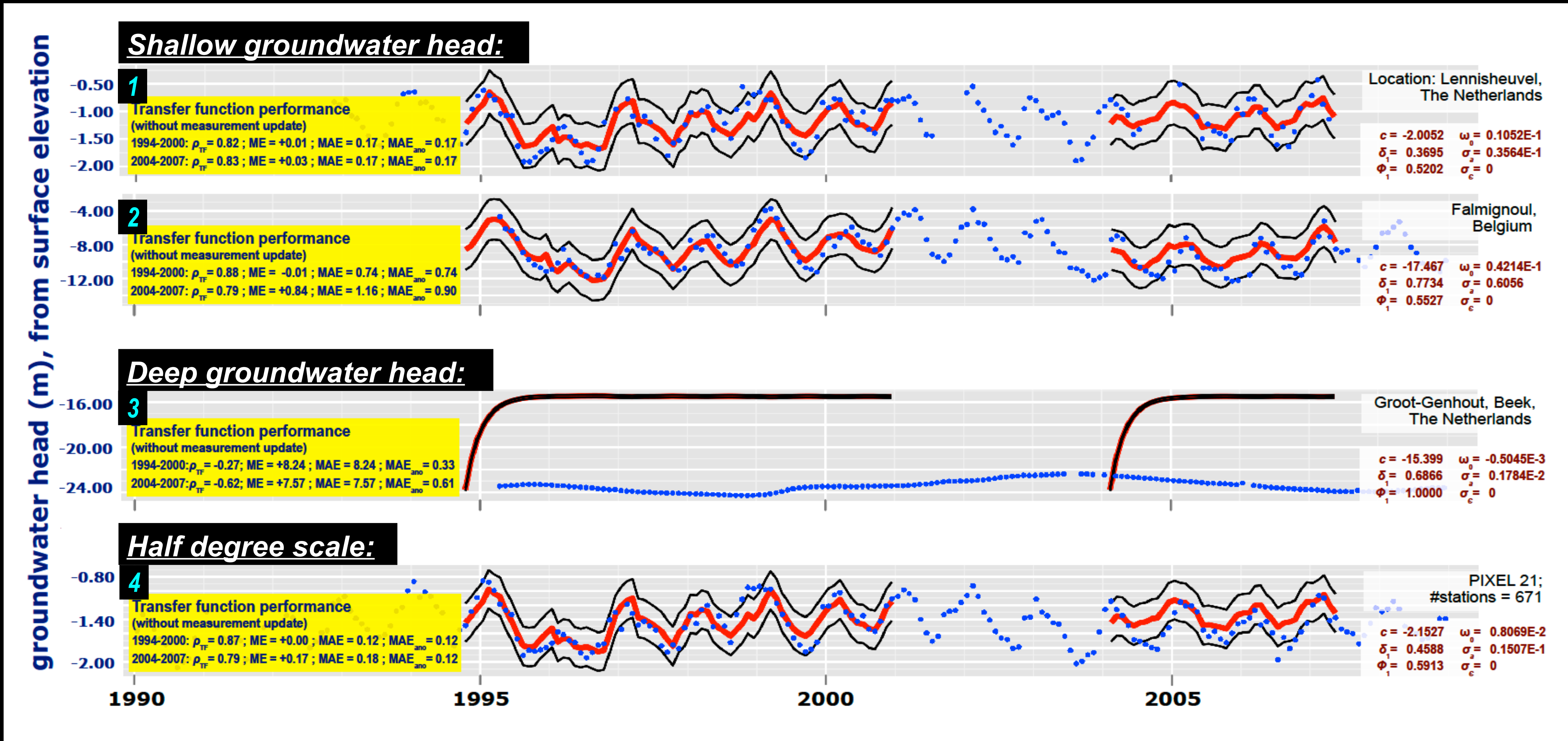
Prediction with measurement update:



- **Calibration:** 1995-2000 ; **Validation:** 2004-2007 *(graphs show time updates)*
- Measurement update intervals: red → a month; yellow → 3 months; black → 4 months

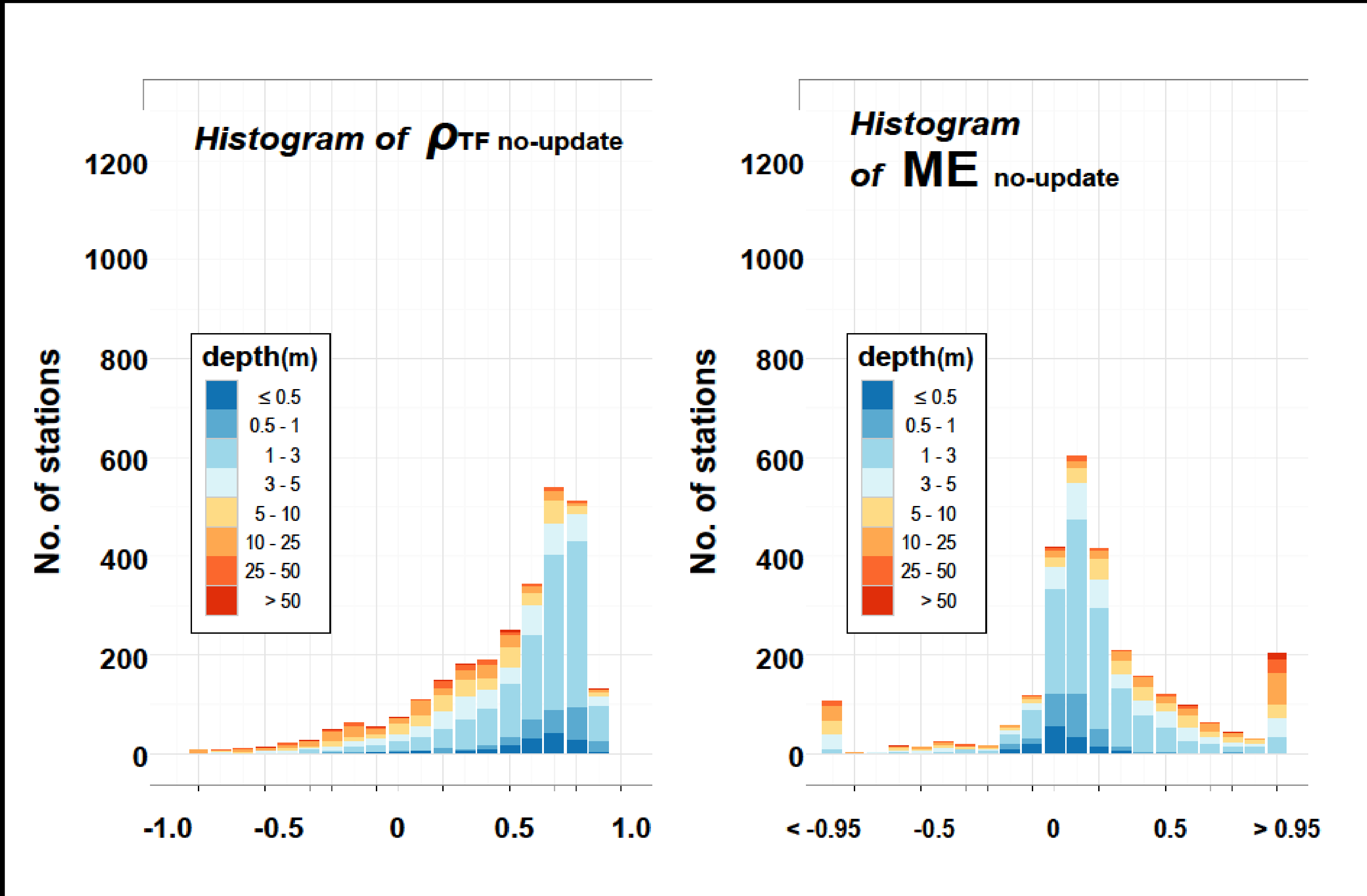
- Good performance is (*partly?*) due to measurement updates.

Prediction without measurement update:



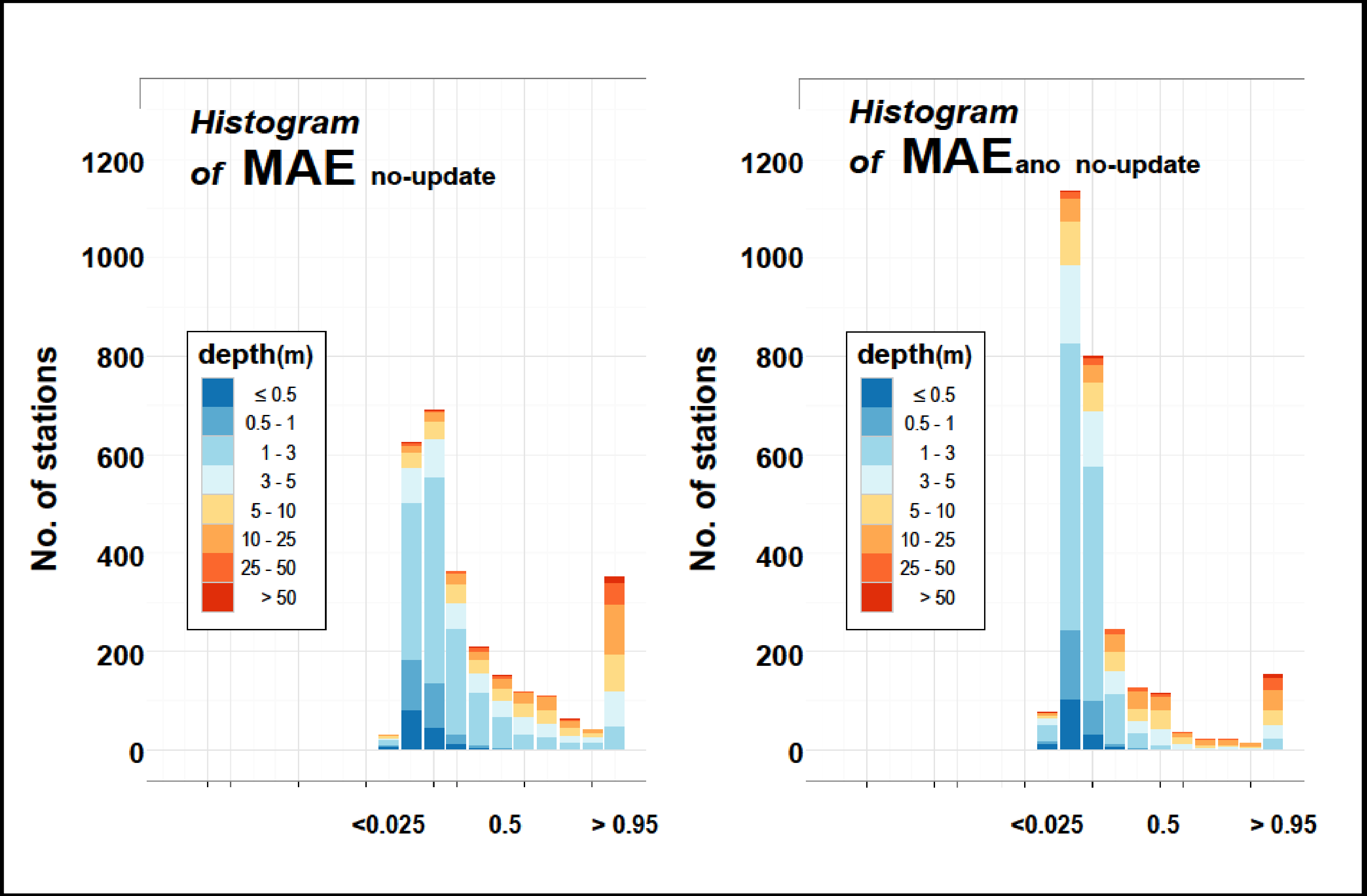
- red: without measurement update; black: 95% confidence interval
- In shallow groundwater, SWI is useful for predicting groundwater heads.

Prediction without measurement update:



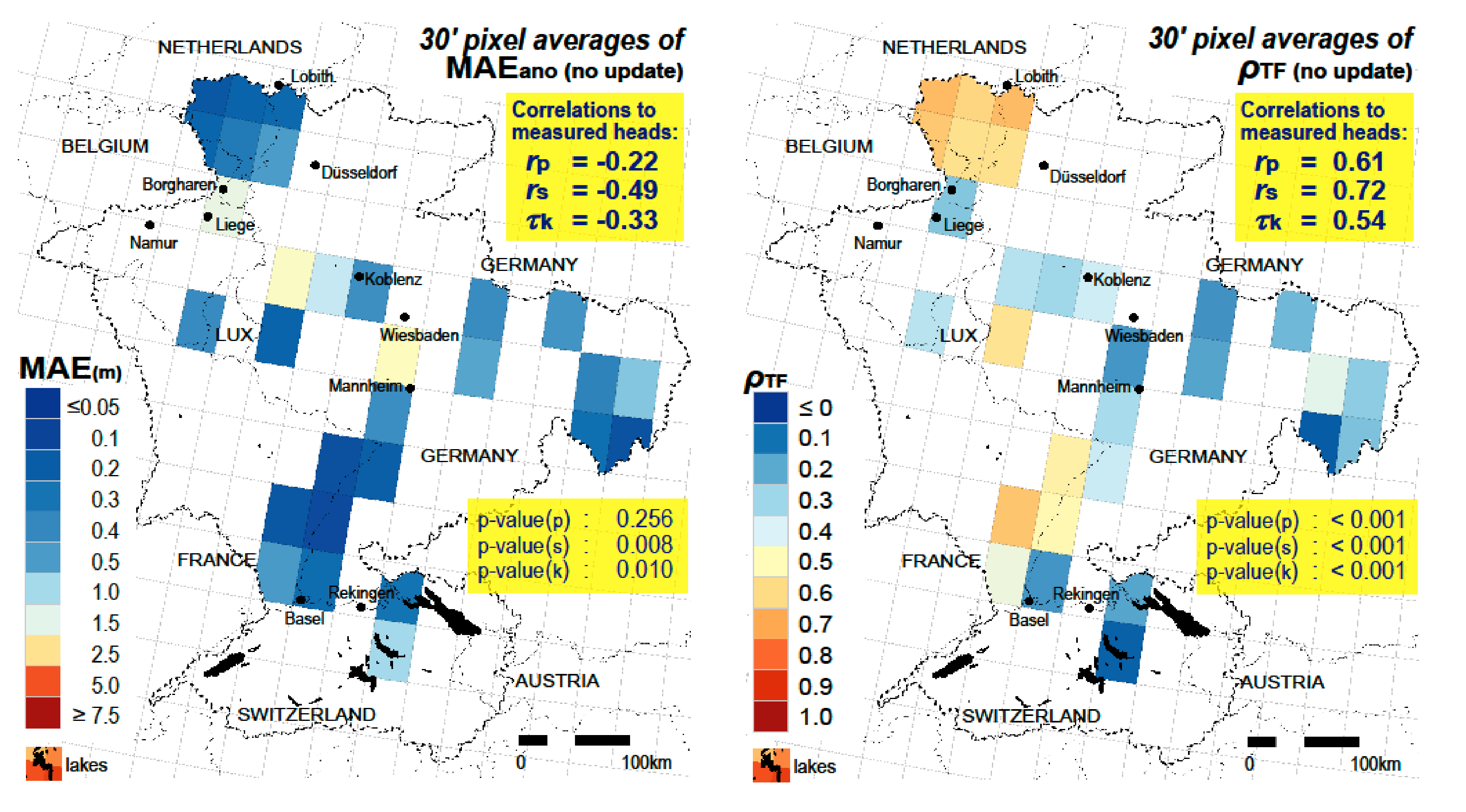
- Performances based on the validation run 2004-2007 # total stations = 2761
- **Timing agreements (ρ_{TF}) are good.** # stats with ρ_{TF} > 0.5 = 1730 ***(63%)***
- But, some with biases (ME); some due to changing parameters (*c*)

Prediction without measurement update:



- MAE: mean absolute errors
- If biases are removed, the error (MAE) will be smaller.

Maps of prediction performance without measurement updates:



- From ρ_{TF} (timing agreement), predictions are better for shallower groundwater.

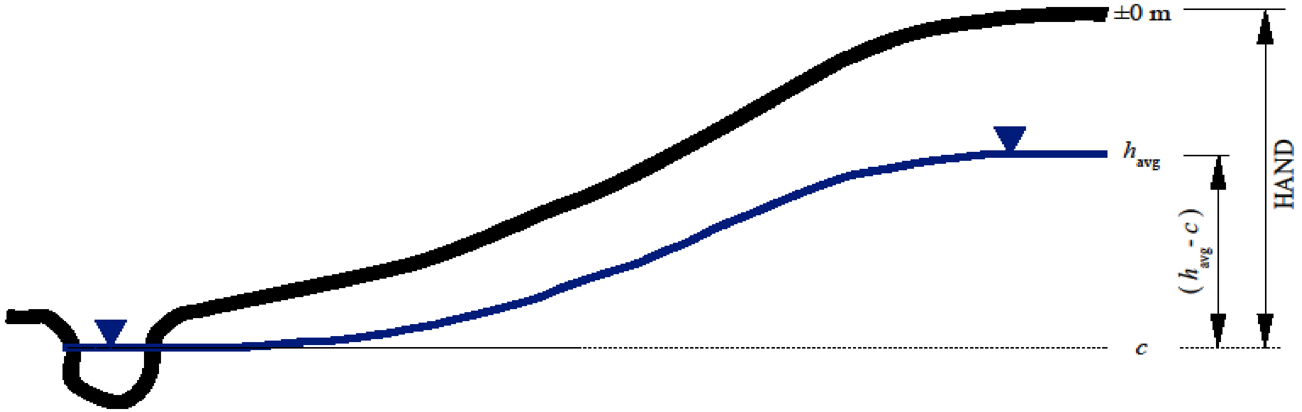
Prediction in unvisited locations:

- Previous exercise: forecasting in time.
- What about spatial predictions / interpolations?

Spatio-temporal predictions:

1. We used few stations (40) ~ data-poor environments
   → Identifying parameters (from the forecasting exercise)
2. TFN parameters are estimated using DEM (30” ~ 1km).
   Derive the regression models: TFN parameters = *f* (DEM)
3. Using estimated parameters (and SWI) to run TFN.

HAND to predict TFN model parameters

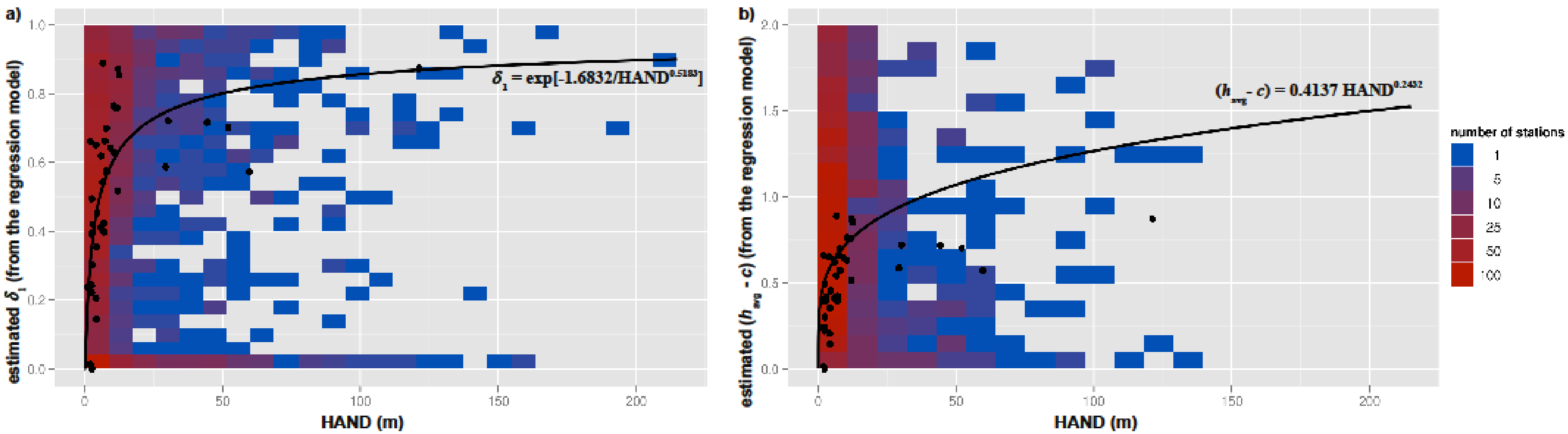


$$c = -\mathrm{HAND}$$

$$(h_{\mathrm{avg}} - c) = A \times \mathrm{HAND}^{B}$$

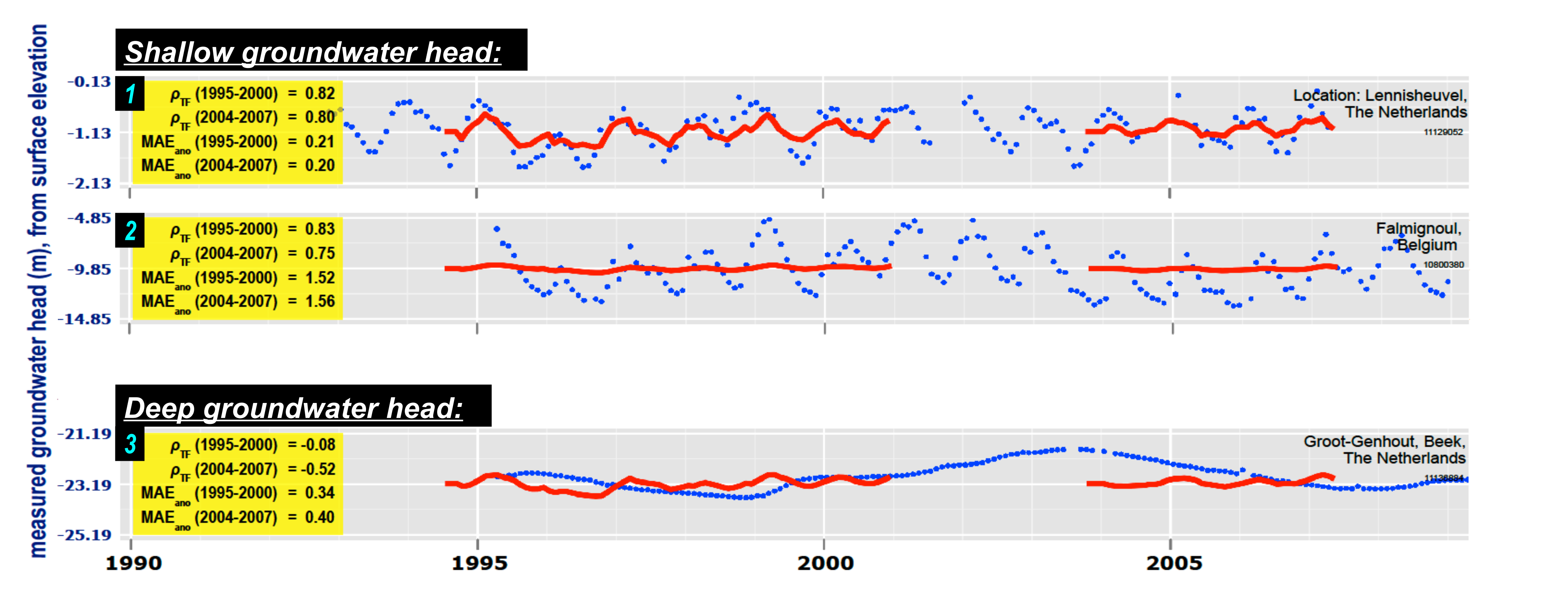
$$\delta_1 = e^{-C \times \left(1/\mathrm{HAND}^{D}\right)}$$

$$\omega_0 = \frac{(h_{\mathrm{avg}} - c)}{\mathrm{SWI}_{\mathrm{avg}}} (1 - \delta_1)$$



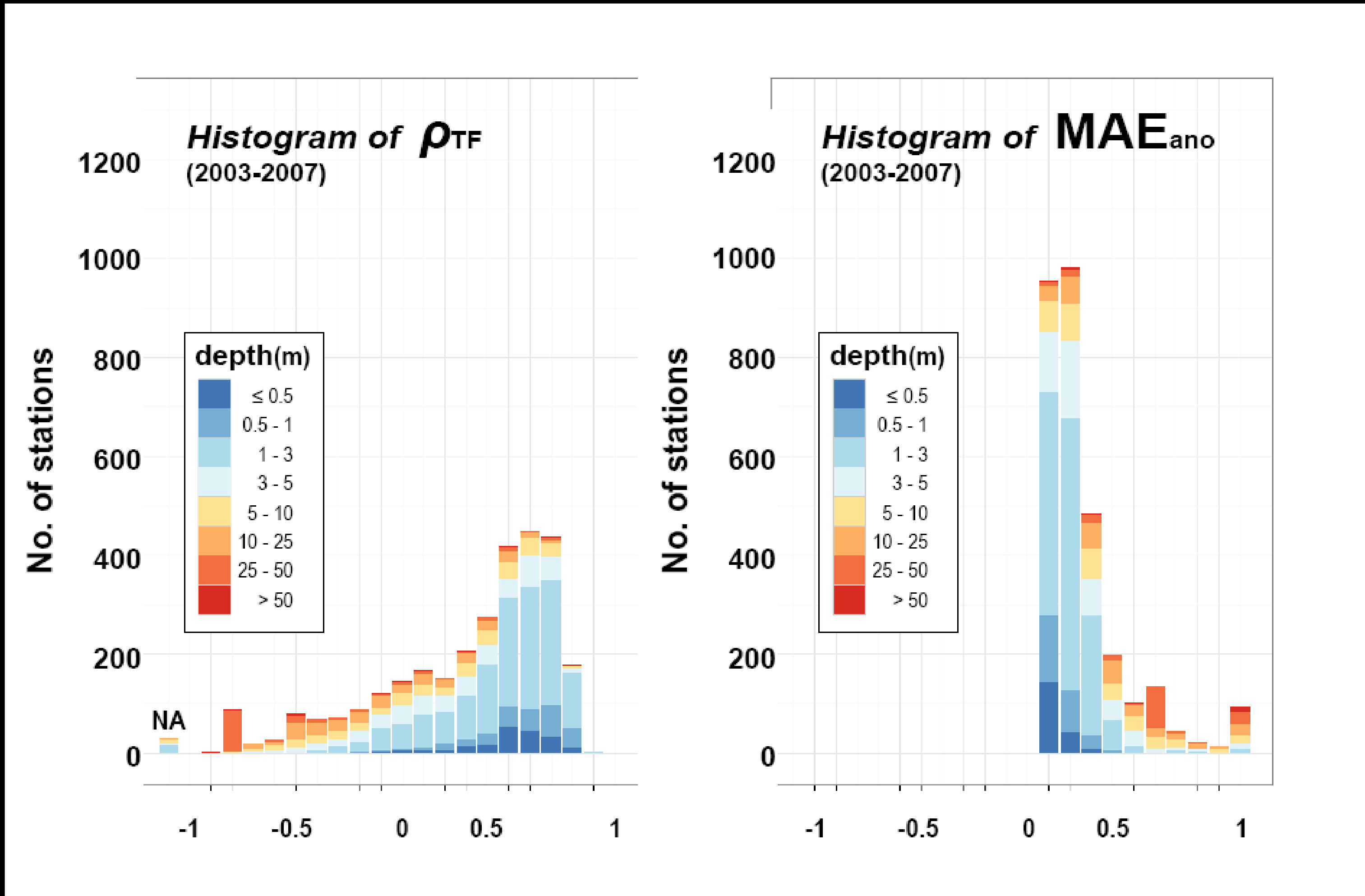
- **Simplification** : groundwater heads follow topography as a subdued replica
- **Limitations** : accuracy of DEM (16 m), not incorporating other variations (e.g. soil types)
- **Motivation** : prediction in un-gauged basins

Spatio-temporal predictions: (parameters are estimated from DEM)



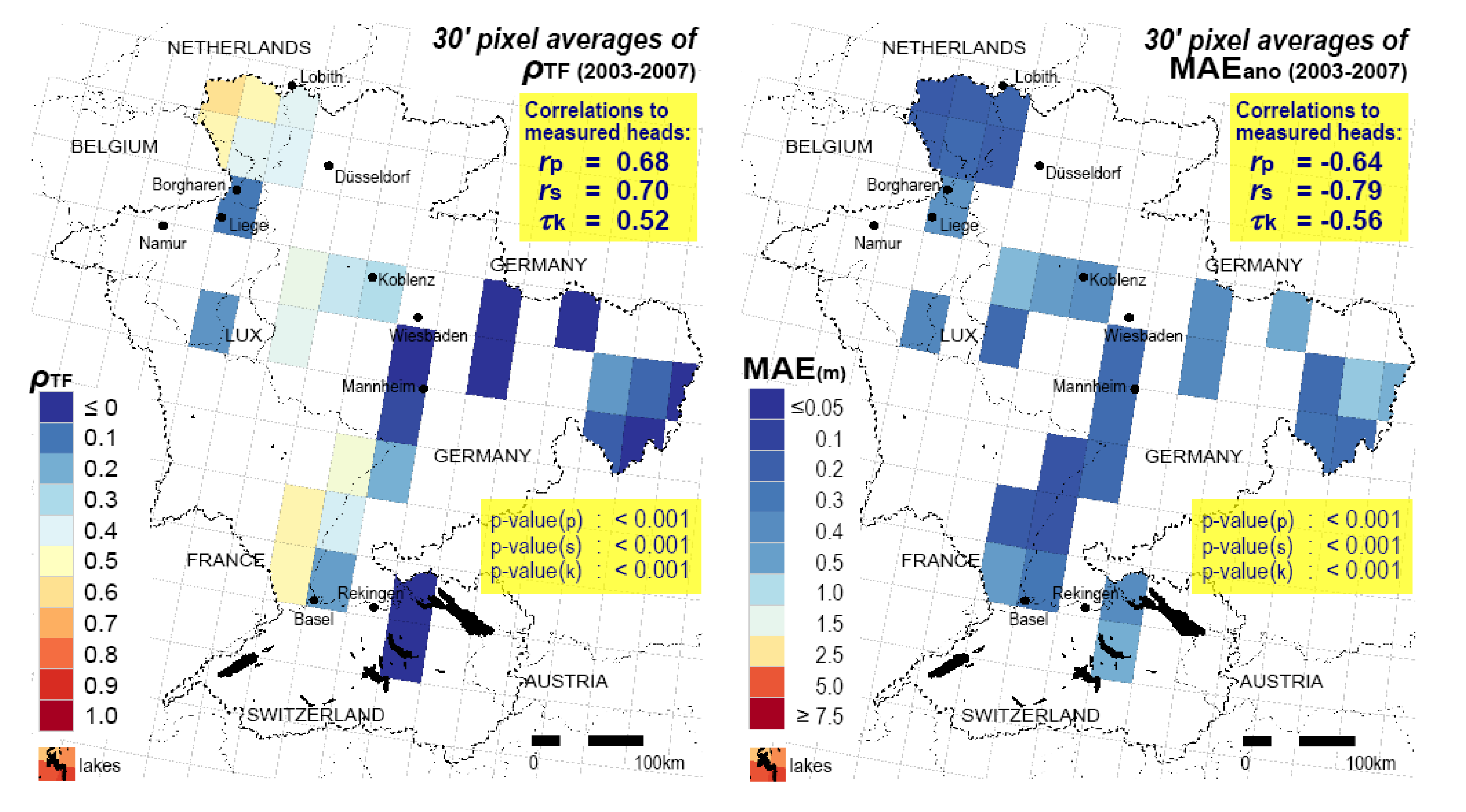
- Example 1: prediction is **reasonably good** (MAE is small and ρ_{TF} is high)
- Example 2: MAE is large, but ρ_{TF} is high (0.83 and 0.72) → *to detect data errors / local phenomena*
- Example 3: deep groundwater (*Please don't expect anything!!*)

Spatio-temporal predictions (histograms):



- Based on the period 2004-2007. # stations = 2925
- Number of stations with $\rho_{TF} > 0.50$ = 1376 ***(47%)***
- Number of stations with $MAE_{ano} < 0.25$ m = 1901 ***(65%)***

Spatio-temporal predictions (maps):



- Predictions are generally better in shallower groundwater.

Conclusions:

- There are **correlations** between ERS SWI and groundwater head time series.
- Correlations are stronger in shallower groundwater.

- SWI time series are **useful** as the input of TFN models for **predicting groundwater heads** in space and time.
- Predictions are better for shallower groundwater.

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