# Soil moisture analysis at DWD

Martin Lange, DWD

# Outline

- NWP model suite - past to present
- Soil moisture analysis at regional and global scale
- From 2d Var to EnKF
- Model soil moisture vs Observation at validation site
- Summary and conclusions

# Regional modelling in COSMO framework

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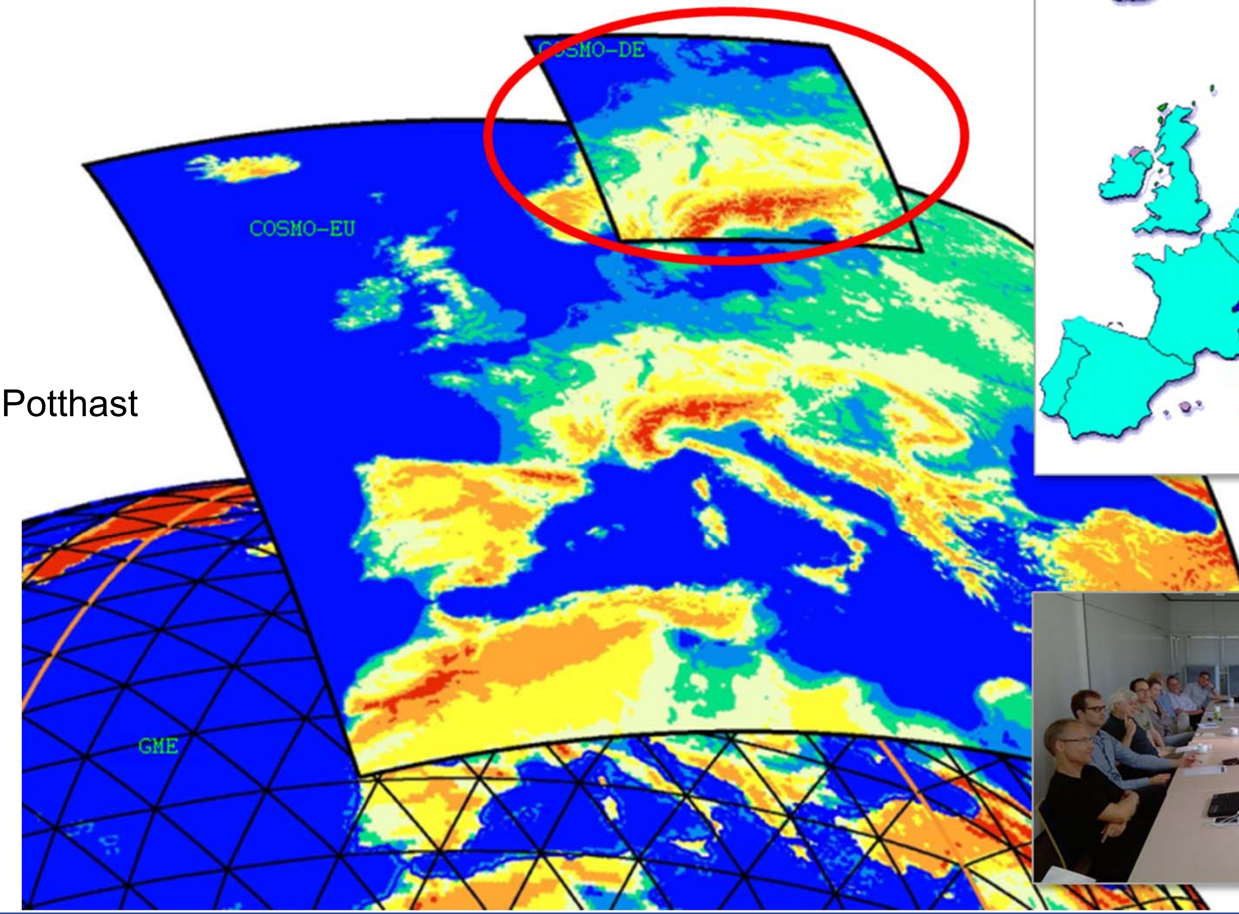
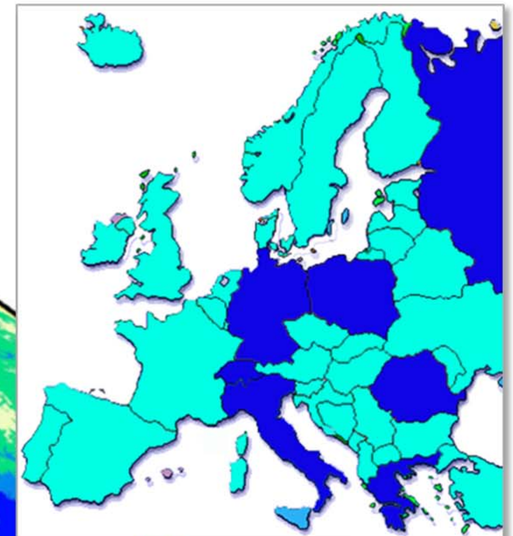
**02-24 Hours**

**High Resolution Modelling**



Courtesy R. Potthast

# Nine NWP generations at DWD from 1966 until today

(1) 1966: **BTP**: Δ ~ **381** km (A ~ 145.161 $km^2$); 1 layer; barotropic (*Area of D: 357.000* $km^2$)

(2) 1967: **BKL**: Δ ~ **381** km (A ~ 145.161 $km^2$); 5 layers; hemispheric model, barocl., dry

(3) 1978: **BKF**: Δ ~ **254** km (A ~ 64.516 $km^2$); 9 layers; hemispheric model, barocl., moist

(4) 1991: **GM**: Δ ~ **190** km (A ~ 36.100 $km^2$); 19 layers; global spectral model

(5) 1999: **GME**: Δ ~ **60** km (A ~ 3.114 $km^2$); 31 layers; icosahedral hexagonal grid

(6) 2004: **GME**: Δ ~ **40** km (A ~ 1.384 $km^2$); 40 layers

(7) 2010: **GME**: Δ ~ **30** km (A ~ 778 $km^2$); 60 layers

(8) 2012: **GME**: Δ ~ **20** km (A ~ 346 $km^2$); 60 layers

(9) 2015: **ICON**: Δ ~ **13** km (A ~ 173 $km^2$); 90 layers; nonhydrostatic model; triang. grid

**factor 29** **factor 839**

The NWP generations are also characterized by increasing complexity of the physical parameterizations, numerical methods and software design.

Moreover, the progress in data assimilation (algorithms as well as types of data used, esp. satellite data) significantly contributes to the steady improvement of forecast quality.

# Forecast quality 1968 - 2016

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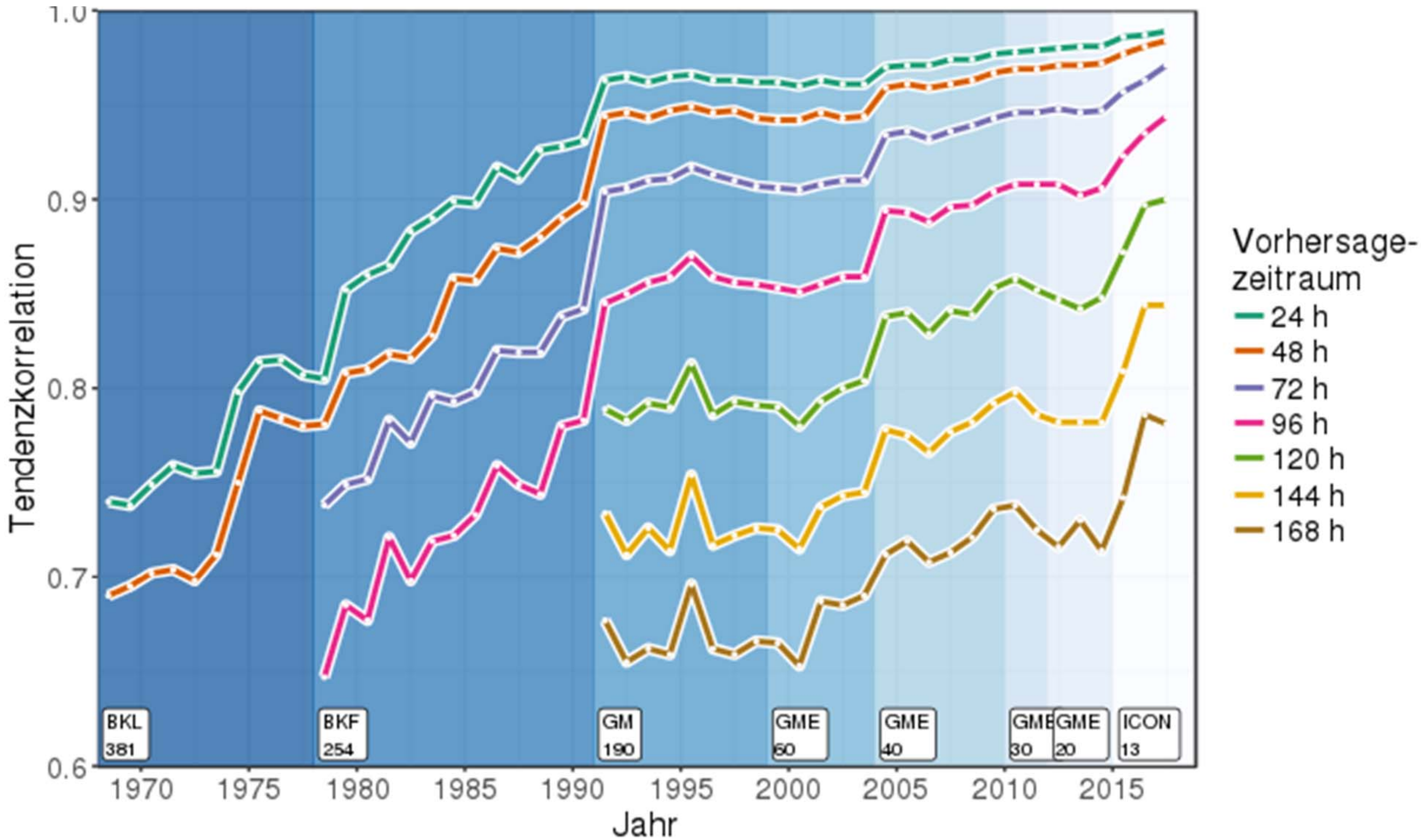
## Tendency correlation of surface pressure for North Atlantic and Central Europe



# TEMP-Verification 850 hPa NH from 2014 to 2017

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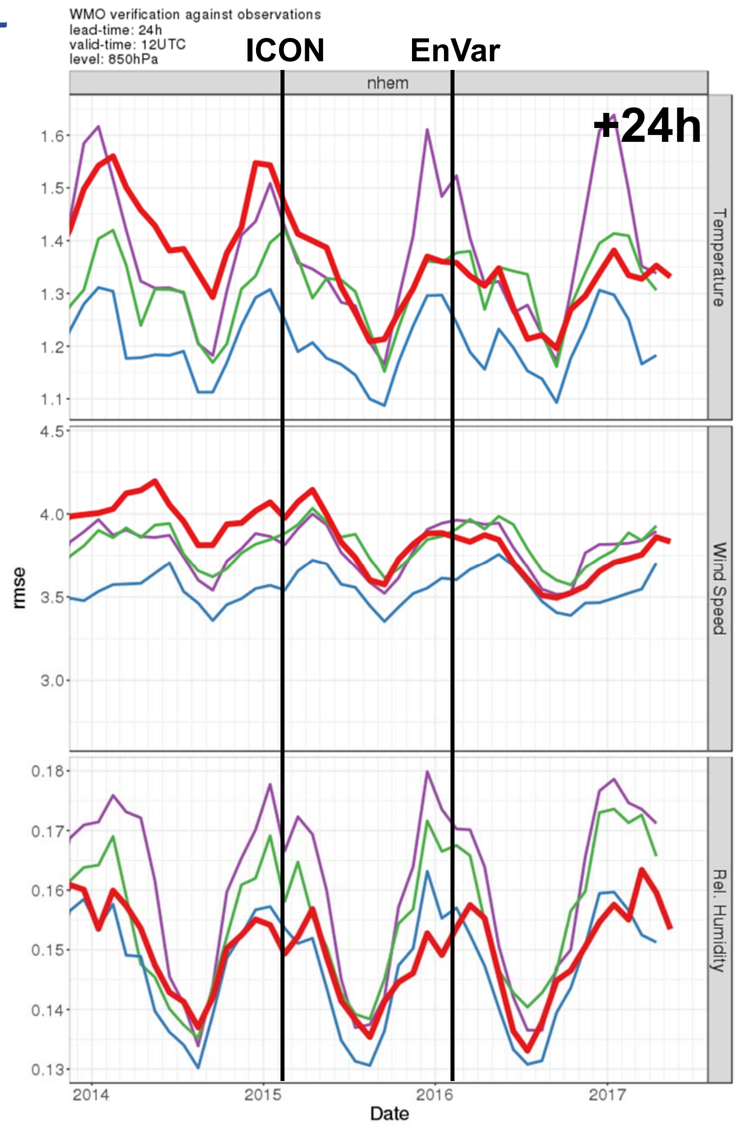


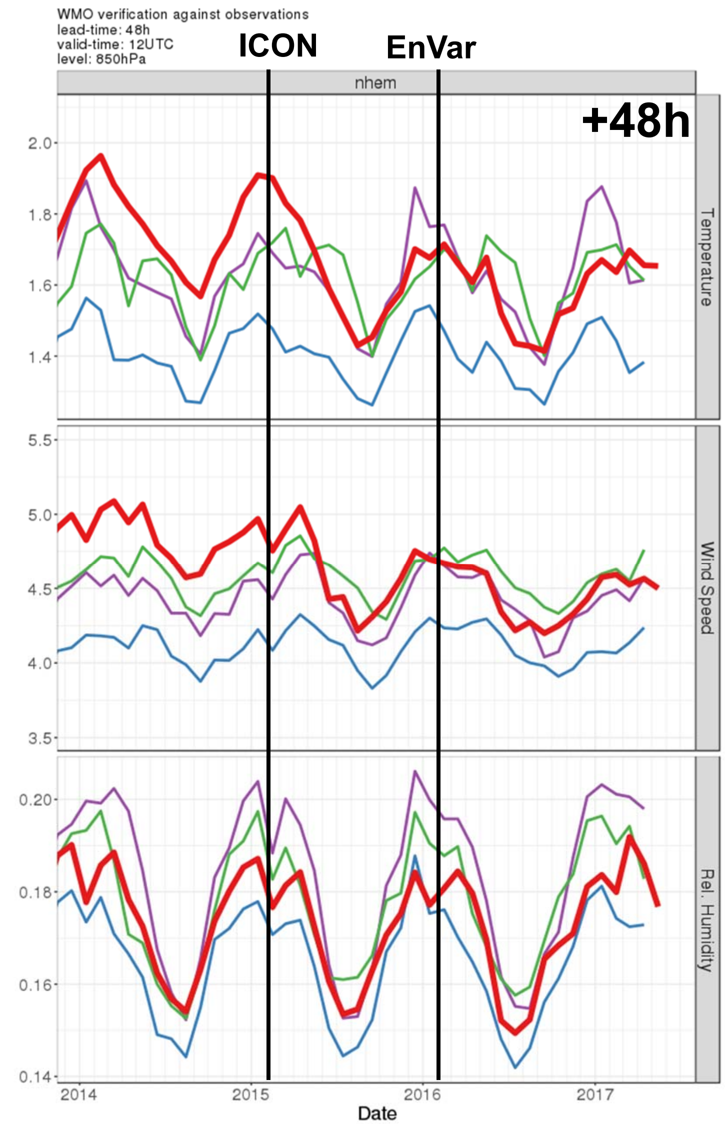


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# Motivation for SMA at DWD

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- J.F. Mahfouf (1991) who showed that soil moisture can be inferred from syonop observations given an appropriate SVAT scheme in an NWP environment.

- Andreas Rhodin et al,. (1999) who showed positive impact of soil moisture assimilation with a 2D var system on the forecast of 2m temperature and rel. humidity in a stand alone version of the short range weather forecast model from DWD (Rhodin et al., .1999).

- Based on the previous work, Reinhold Hess implemented the 2d variational SMA scheme in a Kalman cycled analysis for the regional LM model which became operational in 2000.


- This scheme was able to assimilate not only synoptic observations as the OI, but also satellite measurements. The explicit calculation of grad J by finite differences obtained from perturbed forecasts was an additional advantage which saved recalculation of OI coefficients in case of model changes.
- Therefore it was adopted by most other european weather centers.

# 2d var (z,t) soil moisture analysis applied in LM / COSMO-EU

Cost function penalizes deviations from observations and initial soil moisture content

$$J = (w - w_b)^T B^{-1} (w - w_b) + (T_{2m} - T_{2m}^{obs})^T O^{-1} (T_{2m} - T_{2m}^{obs})$$

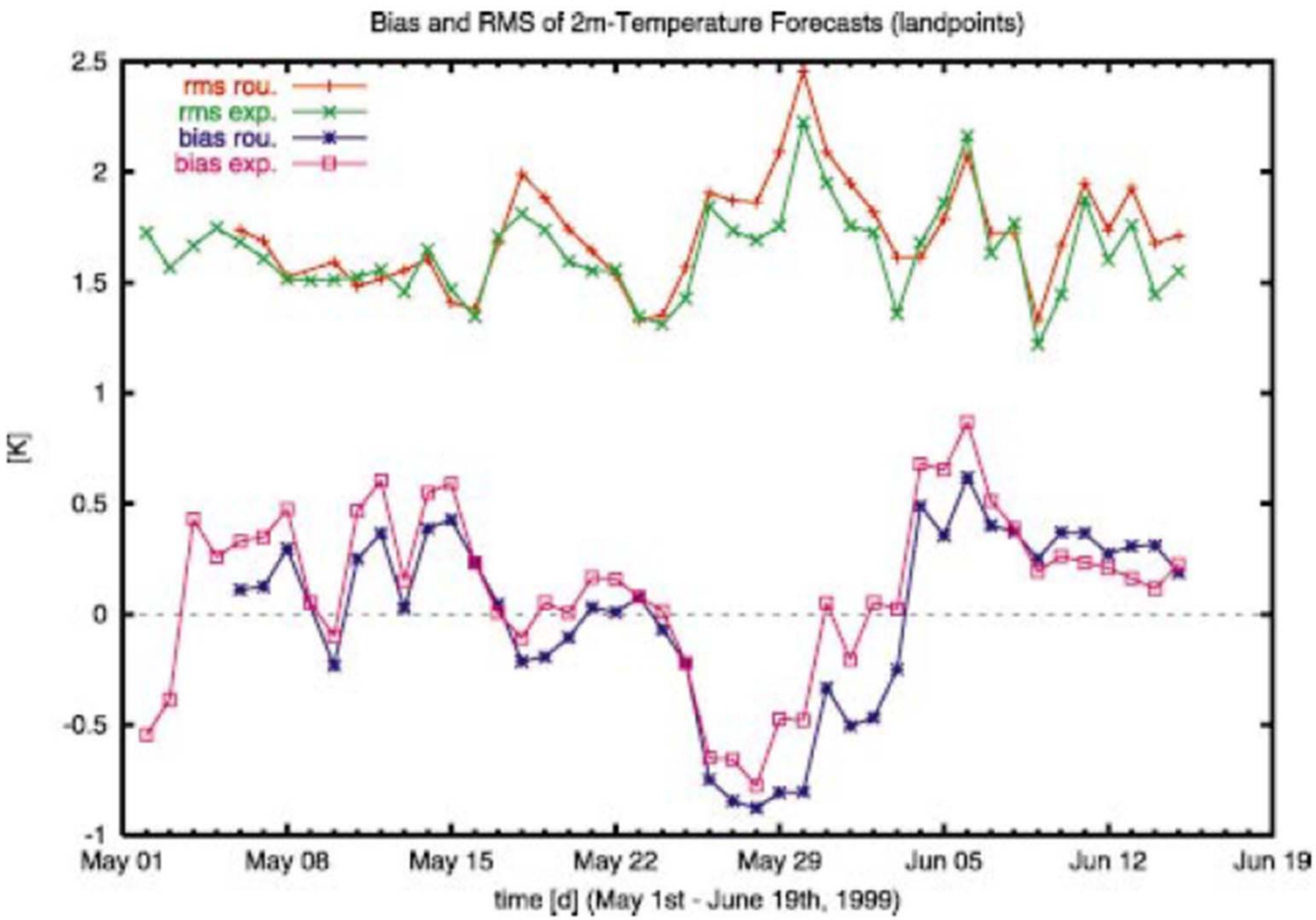
$$\nabla J = 0$$

Analysed soil moisture depends on T2m forecast error and sensitivity $\partial T2m / \partial w$

$$w_{ana} = w_b + \underbrace{(\Gamma_{T2m}^T O^{-1} \Gamma_{T2m} + B^{-1})^{-1}}_{A} \underbrace{\Gamma_{T2m}^T}_{\frac{\partial T_{2m}(12:00.15:00)}{\partial w}} O^{-1} \underbrace{(T_{2m}^{obs} - T_{2m}(w_b))}_{T2m\ fc\ error}$$

The B matrix is consistently updated daily in a Kalman filter cycled analysis

$$B_{t+1} = MAM^T + Q$$


Bias and RMS of 2m-Temperature Forecasts (landpoints)
rms rou.
rms exp.
bias rou.
bias exp.
2.5
2
1.5
1
0.5
0
-0.5
-1
[K]
May 01
May 08
May 15
May 22
May 29
Jun 05
Jun 12
Jun 19
time [d] (May 1st - June 19th, 1999)

## Evaluation in the eldas project

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- The SMA scheme was extensively evaluated in the EU funded ELDAS project which started in 2002 and aimed at the „Development of a European Land Data Assimilation System to predict Floods and Droughts"

- A series of model experiments were conducted using observations of T2m, Rh2m and analysed precipitation which revealed interesting results.

- Positive impact was shown with for both assimilation of T2m and Rh2m, but these results were outperformed by including analysed precipitation. This improved not only the forecast of near surface variables but also on precipitation.

- It was shown that the SMA system can compensate for forecast errors in precipitation by bringing soil moisture back closer to „reality".

# Strong impact of SMA on T2m and Rh2m, but also on precipitation forecast

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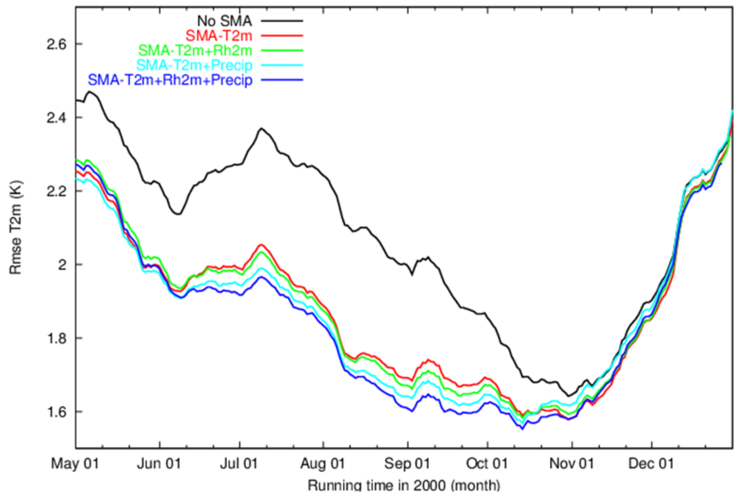
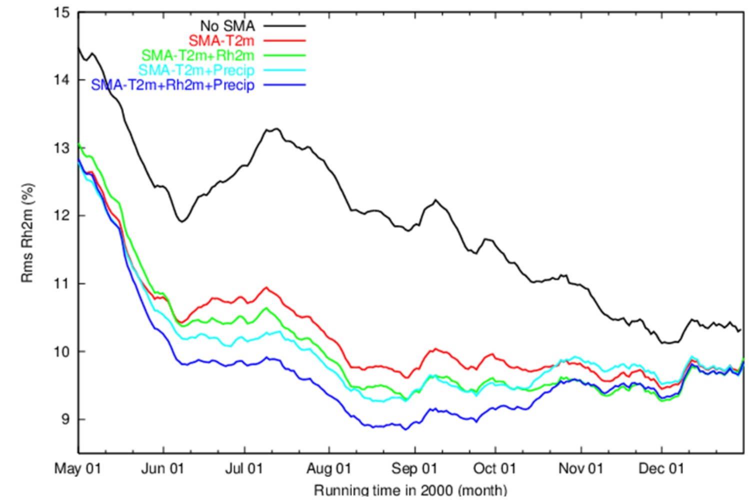
DWD

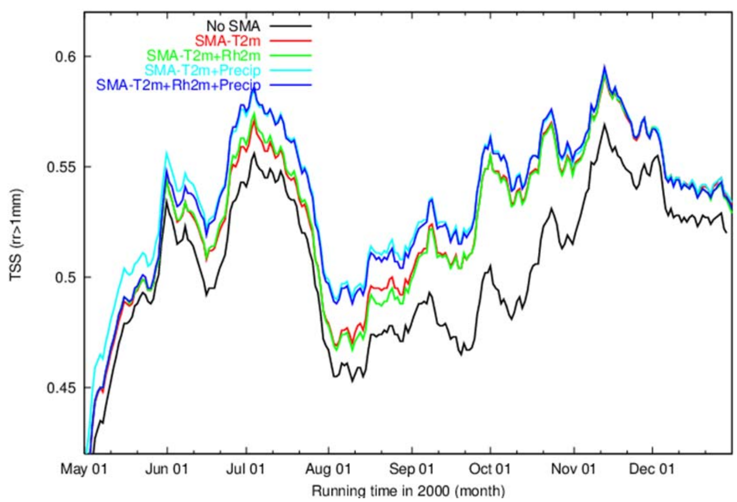
Europe, monthly mean Rmse T2m (12:00, 15:00)



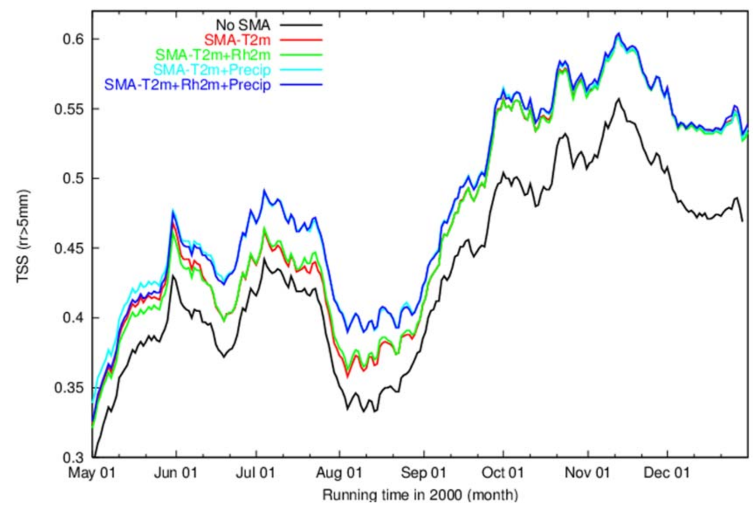

Europe, monthly mean Rmse Rh2m (12:00, 15:00)




True skill score for 24hr accum. precip (prec>1 mm)




True skill score for 24hr accum. precip (prec>5 mm)






**adopted from Hess, Lange, Wergen (2008)**

# Global soil moisture analysis

- For the global system the variational analysis was not considered as an appropriate solution due to the computational cost of the additional forecast runs and as it is cumbersome to maintain in an operational framework. It also led to limits with the operational schedule

- Therefore an SMA scheme was developed which parameterizes the sensitivity of near surface temperature on soil moisture variations. An analytical expression was derived from the relations for evaporation from plants and bare soil.

# Parameterisation of ∂T2m(12:00,15:00)/∂w(0:00) with ∂Lhfl/∂w from penman eqn. at obs time

Surface energy balance equation

$$0 = R_n - Lhfl - Shfl - G$$

Soil moisture variation:

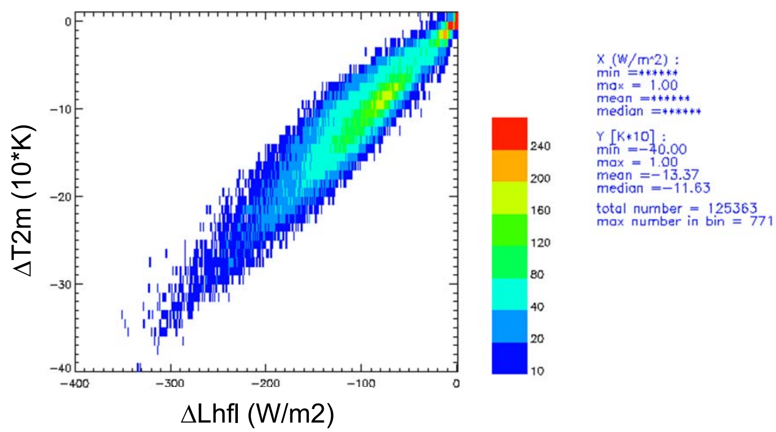
$$\Delta Lhfl \cong -\Delta Shfl$$

$$\Delta Shfl = \rho c_p \frac{(\Delta T_s - \Delta T_{2m})}{\overline{r_a}}$$

$$\Delta Lhfl \cong -\frac{\rho c_p}{\overline{r_a}} \alpha \Delta T_{2m}$$

$$Lhfl = f_{pl}(1 - f_i)(1 - f_{snow}) E_{pot} \frac{r_a}{r_a + r_f}$$

$$\Delta Lhfl(12:00) \sim \Delta T_{2m}(12:00)$$

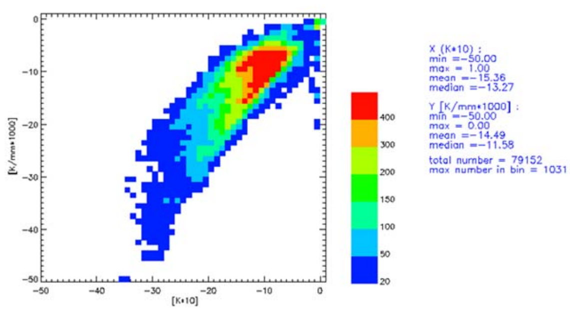


# Parameterisation for  Sensitivity dT2m/dw

Senstivity as derived from Surface energy balance and Penman type equation

$$\frac{\partial T_{2m}}{\partial w_k} = \frac{\alpha \overline{r_a}}{\rho c_p} \frac{Lhfl}{(r_a + r_f)} \frac{1}{f_{LAI}} (1 - \frac{r_s}{r_{s,\max}}) \frac{r_s}{w_{root} - w_{pwp}} \frac{dz_{k,root}}{z_{root}}$$

dT2m/dw
Param / explicit variation




**No further need for additional model runs!**

# Strong impact through the whole boundary layer

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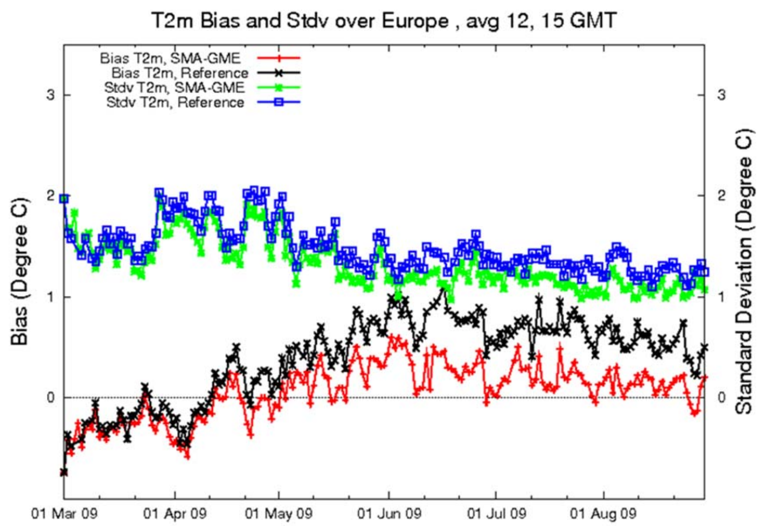
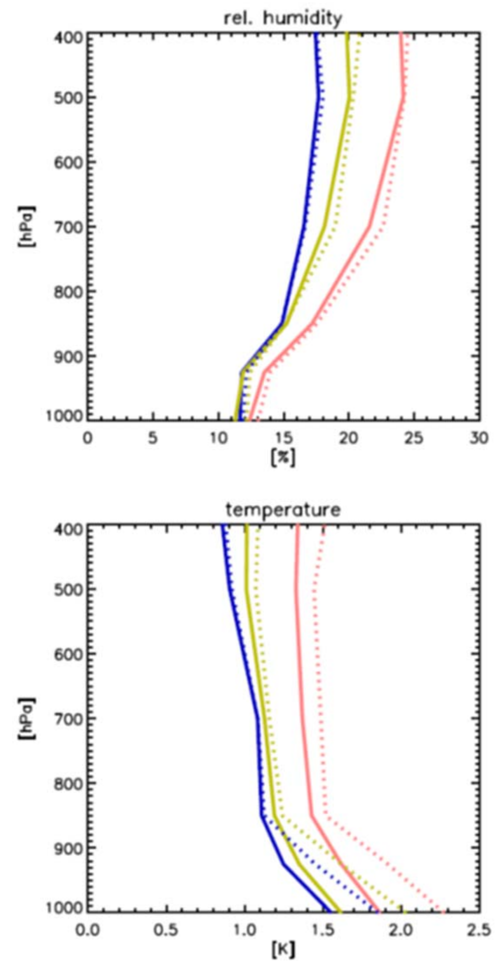
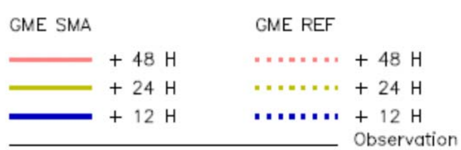



Temp Verification June 2009
Europe



## Satellite obs require new SMA system

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- Present global SMA has been introduced as efficient alternative method to the 2d var analysis used in COSMO-EU and runs in the global system since 2009.
- However it suffers from its limitation to conventional observations. For satellite observations the relation between measured brightness temperature and soil moisture content cant be simply calculated analytically due to the complex forward operator.
- For assimilation of Tb from satellite observations the system has to be replaced.
- Solution which became practically available with introduction of global LETKF: Development of Ensemble based SMA scheme.

Analysis update equation

$$x_a = x_b + \underbrace{\mathrm{B}\,\mathrm{H}^T\left[\mathrm{H}\,\mathrm{B}\,\mathrm{H}^T + \mathrm{O}\right]^{-1}}_{\mathbf{K}}(y - H[x_b])$$

Approximation of B with deviations from ensemble mean

$$\begin{aligned}\mathrm{B}_{ij} &= \overline{(x_b^{(i)} - x_t^{(i)})\,(x_b^{(j)} - x_t^{(j)})} \\ &= \frac{1}{N-1}\sum_{m=1}^{N}(x_b^{(i)} - \overline{x_b^{(i)}})\,(x_b^{(j)} - \overline{x_b^{(j)}})\end{aligned}$$

Linear scenario: HBHT can be derived from covariance of obs equivalents

$$\begin{aligned}H\,\mathrm{B}\,H^T &= H(x_b - \overline{x_b})\,(H(x_b - \overline{x_b}))^T \\ &= (y_b - \overline{y_b})\,(y_b - \overline{y_b})^T\end{aligned}$$

Algorithm computational efficient

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Analogue

$$\begin{aligned} \mathrm{B}\, H^T &= (x_b - \overline{x_b})\,(H(x_b - \overline{x_b}))^T \\ &= (x_b - \overline{x_b})\,(y_b - \overline{y_b})^T \end{aligned}$$

- No horizontal correllations in SMA,
- R diagonal

⇒ Kalman gain can be calculated simply from ensemble forecast at affordable cost

Upscaling of K for the deterministic grid using scaling by soil moisture index to account for changing soil type.

Calculation of increments on deterministic grid

$$x_a - x_b = \mathbf{K}\,(y - H[x_b])$$

Present state at DWD:
SMA is almost coded, first tests are outstanding

Can we benefit from „realistic“ soil moisture obs?

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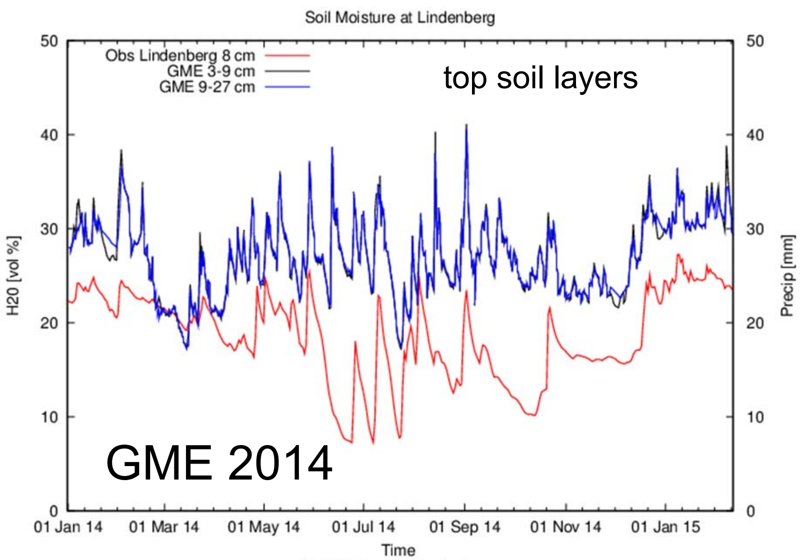
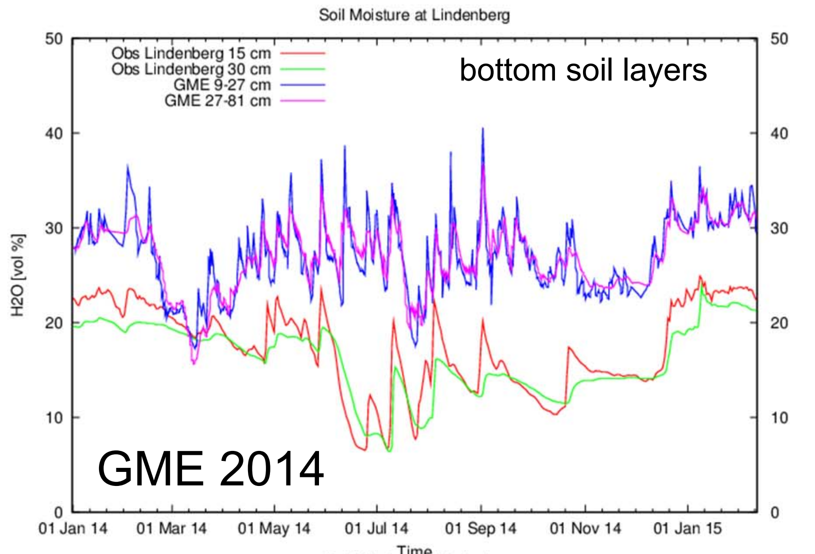
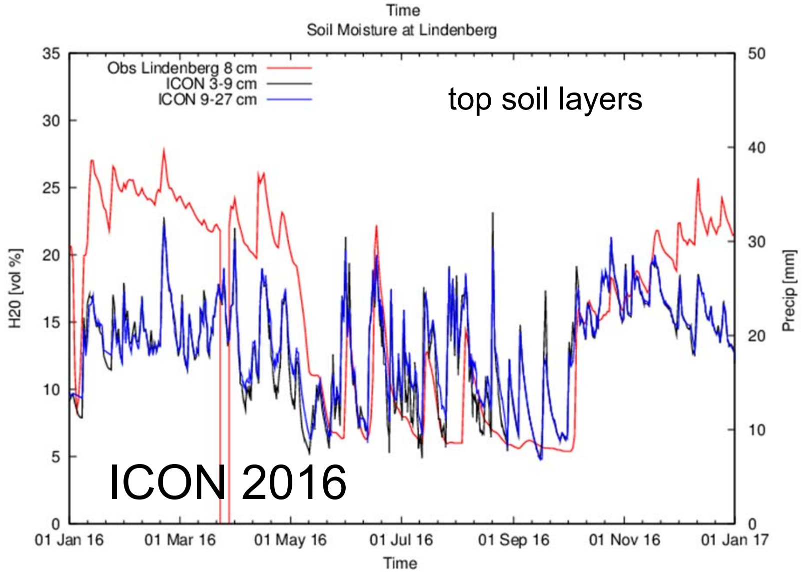
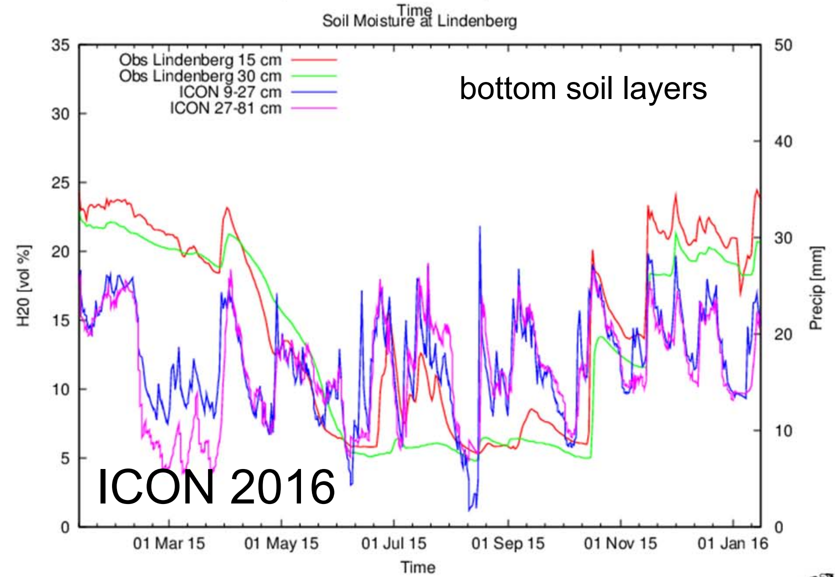
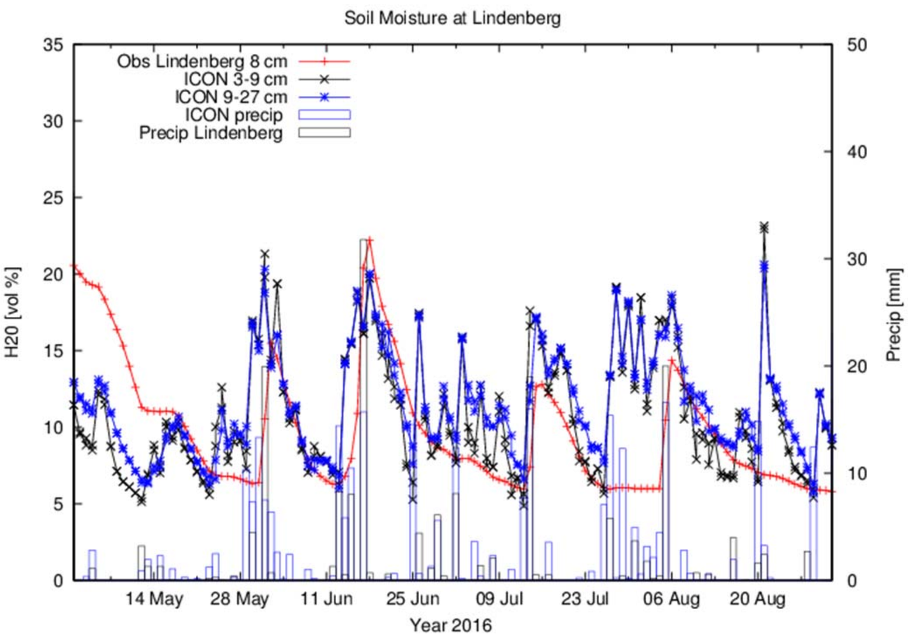
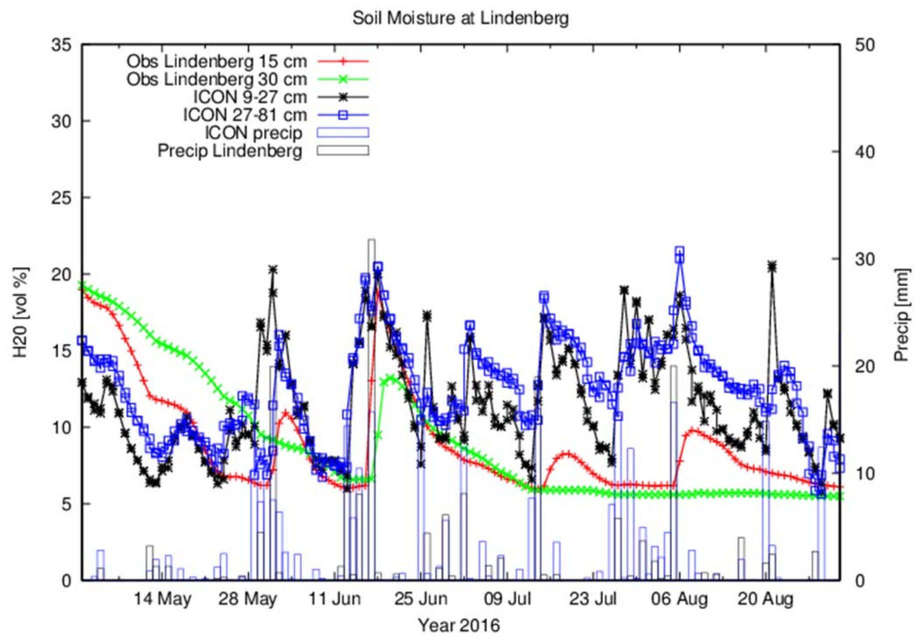



Soil Moisture at Lindenberg
Obs Lindenberg 8 cm
ICON 3-9 cm
ICON 9-27 cm
ICON precip
Precip Lindenberg
H20 [vol %]
Precip [mm]
14 May
28 May
11 Jun
25 Jun
09 Jul
23 Jul
06 Aug
20 Aug
Year 2016


Soil Moisture at Lindenberg
Obs Lindenberg 15 cm
Obs Lindenberg 30 cm
ICON 9-27 cm
ICON 27-81 cm
ICON precip
Precip Lindenberg
H20 [vol %]
Precip [mm]
14 May
28 May
11 Jun
25 Jun
09 Jul
23 Jul
06 Aug
20 Aug
Year 2016

## Satellite obs require new SMA system

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- DWD runs variational soil moisture analysis since 17 years operationally using screen level observations. By design it helps to reduce screen level forecast errors by adjustment of surface fluxes. But it also adjusts soil moisture in case of wrong precip forecast.
- Satellite observations can not be assimilated with the present global system. An ensemble based SMA is developed which is able to solve this gap.
- ELDAS results showed strong positive impact of analysed precipitation on weather forecast. Soil moisture changes derived from consecutive overpasses of SMOS or SMAP satellite may help to correct for precipitation errors on the global scale.

- However at least daily analysis of local soil moisture changes are needed to get used by the SMA system. So temporal disaggregation is required using model information or information from other observing systems.

- Soil texture is an issue in the models as external soil databases does not always match. Parameter estimation for soil texture may alleviate the problem.

- Soil texture based dielectric properties transfer this uncertainty to the foreward operator. Emissivity maps for L-band are required to inversely derive the appropriate soil parameter.

- Model system has improved the last years so it becomes difficult to get positive impact of SMA on weather forecast as it compensates for model biases. However it is the only way to bring soil moisture closer to reality.

# Thank you for your attention!

# Is the model able to benefit from realistic soil moisture?



Measurement site Lindenberg
additional obs for Suisse,
Sweden, Czech., Romania

| | Obs Lindenberg | GME 20km (gpt 67456) | ICON 13 km (gpt 646652) |
|---|---|---|---|
| Geogr. longitude | 14,12 | 14.03 | 14,11 |
| Geogr. latitude | 52,17 | 52.14 | 52.12 |
| Soil type | sand | loam (5) | sand (3) |
| Plant cover (July) | | | 54 % |
| LAI (July) | | | 3.5 |

## Summary

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-However at least daily analysis of local soil moisture changes are needed to get used by the SMA system. So temporal disaggregation is required using model information or information from other observing systems.

-Global radar database would be useful. Fostering exchange between different countries is topic of other working groups.

-Soil texture is an issue in the models as external soil databases does not always match. Parameter estimation for soil texture may alleviate the problem. Soil texture based dielectric properties transfer this uncertainty to the foreward problem. Emissivity maps for L-band are required to reverse the order and to inversely derive the appropriate soil conditions.

Model system has improved the last years so impact of SMA to reduce model bias has reduced.

Analysis update equation

$$x_a = x_b + \mathrm{B\,H}^T \left[\mathrm{H\,B\,H}^T + \mathrm{O}\right]^{-1} (y - H[x_b])$$

Approximation of B with deviations from ensemble mean

$$\begin{aligned} \mathrm{B}_{ij} &= \overline{(x_b^{(i)} - x_t^{(i)})\,(x_b^{(j)} - x_t^{(j)})} \\ &= \frac{1}{N-1} \sum_{m=1}^{N} (x_b^{(i)} - \overline{x_b^{(i)}})\,(x_b^{(j)} - \overline{x_b^{(j)}}) \end{aligned}$$

Linear scenario: HBHT derived from covariance of obs equivalents

$$\begin{aligned} H\,\mathrm{B}\,H^T &= H(x_b - \overline{x_b})\,(H(x_b - \overline{x_b}))^T \\ &= (y_b - \overline{y_b})\,(y_b - \overline{y_b})^T \end{aligned}$$

# Notes

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Improved model and data assimilation system is basic for use of satellite data. In earlier times much efforts in assimilation didn‘t succeed for this reason, this changed the with the latest system we are prepared to make use of indirect observations.

# Modelsystem present and next

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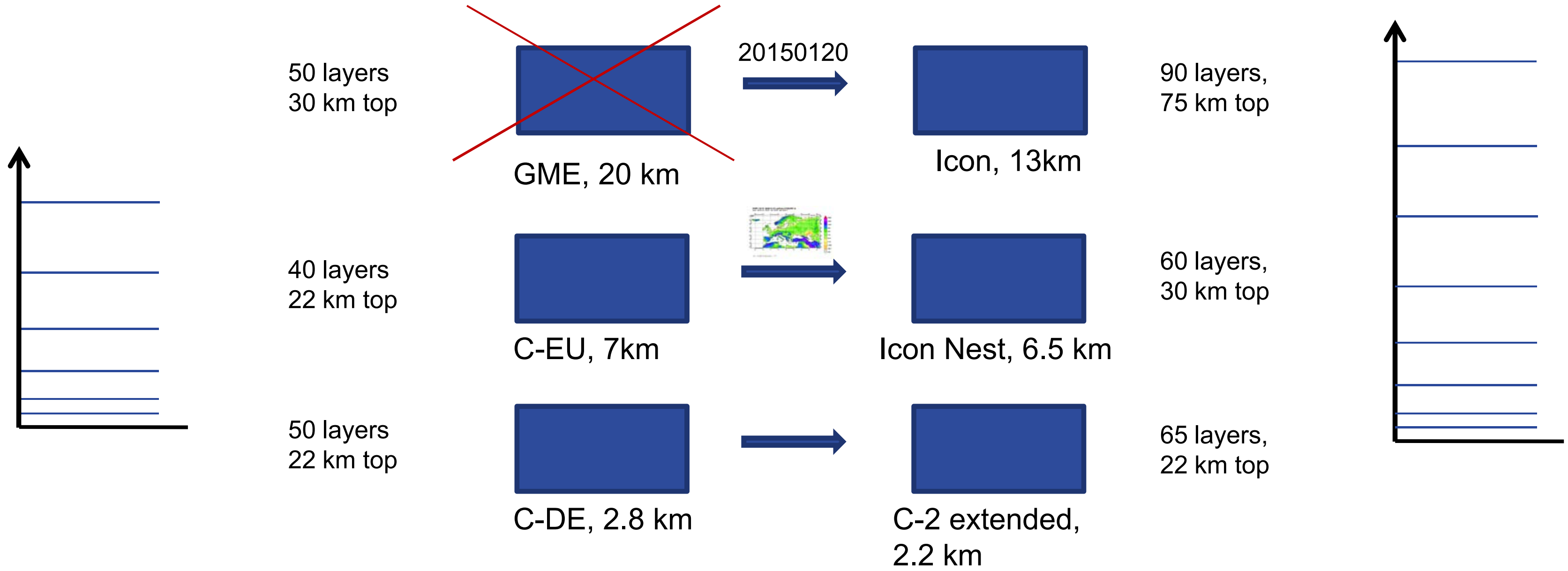
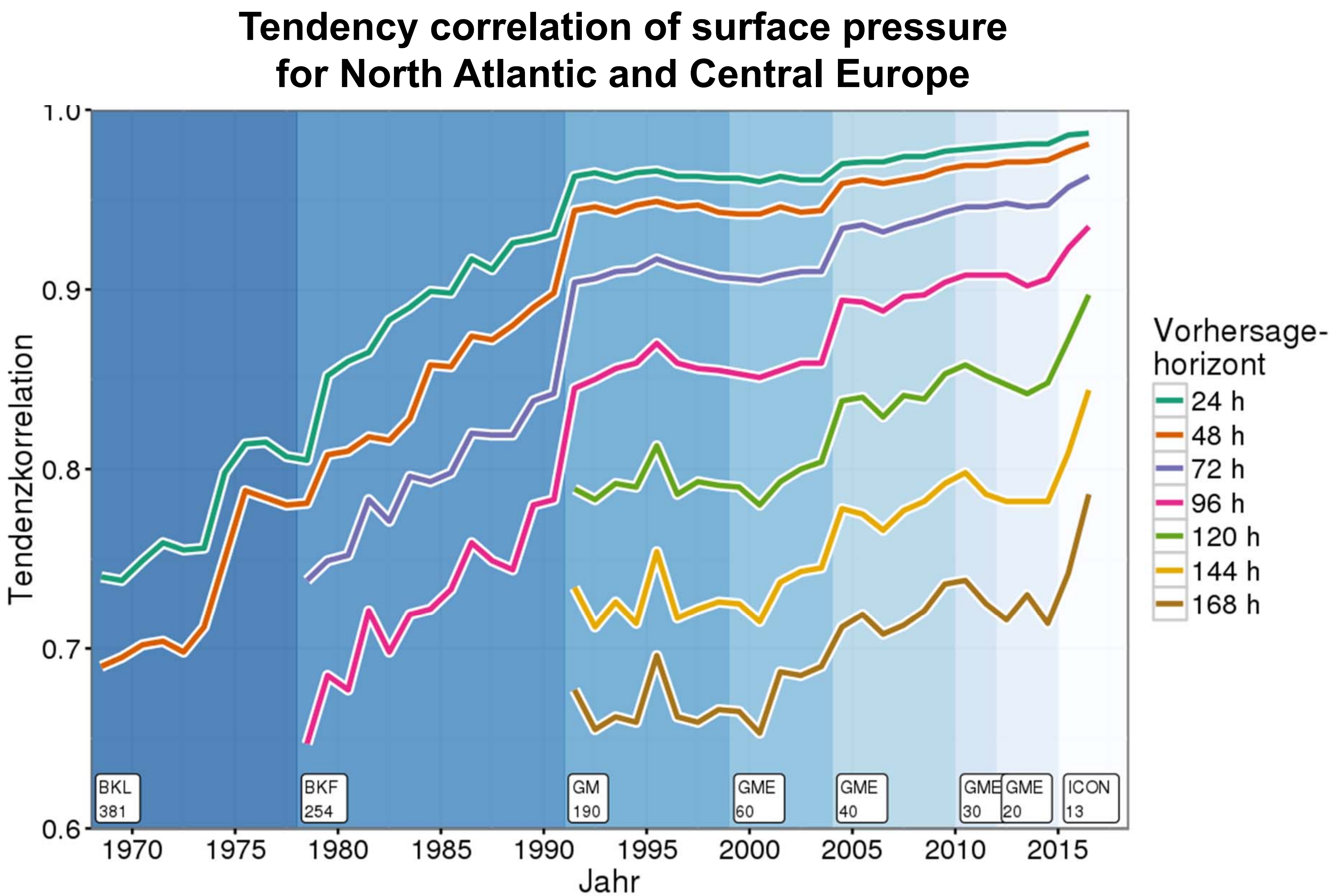



| Model / domain | Spatial resolution | Replaced by | Spatial resolution | Operational implementation at DWD |
|---|---|---|---|---|
| ~~GME / global~~ | ~~20 km~~ | ICON | 13 km | January 2015 |
| COSMO- EU / Europe<br>link to domain figures<br>(orografie) | 7 km<br>40 layers | ICON-Nest<br>Europe extended | 6.5 km<br>60 layers | 2015 |
| Germany | 2.8 km<br>50 layers | COSMO-2 Germany<br>extended to west | 2.2 km,<br>65 layers | End 2015 |

# Verbesserung der Vorhersagequalität 1968 - 2016







http://141.38.40.96:1111/users/ffundel/veri1968/

# TEMP-Verification Europe from 2014 to 2016

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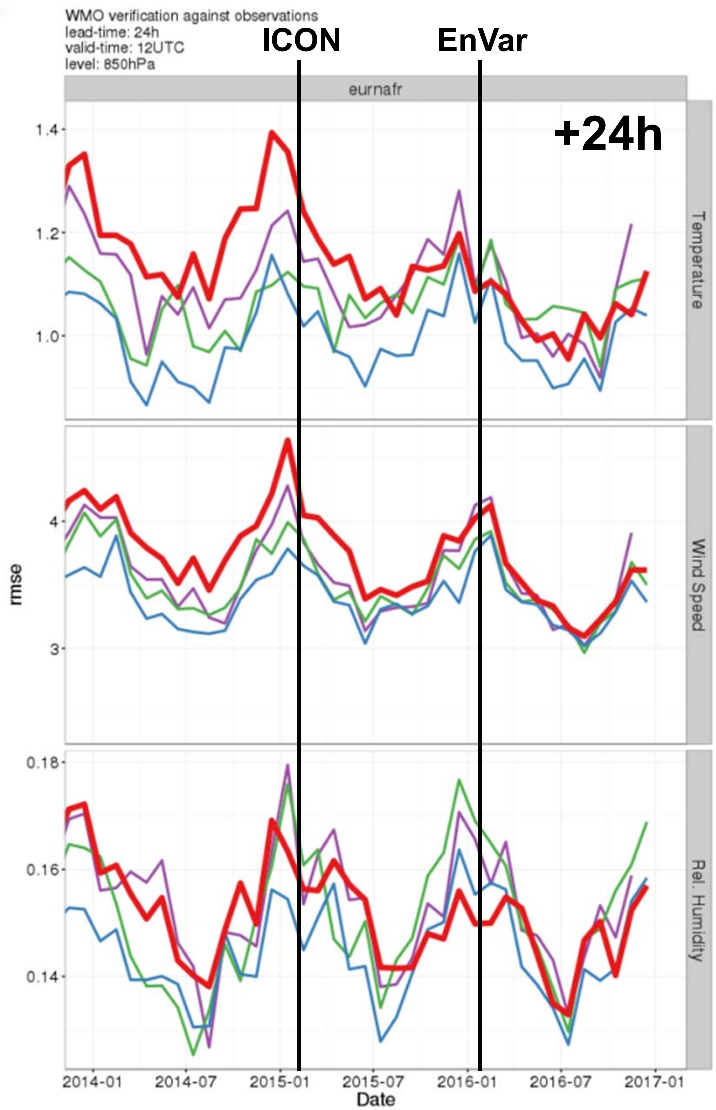


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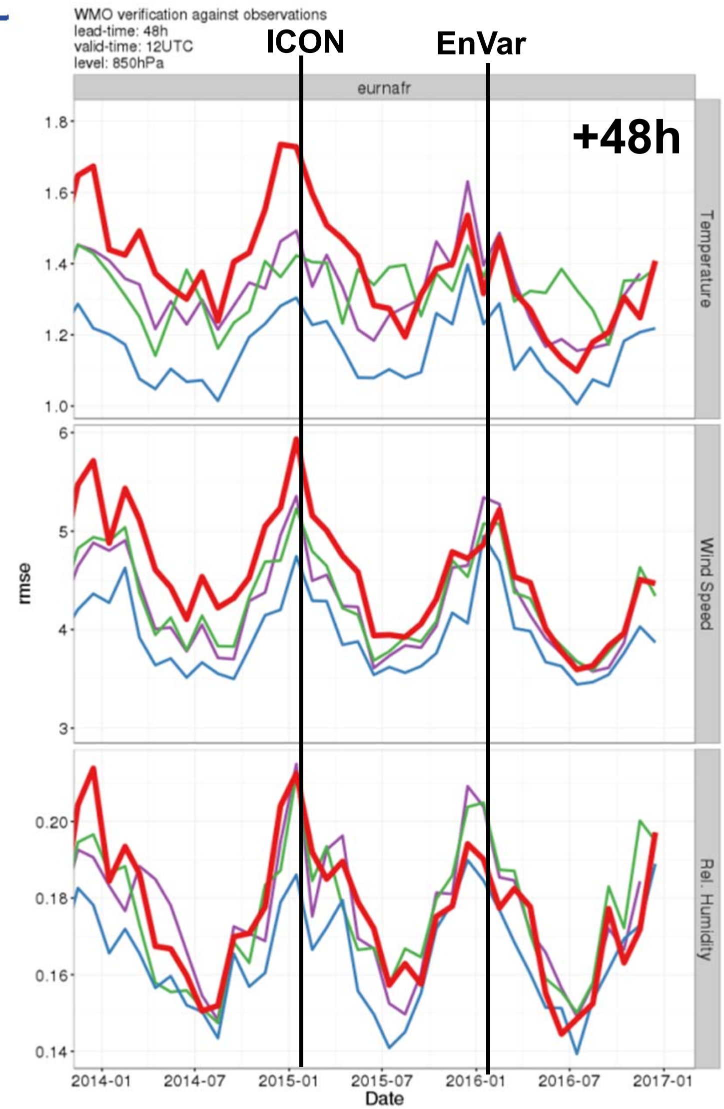


UKMO
Met.Fr.
ECMWF
DWD

# IFS (ECMWF) is not always better than ICON
## RH and T @ 2m, Central Europe, January 2017

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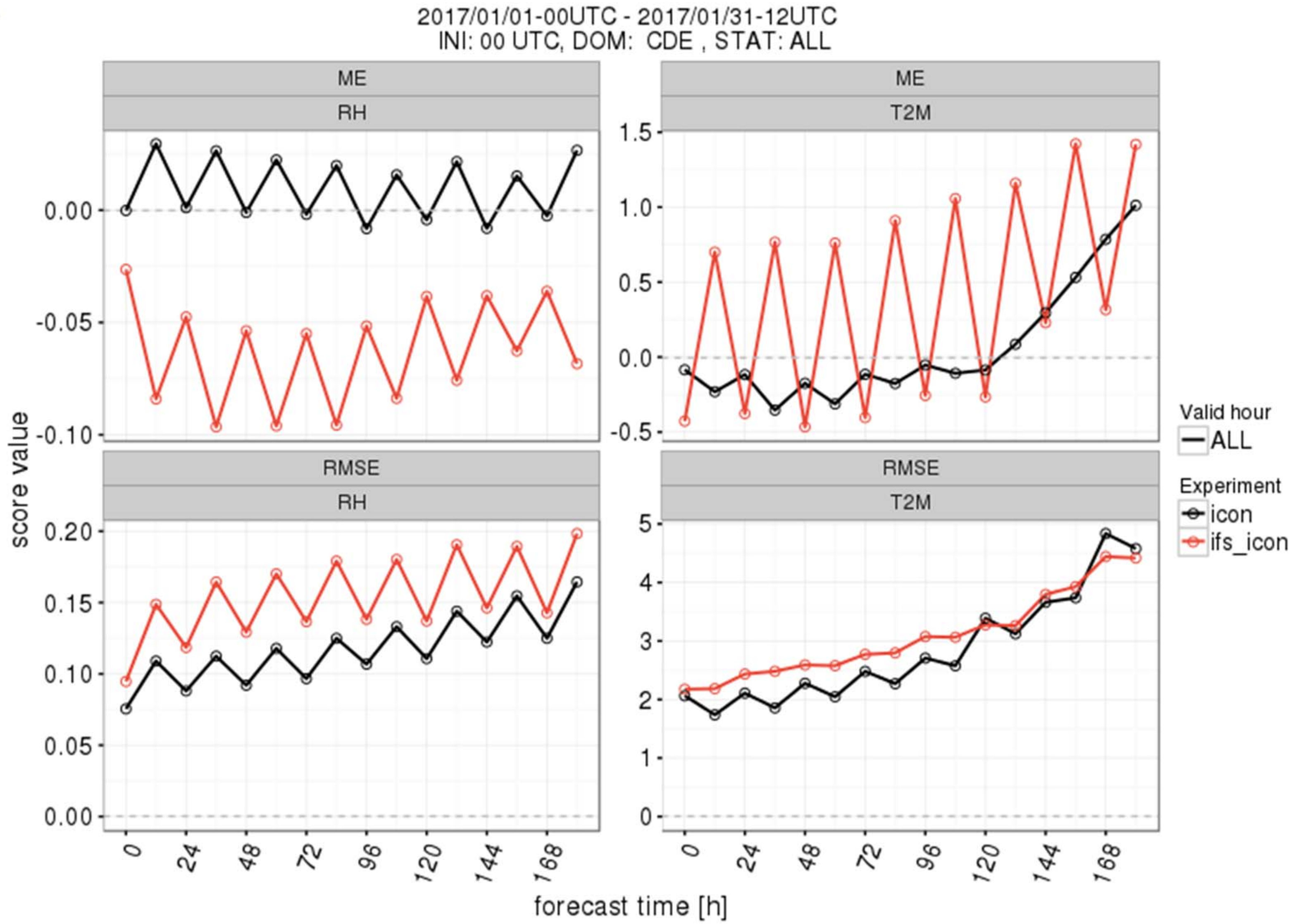
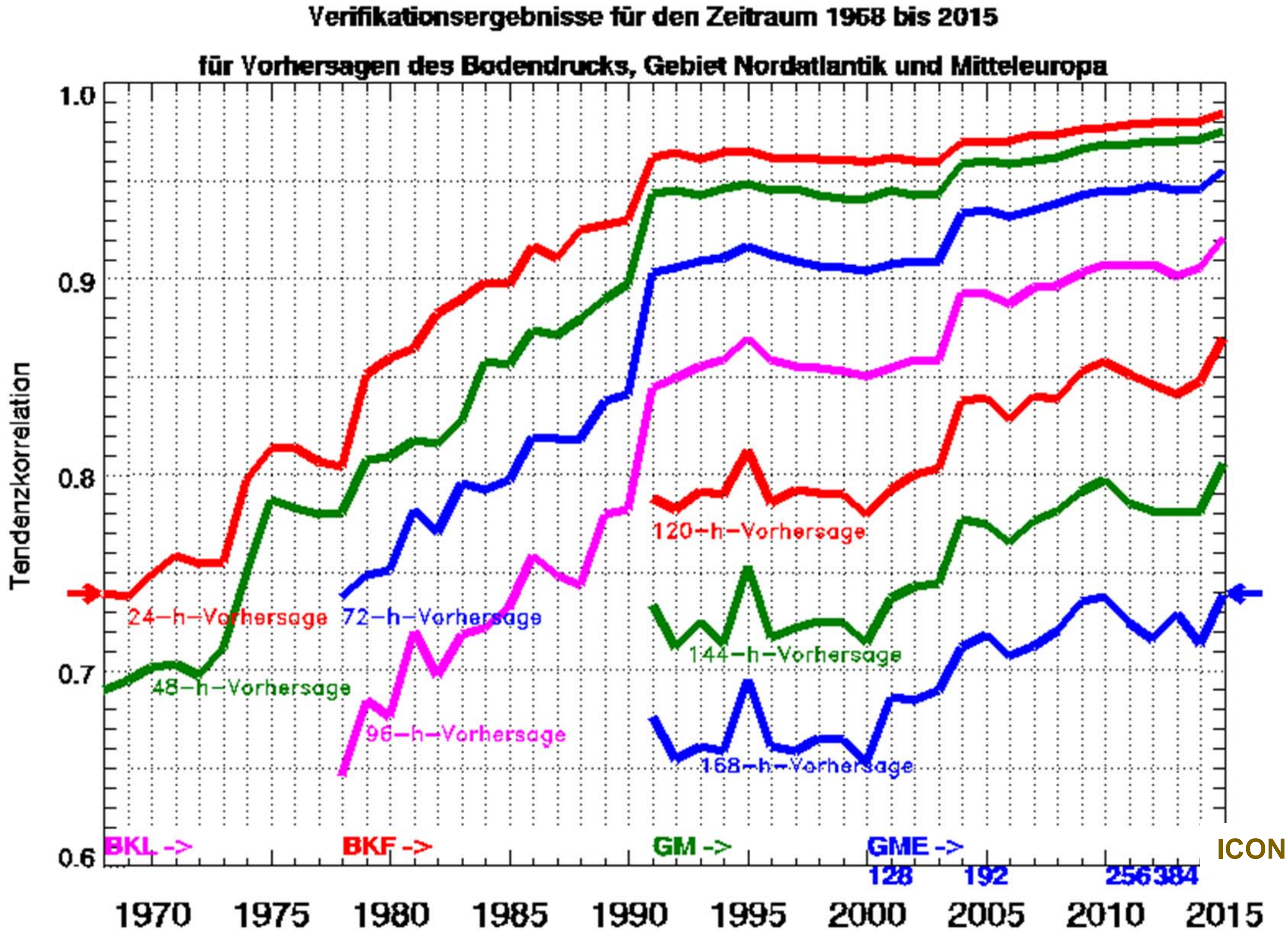



red: IFS (ECMWF), black: ICON

# Verbesserung der Vorhersagequalität 1968 - 2015



Meteorol. Atmos. Phys. 77, 145–154 (2001)

Meteorology and Atmospheric Physics


Deutscher Wetterdienst (DWD), Research and Development, Offenbach, Germany

## Assimilation of screen-level observations by variational soil moisture analysis

**R. Hess**

With 5 Figures

Received August 21, 2000
Revised March 26, 2001

**Summary**

Inaccurate specification of soil moisture contents can result in forecast errors up to several degrees centigrade. Since direct measurements are rarely available, a variational method has been developed that assimilates synoptic measurements of 2 m-temperature in order to specify the moisture contents of the two soil layers of the Local Model at Deutscher Wetterdienst. The analyzed values minimize a cost functional that expresses the differences between model forecast and observed screen-level temperatures. The minimization is performed highly efficiently and only two additional forecasts are required but neither tangent linear nor adjoint. Background state and background error covariance matrix are updated at each analysis step in a Kalman-filter-like cycled scheme, which takes a model error into account. The soil moisture assimilation shows improved 2 m-temperature forecasts in case of high radiative forcing by up to 3 °C for small areas in the presented 6-week trial run. It proved stability and robustness for general weather conditions and has become operational at DWD for the LM on 14 March 2000.

### 1. Introduction

The initialization of soil moisture fields is a severe problem in numerical weather prediction. On the one hand, soil moisture determines the relationship between sensible and latent heat fluxes at the bottom of the atmosphere. Inaccurate soil moisture values can result in near-surface temperature forecast errors up to several degrees centigrade (compare Rhodin et al., 1999). An often experienced significant cold bias of the LM and also of the previously operational model DM at DWD resulted from unrealistic high evaporative fluxes during early sunny spring days. On longer time scales the specification of soil moisture contents influences the entire hydrological budget of the simulation (e.g., Schär et al., 1999).

One the other hand, representative measurements of soil moisture are rarely available. For this reason they were free-running within the Local Model (LM) at Deutscher Wetterdienst (DWD) and only influenced by the hydrological balance between precipitation, evapotranspiration, and water runoff using a bucket soil model up to now (Deutscher Wetterdienst, 1995). However, in case the soil moisture fields are never analyzed by observations, a drift in time to inaccurate values is well possible.

The need for soil moisture initialization without representative measurements has led to interest in indirect determinations. Especially in case of high solar radiative forcing, screen-level temperature and relative humidity strongly depend on the specified soil moisture contents. This soil-atmosphere coupling can be used to exploit information on the soil moisture contents from synoptic measurements. Mahfouf (1991) compared two methods of indirect soil moisture analysis: optimal interpolation and variational analysis. The first one adds increments with statistically derived soil-

# 2d var (z,t) soil moisture analysis applied in COSMO-EU

Cost function penalizes deviations from observations and initial soil moisture content

$$J = (w - w_b)^T B^{-1} (w - w_b) + (T_{2m} - T_{2m}^{obs})^T O^{-1} (T_{2m} - T_{2m}^{obs})$$

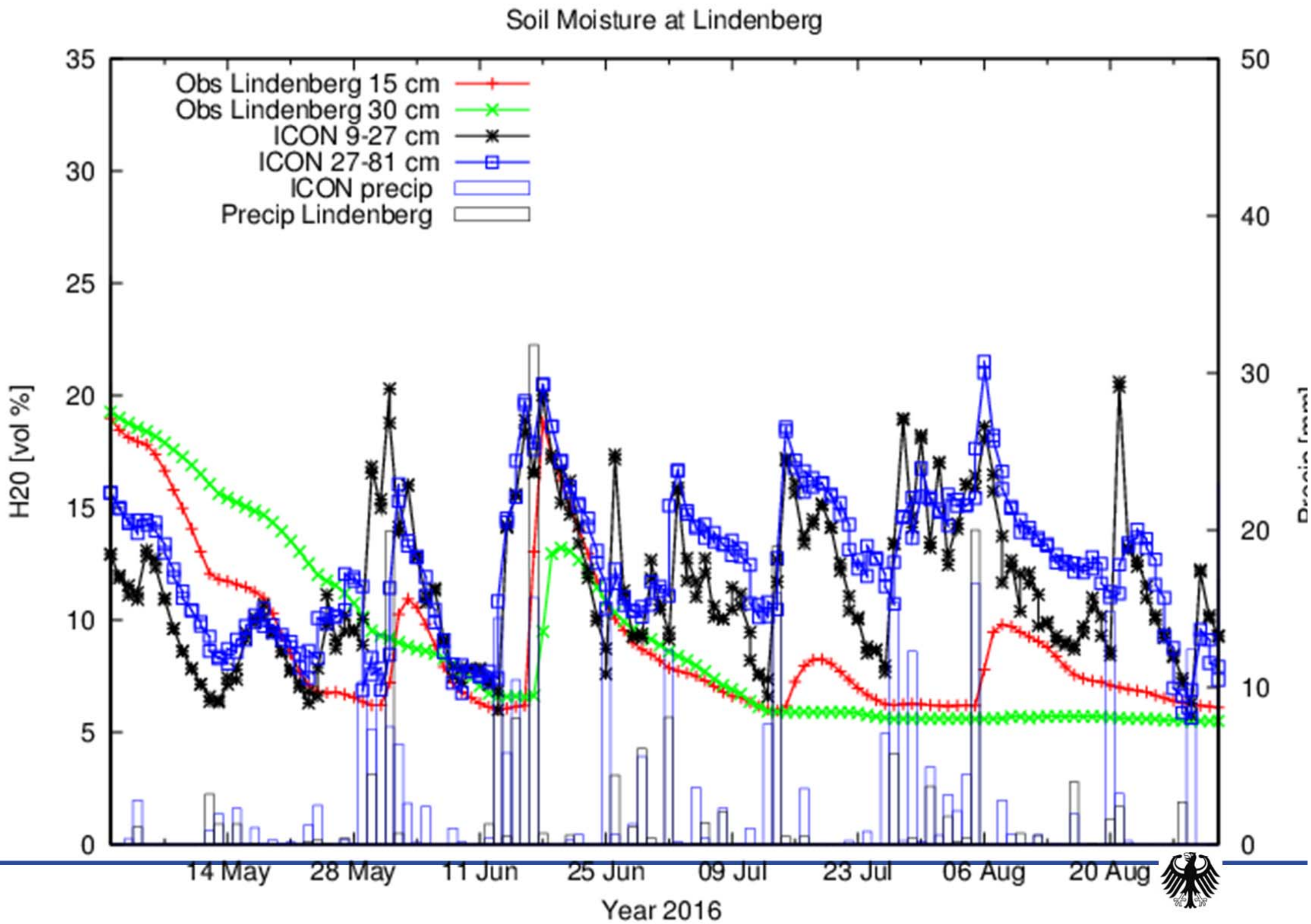
$$\nabla J = 0$$

Analysed soil moisture depends on T2m forecast error and sensitivity ∂T2m/∂w

$$w_{ana} = w_b + (\Gamma_{T2m}{}^T O^{-1} \Gamma_{T2m} + B^{-1})^{-1} \underbrace{\Gamma_{T2m}}_{\frac{\partial T_{2m}(12:00,15:00)}{\partial w(0:00)}}{}^T O^{-1} \underbrace{(T_{2m}^{obs} - T_{2m}(w_b))}_{T2m\ fc\ error}$$

The B matrix is consistently updated daily in a Kalman cycled analysis

Deutscher Wetterdienst
*Wetter und Klima aus einer Hand*



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