On Localised Particle Filters for the Global Weather Prediction Model ICON

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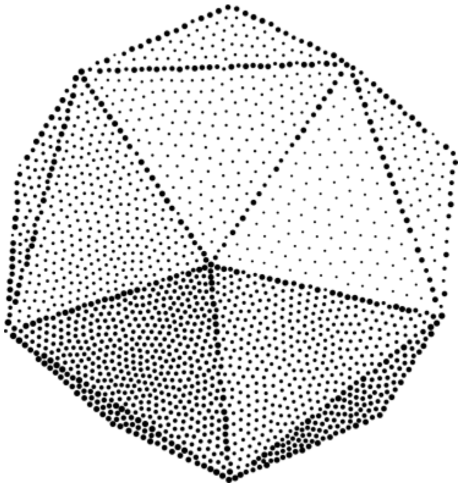
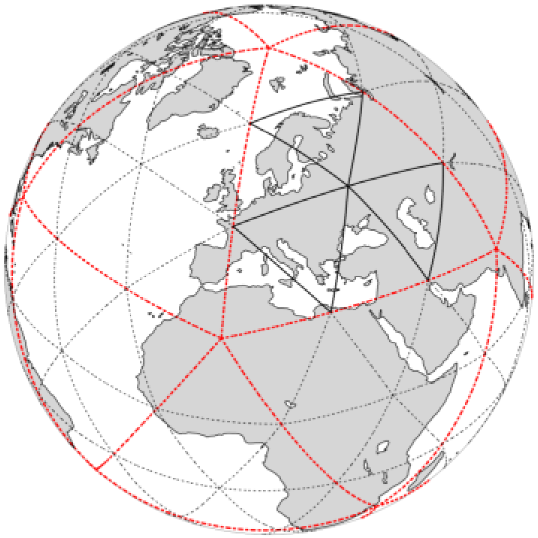
Content

1. The ICON-Model

- Operational NWP model of DWD: ICON (ICOsahedral Nonhydrostatic)
- Two-way NEST over Europe (~6.5 km)
- Resolution: 13 km deterministic
  40 km ensemble (40 member)



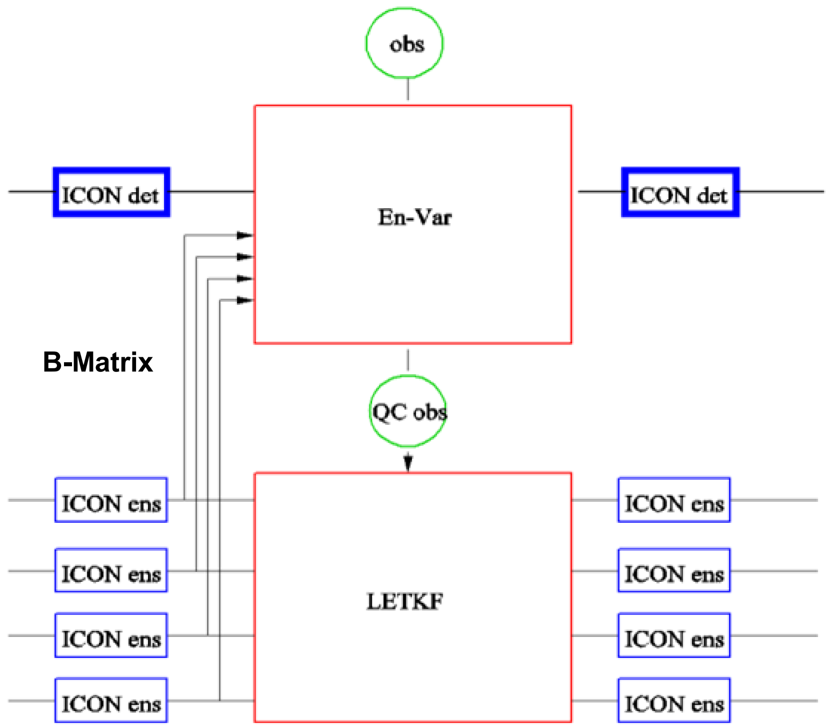


1. DA System at DWD

- Hybrid EnVar operational since January 20, 2016

$$X^a = \bar{x}^b + X^b W$$

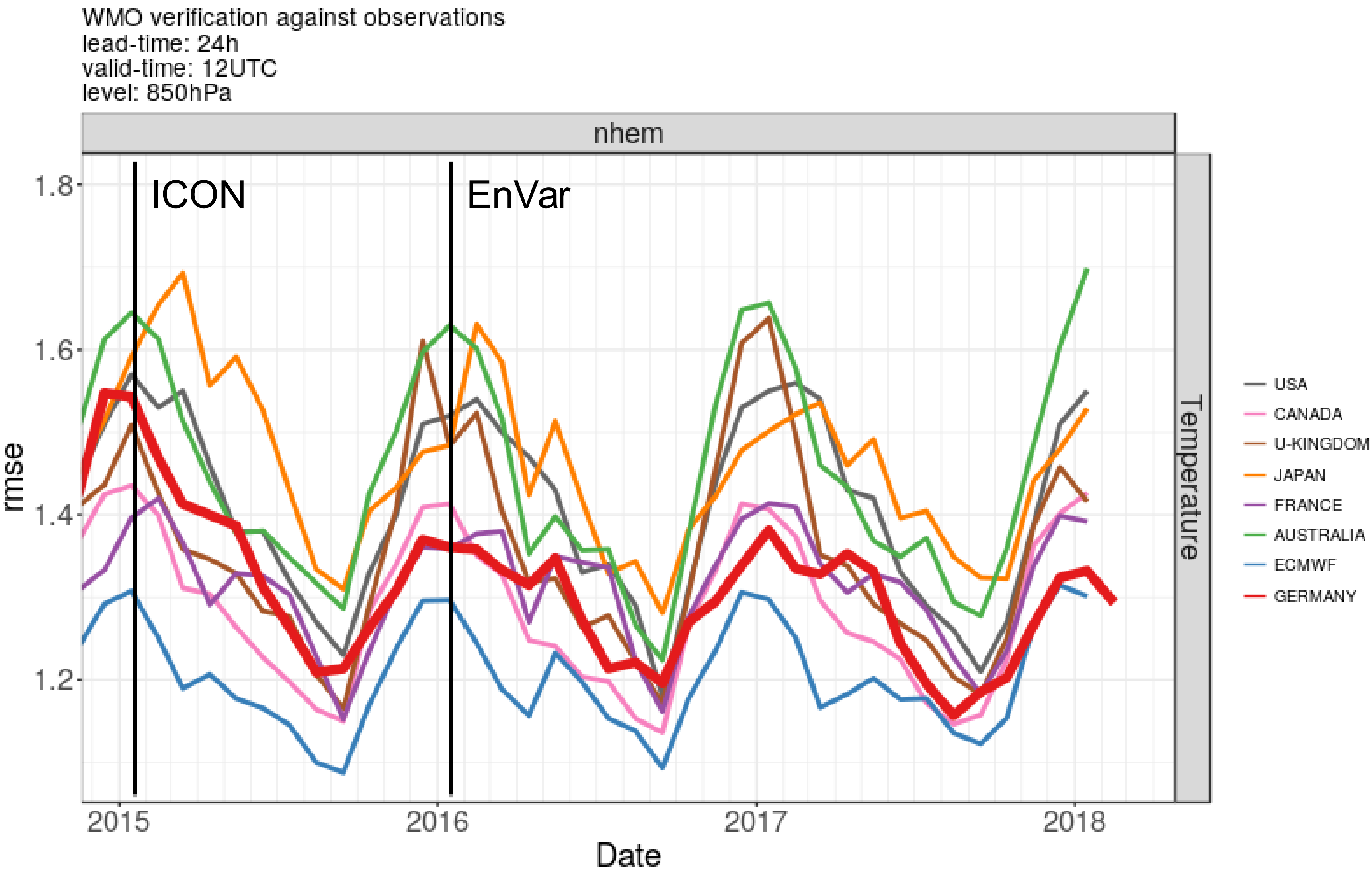
- Following Hunt et al. (2007), (see also Schraff et al., 2016)
- EnVar-B-Matrix: 70% LETKF, 30% Climatology



Global Model Verification Comparison

University of Reading

Deutscher Wetterdienst
Wetter und Klima aus einer Hand



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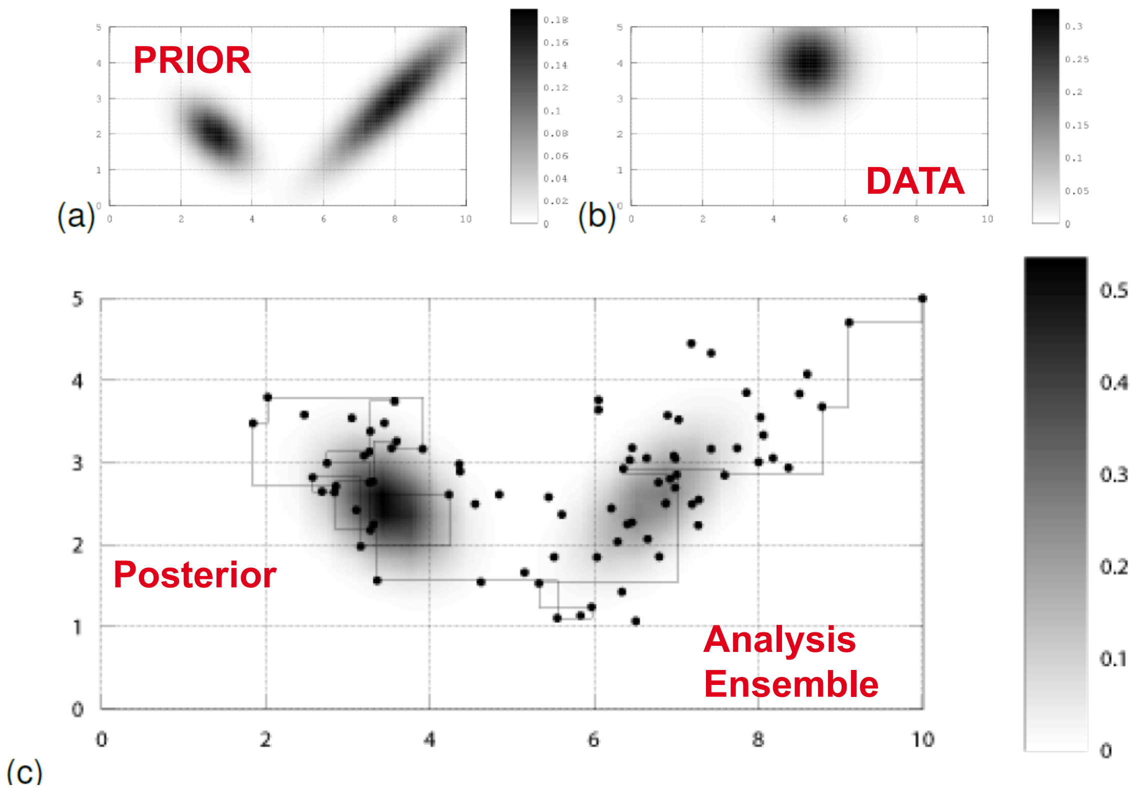
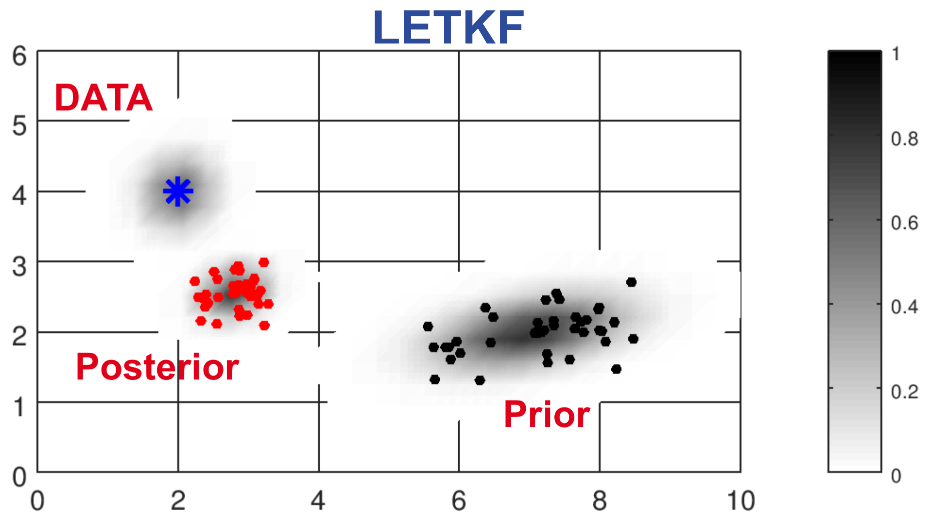
2. Bayesian Filtering via PF

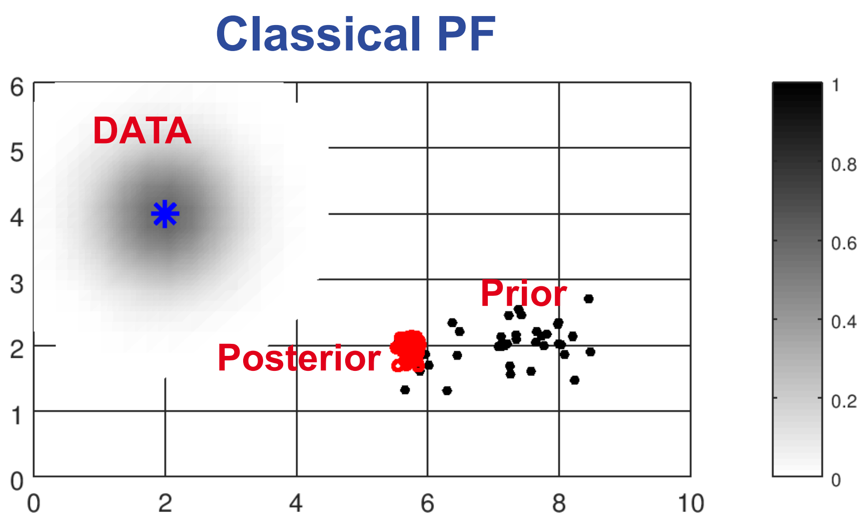
- Our Particle Filters are based on the LETKF philosophy
  - Localisation: as LETKF in ensemble space
  - Adaptivity: tools for spread control

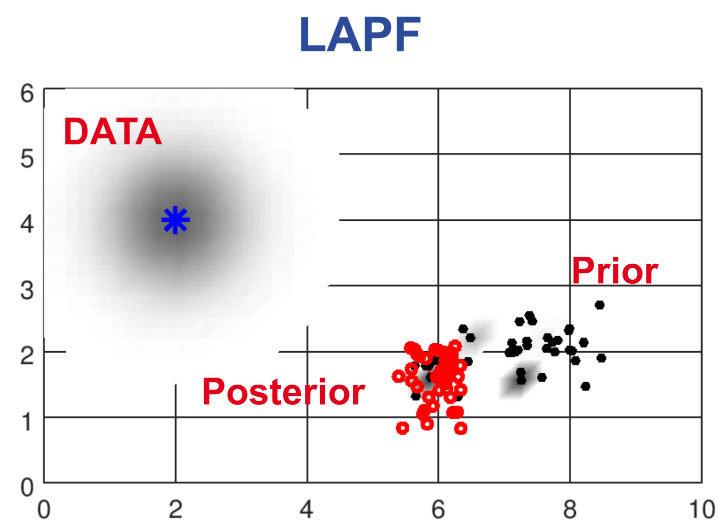


- Able to handle with multi-modal distributions
- Able to handle with Non-Gaussianity

2. Bayesian Filtering via PF







2. Bayesian Filtering via PF

First Step: The Classical Particle Filter

- Employ **Bayes formula** to calculate new analysis distribution

Employ Bayes formula to calculate new analysis distribution

$$p_k^{(a)}(x) := p(x|y_k) = c\, p(y_k|x) p_k^{(b)}(x), \qquad x \in \mathbb{R}^n$$

is a normalization factor:

c is a normalization factor: $\int_X p_k^{(a)}(x)dx = 1$

- To carry out the analysis step at time t_k **a posteriori weights** $p_k^{(a)}$ are calculated

To carry out the analysis step at time a posteriori weights are calculated

$$p_{k,l}^{(a)} = c\, e^{-\frac{1}{2}\left(y-Hx^{(l)}\right)^T R^{-1}\left(y-Hx^{(l)}\right)}$$

is chosen such that

c is chosen such that $\sum_{l=1}^{L} p_{k,l}^{(a)} = L$

Second Step: Classical Resampling

- **Accumulated weights** w_{ac} are defined:

$$w_{ac_0} = 0$$

$$w_{ac_i} = w_{ac_{i-1}} + p_i^a, \qquad i = 1, \dots, L$$

where L denotes the ensemble size

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- Drawing $r_j \sim U([0,1]), j = 1, \dots, L$, set $R_j = j - 1 + r_j$ and define **transform matrix *W*** for the particles by:

Drawing , set and define transform matrix W for the particles by:

$$W_{i,j} = \begin{cases} 1 & if\ R_j \in \left(w_{ac_{i-1}}, w_{ac_i}\right], \\ 0 & otherwise, \end{cases}$$

with $i, j = 1, \dots, L$ with $W \in \mathbb{R}^{LxL}$, $(s,t]$ denotes the interval of values $s < \eta \leq t$.

with , denotes the interval of values .

Third Step: Spread Control

- Based on the adaptive multiplicative **inflation factor** ρ determined by the LETKF

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$$\rho = \frac{\mathrm{E}\left[\boldsymbol{d}_{o-b}^{T}\boldsymbol{d}_{o-b}\right] - \mathrm{Tr}(\mathbf{R})}{Tr(\boldsymbol{H}\boldsymbol{P}^{b}\boldsymbol{H}^{T})}$$

- **Weighting factor** has been chosen, due to the small ensemble size ()

- **Weighting factor** α has been chosen, due to the small ensemble size ($L = 40$)

$$\rho_k = \alpha\tilde{\rho}_k + (1-\alpha)\rho_{k-1}$$

2. Bayesian Filtering via PF

Third Step: Spread Control

-
- **Perturbation factor σ** is used to add spread to the system

$$\sigma = \begin{cases} c_0, & \rho < \rho^{(0)} \\ c_0 + (c_1 - c_0) * \dfrac{\rho - \rho^{(0)}}{\rho^{(1)} - \rho^{(0)}}, & \rho^{(0)} \le \rho \le \rho^{(1)} \\ c_1, & \rho > \rho^{(1)} \end{cases}$$

where , , and , with
if and if

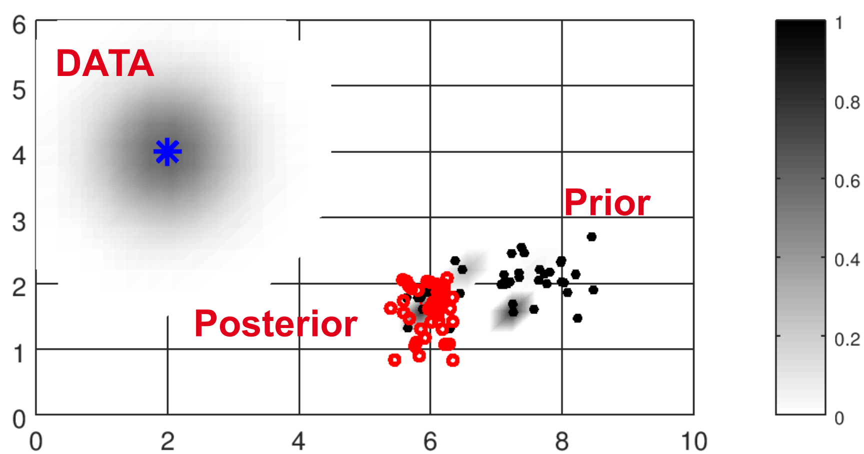
where $c_0 = 0.02$, $c_1 = 0.2$, $\rho^{(0)} = 1.0$ and $\rho^{(1)} = 1.4$, with $\sigma = c_1$ if $\rho \ge \rho^{(1)}$ and $\sigma = c_0$ if $\rho \le \rho^{(0)}$

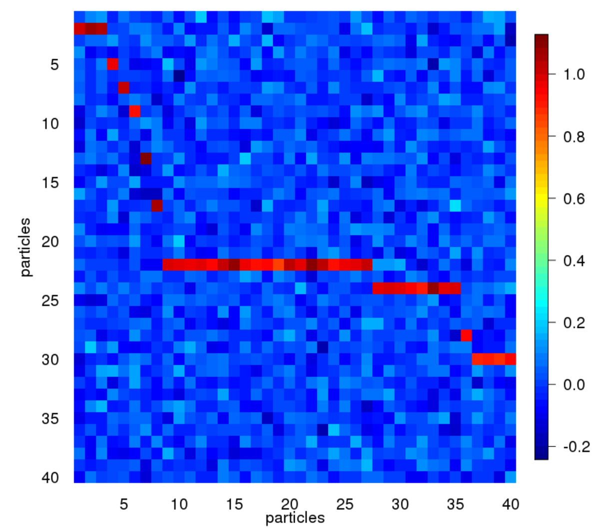
Fourth Step: Gaussian Resampling

- **Weights W** are modified by applying the **pertubation factor σ**

$$W = W + R_{nd} * \sigma$$

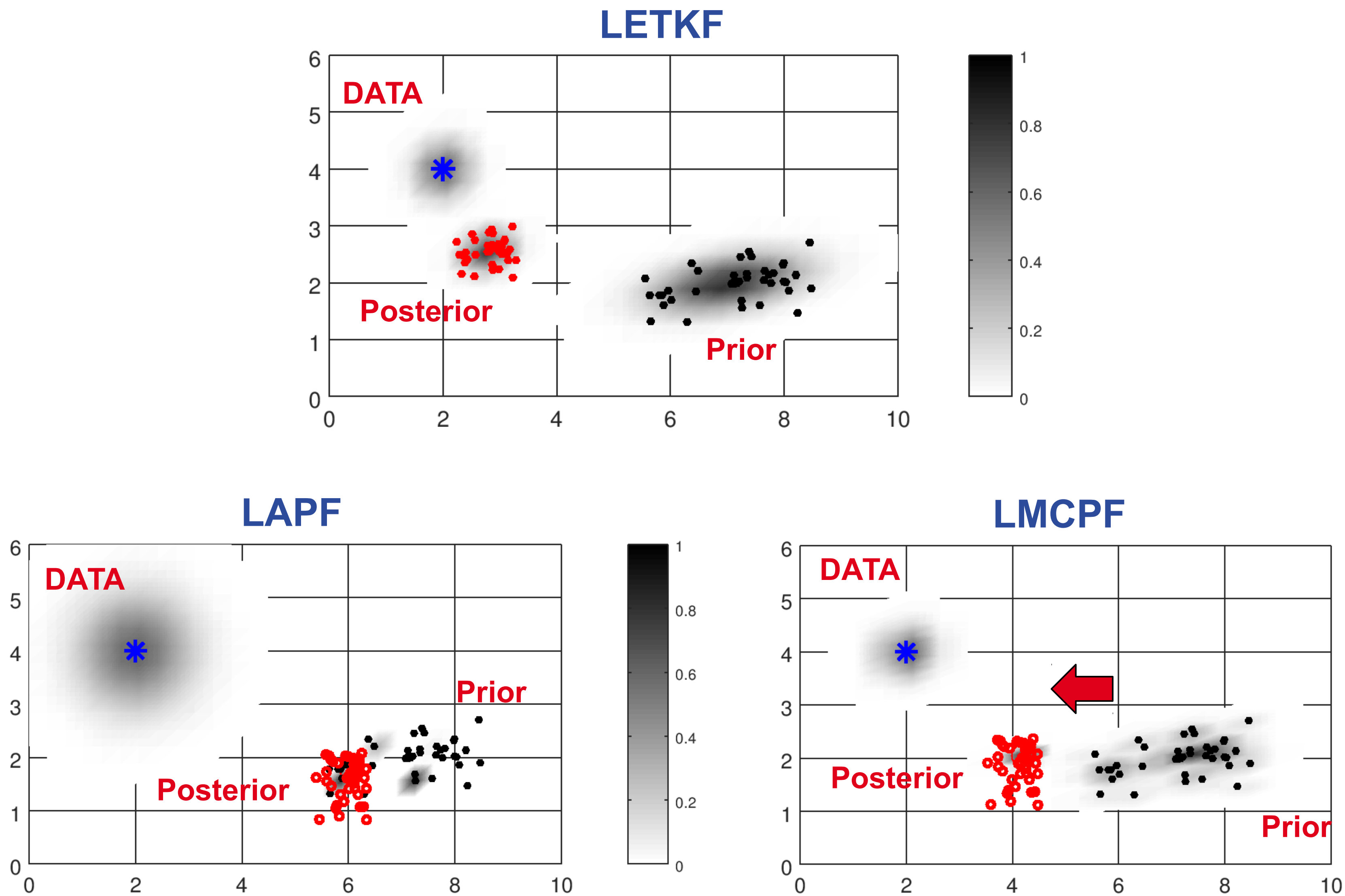
with R_{nd} normally distributed random numbers





An example for a W-Matrix after applying σ determined with the LAPF for 60°N/90°O ≈500 hPa, 26.05.2016 0 UTC is shown.
➔ 10 particles are chosen

4. The LMCPF


LETKF
DATA
Posterior
Prior
0
1
2
3
4
5
6
0
2
4
6
8
10
0
0.2
0.4
0.6
0.8
1
LAPF
DATA
Prior
Posterior
LMCPF
DATA
Posterior
Prior

Fourth Step: Gaussian Resampling

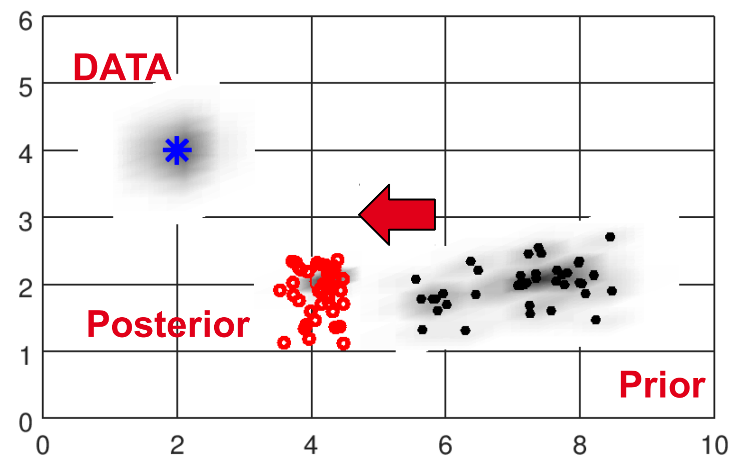
- **Weights W** are calculated by drawing from the posterior

- **Weights W** are calculated by drawing from the posterior

$$W = \underbrace{W + A_{shift} * W}_{\text{Centers of posterior RBFs}} + \underbrace{B_{post} * R_{nd} * \sigma}_{\text{Shape of posterior RBFs}}$$

with R_{nd} normally distributed random numbers,
A_{shift} and B_{post} calculated with Gaussian radial basis function (rbf) Approximation for prior density and observation error

with normally distributed random numbers,
and calculated with Gaussian radial basis function (rbf) Approximation for prior density and observation error



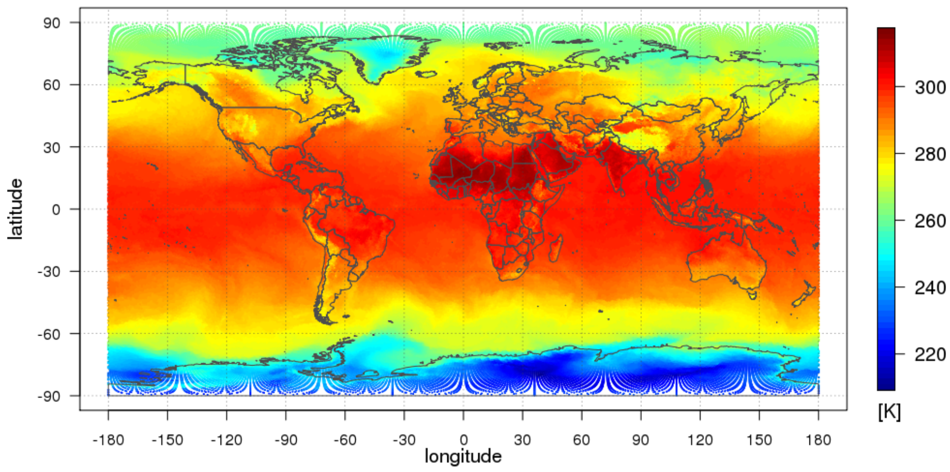
➢ It is an **explicit calculation** of the **Bayes posterior** based on **radial basis function approximation** of the prior.

5. Numerical Testing

Experimental set-up

- Full ensemble: 40 members
- Reduced resolution:
  - 26km deterministic
  - 52km ensembles
- Period:
  01.05.2016 – 31.05.2016

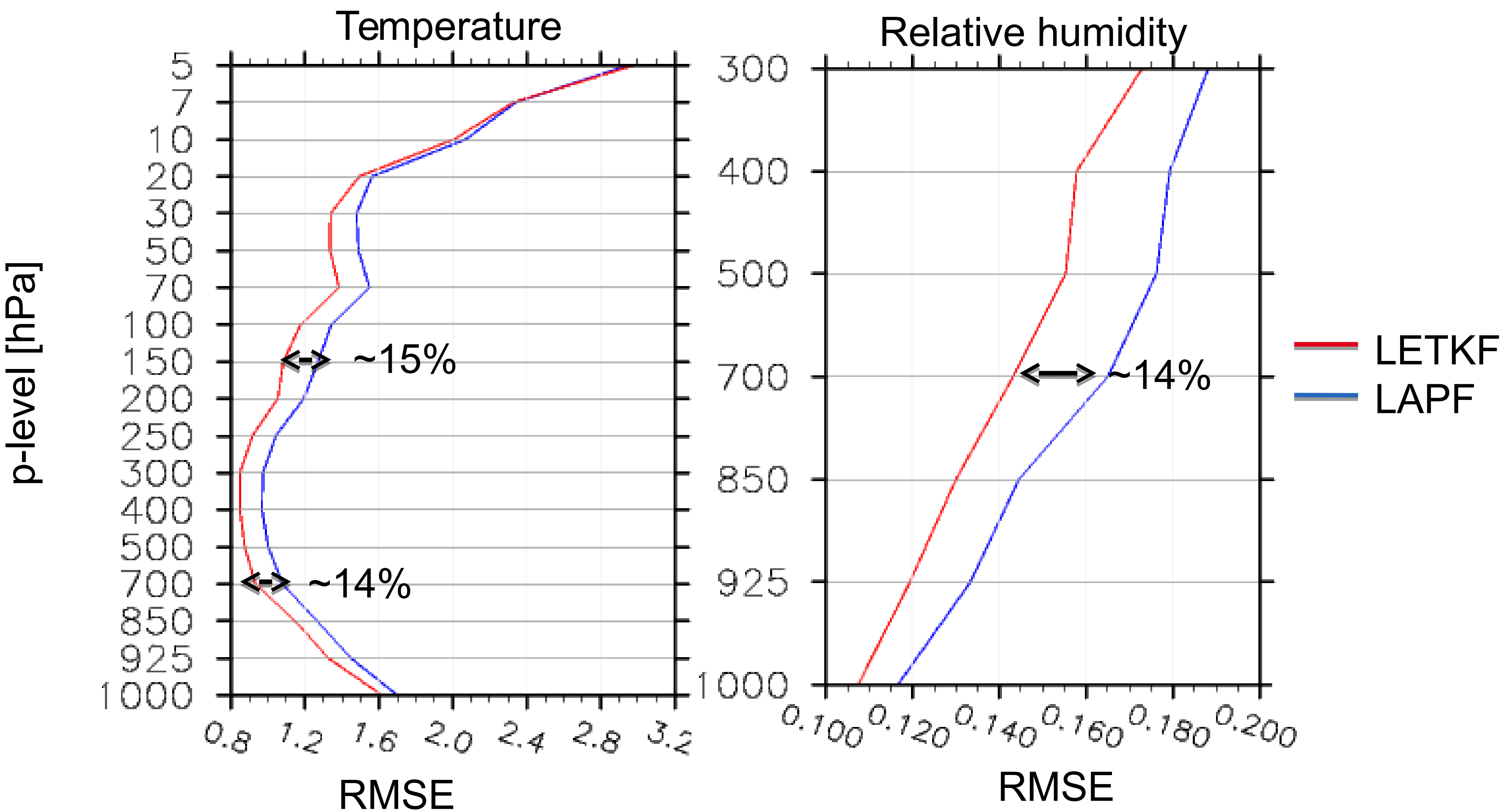
T [K] at 03.05.2016 15 UTC ~1000 hPa



5. Numerical Testing
Assimilation Cycle

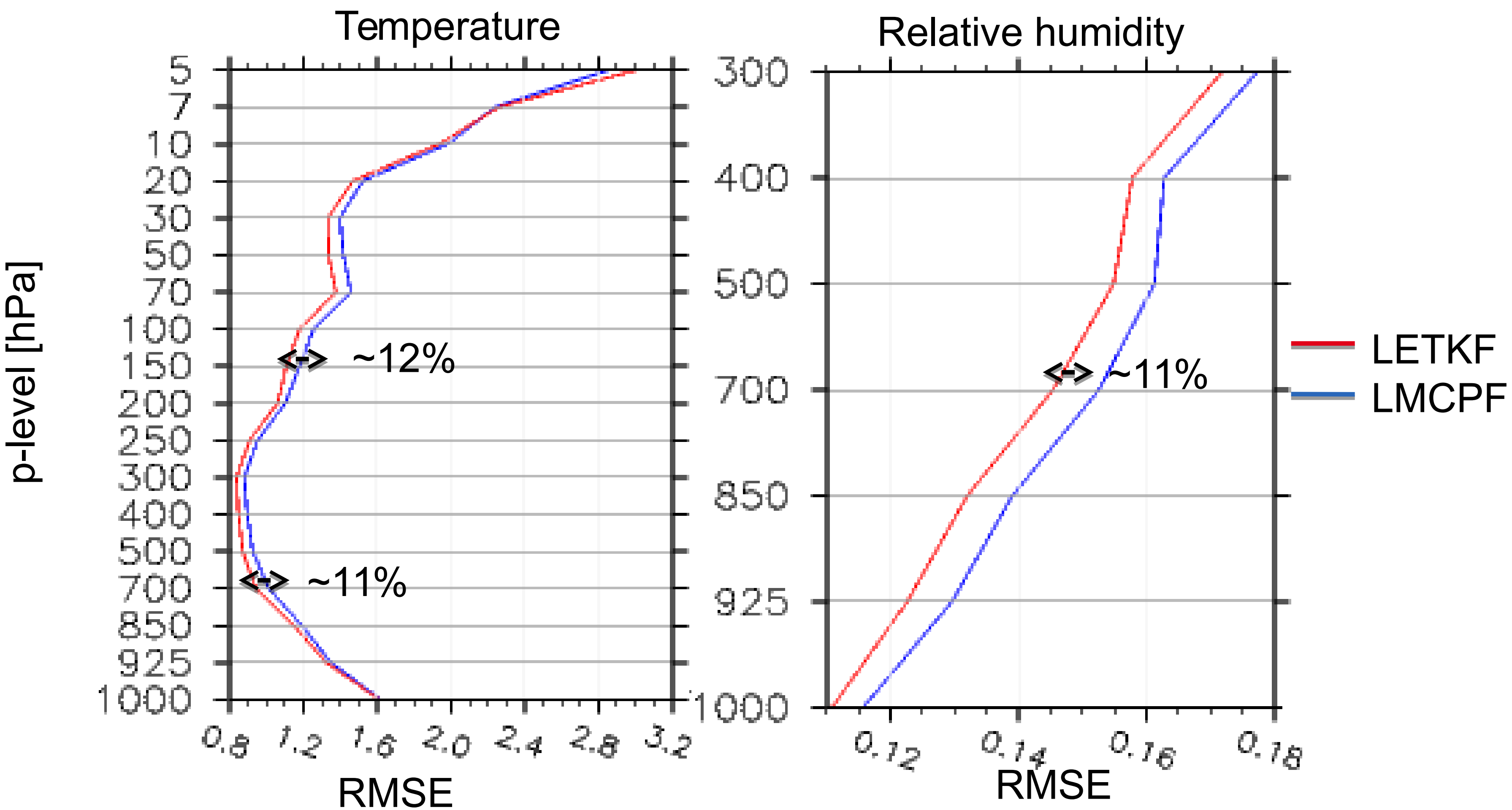
5. Numerical Testing - LAPF

Global **RMSE** for **obs-fg** statistics (Radiosondes vs. Model)
Period: 08.05.2016 – 31.05.2016



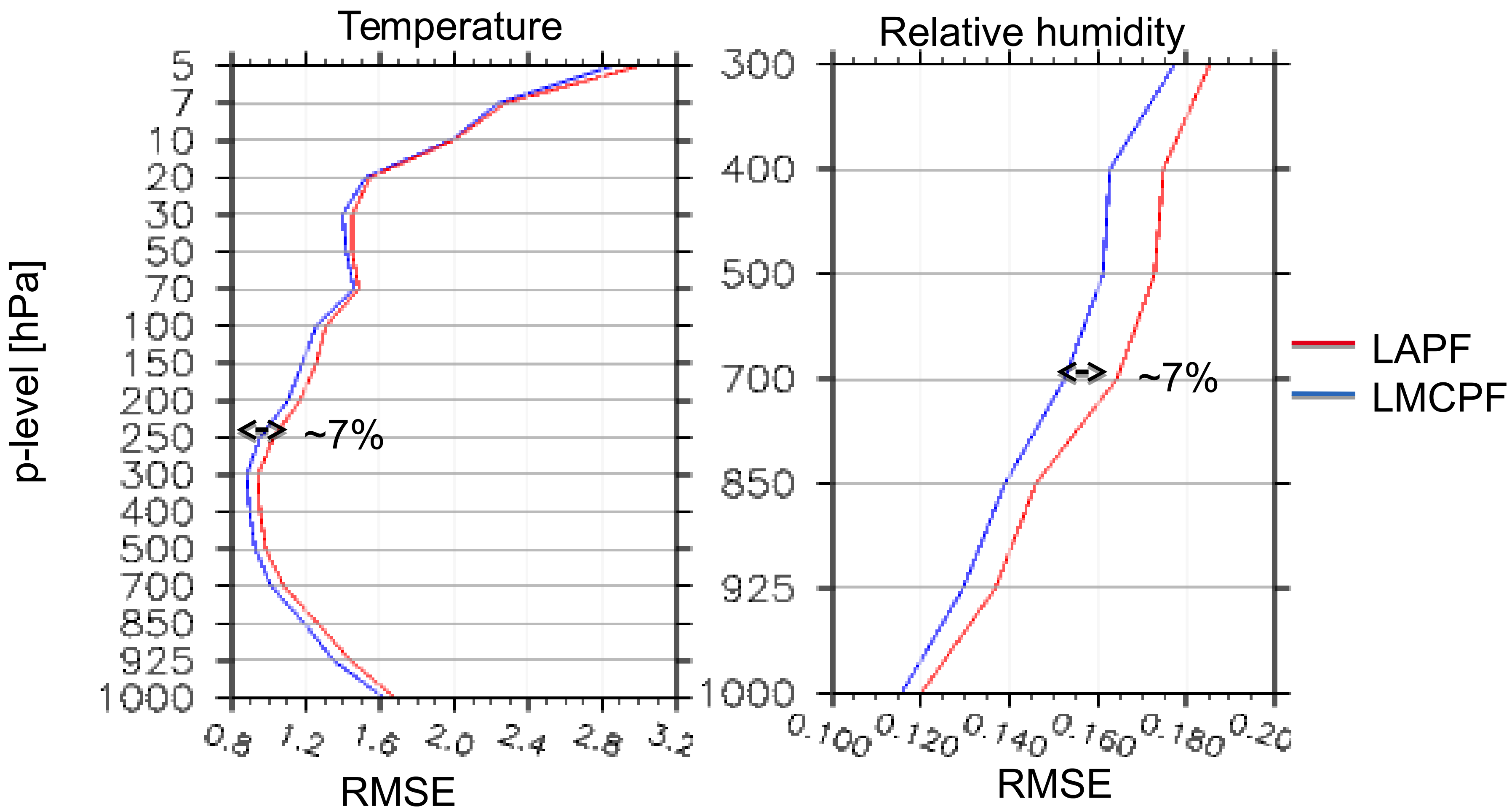
5. Numerical Testing - LMCPF

Global **RMSE** for **obs-fg** statistics (Radiosondes vs. Model)
Period: 08.05.2016 – 22.05.2016



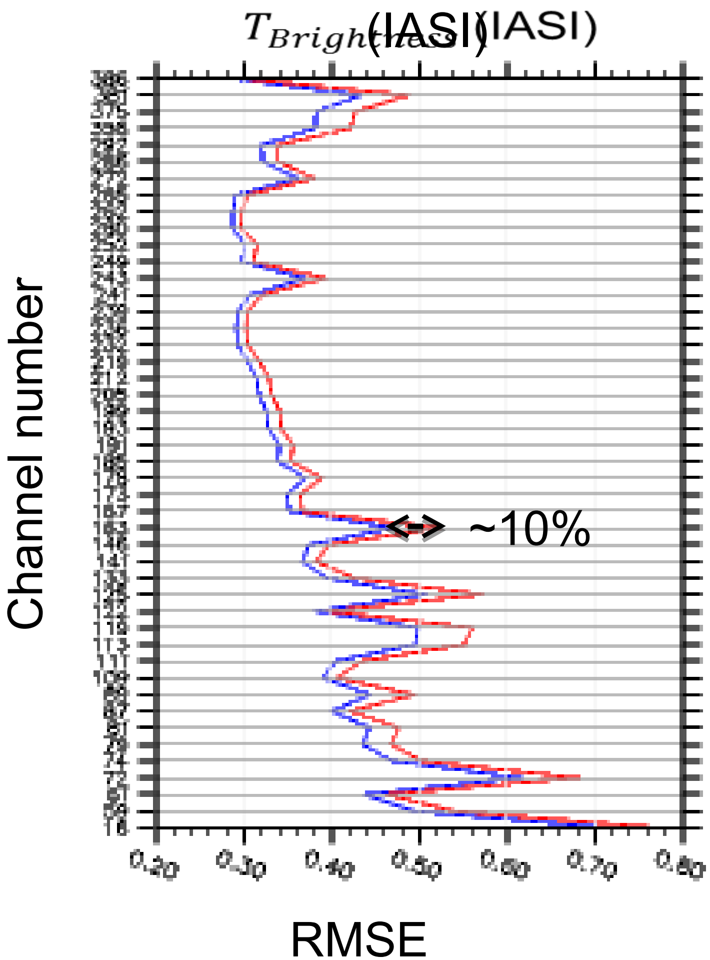
5. Numerical Testing

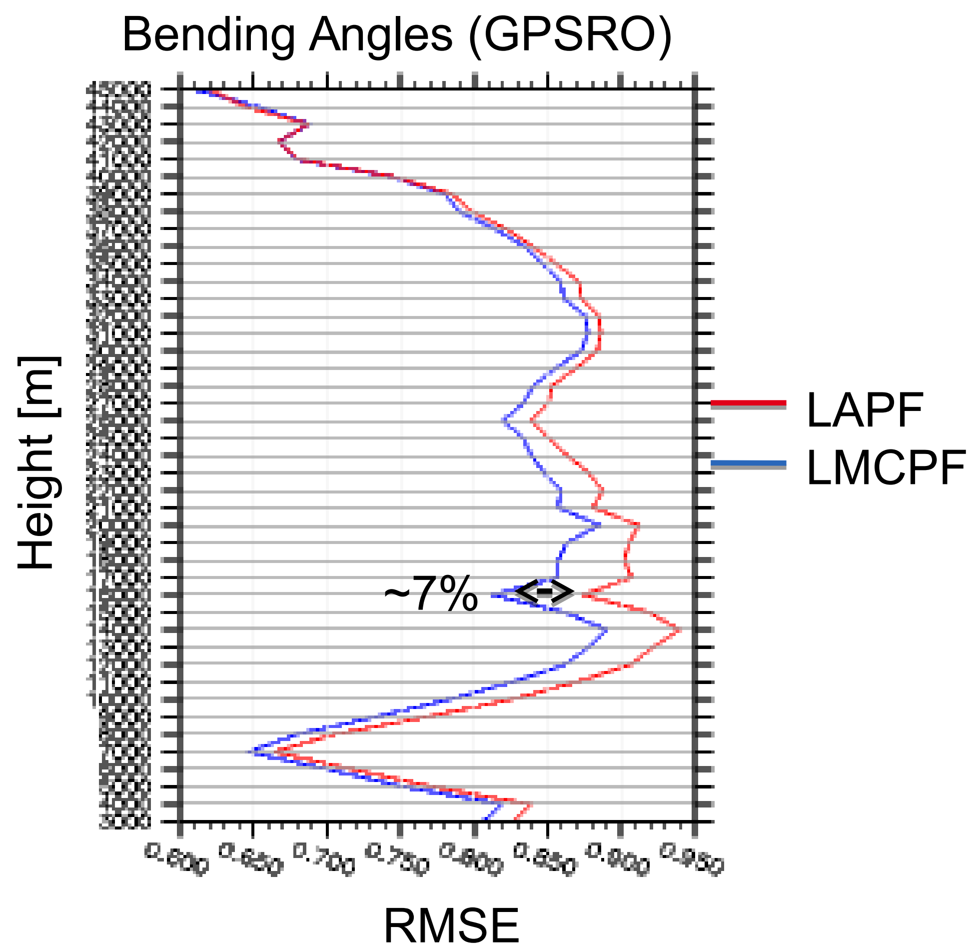
Global **RMSE** for **obs-fg** statistics (Radiosondes vs. Model)
Period: 08.05.2016 – 22.05.2016



5. Numerical Testing

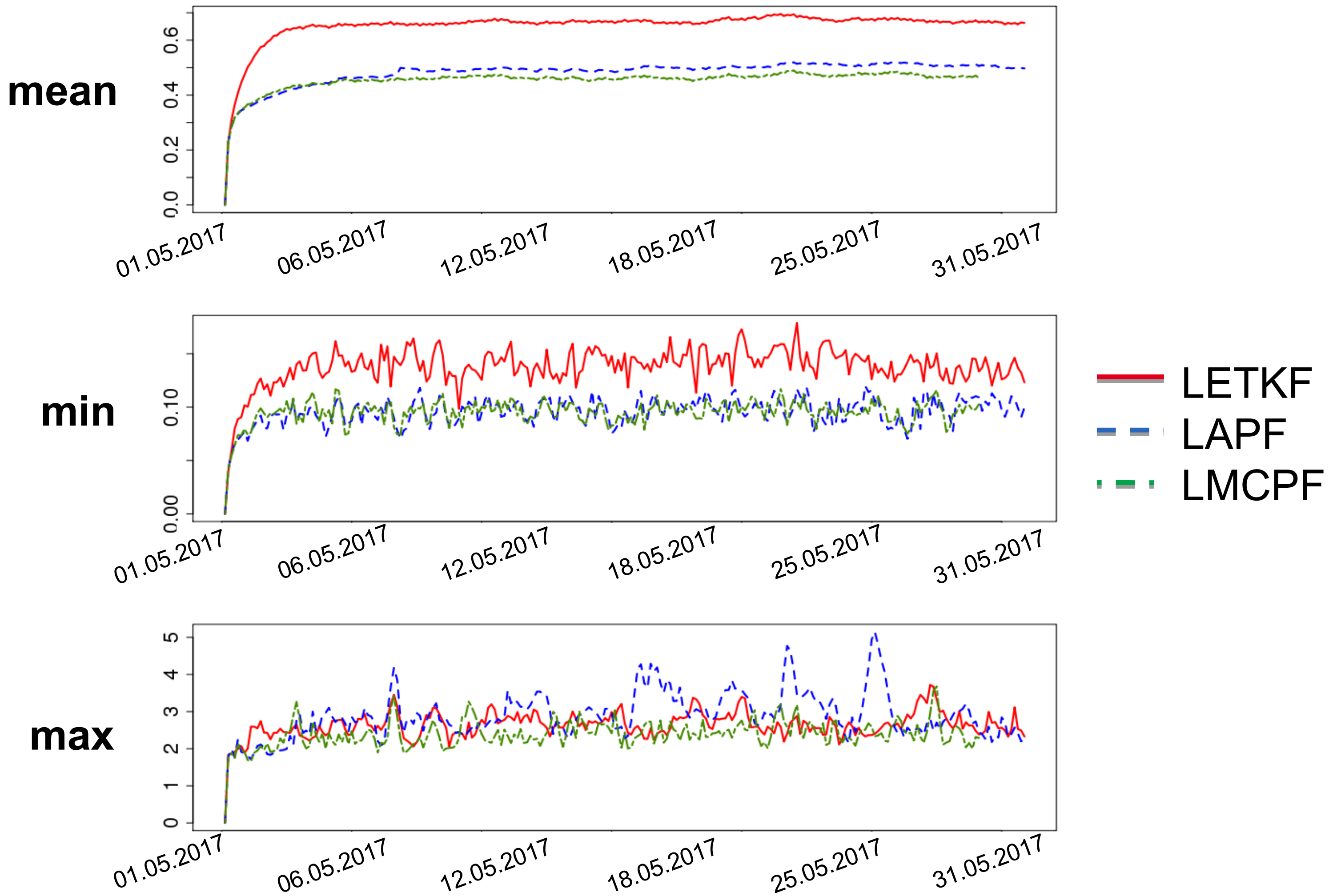
Global **RMSE** for **obs-fg** statistics
Period: 08.05.2016 – 22.05.2016





5. Numerical Testing

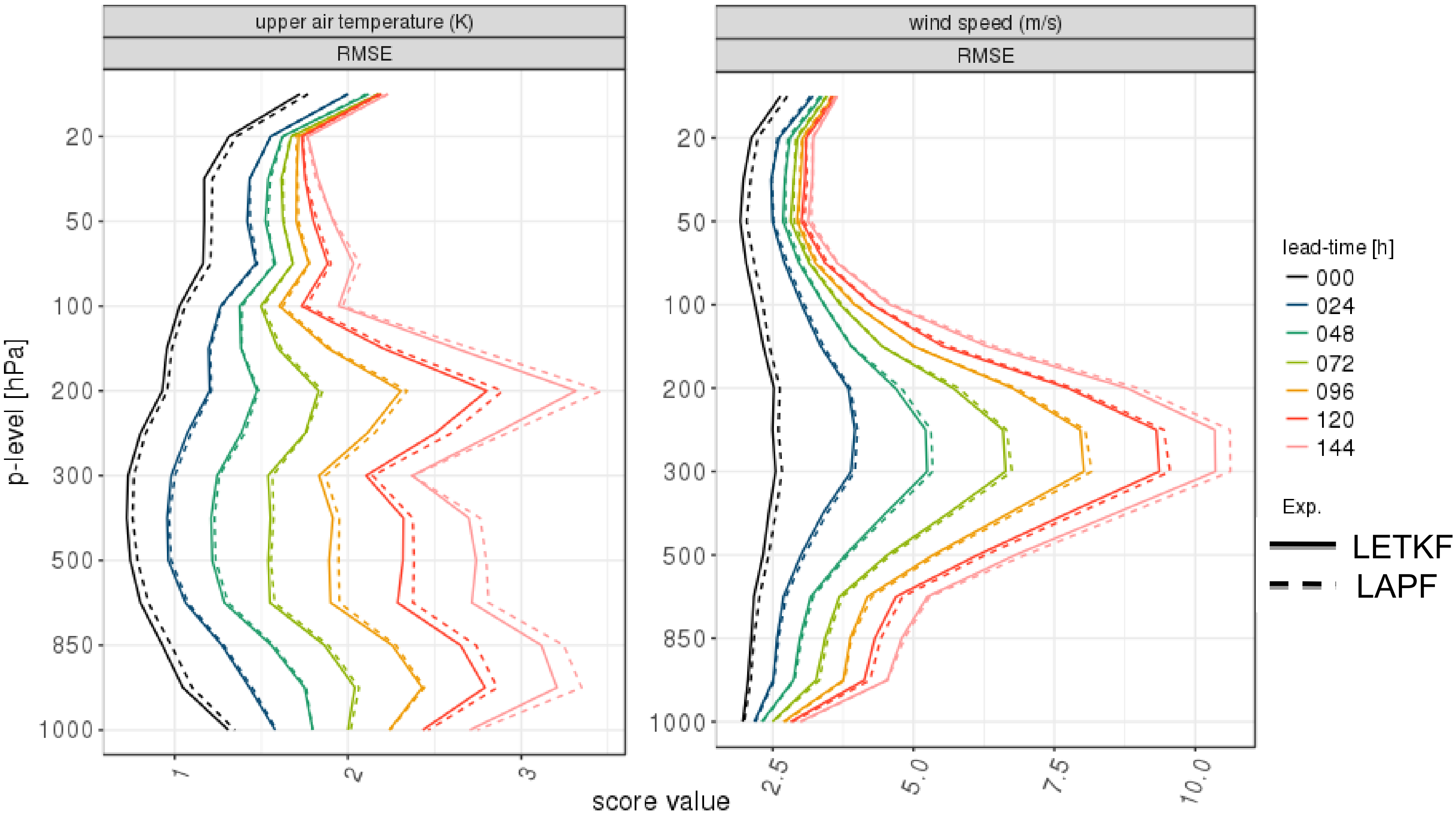
Global **spread** of T [K] ~ 500 hPa



5. Numerical Testing
Forecast Cycle

5. Numerical Testing - LAPF

Global verification of **different lead times against Radiosondes**
Period: 02.05.2016 – 24.05.2016



6. Summary

- LAPF and LMCPF implemented in an operational NWP system
- Both Particle Filters are able to provide reasonable atmospheric analysis in a large-scale environment and are running stably over a period of one month

- The LMCPF outperforms the LAPF but not yet the LETKF, but both Particle Filters nearly reach the results of the operational LETKF

➢ Both Particle Filters are showing promising results; further tuning is in progress.

References

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- Brian Hunt, Eric Kostelich and Istvan Szunyogh. *“Efficient data assimilation for spatiotemporal chaos: A local ensemble transform Kalman filter”*. Physica D: Nonlinear Phenomena, 2007
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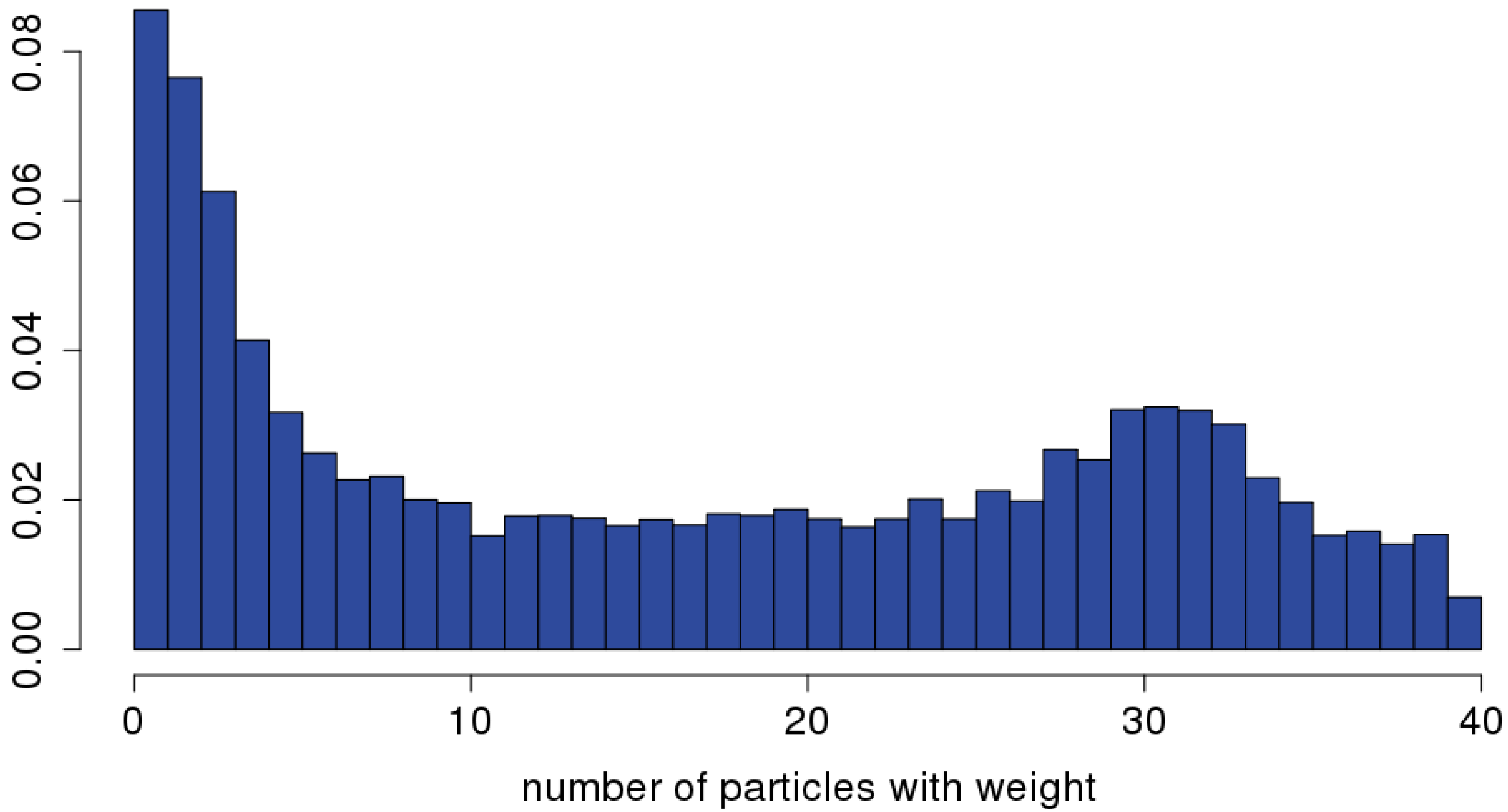
- Peter Jan van Leeuwen, Yuan Cheng and Sebastian Reich. *“Nonlinear Data Assimilation”*. Frontiers in Applied Dynamical Systems: Reviews and Tutorials. Springer, 2015

Thanks for the attention!

Appendix

Appendix

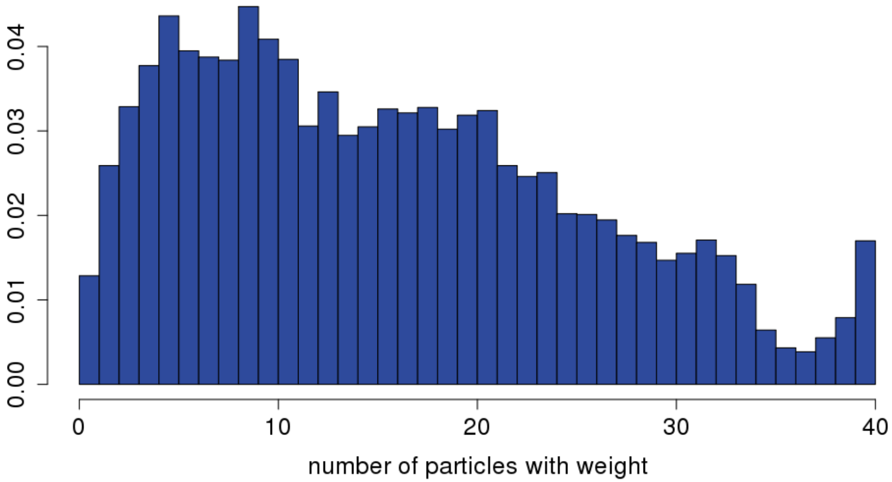
Global histogram of number of particles with weight
31.05.2016 21 UTC ~1000 hPa



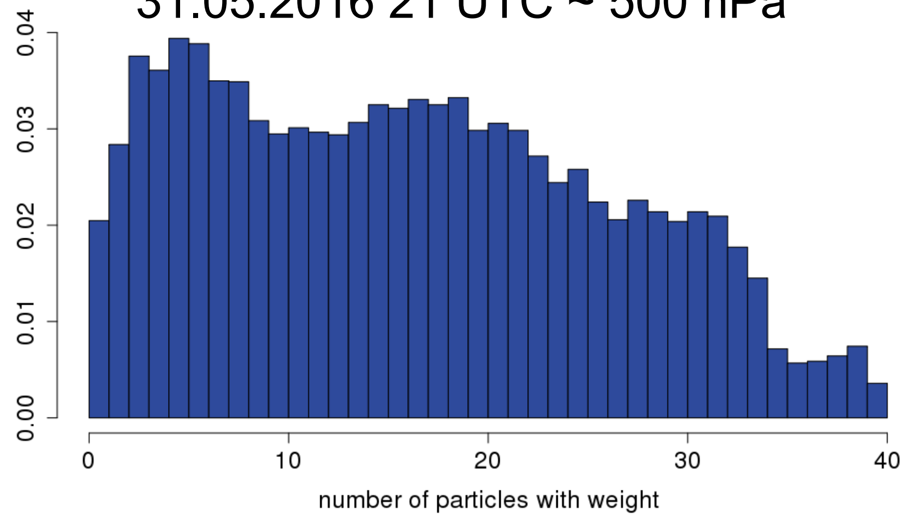
Appendix

Global histograms of number of particles with weight

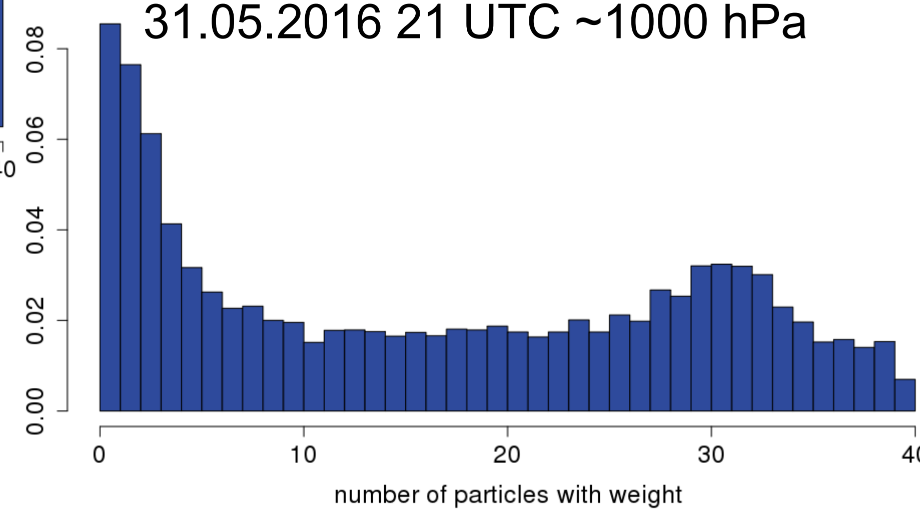
31.05.2016 21 UTC ~ 100 hPa



31.05.2016 21 UTC ~ 500 hPa

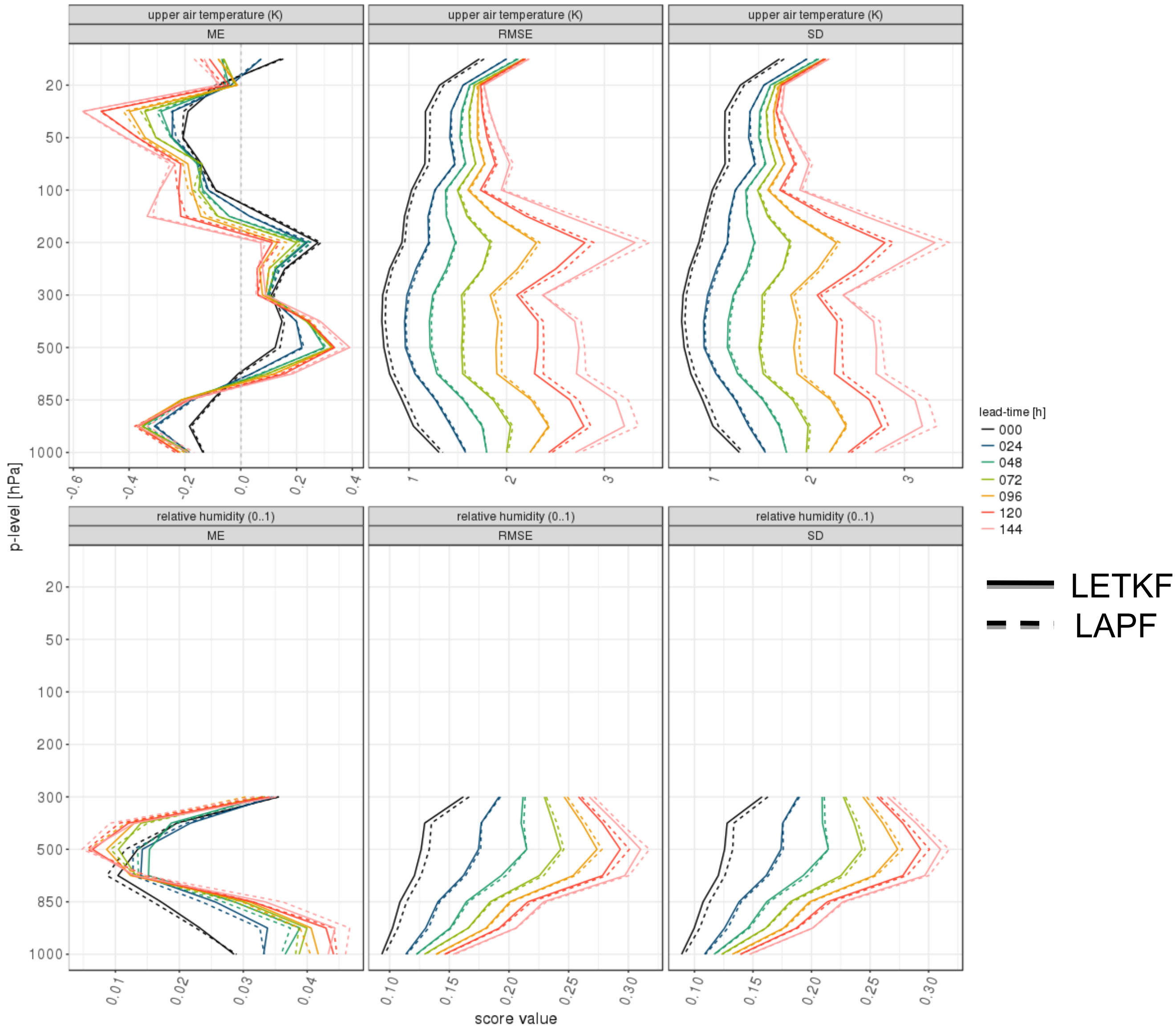


31.05.2016 21 UTC ~1000 hPa

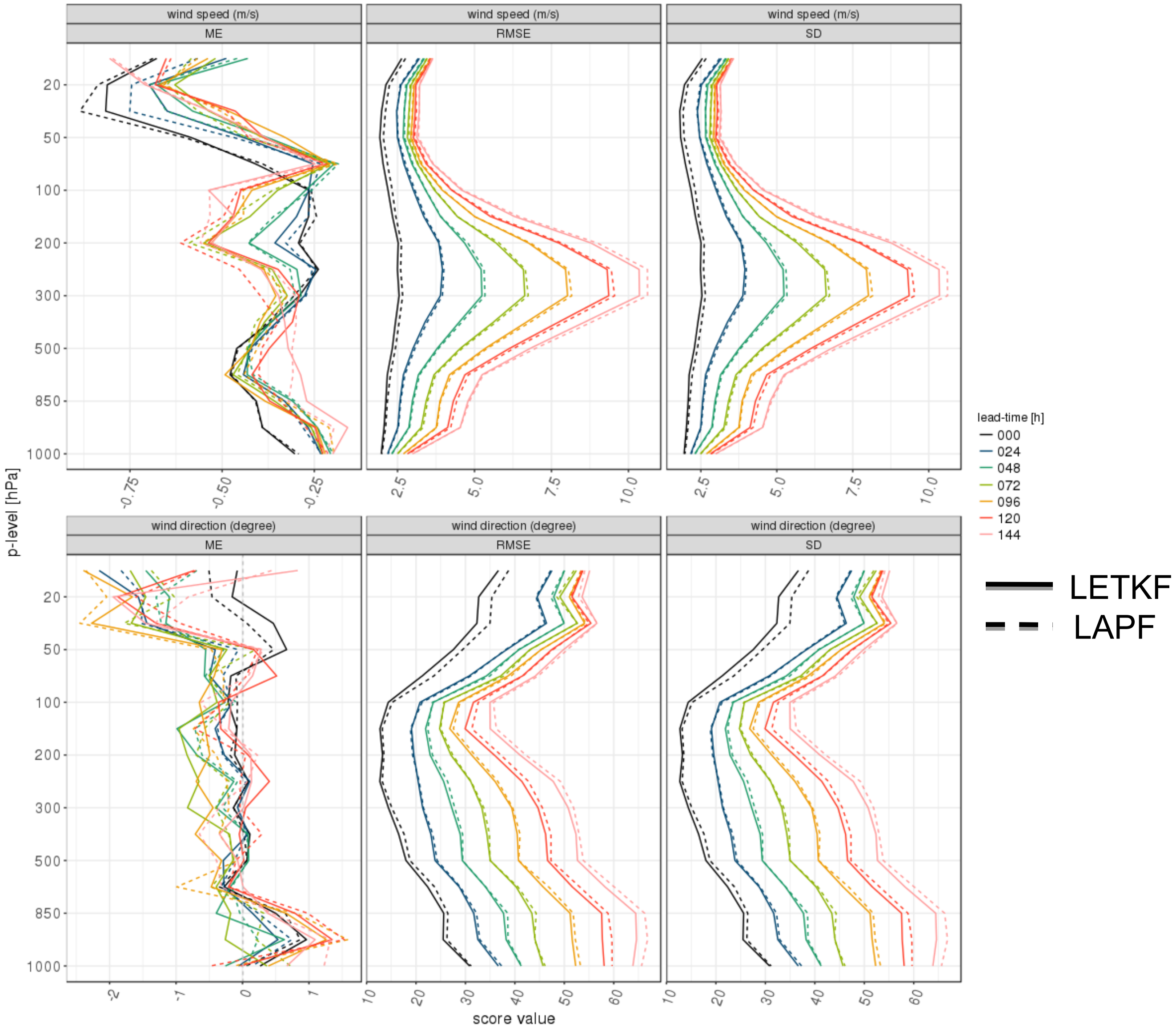


Appendix

Global verification of **different lead times against Radiosondes**
Period: 02.05.2016 – 24.05.2016



Appendix



Global verification of **different lead times against Radiosondes**
Period: 02.05.2016 – 24.05.2016