Nonlinear Methods for Data Assimilation and Inversion

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DWD & University of Reading

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Anne Walter
Andreas Rhodin
Nora Schenk
Peter-Jan van Leeuwen
…
and many people of DWD Data Assimilation (FE12)

Contents

1. Framework **Operational Numerical Weather Prediction** (NWP): **Earth System Modeling!**
2. Discussion of **Ensemble (+Particle) Methods**
3. Global+LAM+LES Model: **ICON** and **ICON-EPS** and the **LEKTF+EnVAR/KENDA** System
4. **LAPF & LMCPF Particle Filters** for Non-Gaussian Distributions – Details and Results

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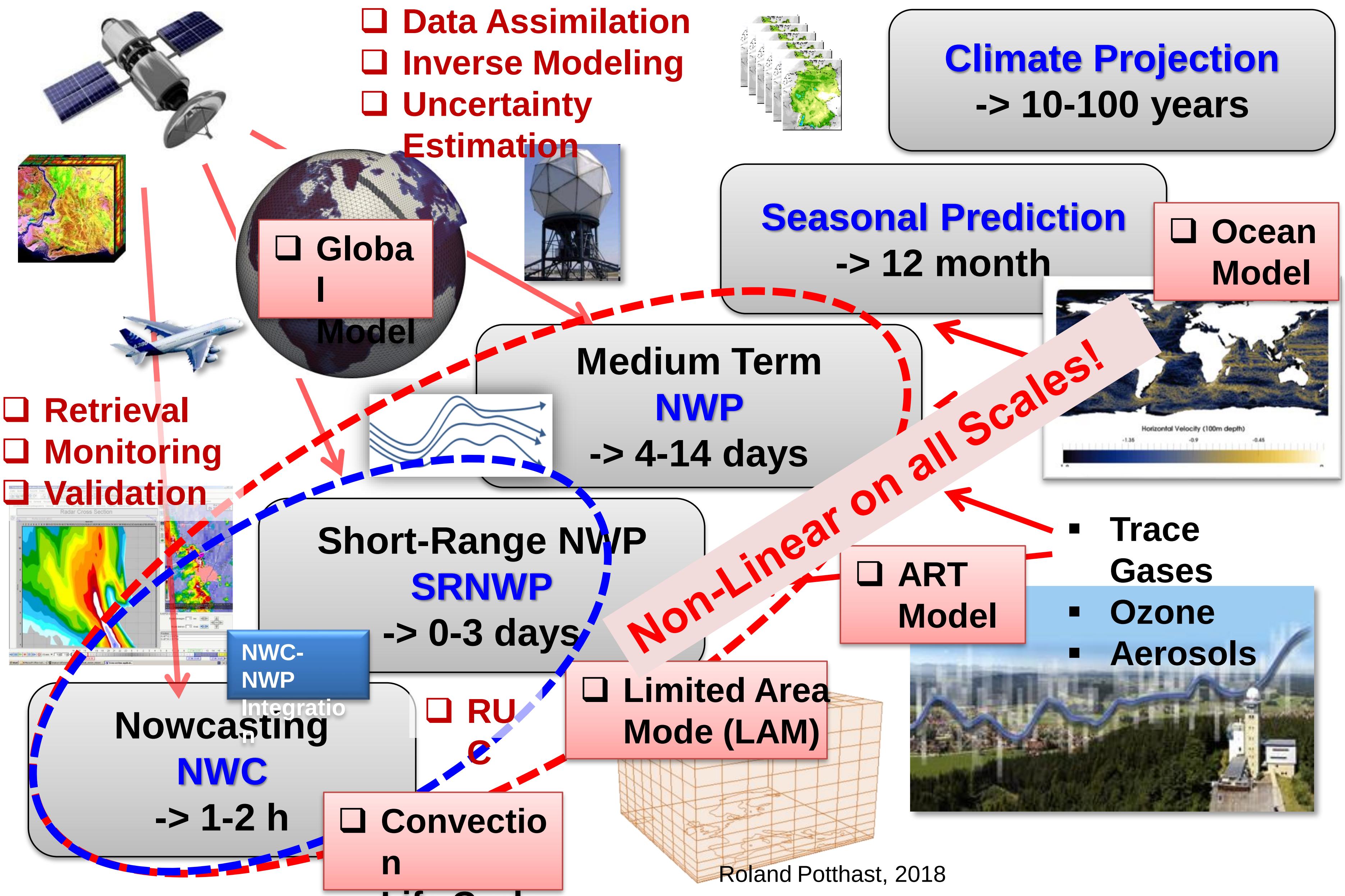
Framework Numerical Weather Prediction



Roland Potthast, 2018

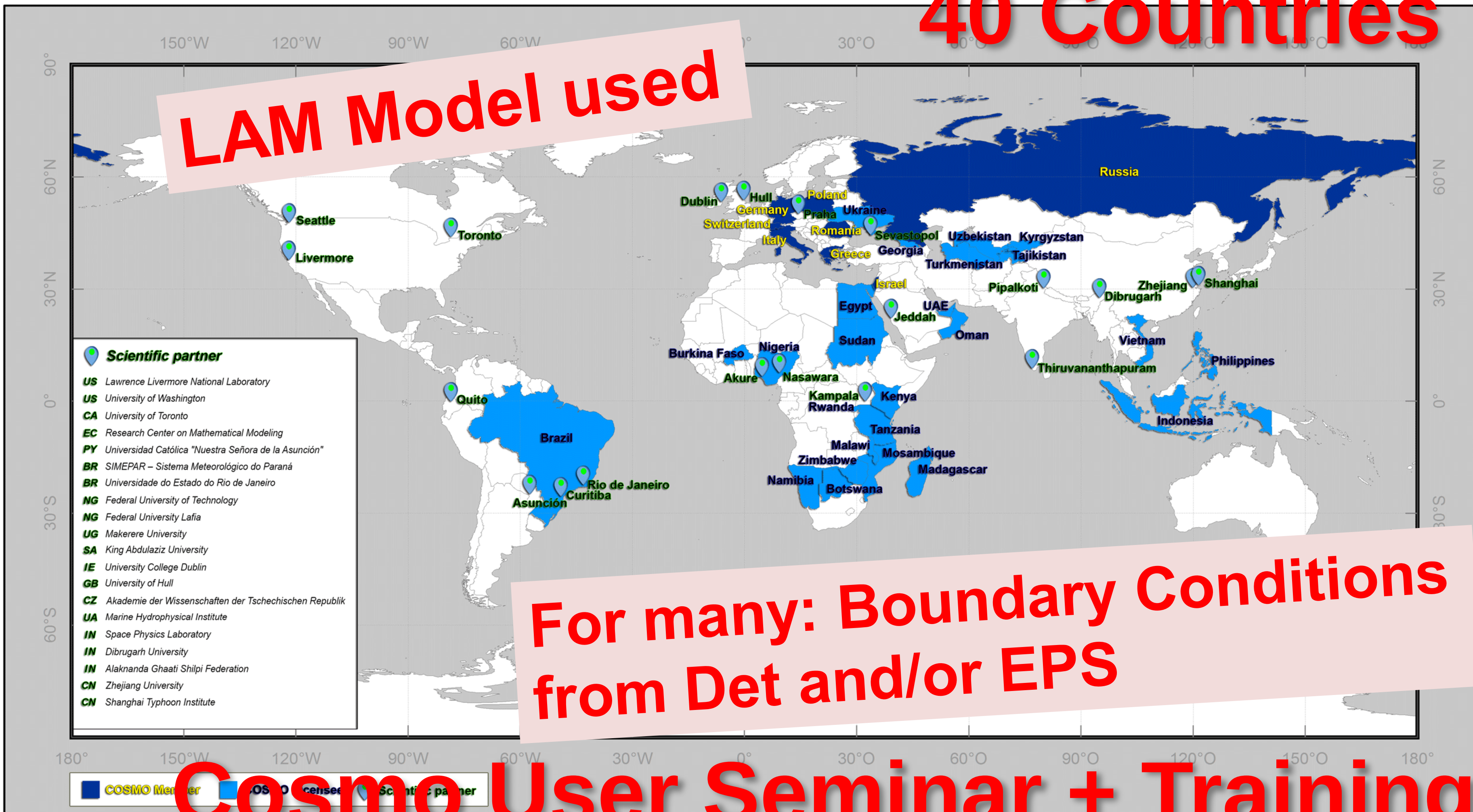
CONSORTIUM FOR SMALL SCALE MODELING

COSMO

Deutscher Wetterdienst
Wetter und Klima aus einer Hand
DWD

40 Countries

LAM Model used

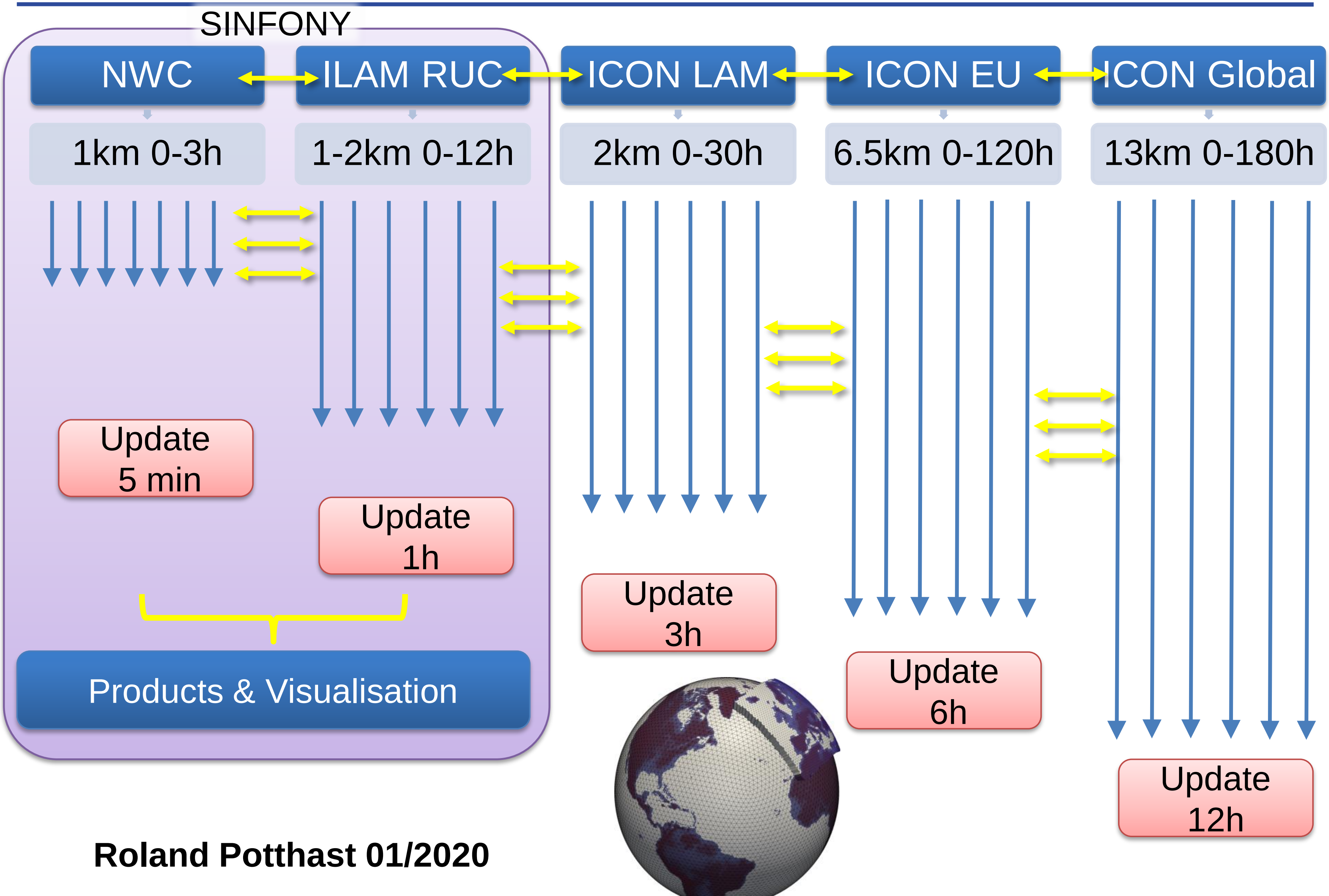


For many: Boundary Conditions from Det and/or EPS

Cosmo User Seminar + Training Course + Symposium

DWD Model Configurations

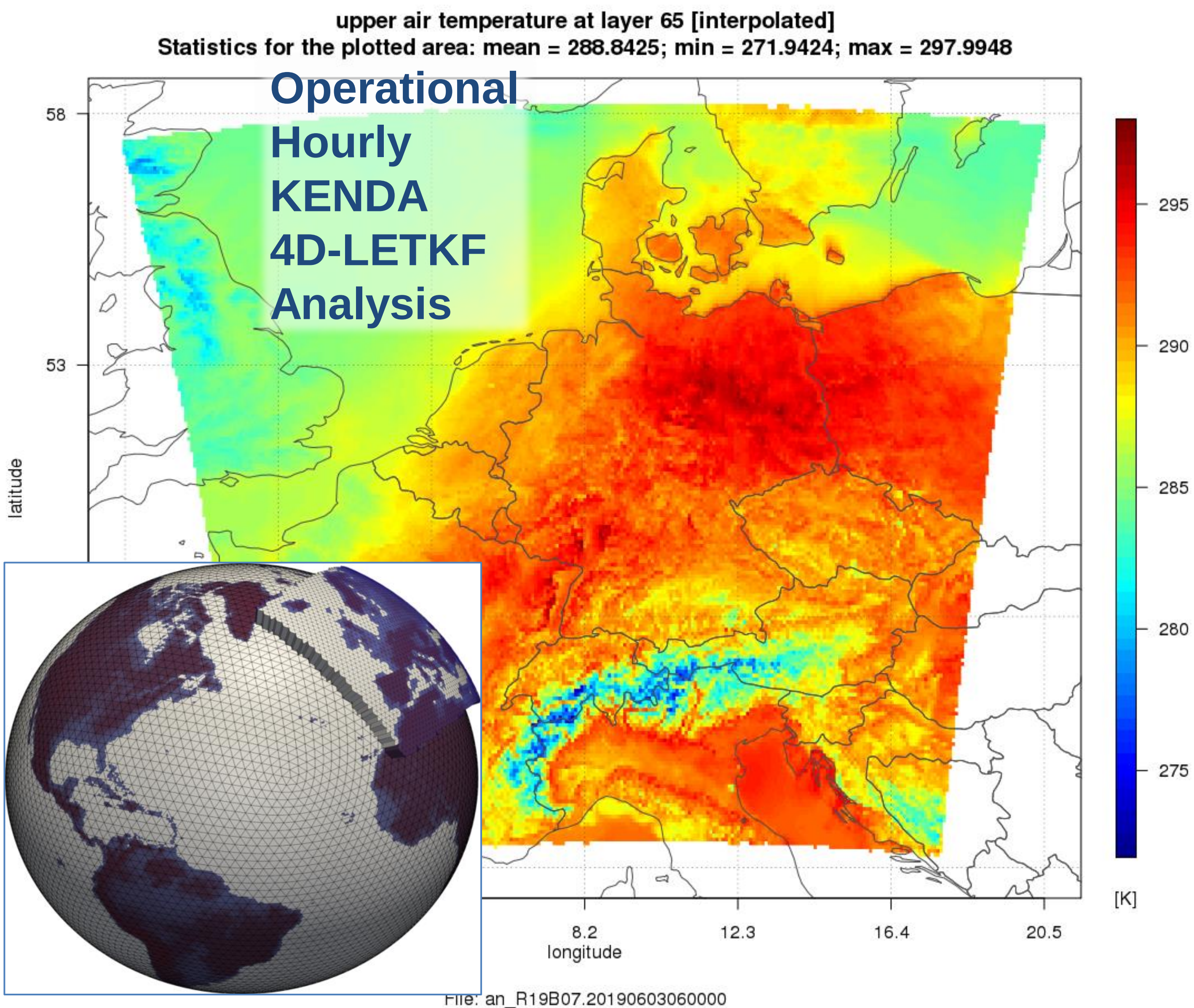
Deutscher Wetterdienst
Wetter und Klima aus einer Hand



Roland Potthast 01/2020

ICON Global, EU and D2

Deutscher Wetterdienst
Wetter und Klima aus einer Hand



OPERATIONS

AIREP
MODE-S
PILOT
TEMP
DRIBU
SYNOP
RADAR LHN
RADAR RW

Development

RADAR 3D
SYNOP T,RH
RADAR OBJ
SEVIRI IR
SEVIRI VIS
Lightning LPI
MWR
GB Remote
Crowd Source
RADAR DualP

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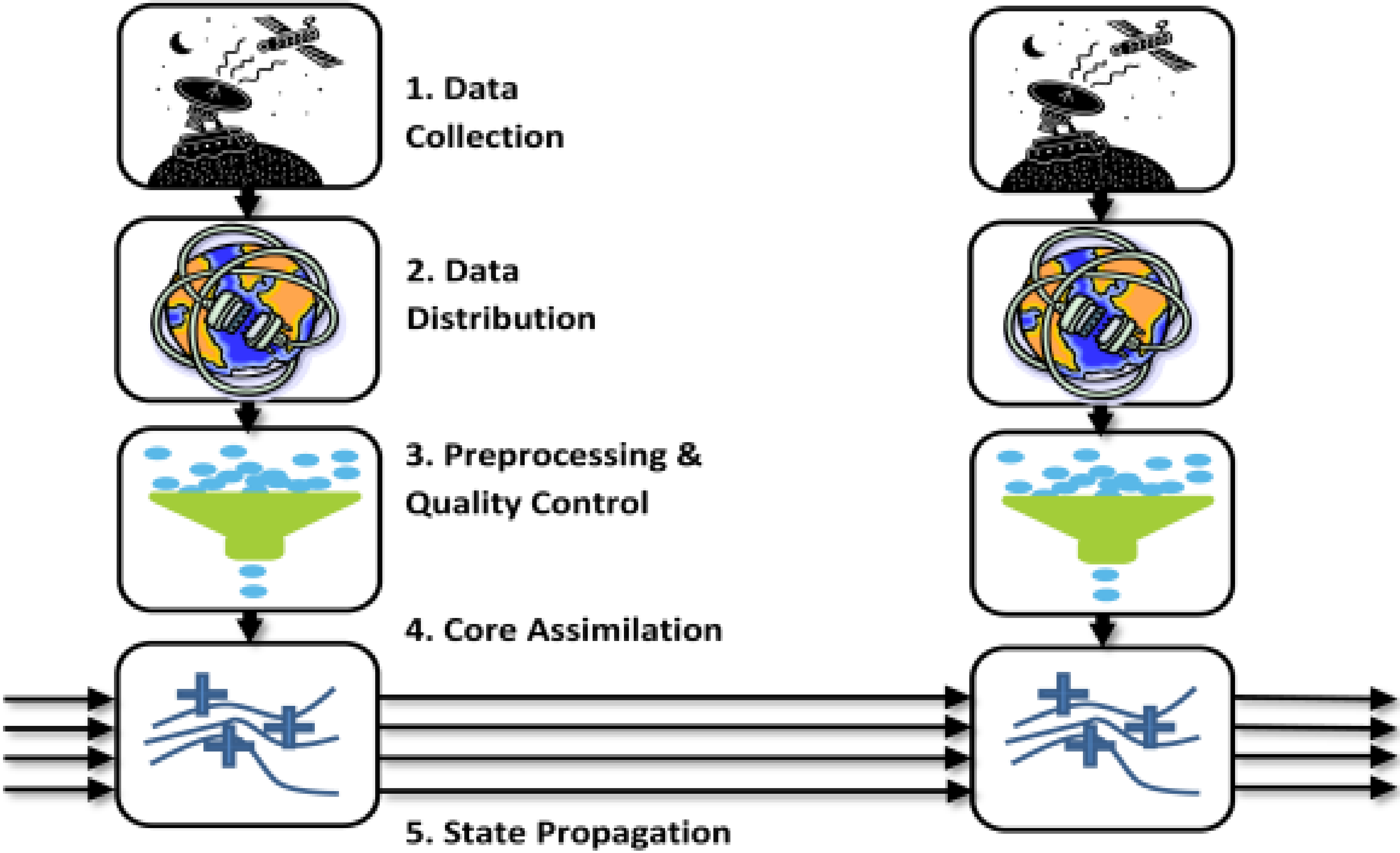
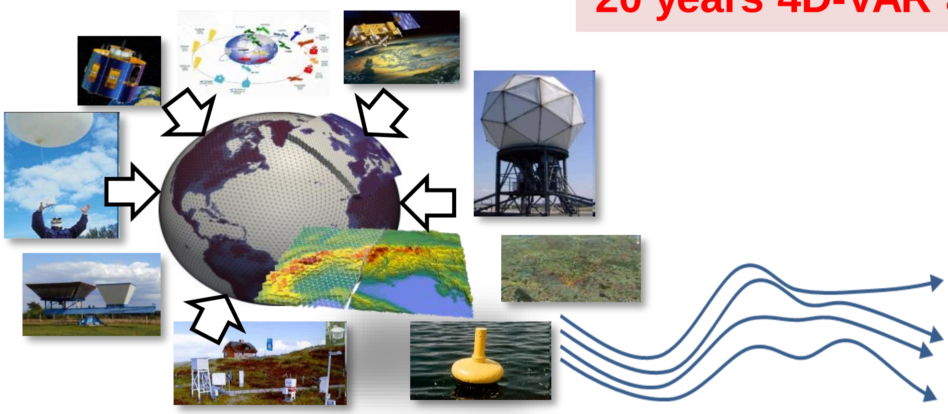
Data Assimilation Cycling

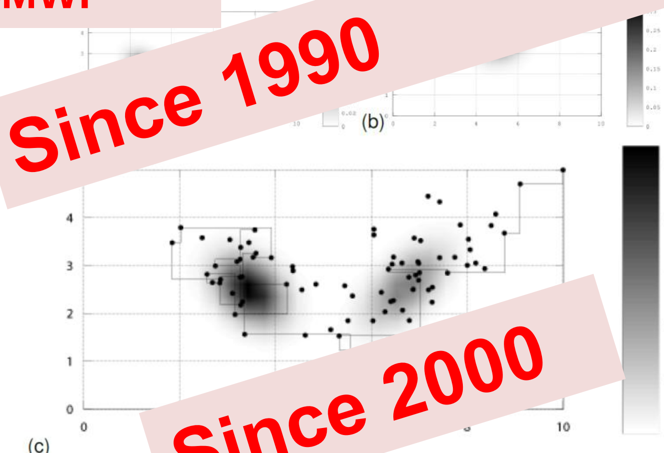


Data Assimilation Methods

- Why **variational** Data Assimilation (3D/4D-VAR)?

20 years 4D-VAR at ECMWF





Since 1990

- Why **Ensemble** Data Assimilation (EDA)

Since 2000

- Why **Hybrid** Methods? (3D/4D-EnVAR)

Since 2010

- Why Particle **Filters**? (PF,GPF,ETPF,LAPF,LMCPF)

Since 2020

☺

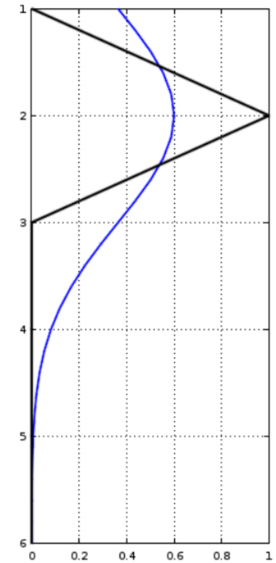
Variational Analysis (3D/4D-VAR)

The minimization of

Obs Operator

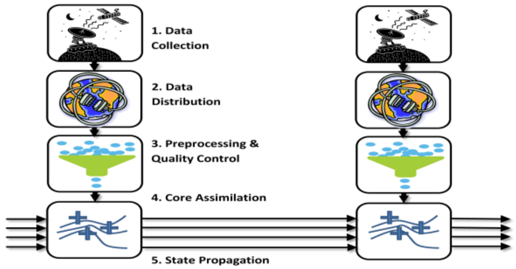
$$J(x) = \|x - x^b\|^2_{B^{-1}} + \|y - Hx\|^2_{R^{-1}}$$

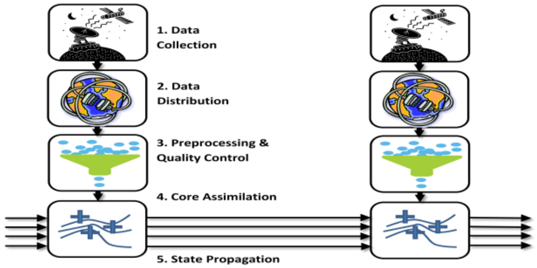
leads to the **analysis**

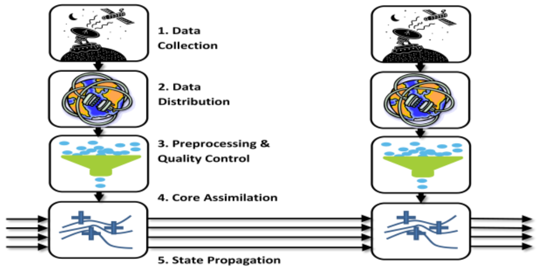


$$x^a = x^b + B\,H^T\left(R + H\,B\,H^T\right)^{-1}(y - Hx^b)$$

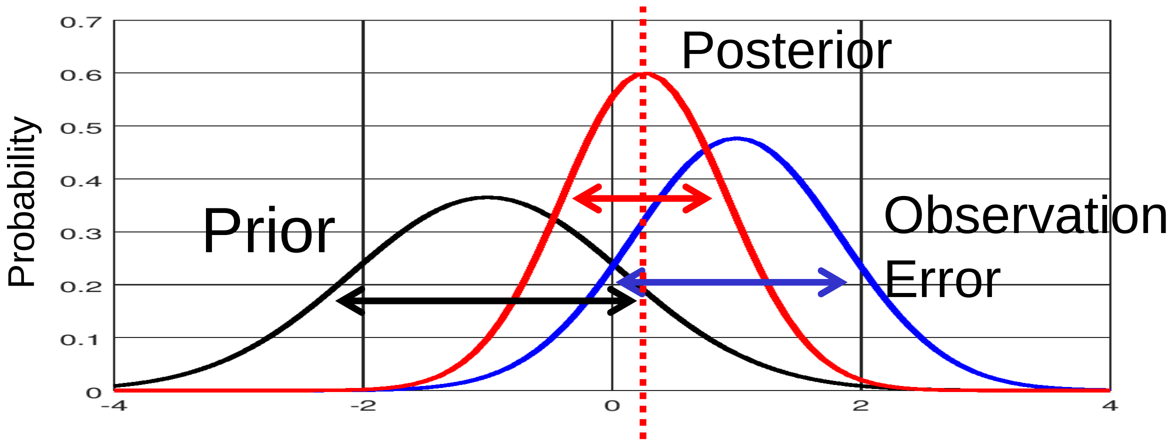
This is the mother of all data assimilation formulas







Stochastic View ⇔ Minimization



Var == Mean/ ML estimator!

- **Gaussian Prior**

$$p(x) = e^{-\frac{1}{2}(x-x^b)^T B^{-1}(x-x^b)}$$

- **Gaussian Data Error**

$$p(y|x) = e^{-\frac{1}{2}(y-Hx)^T R^{-1}(y-Hx)}$$

Maximum Likelyhood Estimator = Minimization of Functional = 3/4DVar

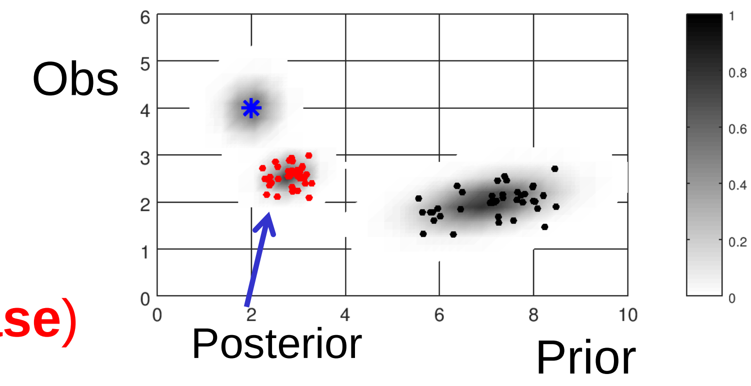
- **Gaussian Posterior**

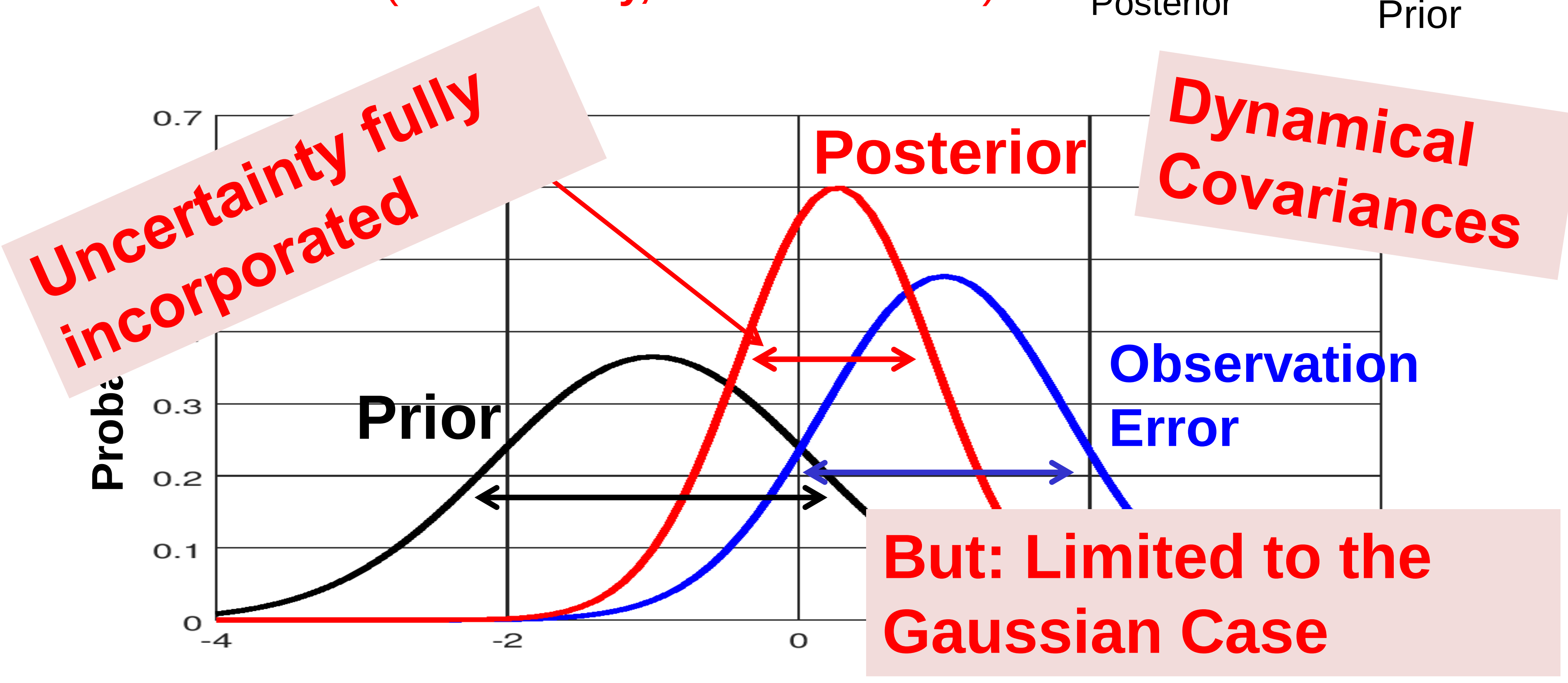
$$p(x|y) = c\, e^{-\frac{1}{2}\left\{\overbrace{(x-x^b)^T B^{-1}(x-x^b)+(y-Hx)^T R^{-1}(y-Hx)}\right\}}$$

Kalman Filter & Uncertainty Estimation

Basic Idea of the Kalman Filter

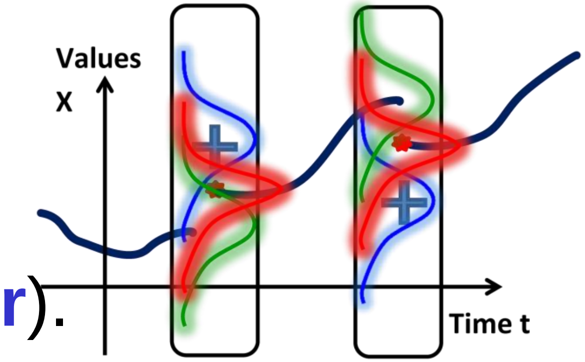
- **Sequentiel** Assimilation of Data
- Do not only adapt the mean, but also the **Covariance B (Uncertainty, Gaussian Case)**



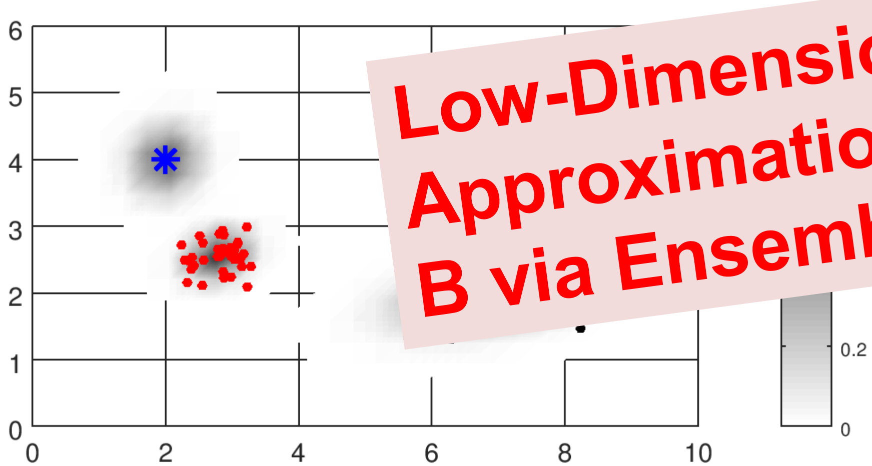


EDA: Ensemble Kalman Filter (EnKF)

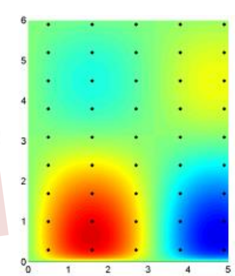
- Kalman Filter needs B update => **expensive**!
- **Estimate** B based on an ensemble of forecasted states (**stochastic estimator**).

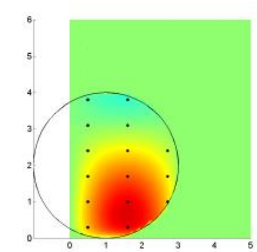


B will be **flow-dependent** and variable, depending on the **model dynamics** and on the **observations**



Low-Dimensional Approximation to full B via Ensemble!

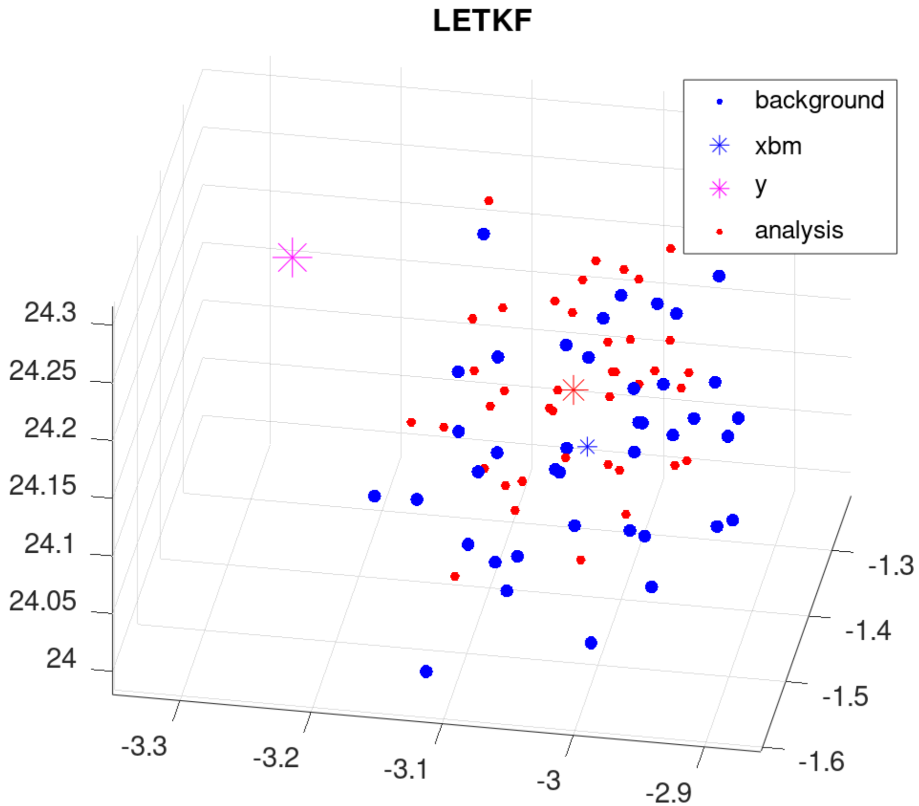




Needs

Localized: LETKF

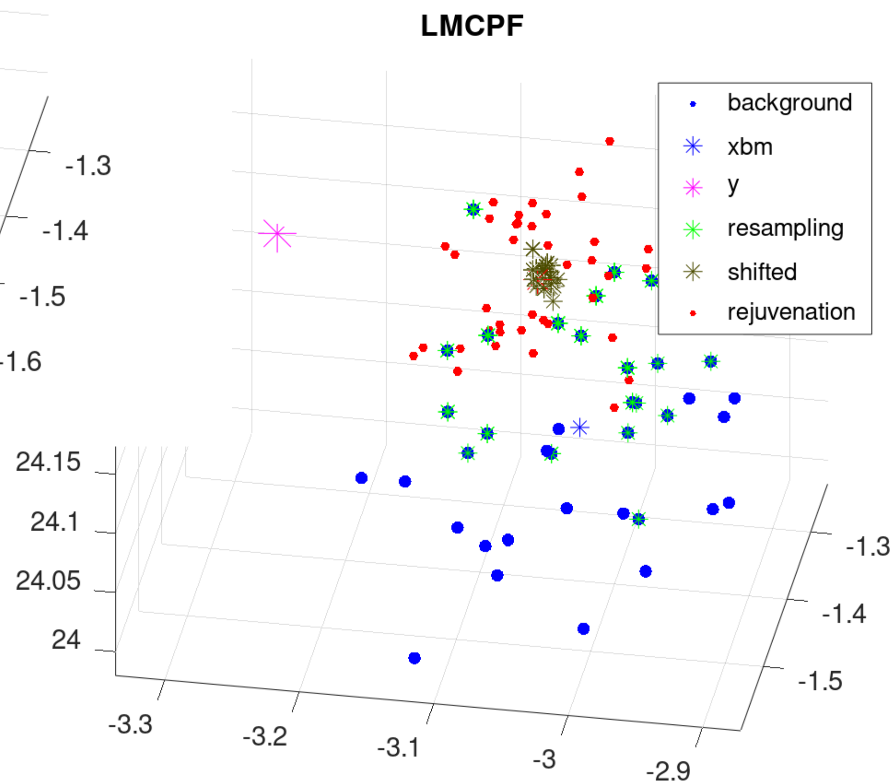
Ensemble Methods & PF



What does a particle stand for?

Drawn from some distribution:

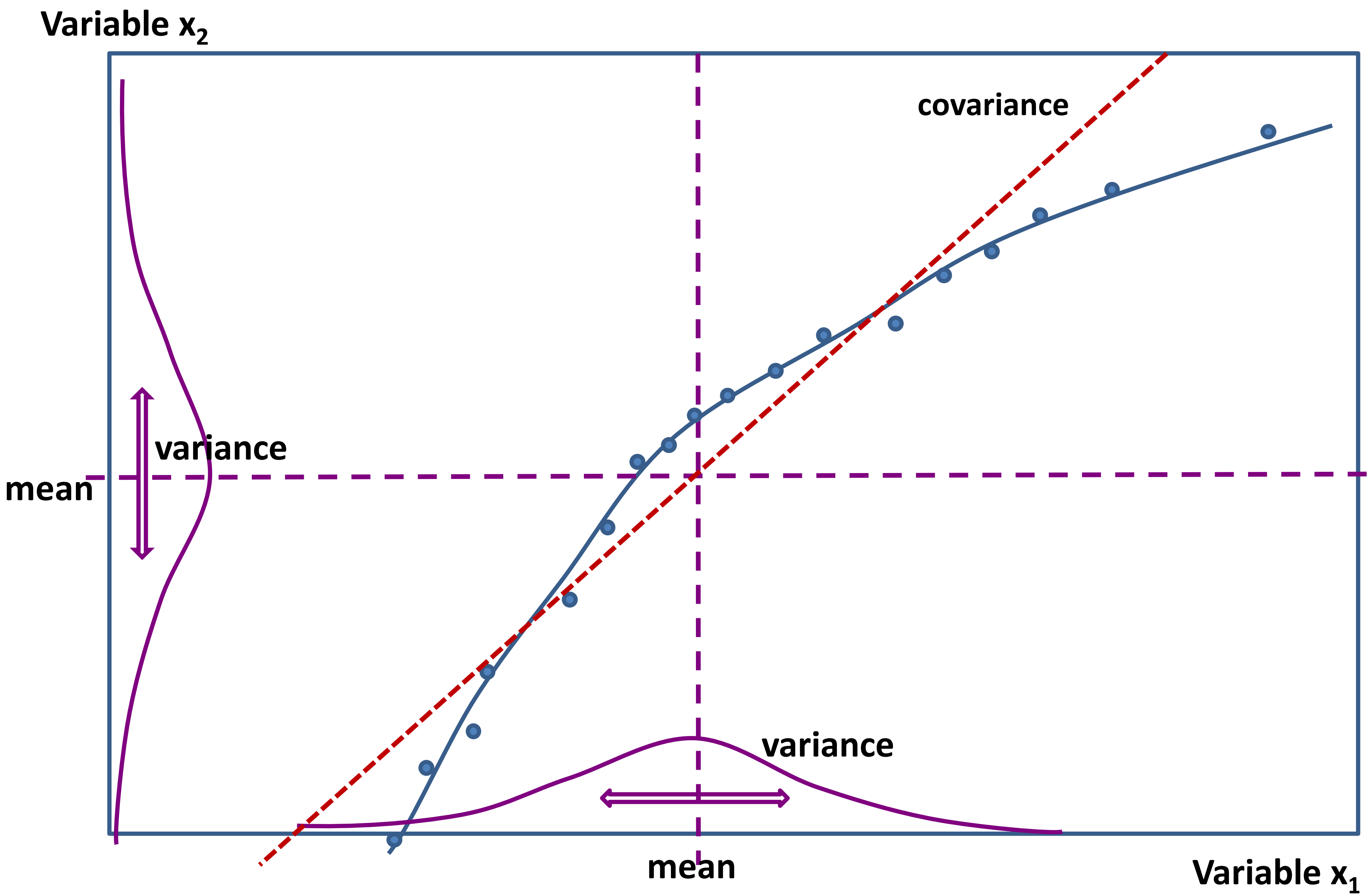
Representing the Distribution



Basics

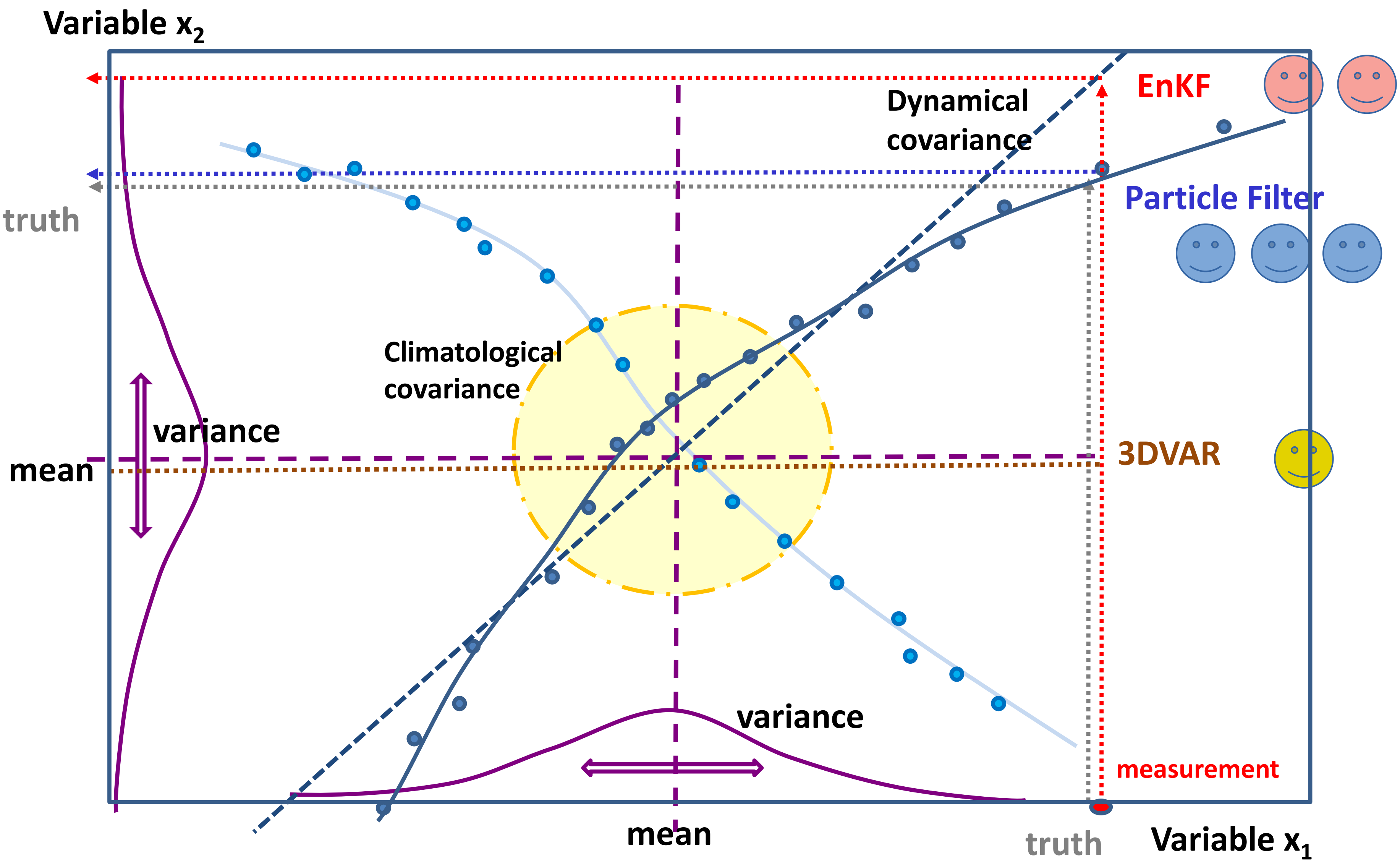
- Background
- Observation
- Weights
- Resampling

3D-VAR, EnKF and PF



3D-VAR, EnKF and PF

Deutscher Wetterdienst
Wetter und Klima aus einer Hand



Curse of Dimensionality

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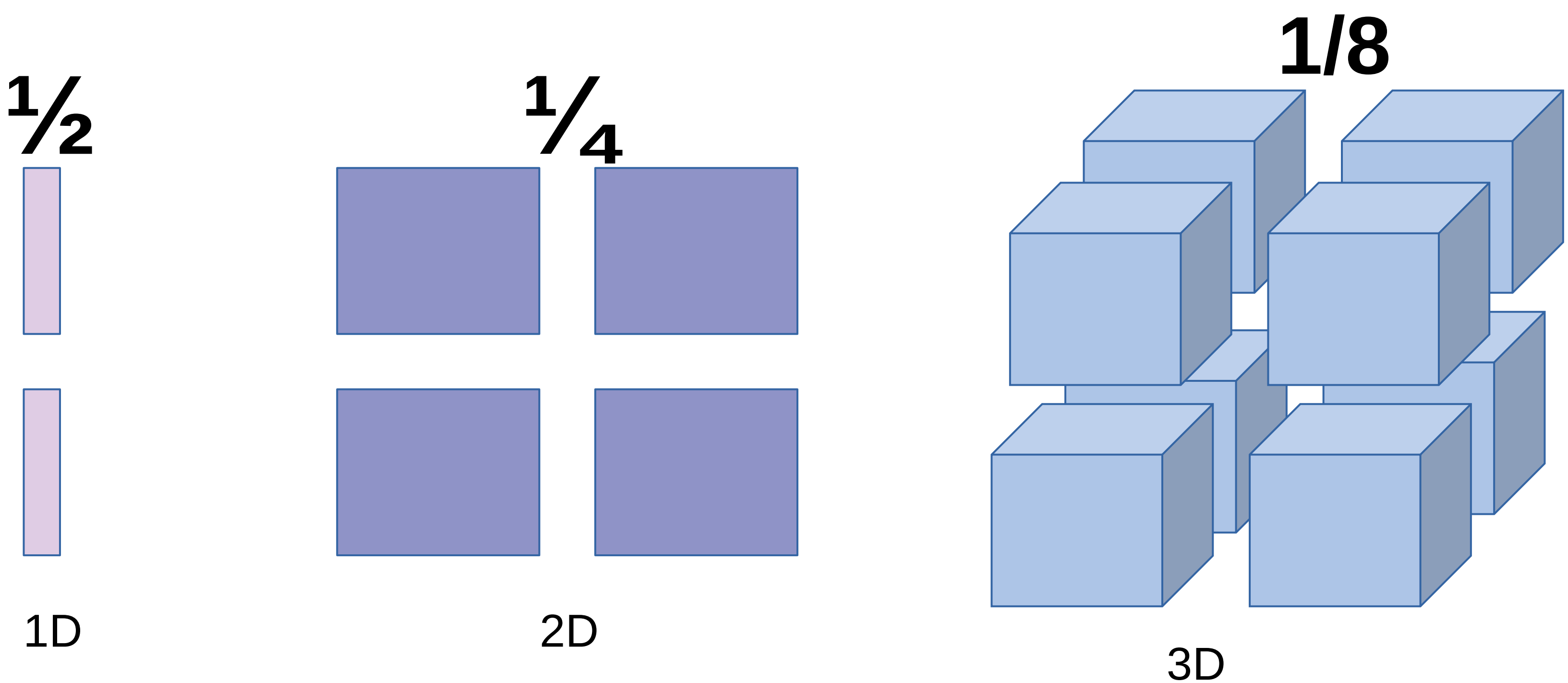
1) Curse of Dimensionality

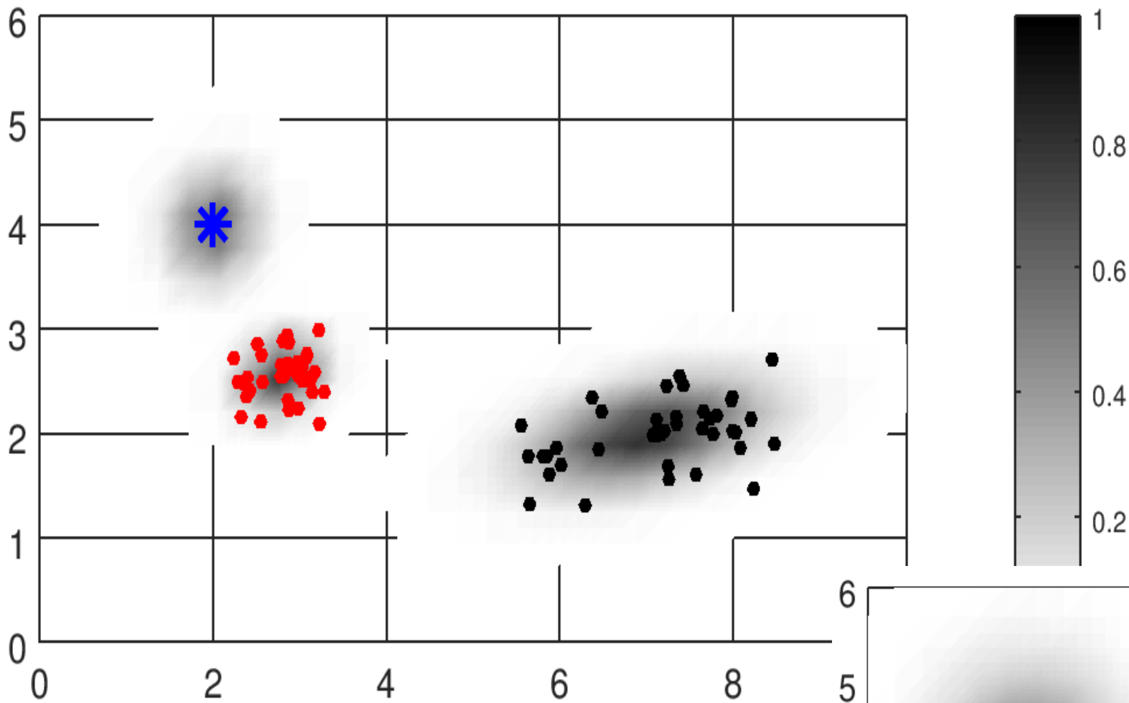
2) Low Ensemble Number

3) Dynamical System Errors

Practically you cannot sample from high-dimensional spaces!

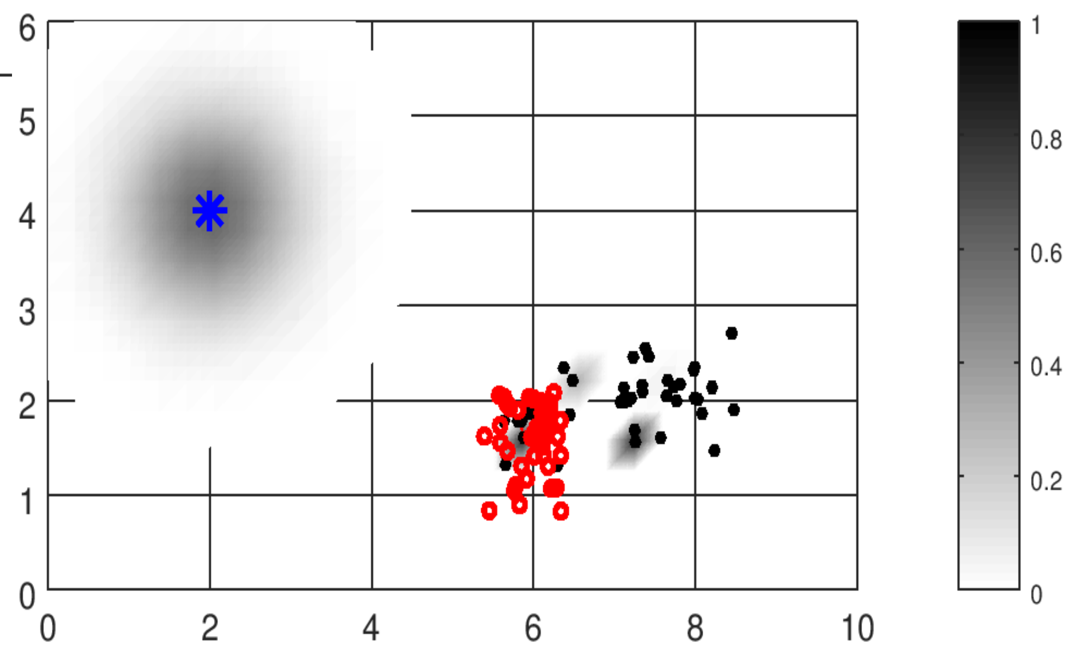


LAPF Basic Idea

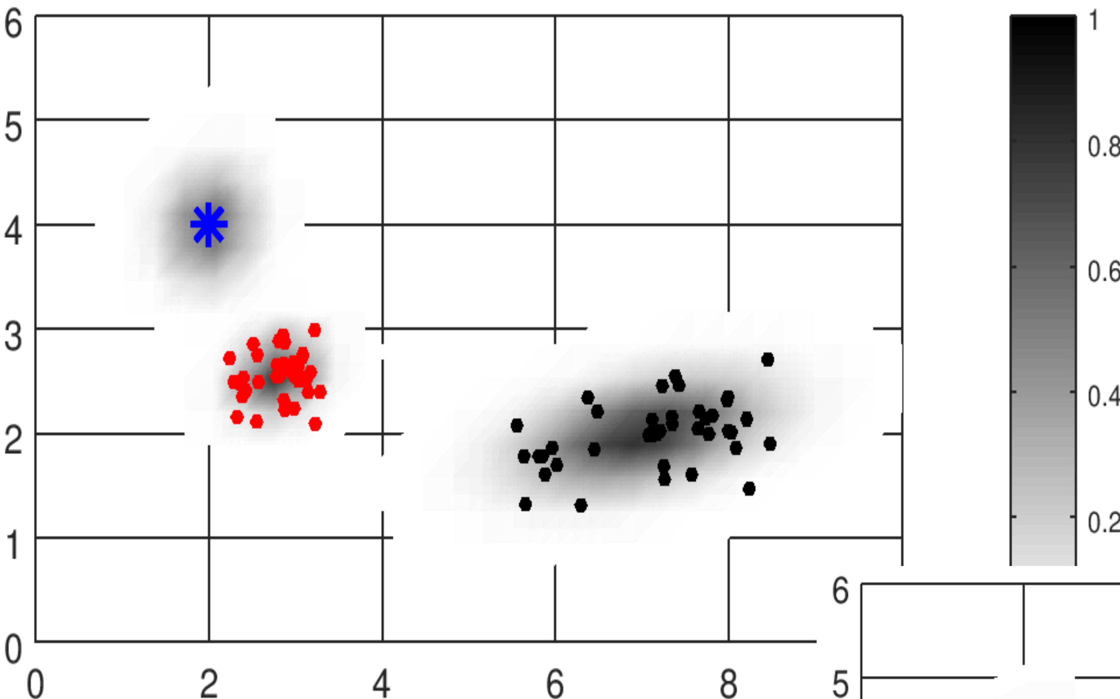


LETKF =
Move ensemble as for Gaussian distribution

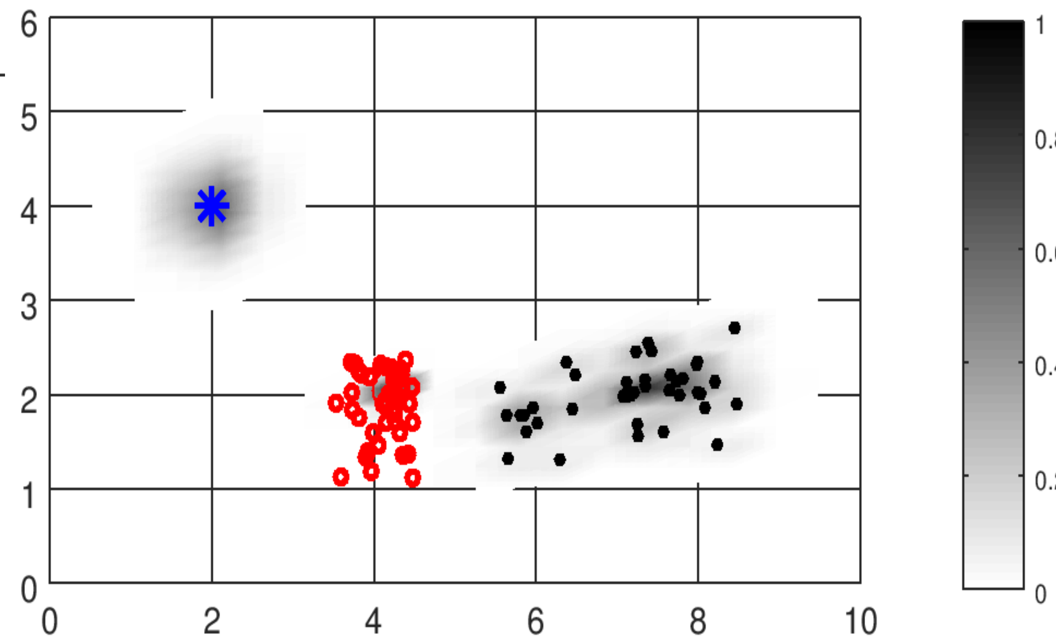
Classical PF =
Select Particle according to its weight



LAPF/LMCPF Basic Idea



LETKF =
Move ensemble as for Gaussian distribution



LMCPF =
Each particle a Gaussian + PF weights

LAPF Development Summary

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1. Localized Adaptive Particle Filter (**LAPF**) first high-dimensional sampling tests in Summer 2015 (c.f. Inverse Modeling by Nakamura & Potthast)
2. Implemented in **DACE** (Data Assimilation Coding Environment) for the *global ICON Model,* first stable runs in 2016 by Anne Walter (c.f. Potthast, Walter, Rhodin MWR 2019)
3. Extension to Localized Adaptive Mixture Coefficient Particle Filter (**LMCPF**) 2018 by Walter and RP
4. Implemented **LMCPF** for *global ICON Model* since 2018 (Walter, RP), Diskussions with Peter-Jan van Leeuwen, Alternative PF for ICON+DACE
5. LAPF and LMCPF implemented in DACE for *COSMO Convective Scale Model*, first stable runs in Nov 2018 by RP
6. Implemented **LMCPF** for *ICON D2* (convective scale), stable runs in Nov 2019, by RP
7. Lorenz 63 and 96 Implementations of **LAPF/LMCPF** and Testing (Nora Schenk & RP 2019 & 2020)
8. Implementation of **LMCPF** in *Speedy Model* by Miyoshi and Kotsuki, RIKEN (2019)
9. Testing **LMCPF** with SEVIRI VIS Reflectance Assimilation (2019/2020), Lilo Bach & RP

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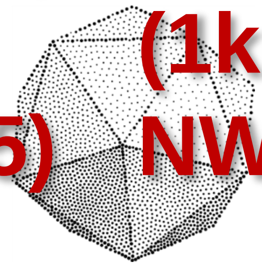
Global NWP Modelling: Det + EPS – Reality + Goals

1) ICON Model 13km
2) Nest over Europe (6.5km; 2-way)
3) ICON-LAM D2
4) Nest over Germany (1km; 2-way) D1
5) NWC Ensemble



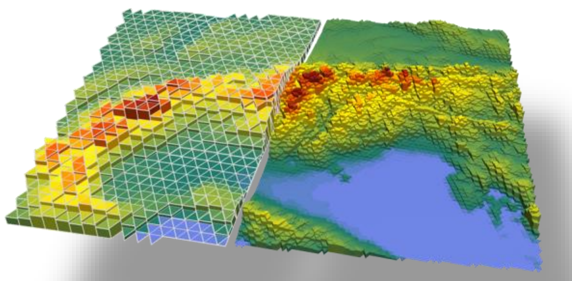
- 3h cycles global+Europe: 180h fc
- 1h ana cycle LAM, 3h fc cycle: 27h fc
- RUC cycle 1h: 6-12h fc

$$\frac{\partial v_n}{\partial t} + (\zeta + f)v_t + \frac{\partial K}{\partial n} + w\frac{\partial v_n}{\partial z} = -c_{pd}\theta_v \frac{\partial \pi}{\partial n}$$

$$\frac{\partial w}{\partial t} + \vec{v}_h \cdot \nabla w + w\frac{\partial w}{\partial z} = -c_{pd}\theta_v \frac{\partial \pi}{\partial z} - g$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\vec{v}\rho) = 0$$

$$\frac{\partial \rho\theta_v}{\partial t} + \nabla \cdot (\vec{v}\rho\theta_v) = 0$$



Full Observation System

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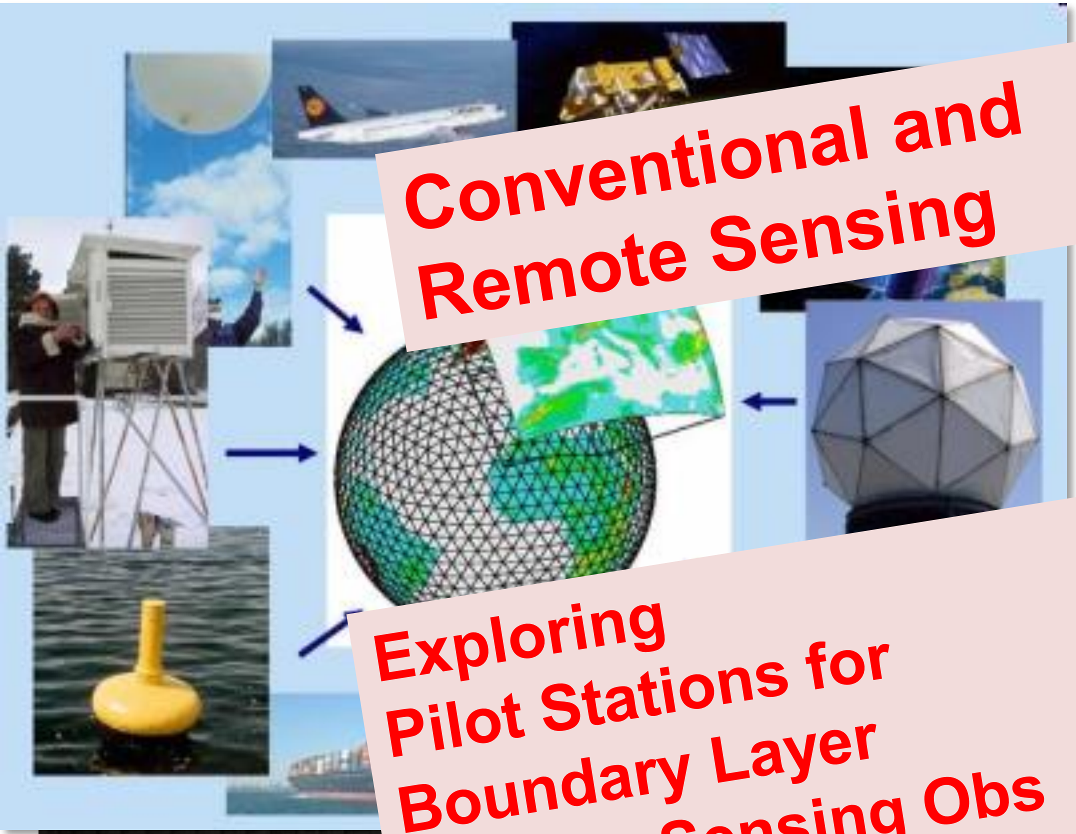
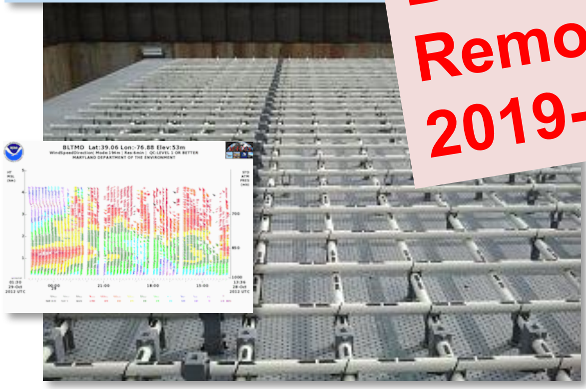
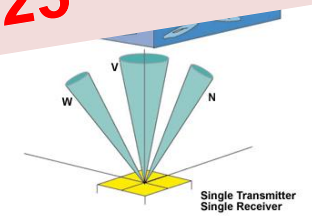


Conventional and Remote Sensing

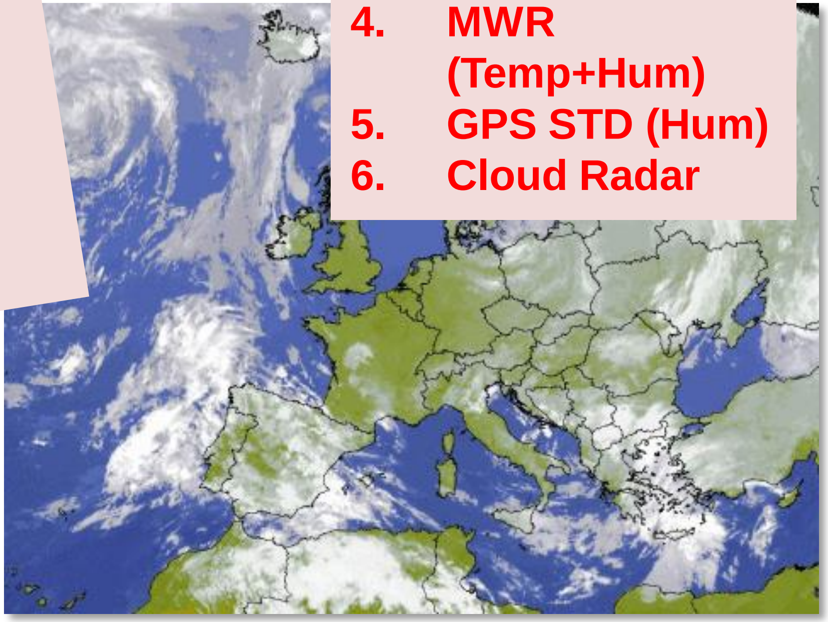
1. Doppler-LIDAR (Wind)
2. DIAL (Humidity)
3. Raman LIDAR (Temp+Hum)
4. MWR (Temp+Hum)
5. GPS STD (Hum)
6. Cloud Radar

Exploring Pilot Stations for Boundary Layer Remote Sensing Obs 2019-2025

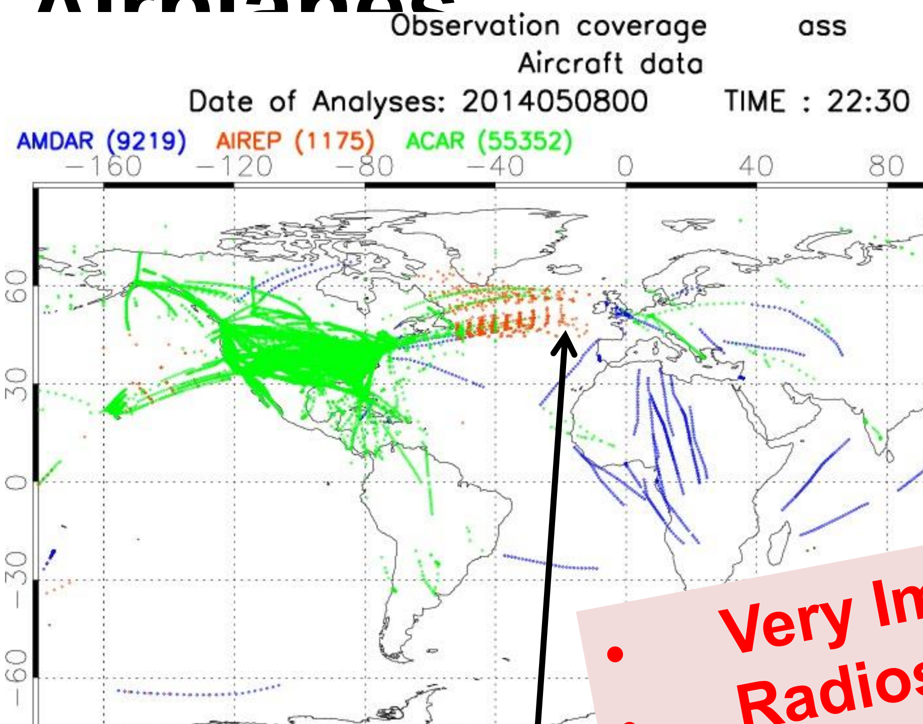


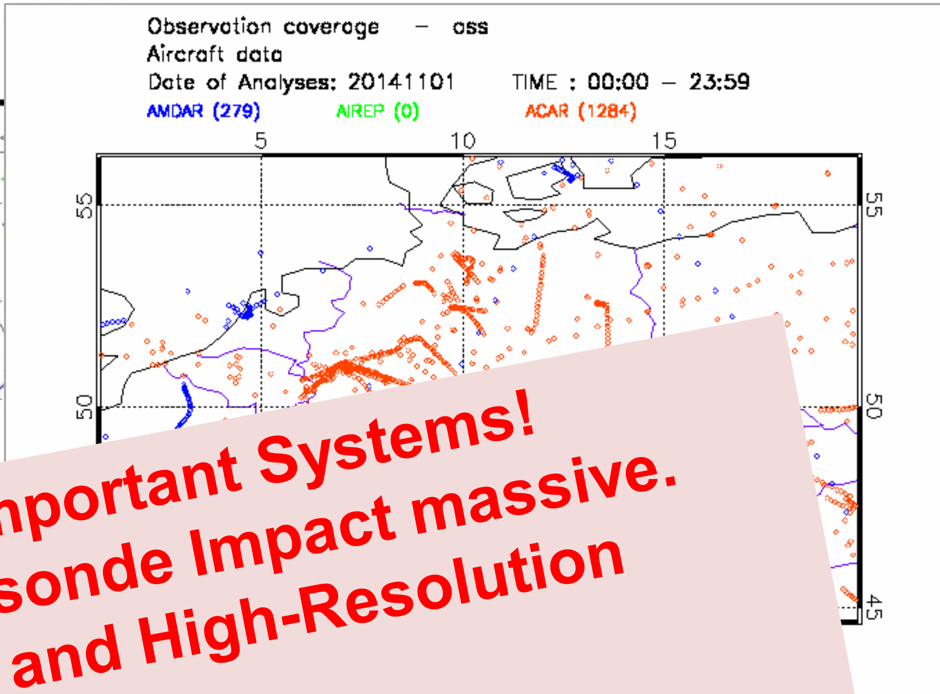


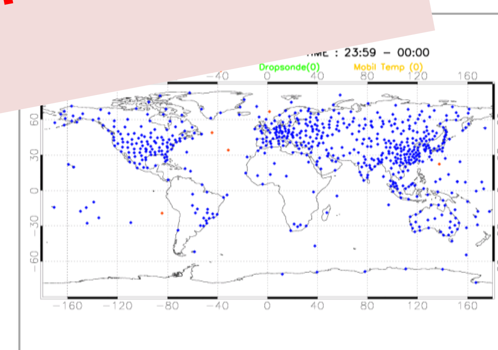
Wind-Profiler



Conventional Synop + Airplanes







- Very Important Systems!
- Radiosonde Impact massive. Drifts and High-Resolution Used.
- Mode-S Operational over Germany (KENDA)

Observations: Geostationary Satellites

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Wetter und Klima aus einer Hand

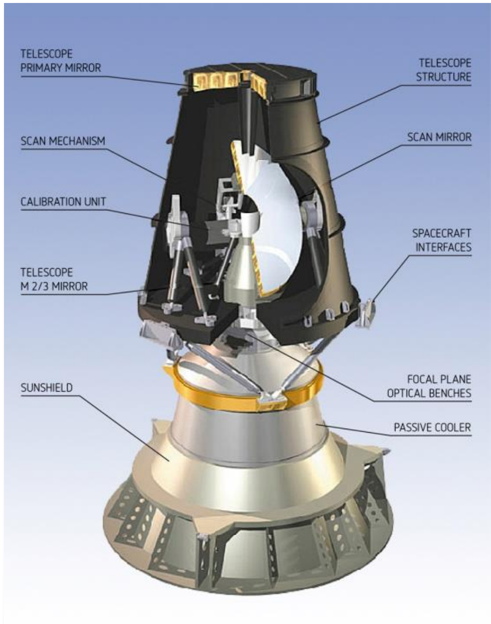
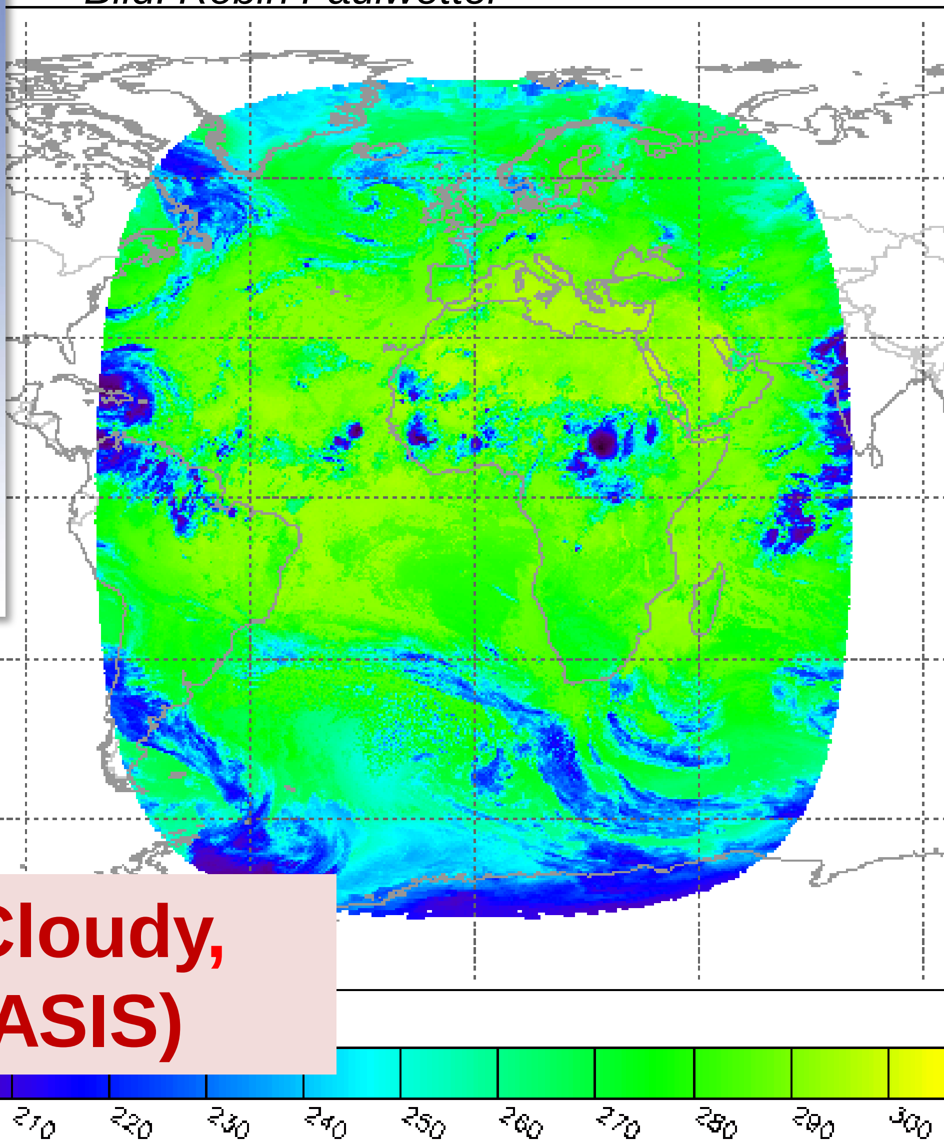
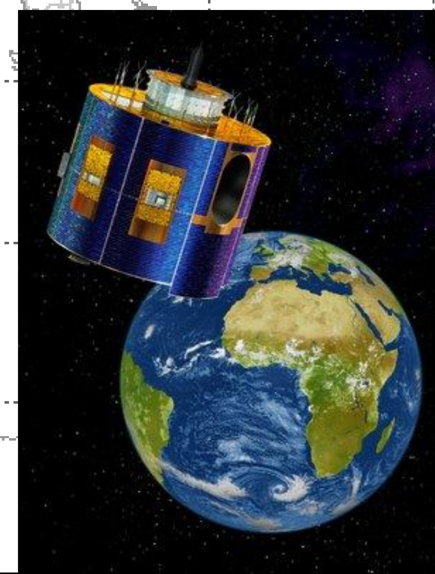


Bild: Robin Faulwetter



SEVIRI
Visible,
Near Infrared,
Infrared



Clear and Cloudy,
IR, VIS (MFASIS)

Observations: Polar Orbiting Satellites

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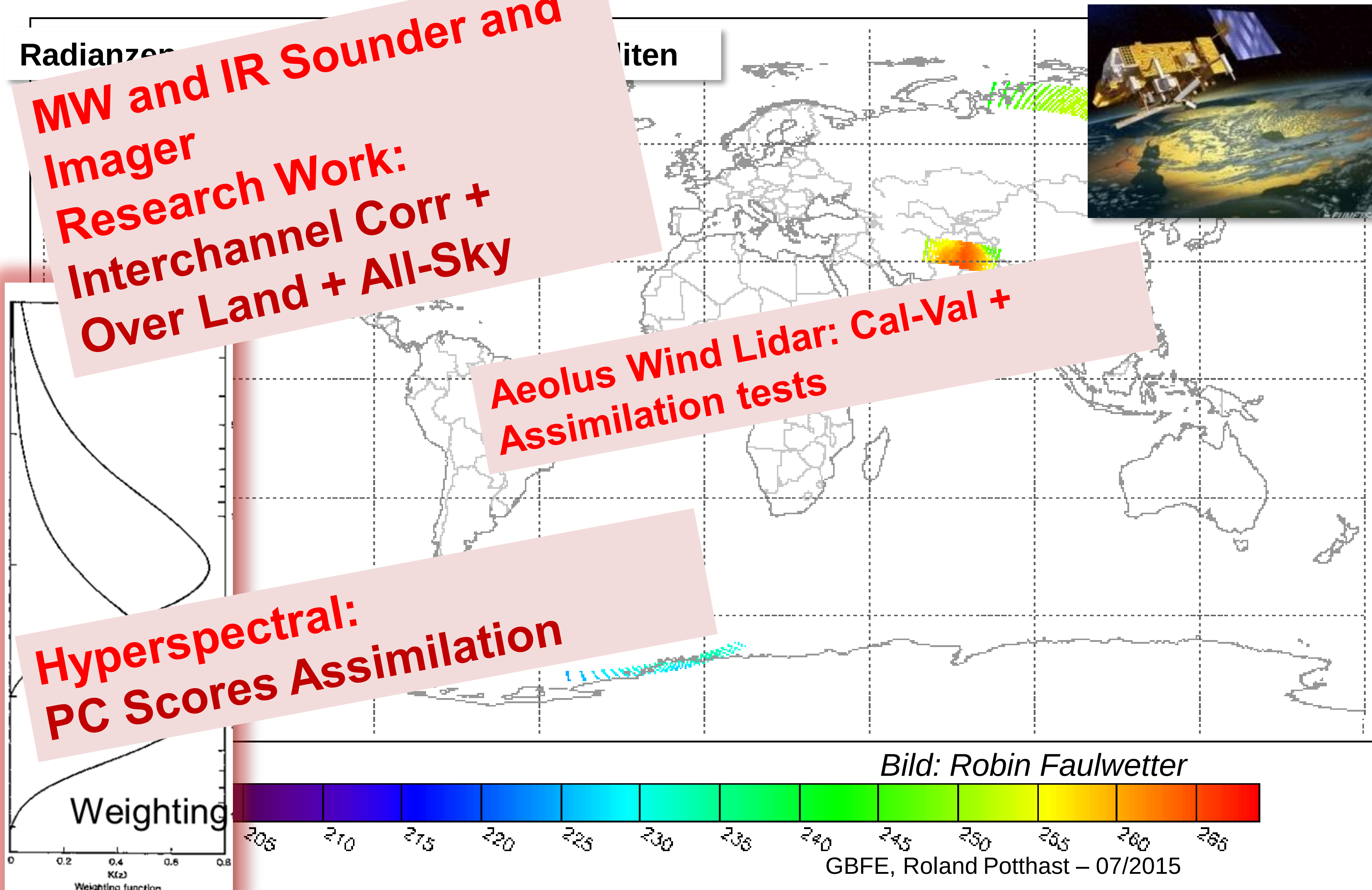
Wetter und Klima aus einer Hand



MW and IR Sounder and Imager
Research Work:
Interchannel Corr +
Over Land + All-Sky

Aeolus Wind Lidar: Cal-Val +
Assimilation tests

Hyperspectral:
PC Scores Assimilation

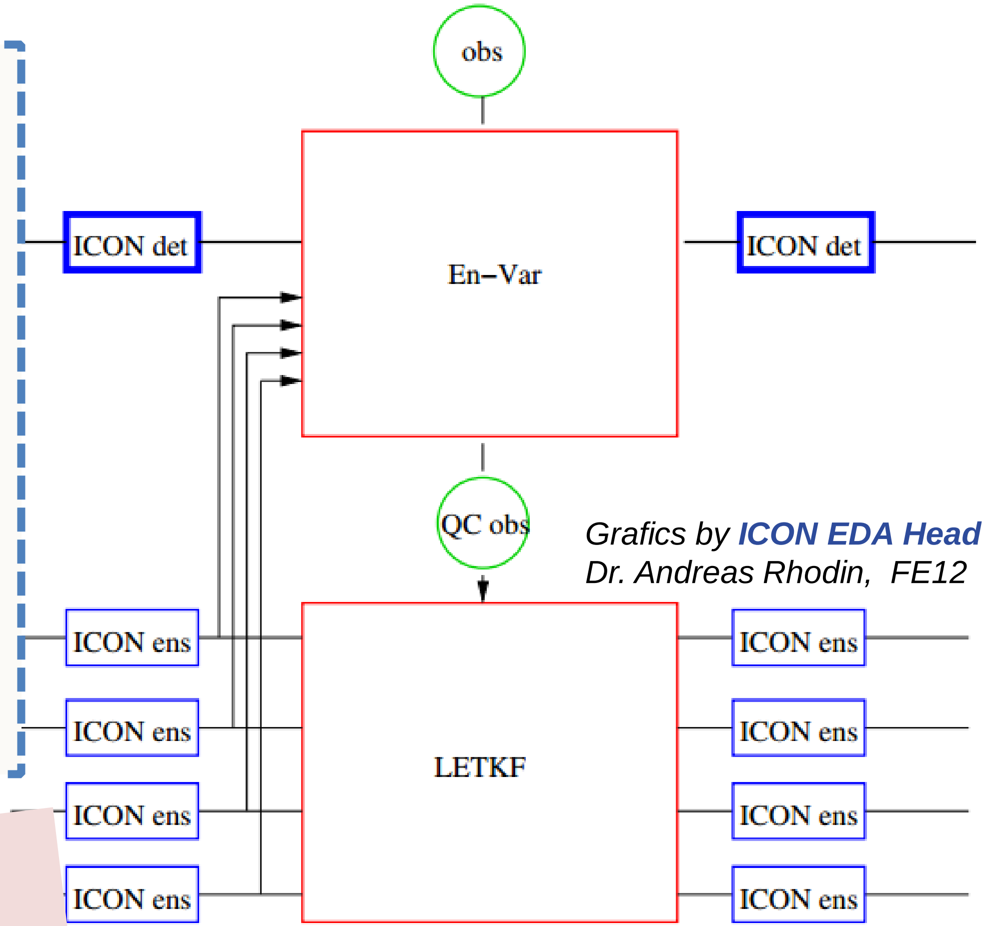
Ensemble Datenassimilation EnVar

Operational since January 2016

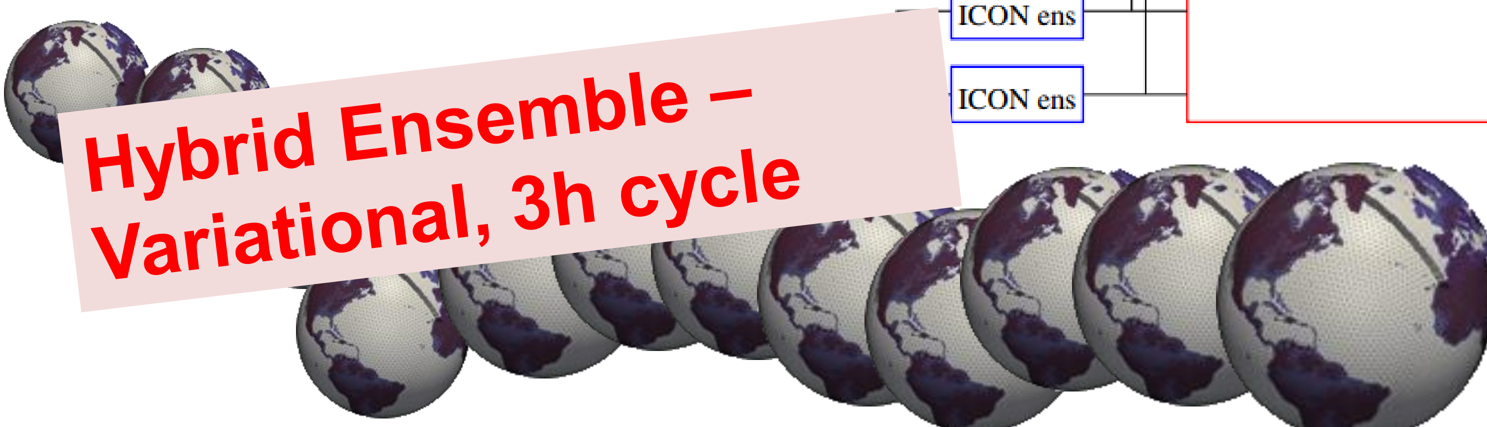
Deutscher Wetterdienst
Wetter und Klima aus einer Hand

We are running **ICON EDA** in our Routine since *Jan 2016*

- 40 Members each with 40km global resolution and 20km NEST over Europe
- 1 deterministic 13km/6.5km
- **EPS forecasts** 40 Members 7 Days + 1 Deterministic
- Output for convective-scale EDA/EPS
- **Hybrid System**



*Grafics by **ICON EDA Head** Dr. Andreas Rhodin, FE12*



Hybrid Ensemble – Variational, 3h cycle

Hybrid Methods: EnVAR Scores

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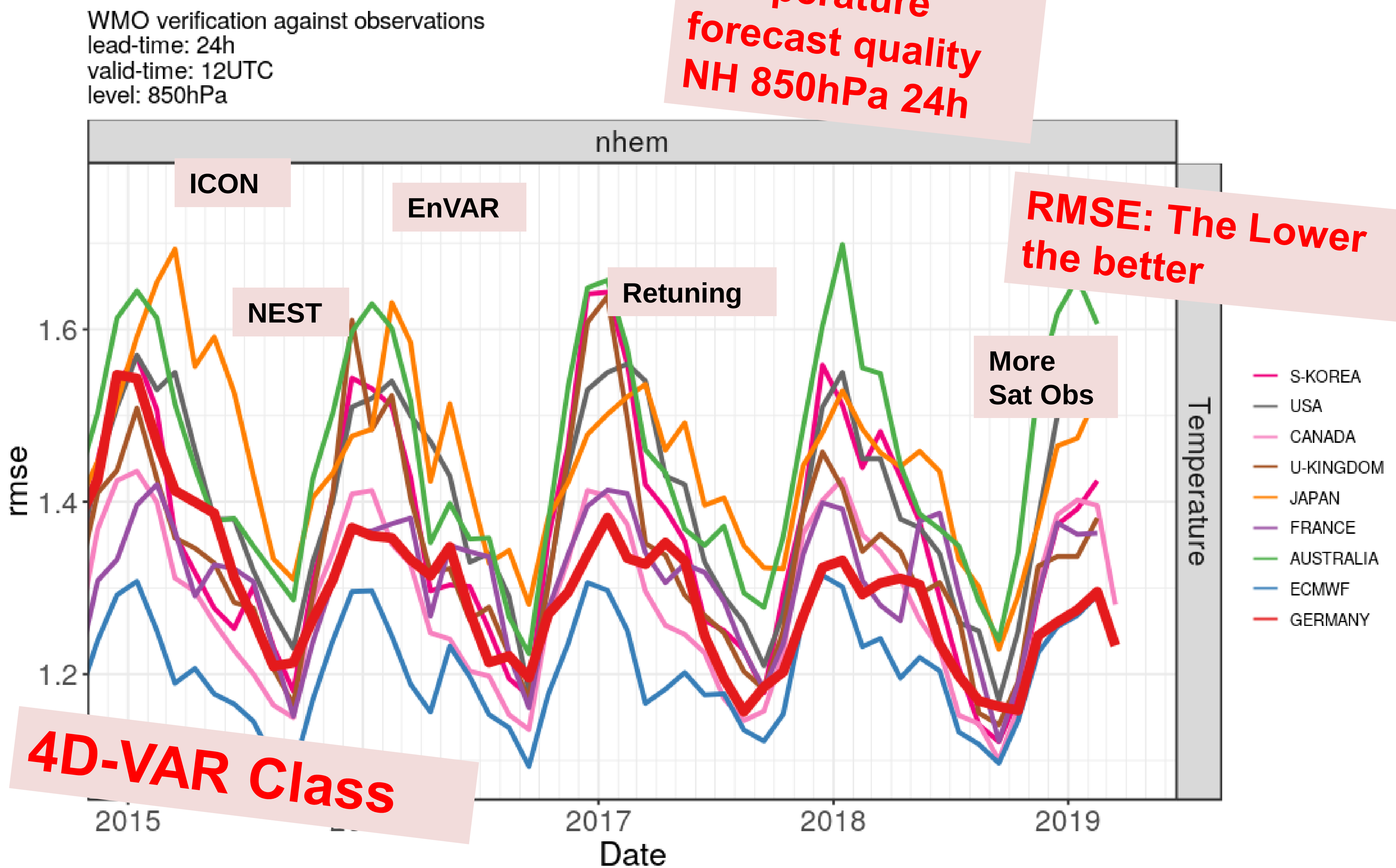
Wetter und Klima aus einer Hand

Temperature forecast quality NH 850hPa 24h



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Hybrid Methods: EnVAR Scores

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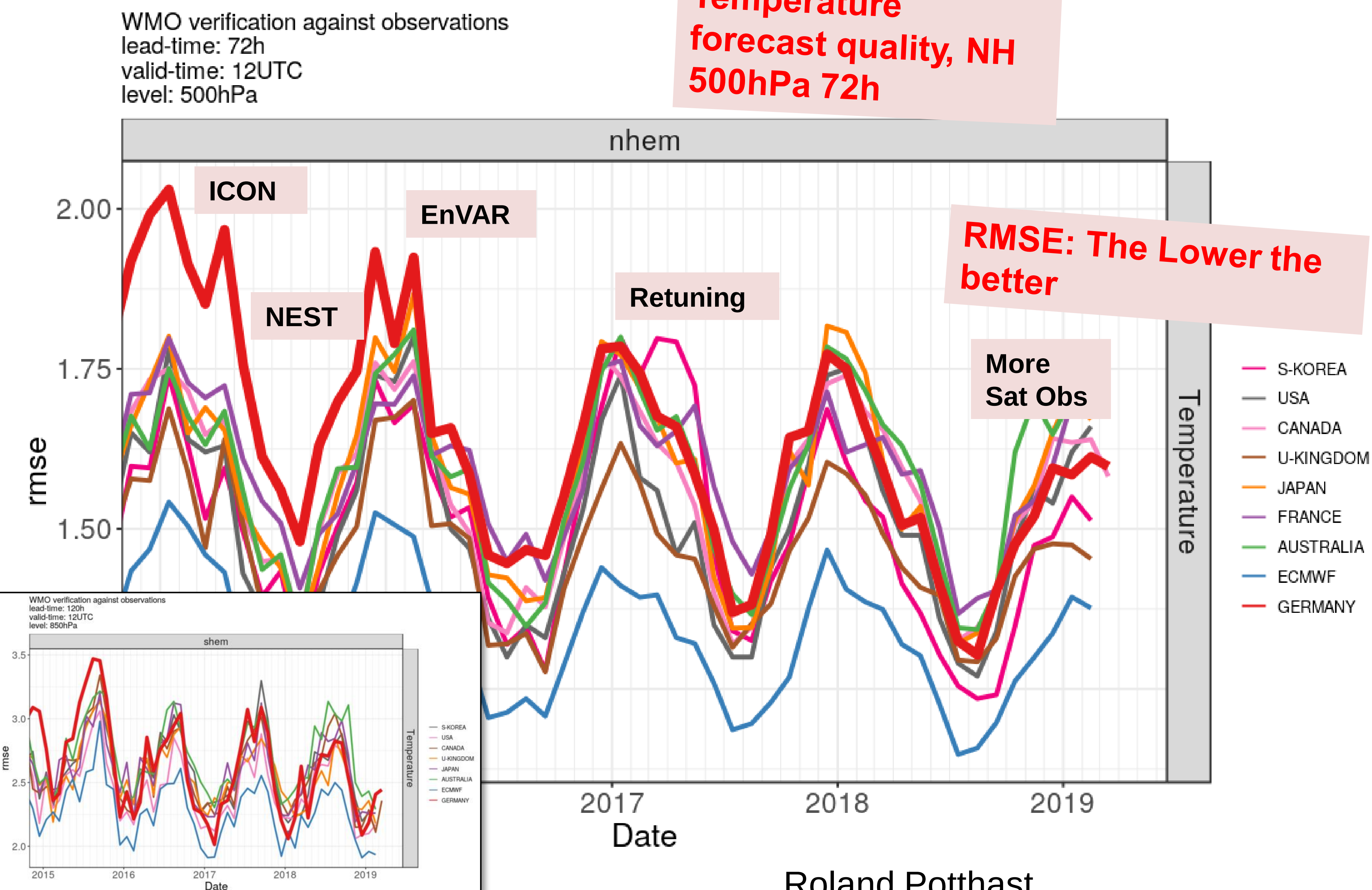

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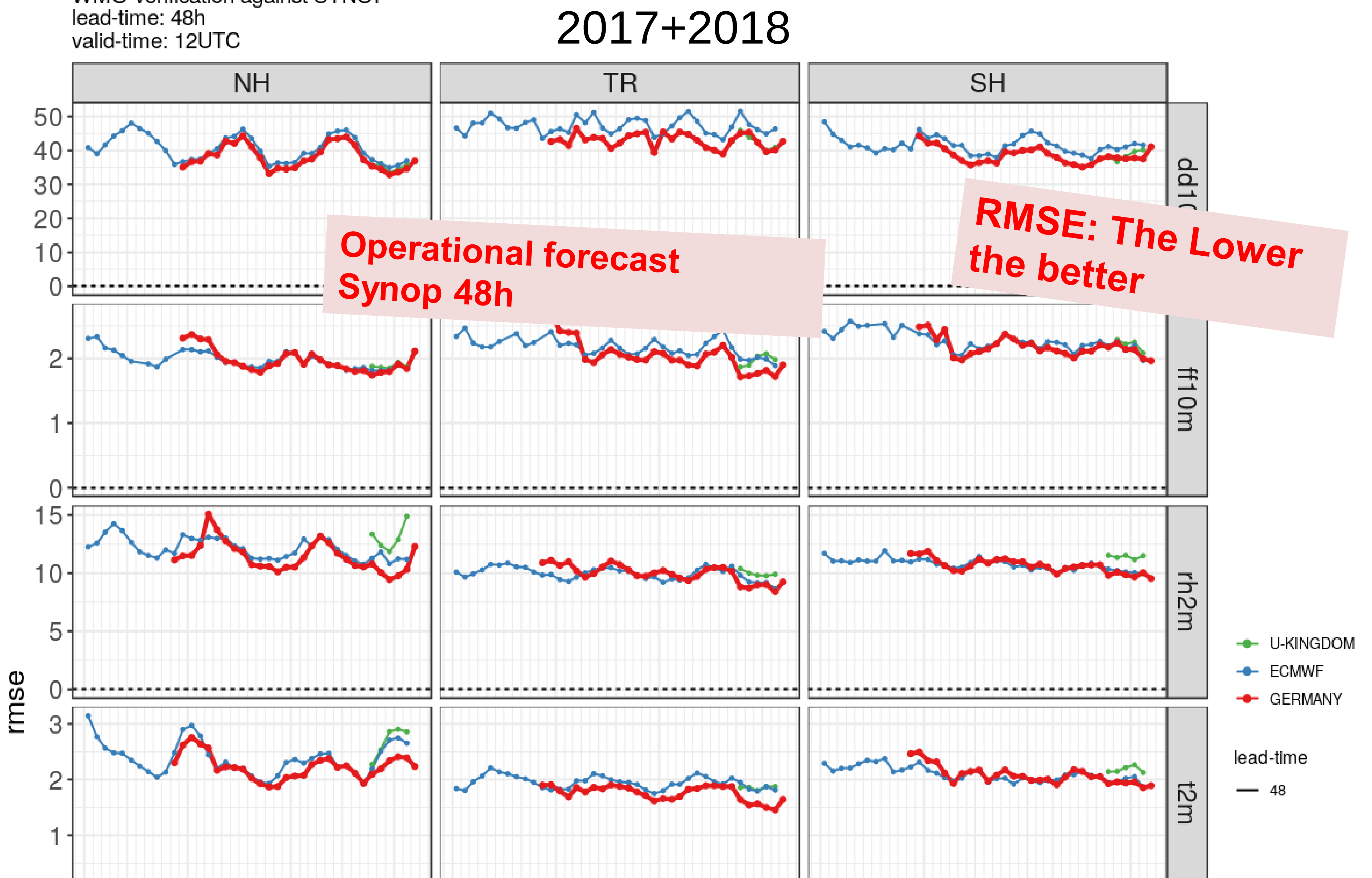
Hybrid Methods: EnVAR Scores

WMO verification against SYNOP
lead-time: 48h
valid-time: 12UTC

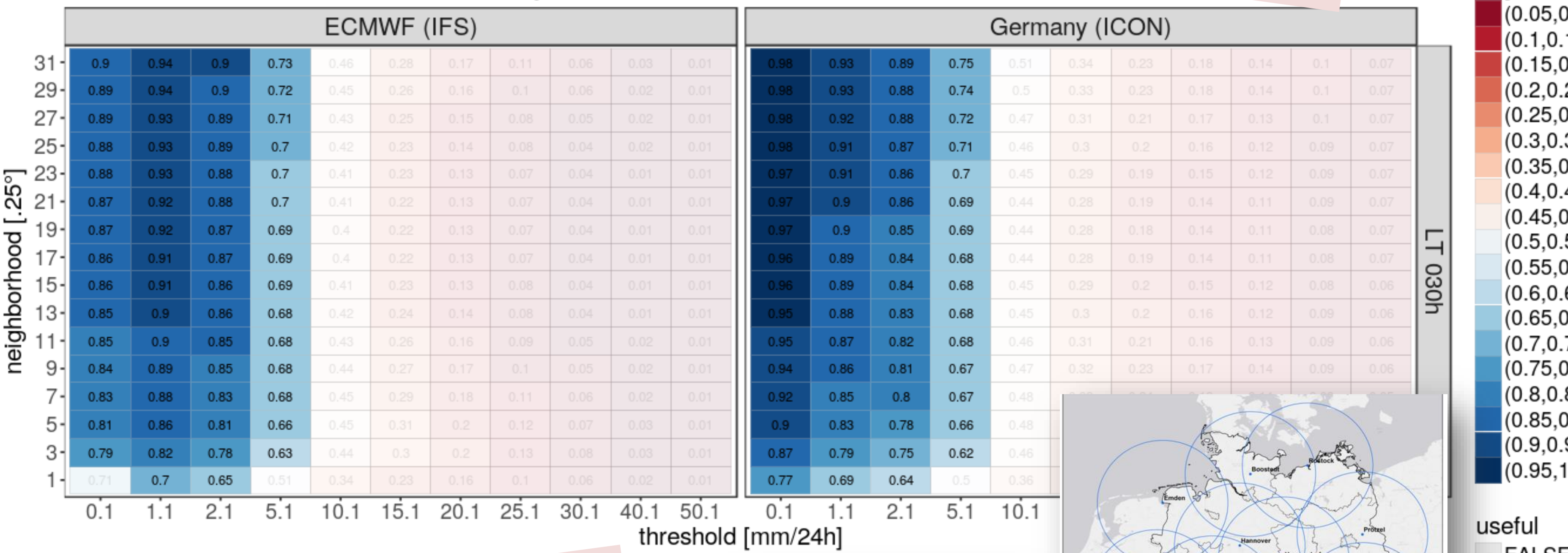


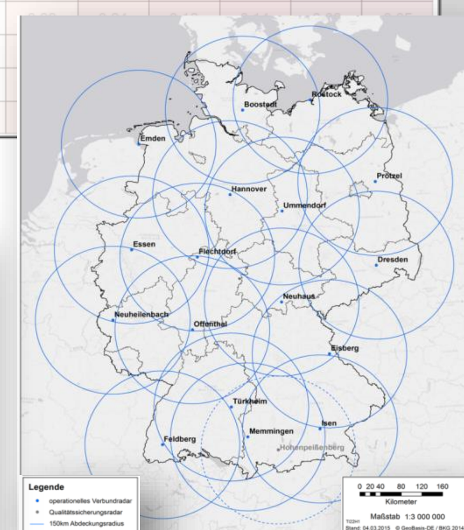
Hybrid Methods: EnVAR Scores

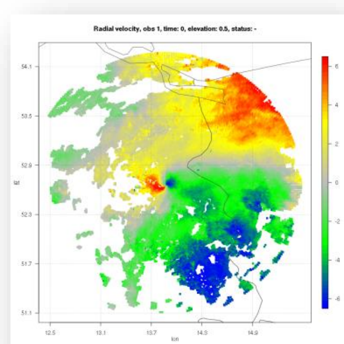
Deutscher Wetterdienst
Wetter und Klima aus einer Hand

FSS: the higher the better

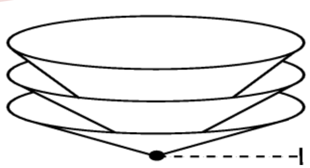
OBS: german radar (rw) 06UTC-06UTC
PRED: rr_24h (0.25°)
INI: 00UTC
CASES: ECMWF (IFS) 90, Germany (ICON) 90







Operational forecast Precipitation vs RADAR



Contents

University of Reading

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Wetter und Klima aus einer Hand

LAPF & LMCPF: Weights

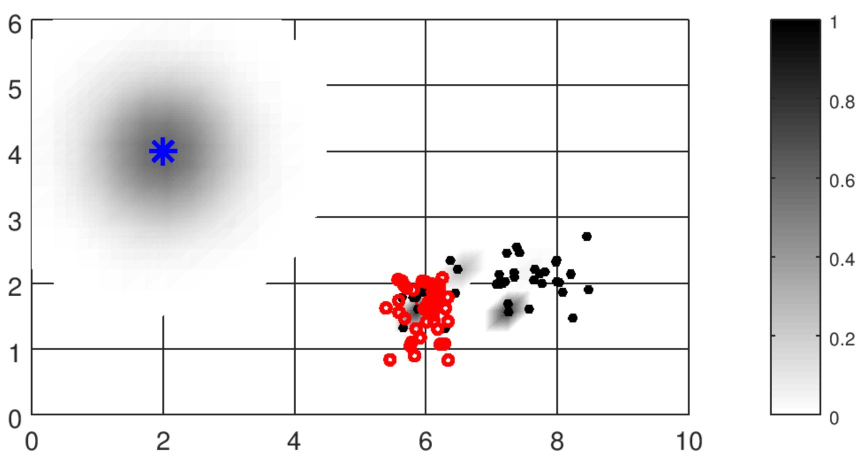
Deutscher Wetterdienst
Wetter und Klima aus einer Hand

$$w_\ell := e^{-\frac{1}{2}(y-Hx^{(\ell)})^T R^{-1}(y-Hx^{(\ell)})}, \quad \ell = 1, \ldots, L$$

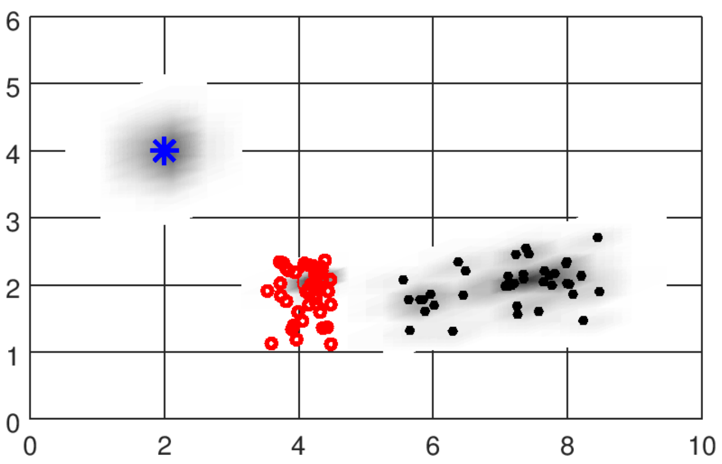
$$w_{tot} := \sum_{\ell=1}^{L} w_\ell .$$

We need a selection based on relative weights!

LAPF



LMCPF



LAPF & LMCPF: Ansatz

- **Kalman Filter**

Best Estimator

$$x^{(a)} = x^{(b)} + BH^T(R + HBH^T)^{-1}(y - Hx^{(b)})$$

$$K = BH^T(R + HBH^T)^{-1} \qquad \tilde{B} = (I - KH)B$$

Kalman Matrix

Update B Matrix

Ensemble B Estimator

$$\bar{x} := \frac{1}{L}\sum_{\ell=1}^{L} x^{(\ell)}$$

$$\boxed{B = \frac{1}{L-1} X X^T}$$

$$X = \left(x^{(1)} - \bar{x}, \ldots, x^{(L)} - \bar{x}\right) \quad \in \mathbb{R}^{n \times L}.$$

LAPF & LMCPF: Transform

- **Transformed Kalman Filter**

$$
\begin{aligned}
x^{(a)} &= x^{(b)} + BH^T(R + HBH^T)^{-1}(y - Hx^{(b)}) \\
&= x^{(b)} + \gamma \boxed{XX^T} H^T (R + \gamma H \boxed{XX^T} H^T)^{-1}(y - Hx^{(b)}) \\
&= x^{(b)} + \gamma X \boxed{Y^T(R + \gamma YY^T)^{-1}}(y - Hx^{(b)}) \\
&= x^{(b)} + \gamma X \boxed{(I + \gamma Y R^{-1} Y^T)^{-1} Y^T R^{-1}}(y - Hx^{(b)})
\end{aligned}
$$

$$\boxed{A = Y R^{-1} Y^T}$$

$$\boxed{B = \frac{1}{L-1} XX^T}$$

$$\boxed{Y := HX}$$

$$\boxed{Y^T(R + \gamma YY^T)^{-1} = (I + \gamma Y^T R^{-1} Y)^{-1} Y^T R^{-1}}$$

LAPF & LMCPF: Transform

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

$$\boxed{Y := HX}$$

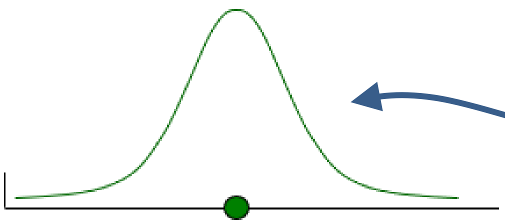
$$\begin{aligned}
\tilde{B} &= (I - KH)B \\
&= (I - BH^T(R + HBH^T)^{-1}H)B \\
&= \Big(I - \gamma X \boxed{X^T H^T}(R + \gamma \boxed{HX}\boxed{X^T H^T})^{-1} H\Big)\gamma X X^T \\
&= X\Big(I - \gamma \boxed{Y^T(R + \gamma Y Y^T)^{-1}} Y\Big)\gamma X^T \\
&= X\Big(I - \gamma \boxed{(I + \gamma Y^T R^{-1} Y)^{-1} Y^T R^{-1}} Y\Big)\gamma X^T \\
&= X\Big((I + \gamma Y^T R^{-1} Y)^{-1}(I + \gamma Y^T R^{-1} Y - \gamma Y^T R^{-1} Y\Big)\gamma X^T \\
&= X(I + \gamma Y^T R^{-1} Y)^{-1}\gamma X^T \\
&= X(\frac{1}{\gamma} I + Y^T R^{-1} Y)^{-1} X^T
\end{aligned}$$

$$\boxed{Y^T(R + \gamma Y Y^T)^{-1} = (I + \gamma Y^T R^{-1} Y)^{-1} Y^T R^{-1}}$$

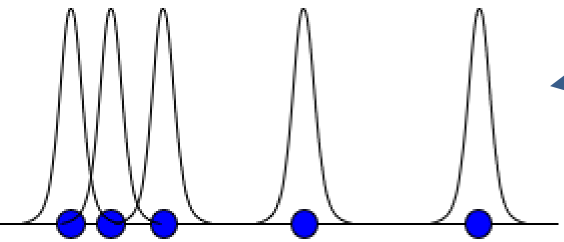
Transform for any Gaussian Particle

LAPF & LMCPF: Mixture

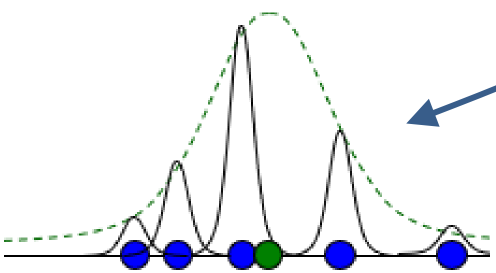
Superposition p(x)



$$
\begin{aligned}
p(x|y) &= c p(y|x) \cdot p(x) \\
&= c e^{-\frac{1}{2}(y-Hx)^T R^{-1}(y-Hx)} \sum_{\ell=1}^{L} p_G(x - x^{(\ell)}) \\
&= c \sum_{\ell=1}^{L} e^{-\frac{1}{2}(y-Hx)^T R^{-1}(y-Hx)} p_G(x - x^{(\ell)}),
\end{aligned}
$$



Gaussian Mixture Case



$$
p_G(x - x^{(\ell)}) = \tilde{c} e^{-\frac{1}{2}(x-x^{(\ell)})^T G^{-1}(x-x^{(\ell)})}
$$

Explicit Calculations possible for each term

We need a selection based on relative weights!

LAPF & LMCPF: Weights

Projection onto Ensemble Space

Derivation by Anne Walter, Andreas Rhodin and RP (MWR 2019)

Abbreviating $A := \mathbf{Y}^T \mathbf{R}^{-1} \mathbf{Y}$ and $C := A^{-1} \mathbf{Y}^T \mathbf{R}^{-1} (\mathbf{y}^o - \overline{\mathbf{y}}^b)$

Projection Operator

$$P(\mathbf{y}^o - \overline{\mathbf{y}}^b) = \mathbf{Y}(\mathbf{Y}^T \mathbf{R}^{-1} \mathbf{Y})^{-1} \mathbf{Y}^T \mathbf{R}^{-1} (\mathbf{y}^o - \overline{\mathbf{y}}^b),$$

Projected discrepancy

$$P(\mathbf{y}^o - H\mathbf{x}^{(\ell)}) = \mathbf{Y} A^{-1} \mathbf{Y}^T \mathbf{R}^{-1} ((\mathbf{y}^o - \overline{\mathbf{y}}^b) - \mathbf{Y} e_\ell)$$

Exponent

$$= \mathbf{Y}(C - e_\ell), \quad \ell = 1, \ldots, L.$$

$$P(\mathbf{y}^o - H\mathbf{x}^{(\ell)})]^T \mathbf{R}^{-1} P(\mathbf{y}^o - H\mathbf{x}^{(\ell)}) = [C - e_\ell]^T A [C - e_\ell], \quad \ell = 1, \ldots, L,$$

Weights

$$w_{k,\ell} = c e^{-\frac{1}{2}[C - e_\ell]^T A [C - e_\ell]}, \quad \ell = 1, \ldots, L.$$

LAPF & LMCPF: Ingredients

Deutscher Wetterdienst
Wetter und Klima aus einer Hand
DWD

Derivation by Anne Walter, Andreas Rhodin and RP (MWR 2019)

Ensemble Transform

Ensemble Transform as for LETKF $X\, w_m$

Localization

Localization on R as for LETKF

$$A := \mathbf{Y}^T \mathbf{R}^{-1} \mathbf{Y} \text{ and } C := A^{-1} \mathbf{Y}^T \mathbf{R}^{-1} (\mathbf{y}^o - \bar{\mathbf{y}}^b)$$

Move Particle (Shift)

Move each particle as LETKF moves the mean, but now individually calculated

Adaptivity via O-B

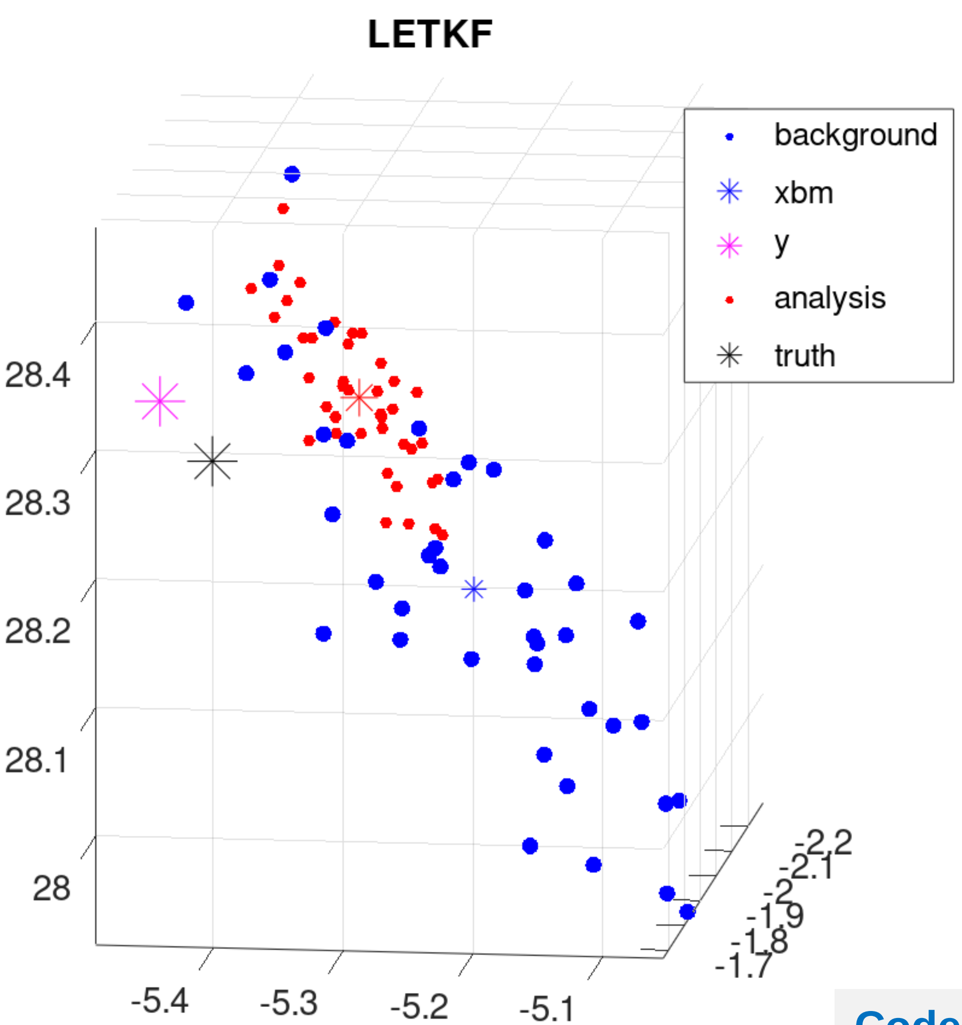
$$\mathrm{E}\left[\boldsymbol{d}_{o-b}^T \boldsymbol{d}_{o-b}\right] = \mathrm{Tr}(\mathbf{R}) + \rho\, \mathrm{Tr}(\boldsymbol{H}\boldsymbol{P}^b \boldsymbol{H}^T)$$

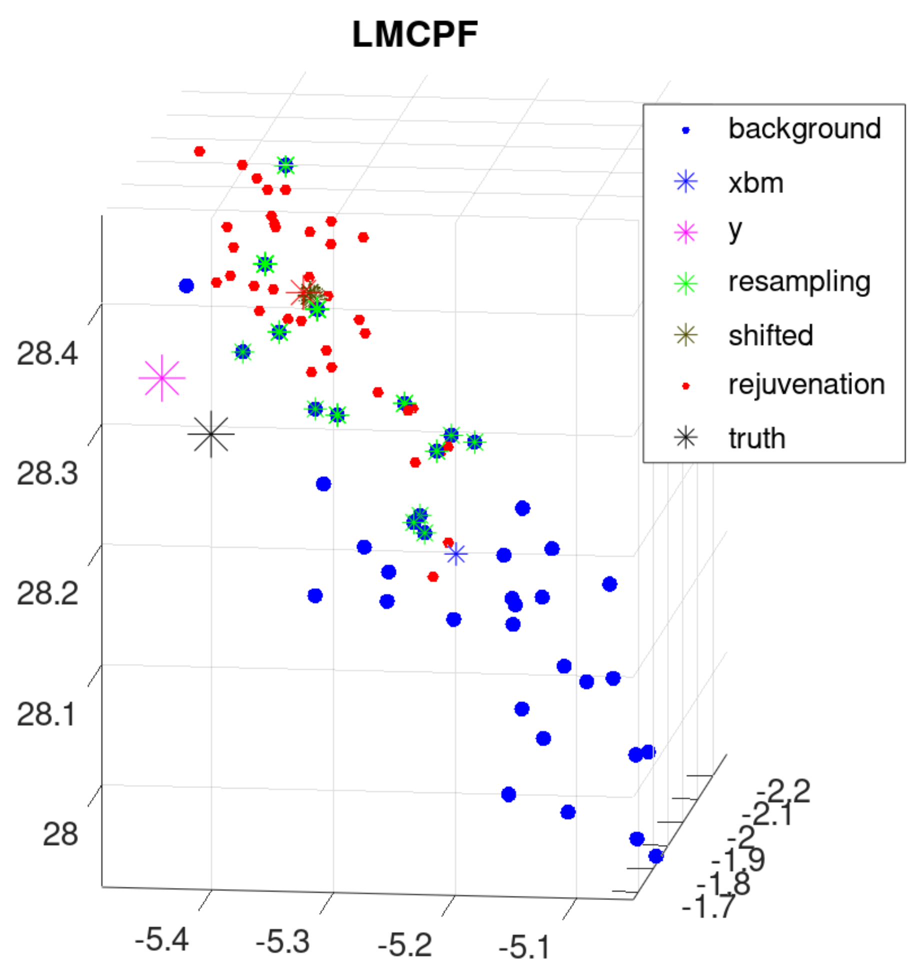
Resampling

Modulated resampling in ensemble space around each remaining particle adaptively based on ρ

4) LMCPF for Lorenz Examples

Deutscher Wetterdienst
Wetter und Klima aus einer Hand





Code by
Nora Amelie Schenk & RP

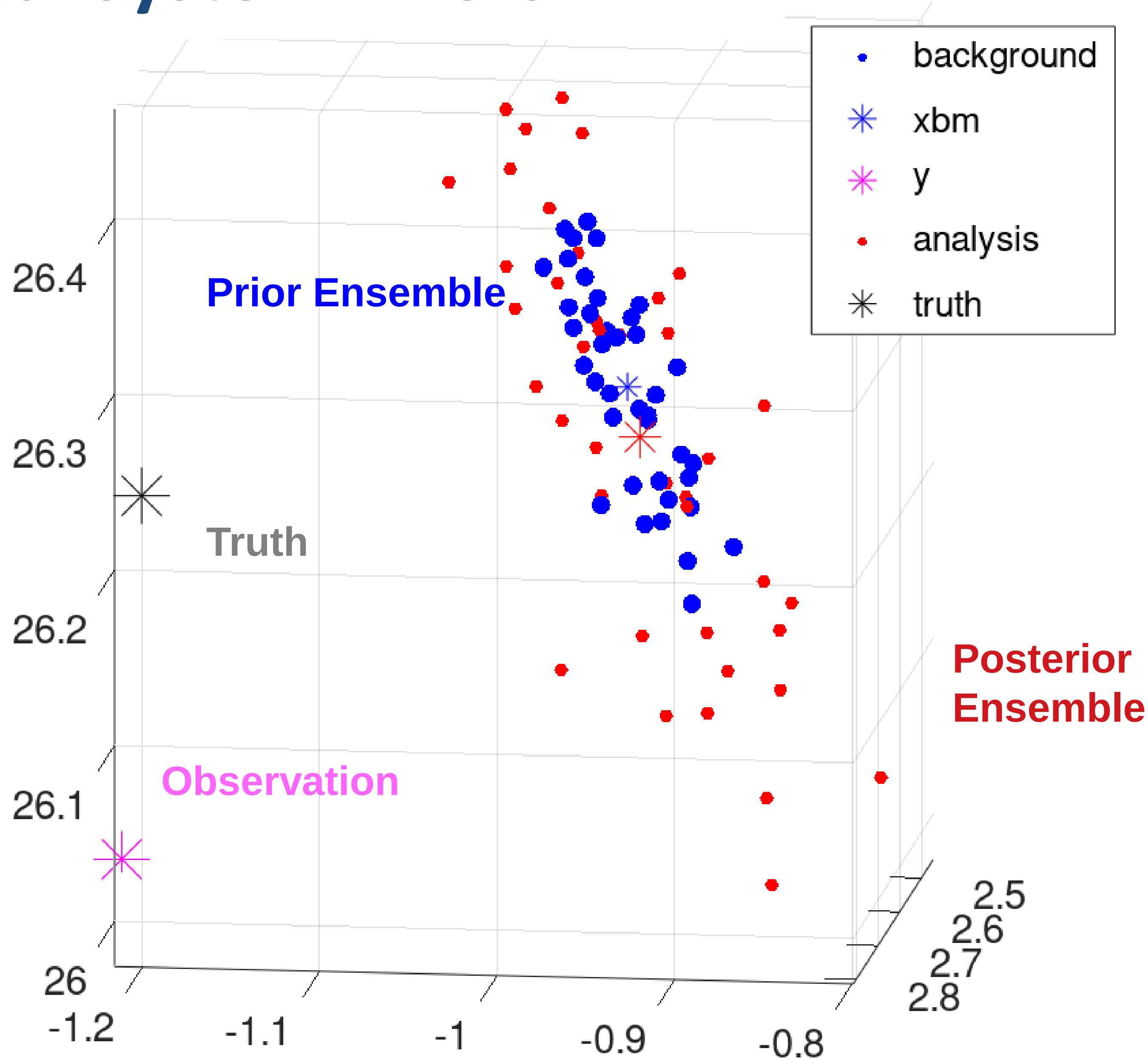
Dynamical System Errors

Lorenz 63 System Simulation

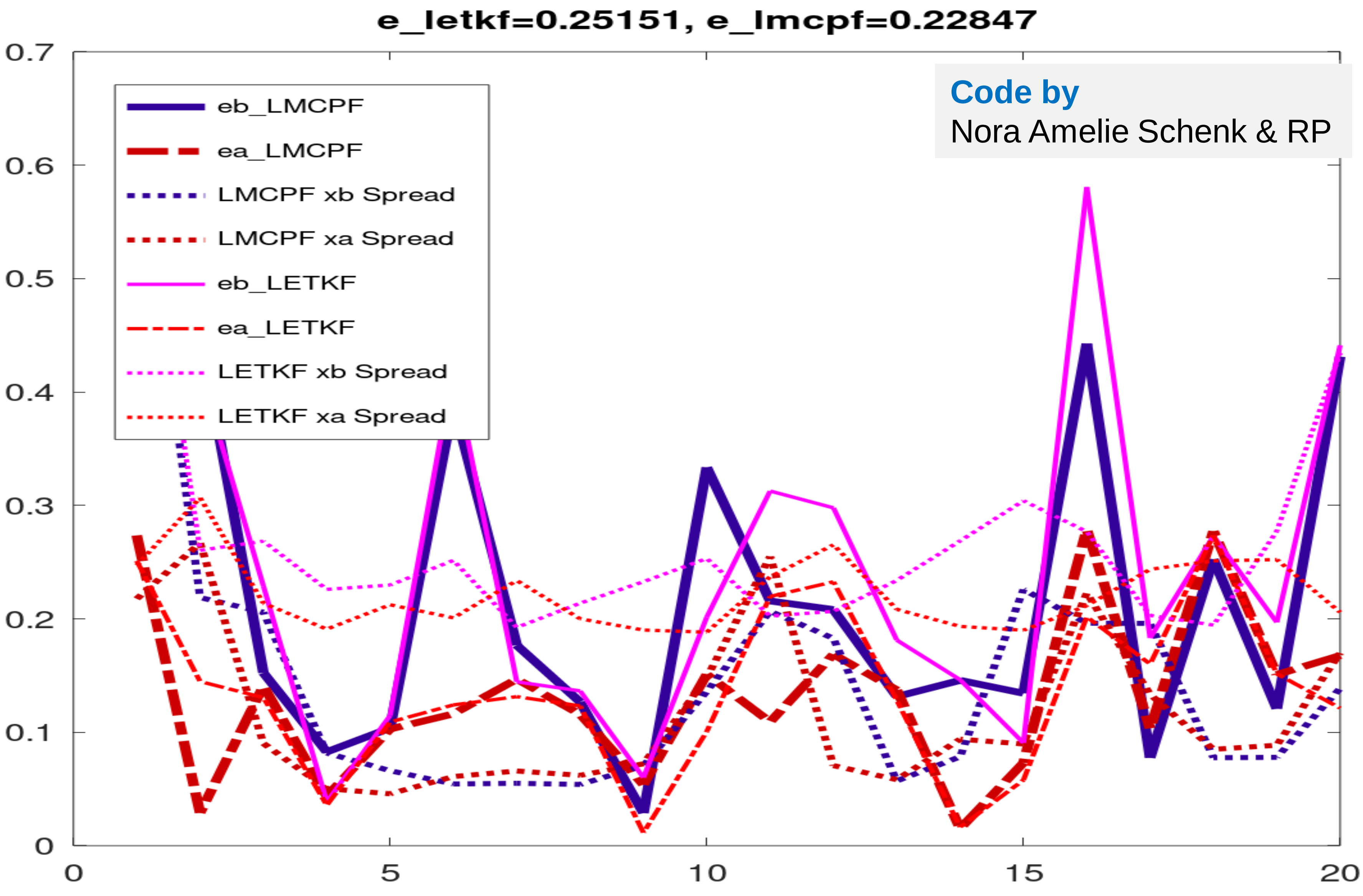
40 Members LETKF

Natural Run Sigma = 10

Assimilation Run Sigma = 10.5



LMCPF for Lorenz Examples

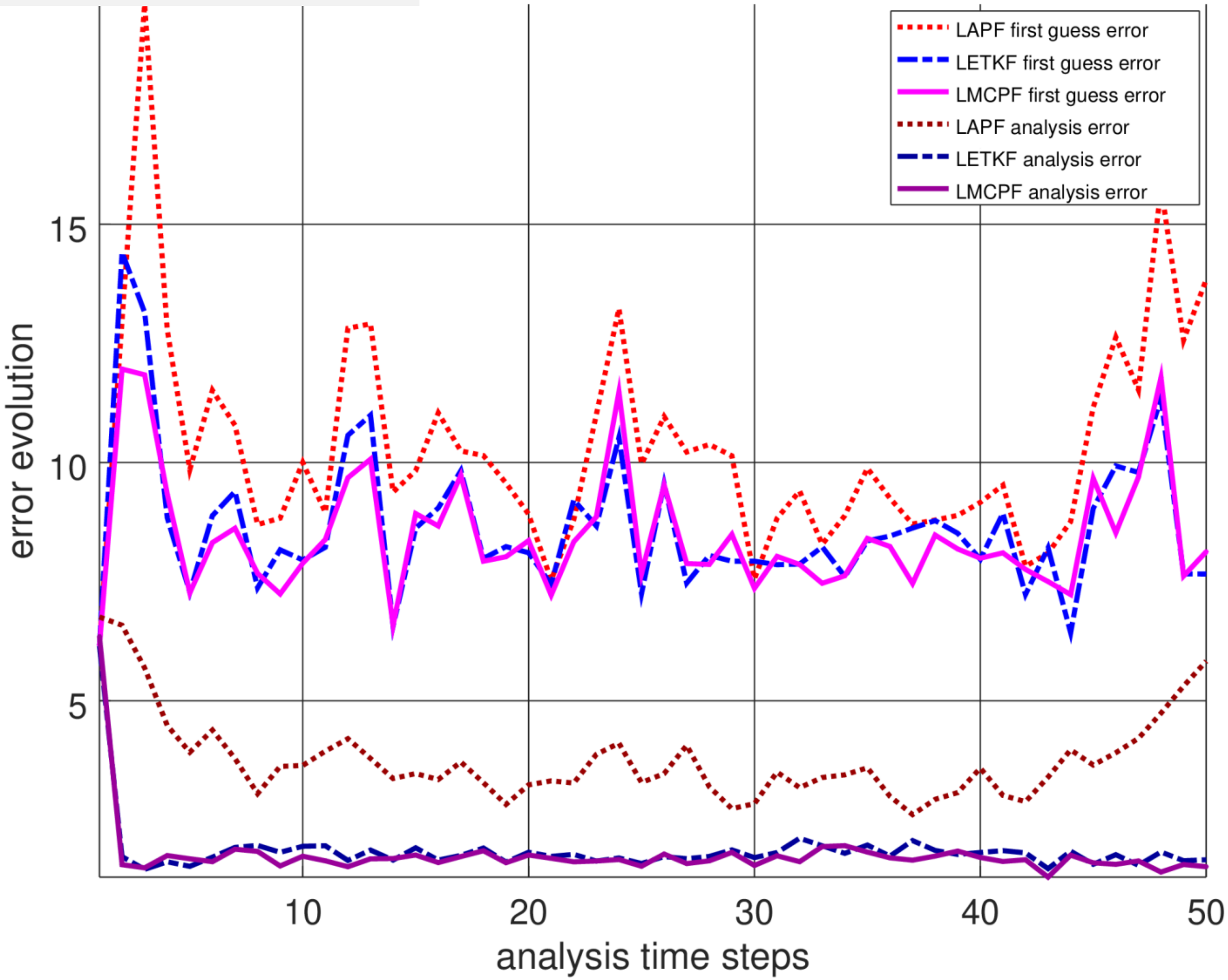


Code by
Nora Amelie Schenk & RP

LMCPF for Lorenz Examples

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Code by
Nora Amelie Schenk & RP



Lorenz 96

100 Variables

20 Ensemble Members

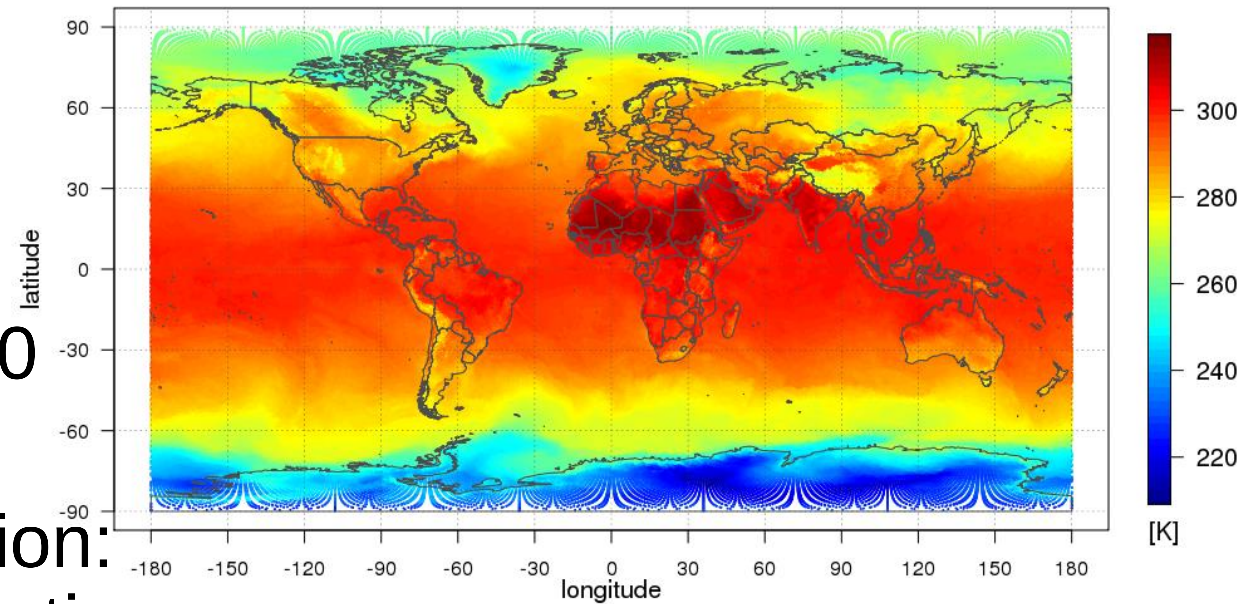
50 Assimilation Cycles

Comparing

LAPF
LMCPF
LETKF

Large-Scale Experimental Set-up

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



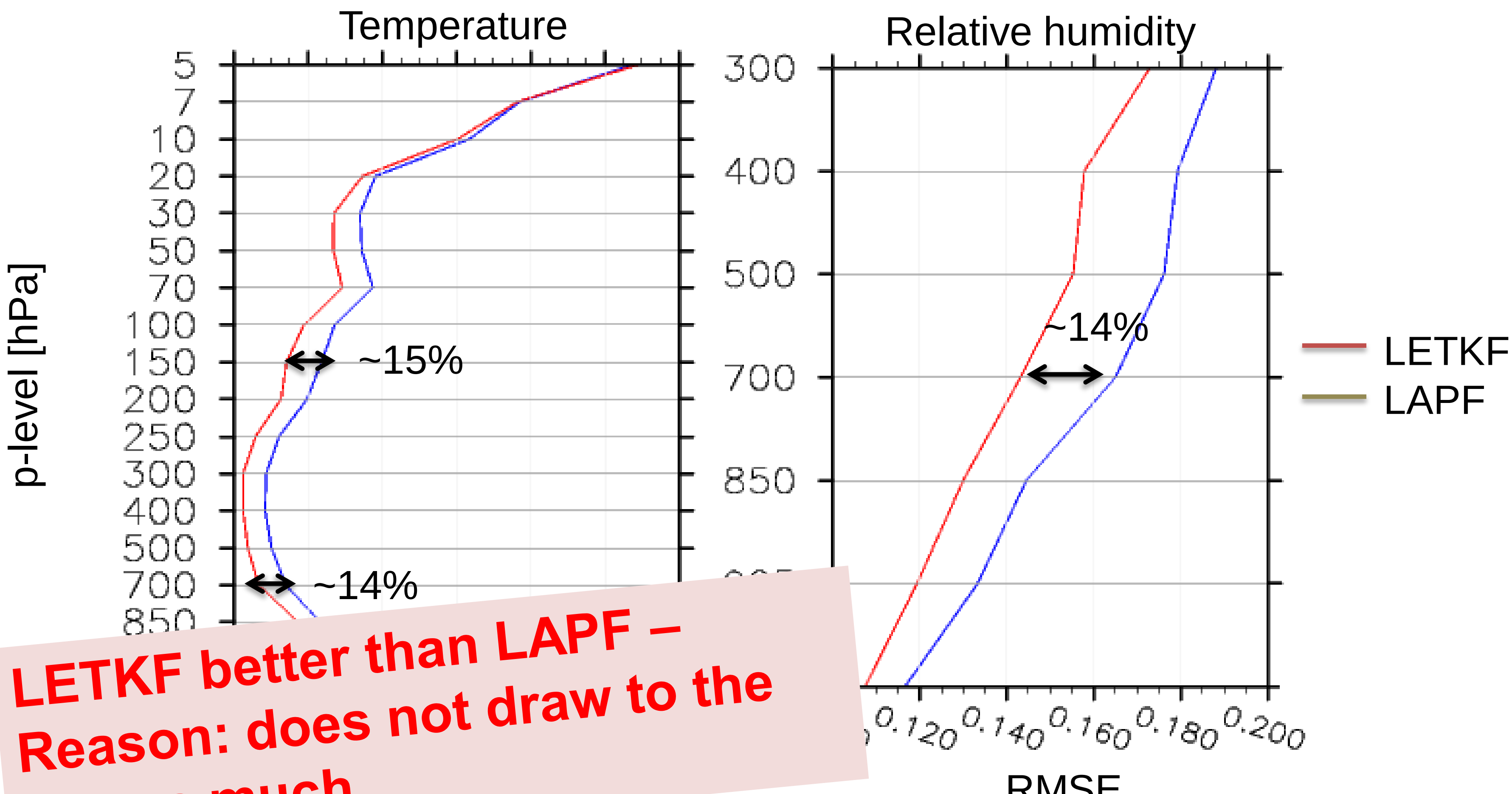
Experiments programmed and carried out by Anne Walter, DWD& Uni Reading, and Roland Potthast, DWD& Uni Reading

In Cooperation with Peter-Jan van Leeuwen , Uni Reading

LAPF Scores vs LETKF

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

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

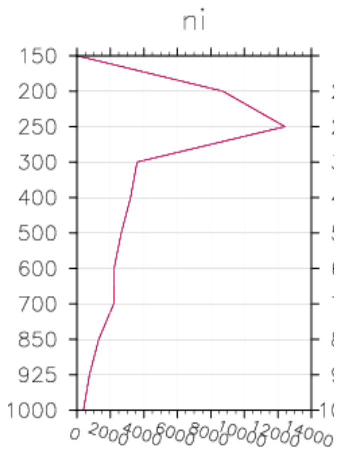


LETKF better than LAPF – Reason: does not draw to the obs as much

Experiments programmed and carried out **by Anne Walter, DWD & Uni Reading**, and Roland Potthast, DWD & Uni Reading

LMCPF Scores vs LETKF

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

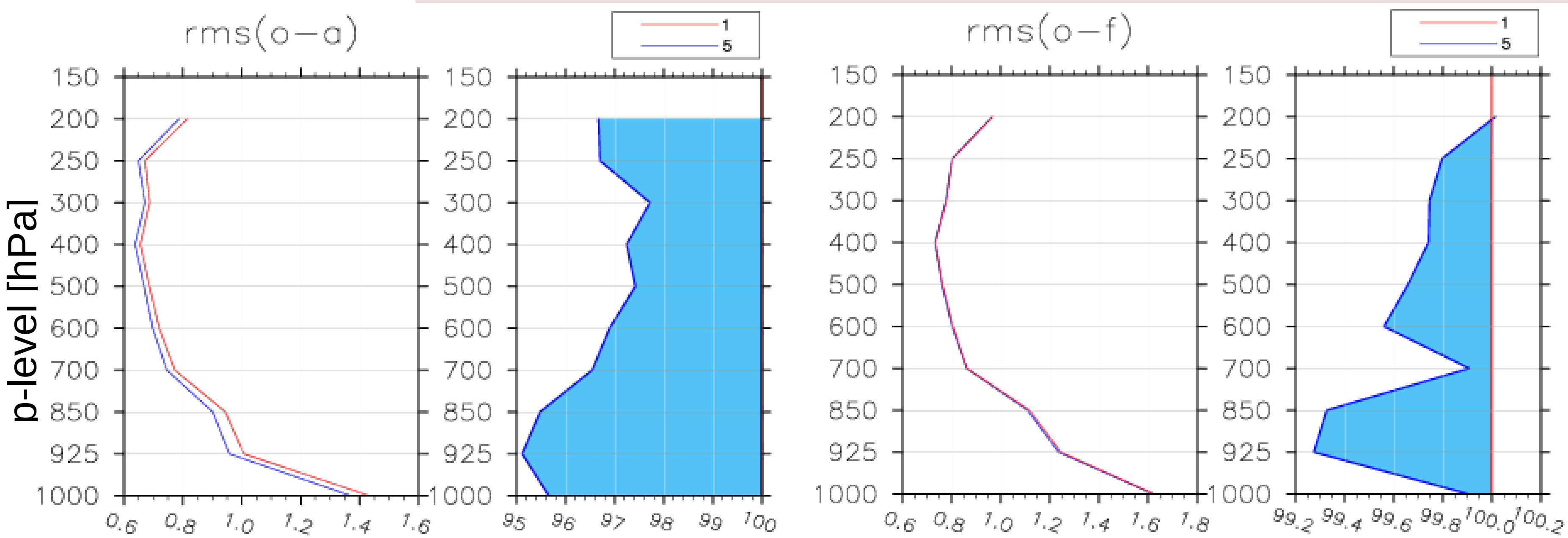


Global **RMSE** for **obs-fg** statistics (AIREP vs. Model)
Period: 08.05.2016 – 22.05.2016

LETKF
LMCPF

Temperature o-a and o-f

LMCPF: Uncertainty based Move works

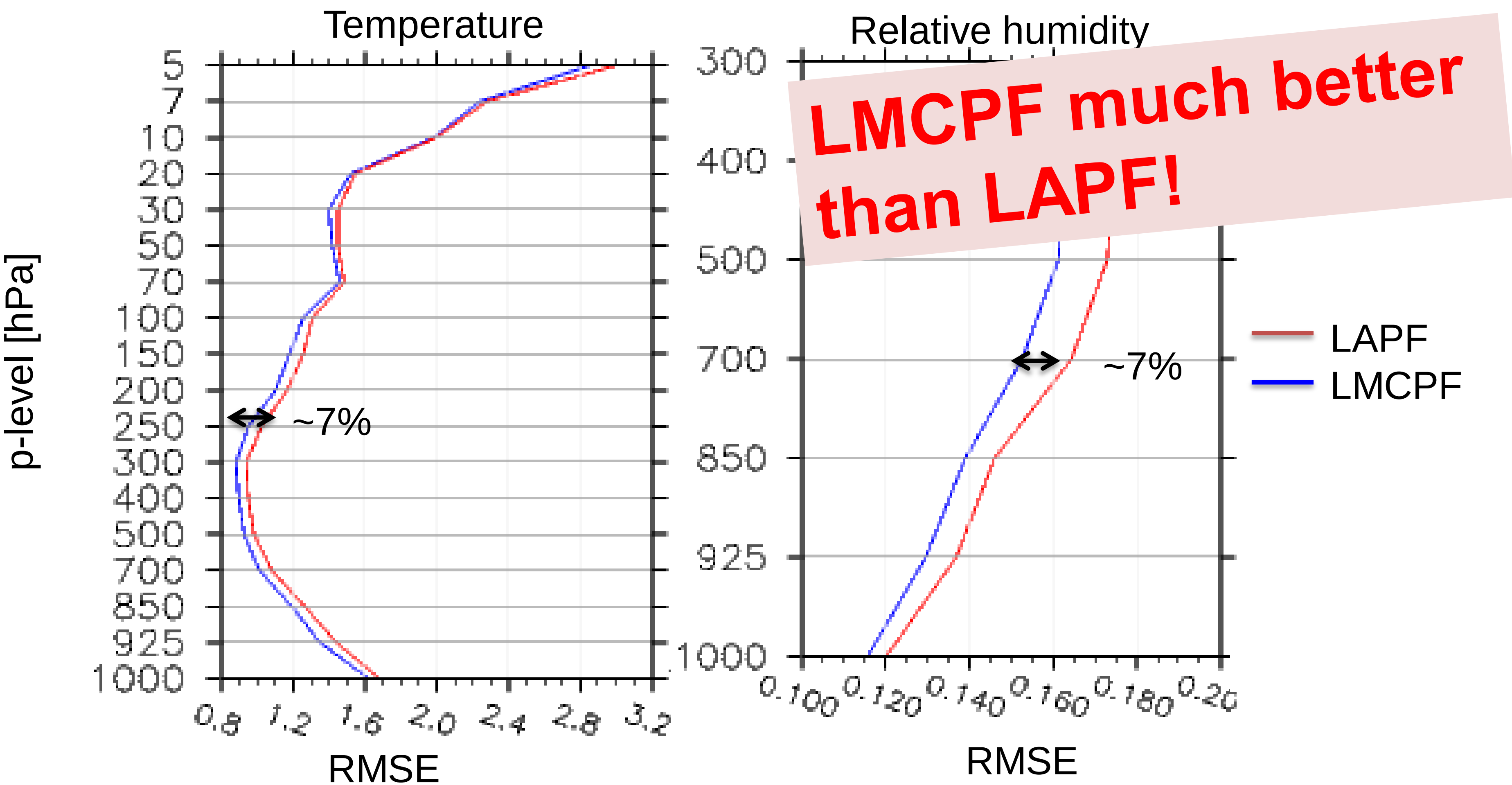


Experiments programmed and carried out **by Anne Walter, DWD & Uni Reading**, and Roland Potthast, DWD & Uni

LMCPF Scores vs LAPF

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

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

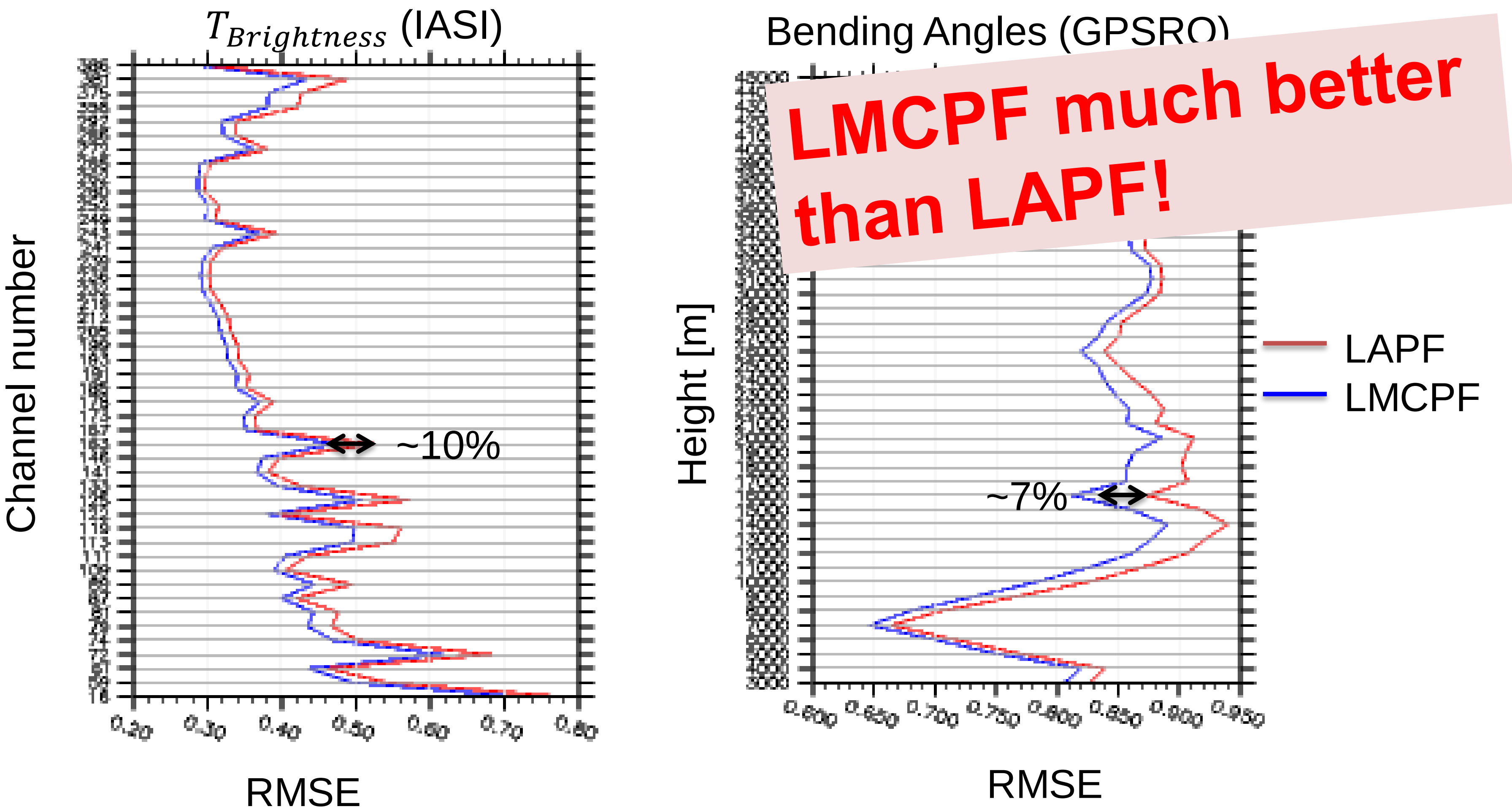


Experiments programmed and carried out **by Anne Walter, DWD & Uni Reading**, and Roland Potthast, DWD & Uni Reading

LMCPF Scores vs LAPF

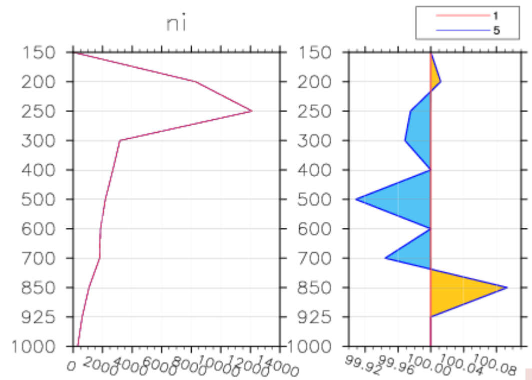
Deutscher Wetterdienst
Wetter und Klima aus einer Hand

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



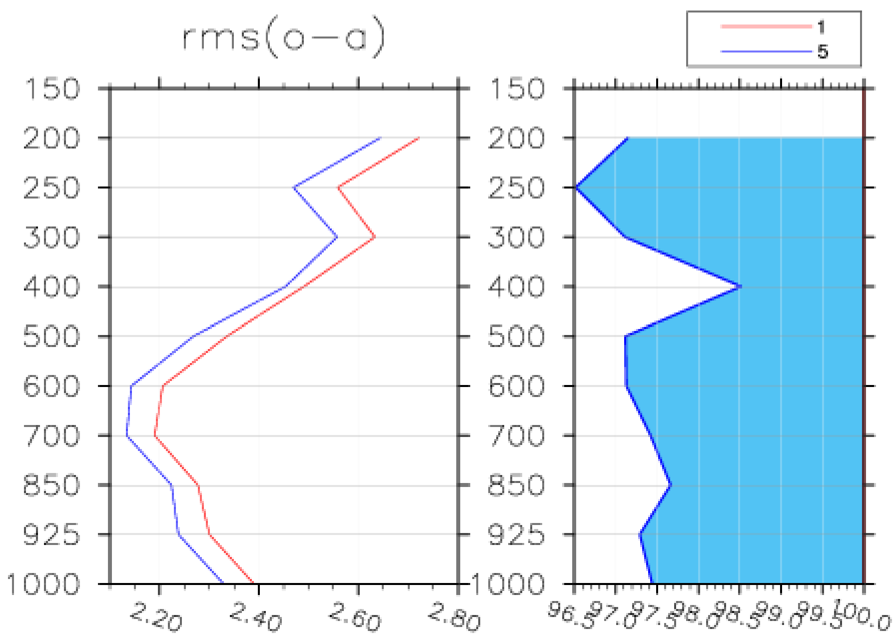
Experiments programmed and carried out **by Anne Walter, DWD & Uni Reading**, and Roland Potthast, DWD & Uni

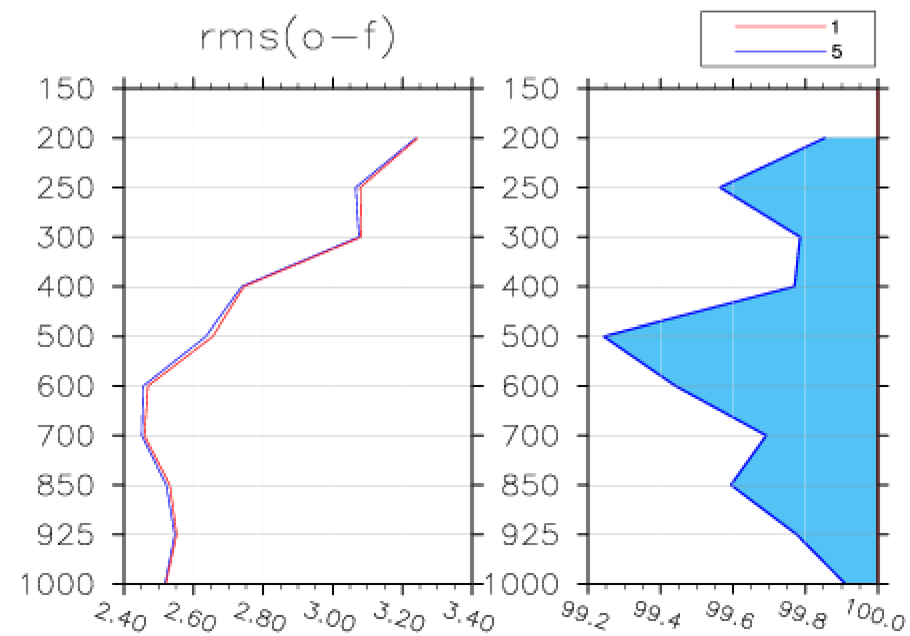
New LMCPF Scores vs



WIND o-a and o-f

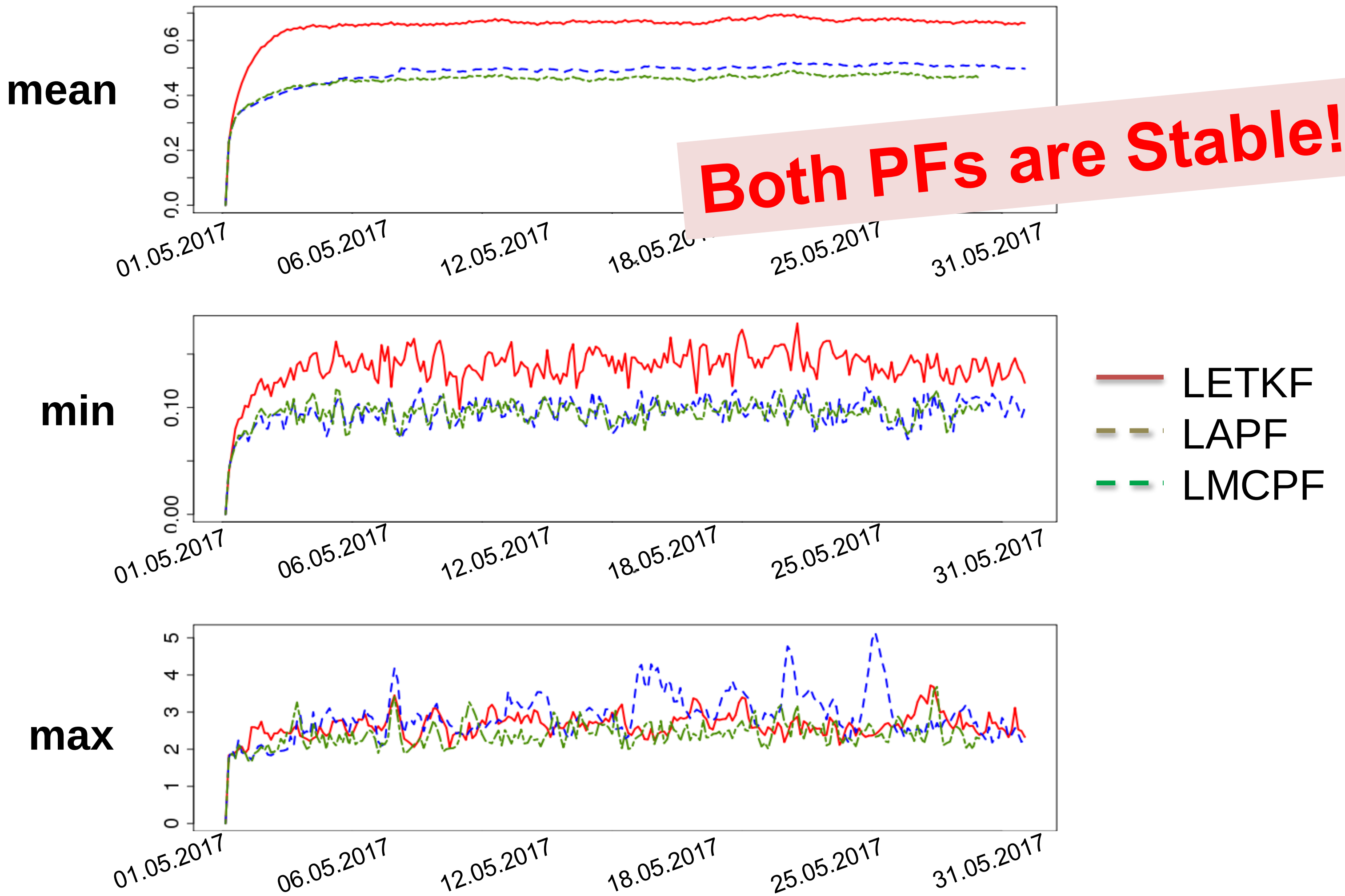
LMCPF: Uncertainty based Move works





LAPF Spread vs LMCPF & LETKF

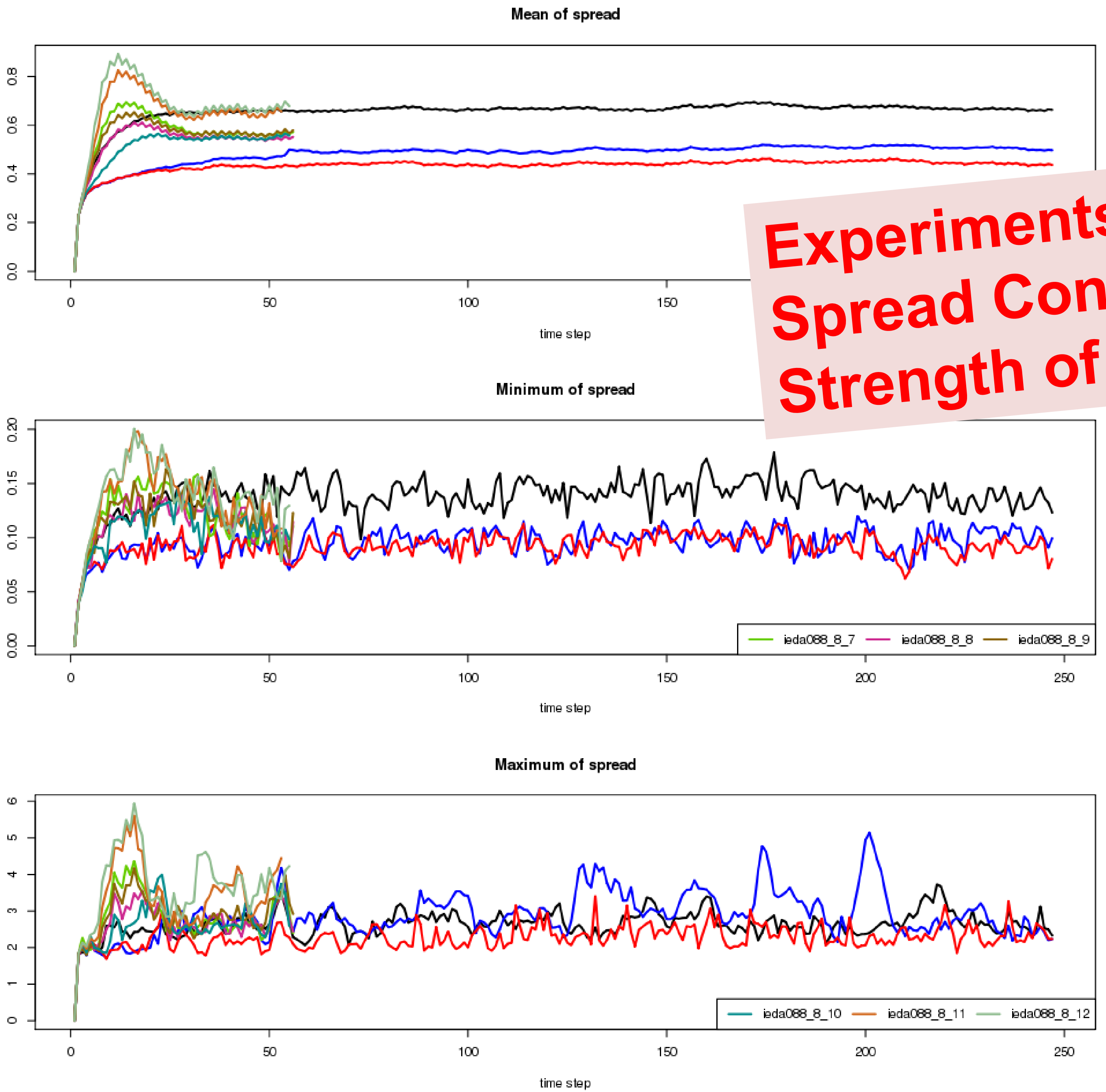
Global **spread** of T [K] ~ 500 hPa



Both PFs are Stable!

Experiments programmed and carried out **by Anne Walter, DWD & Uni Reading**, and Roland Potthast, DWD & Uni

Statistics for spread at level 64 for variable T



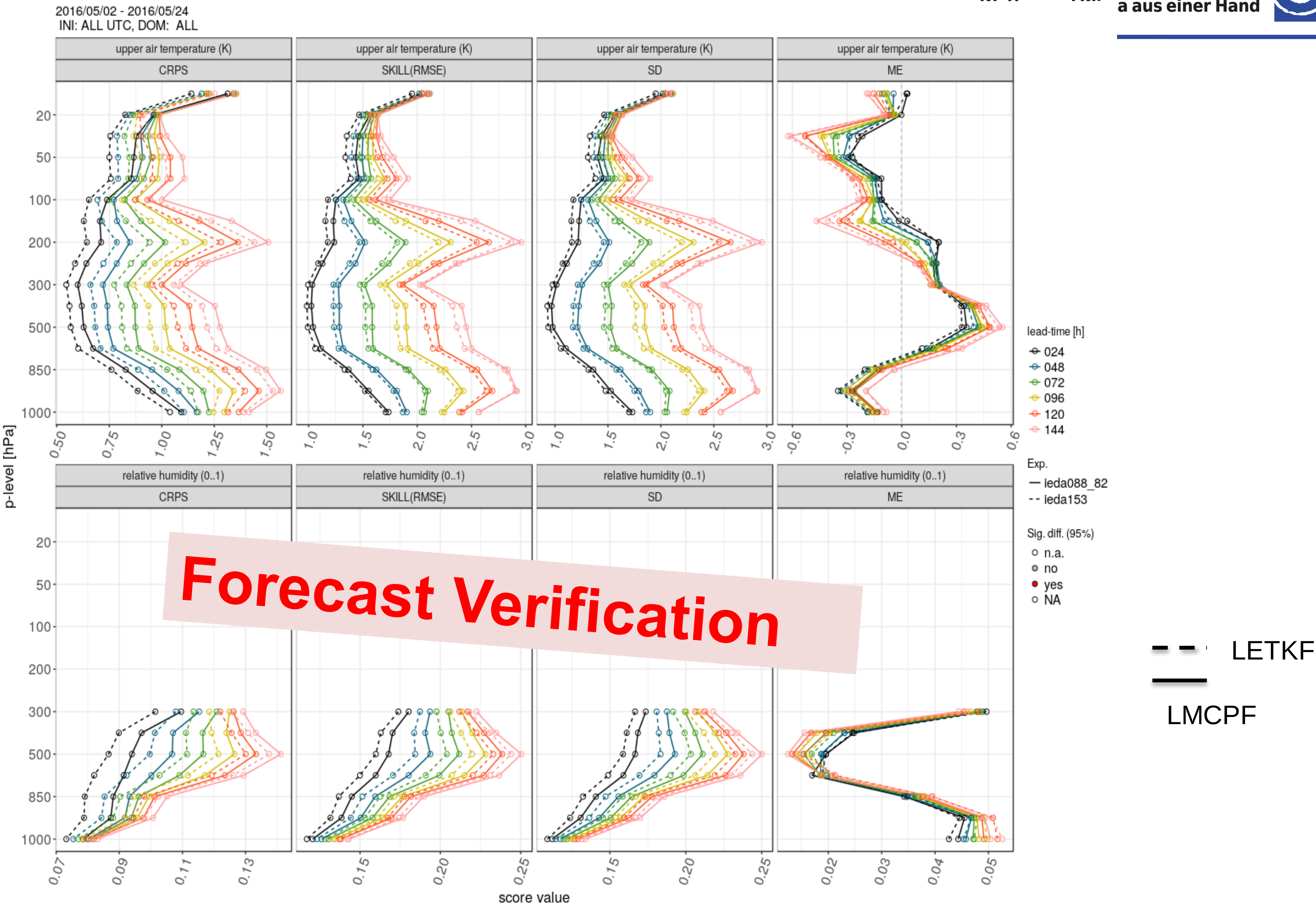
eutscher Wetterdienst
tter und Klima aus einer Hand

DWD

Experiments with Spread Control and Strength of Shifts

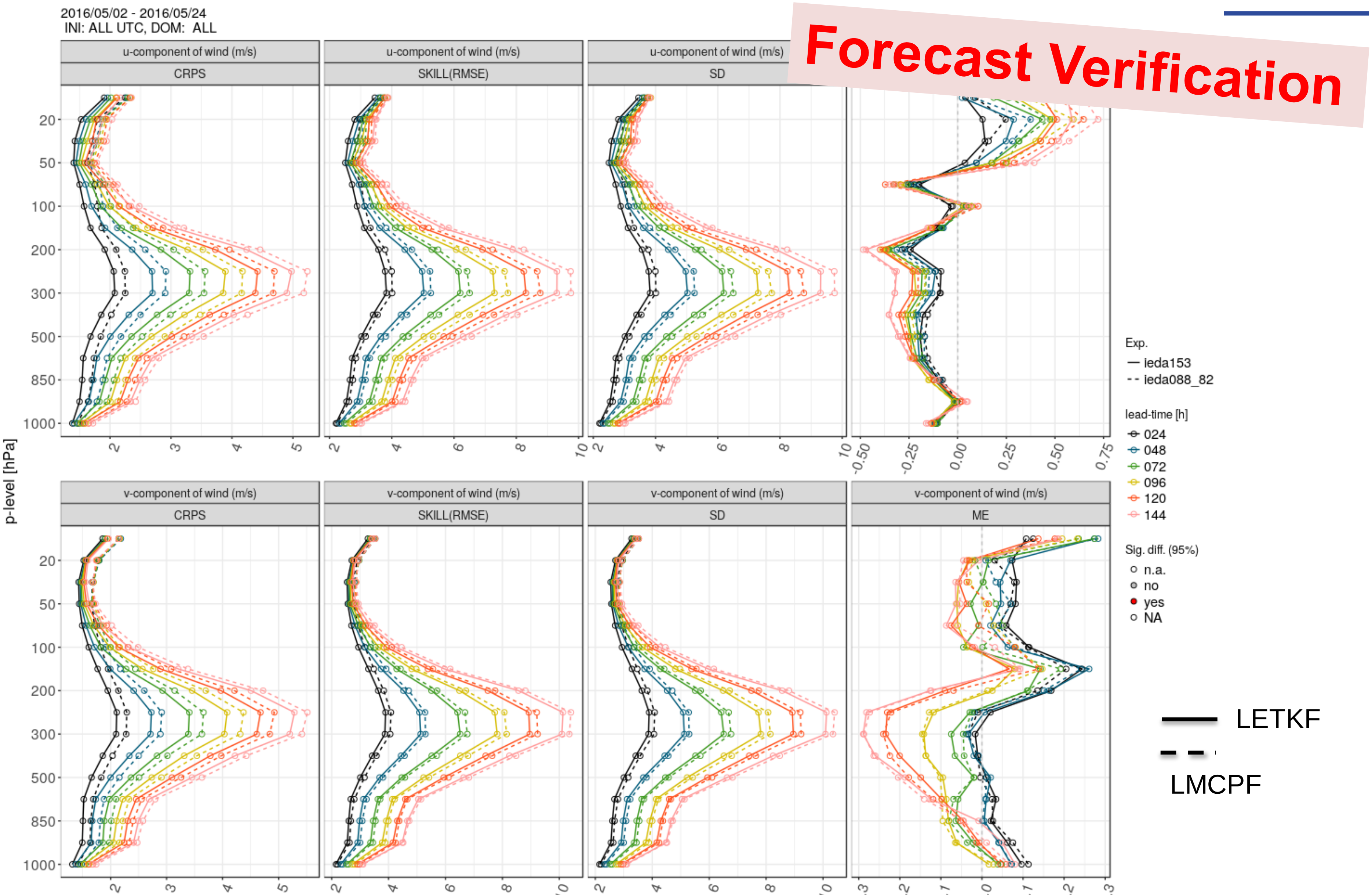
LMCPF Scores vs LETKF

DWD
Deutscher Wetterdienst
a aus einer Hand



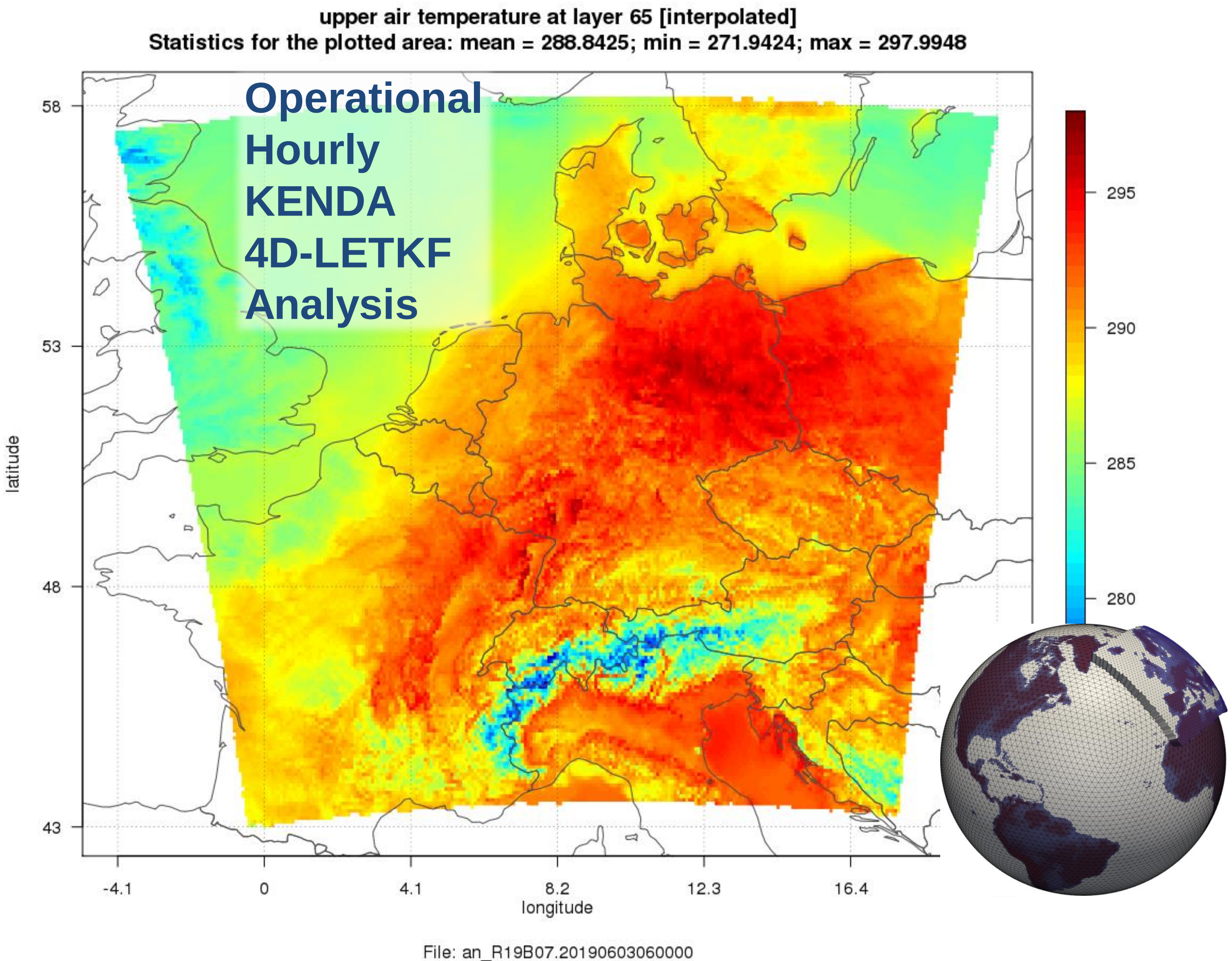
Experiments programmed and carried out **by Anne Walter, DWD & Uni Reading**, and Roland Potthast, DWD & Uni

LMCPF Scores vs LETKF



Experiments programmed and carried out **by Anne Walter, DWD & Uni Reading**, and Roland Potthast, DWD & Uni Reading

LMCPF vs LETKF for ICON D2



OPERATIONS

AIREP
MODE-S
PILOT
TEMP
DRIBU
SYNOP
RADAR LHN
RADAR RW

Development

RADAR 3D
SYNOP T,RH
RADAR OBJ
SEVIRI IR
SEVIRI VIS
Lightning LPI
MWR
GB Remote
Crowd Source
RADAR DualP

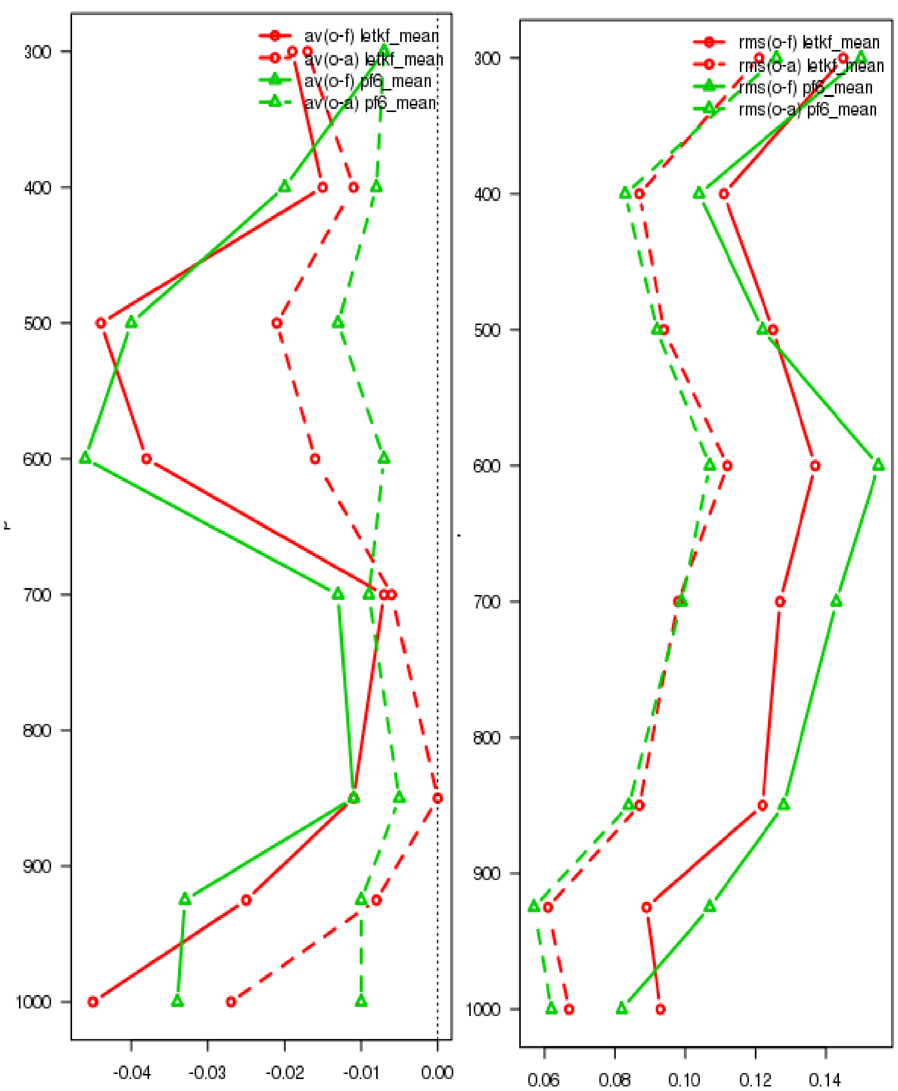
LMCPF vs LETKF for ICON D2

Conventional + all-sky SEVIRI VIS

Deutscher Wetterdienst
Wetter und Klima aus einer Hand
DWD

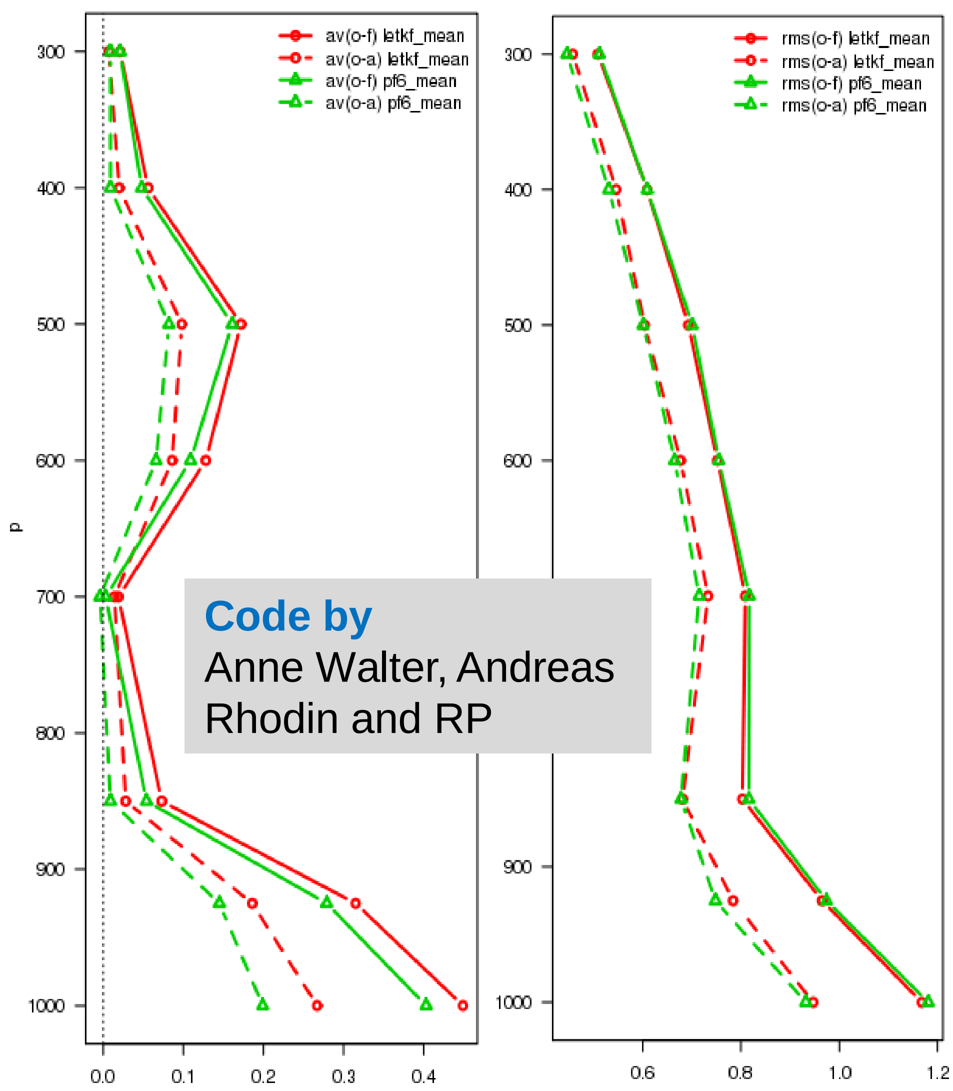
RH

av RMSE



T

av RMSE

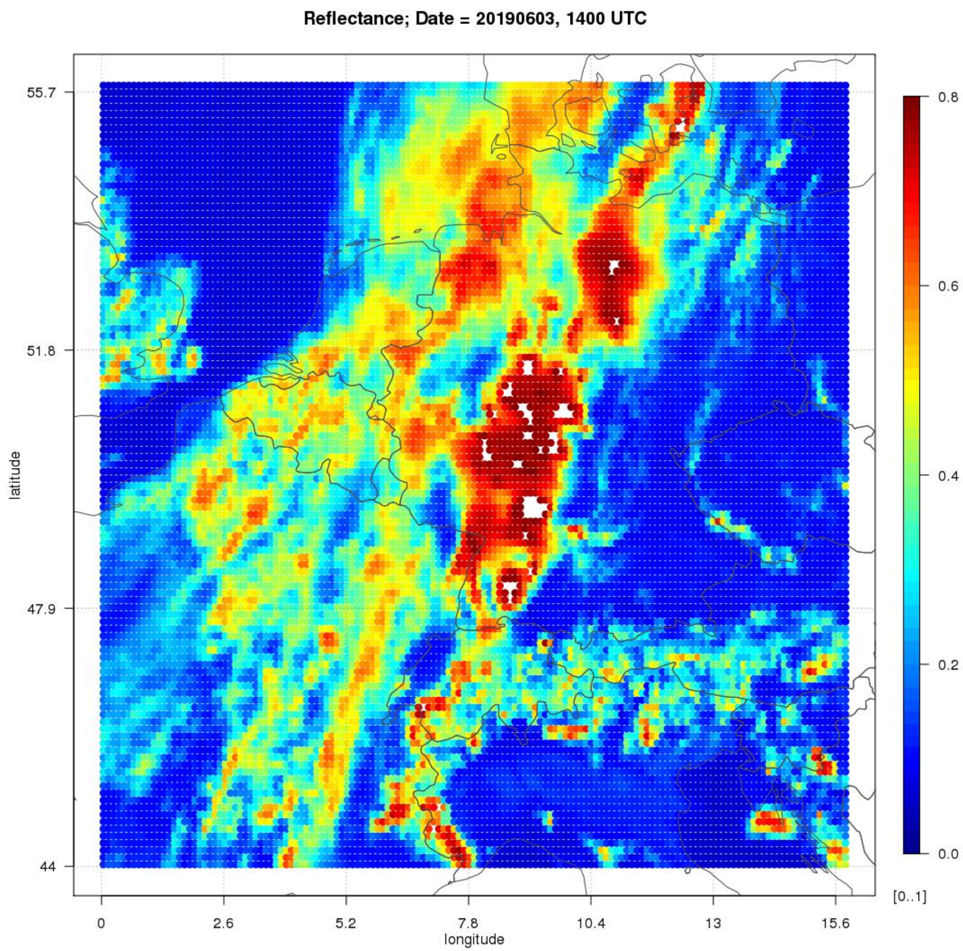


Code by
Anne Walter, Andreas Rhodin and RP

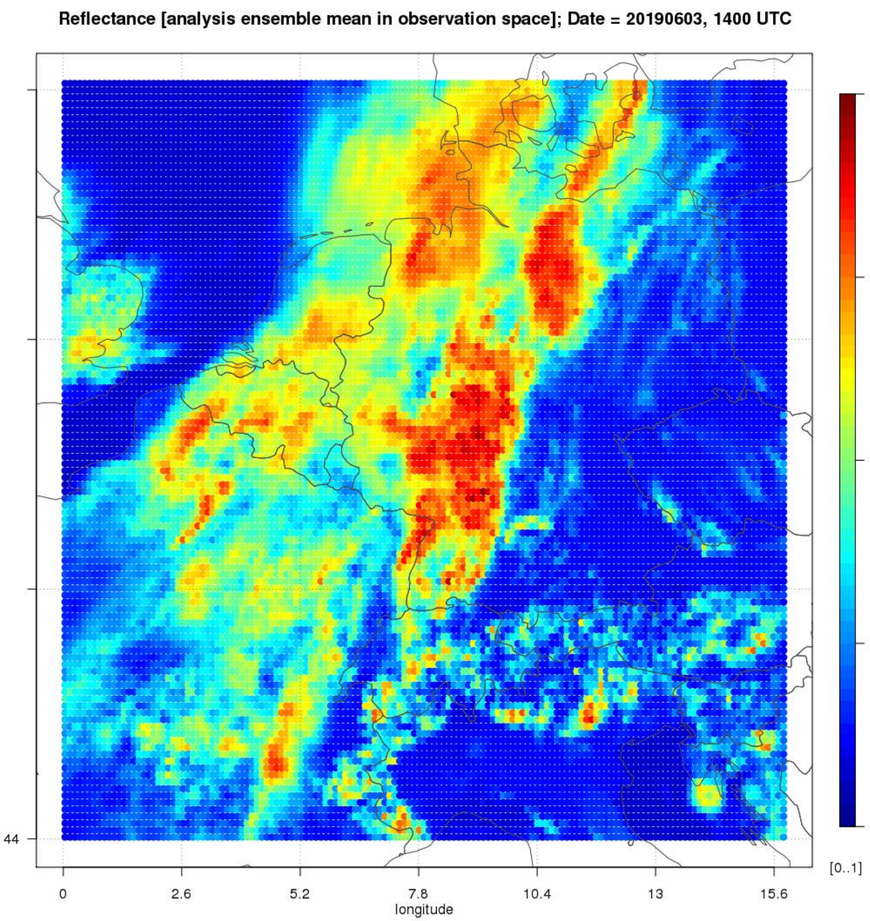
LMCPF vs LETKF for ICON D2

Conventional + all-sky SEVIRI VIS

Deutscher Wetterdienst
Wetter und Klima aus einer Hand



LETKF Analysis
Ensemble Mean



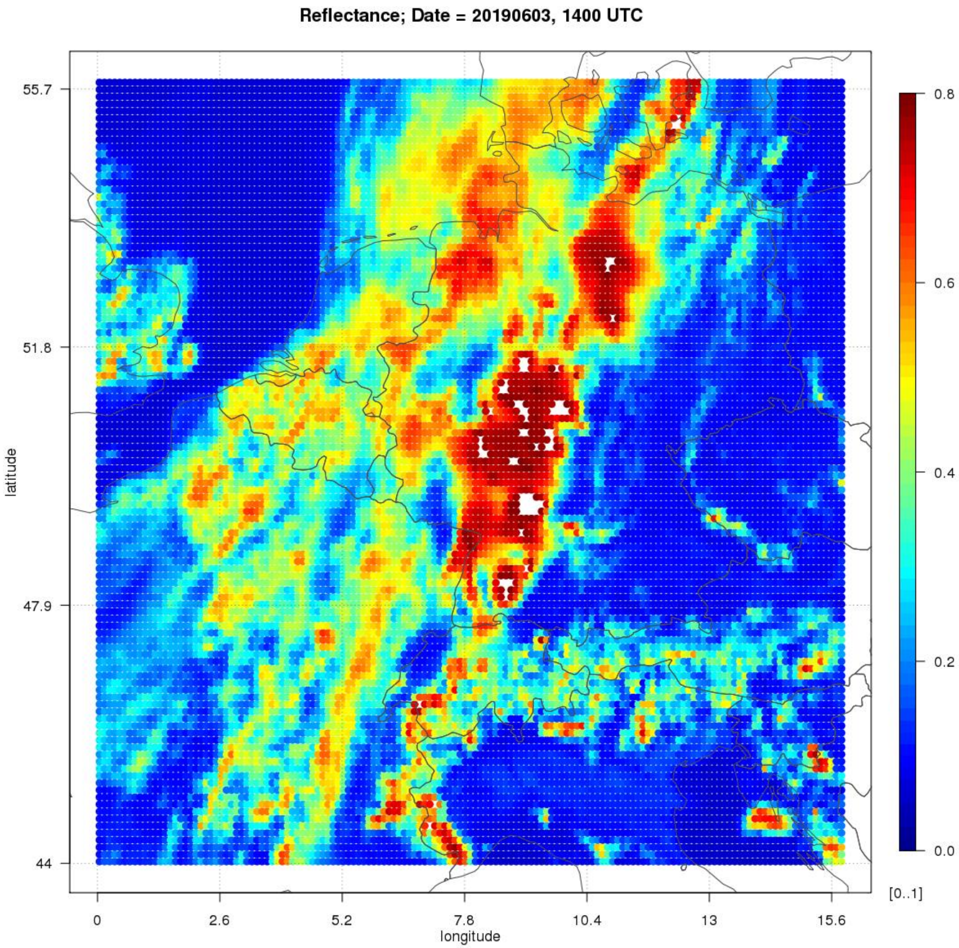
Observations

Evaluation by
Liselotte Bach
and RP

LMCPF vs LETKF for ICON D2

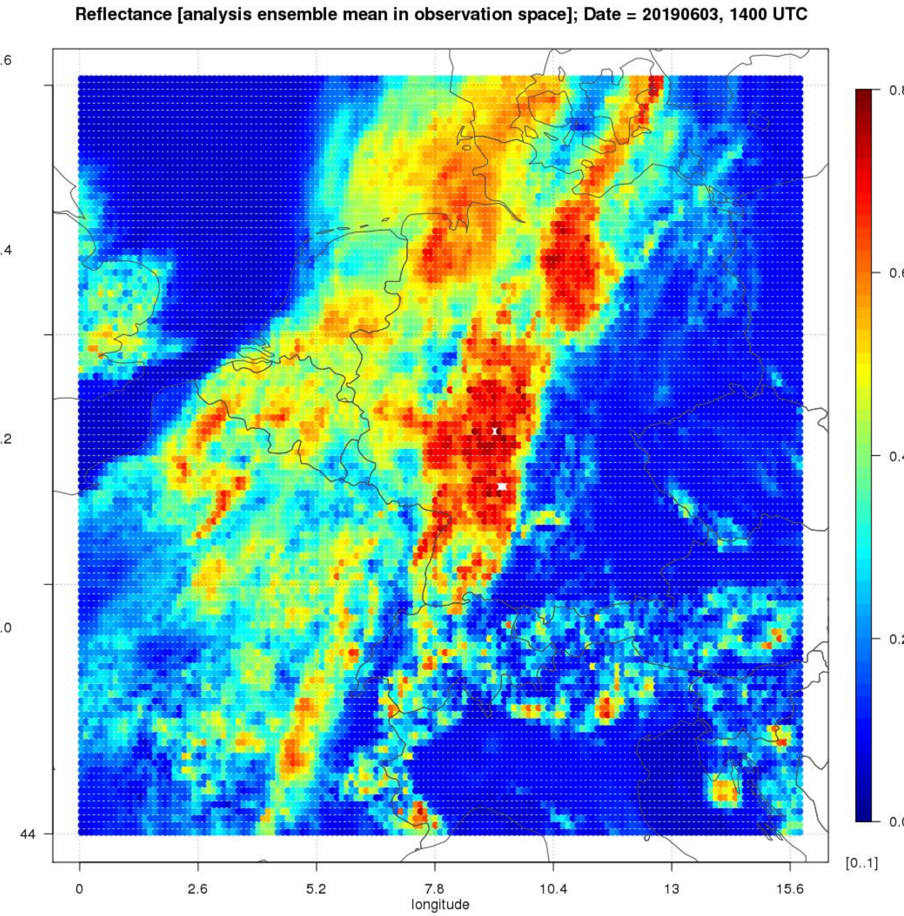
Conventional + all-sky SEVIRI VIS

Deutscher Wetterdienst
Wetter und Klima aus einer Hand



Observations

LMCPF Analysis
Ensemble Mean

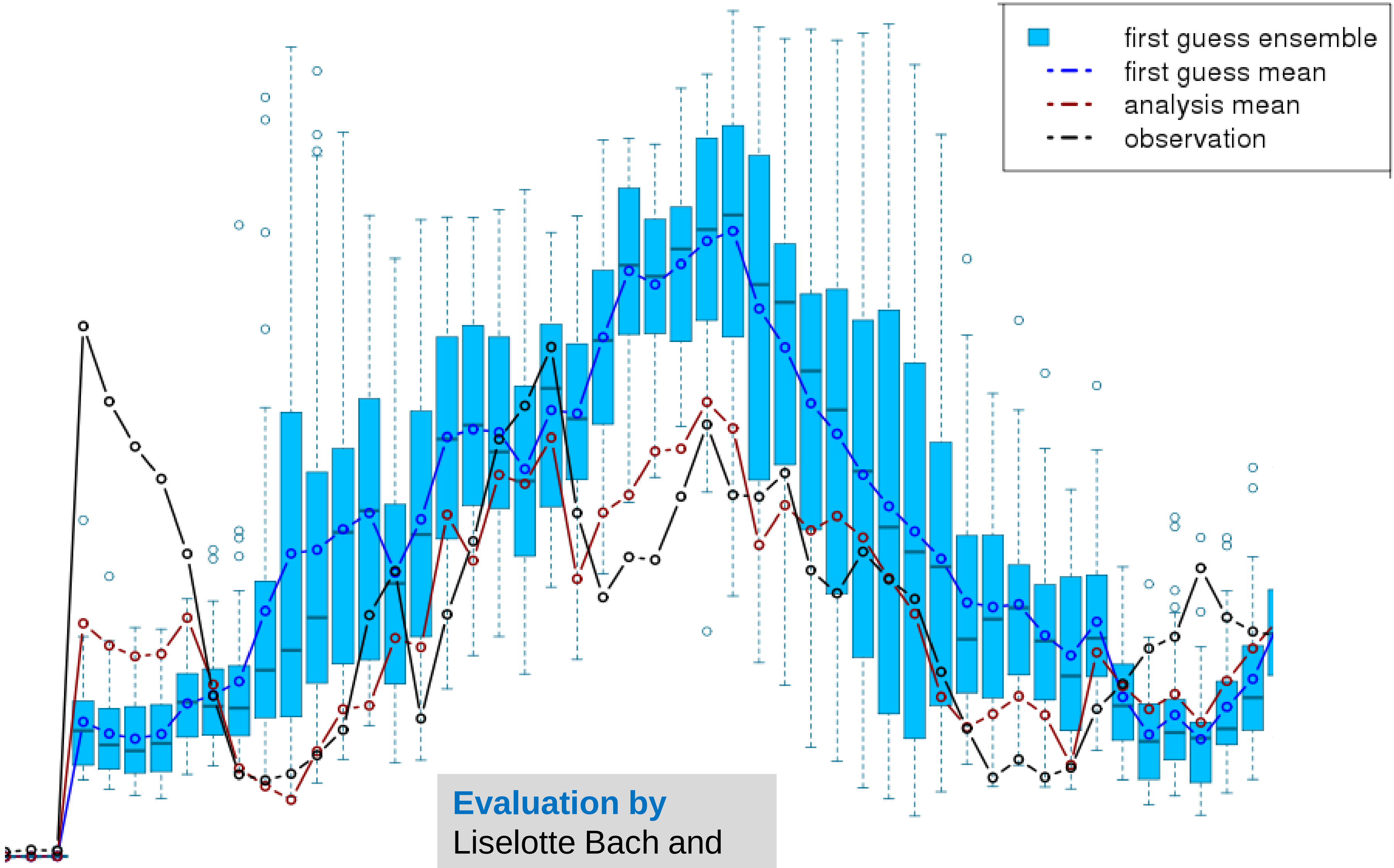


Evaluation by
Liselotte Bach
and RP

LMCPF vs LETKF for ICON D2

Conventional + all-sky SEVIRI VIS

Deutscher Wetterdienst
Wetter und Klima aus einer Hand



Evaluation by
Liselotte Bach and
Nora Amelie Schenk

LMCPF vs LETKF for ICON D2

Conventional + all-sky SEVIRI VIS

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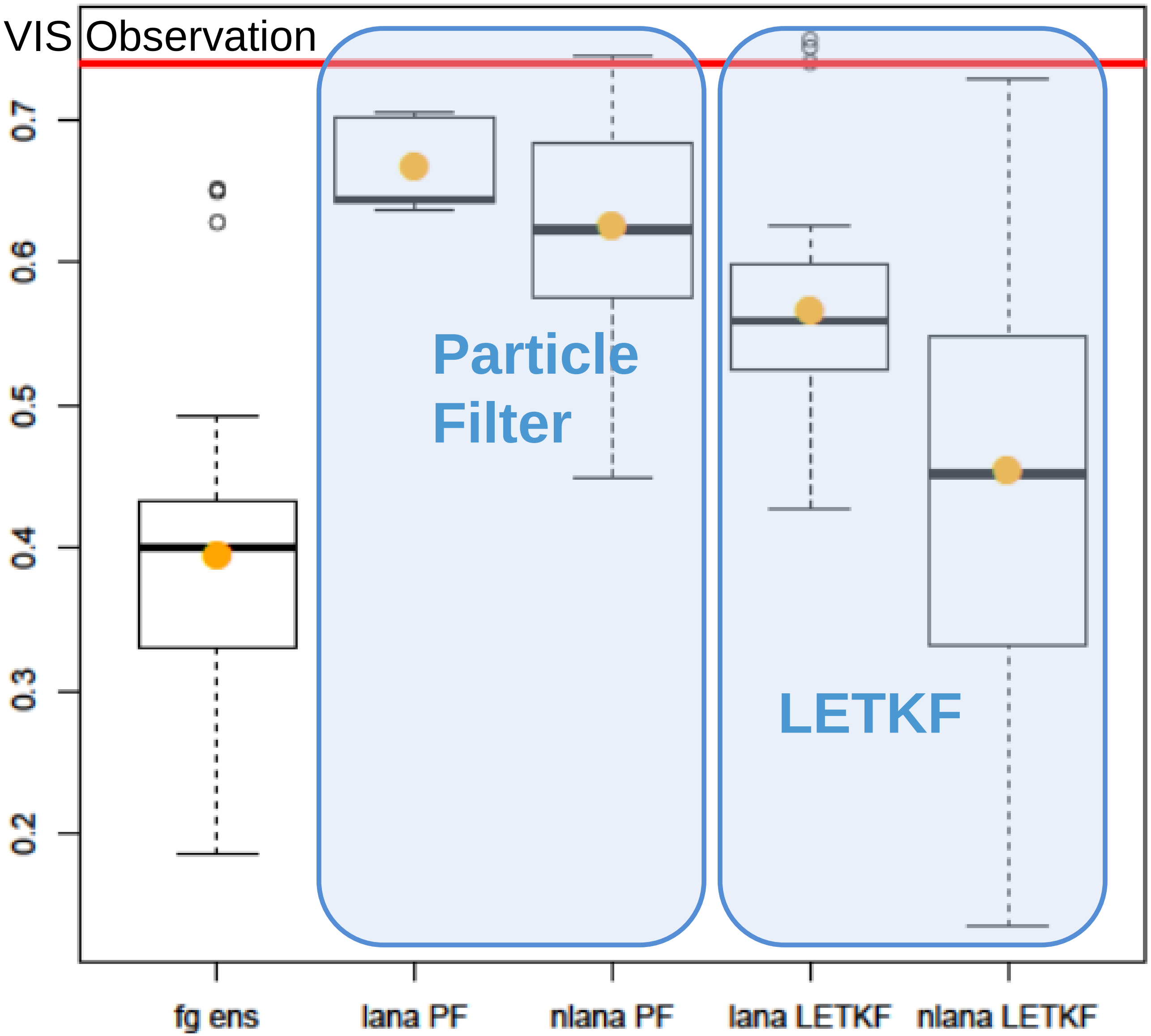
Wetter und Klima aus einer Hand



Graphics by
Liselotte Bach
Nora Amelie Schenk
Christian Welzbacher

Linear Analysis Distributions

vs

Non-linear Analysis Distributions

PF vs LETKF

Summary

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

(1) LAPF and LMCPF extend the capabilities of the LETKF

(2) Ensemble Transform, Localization, Adaptive Spread Control – LETKF, LAPF and LMCPF use the same tools

(3) Gaussian Particles allow to move towards Obs in Ensemble Space

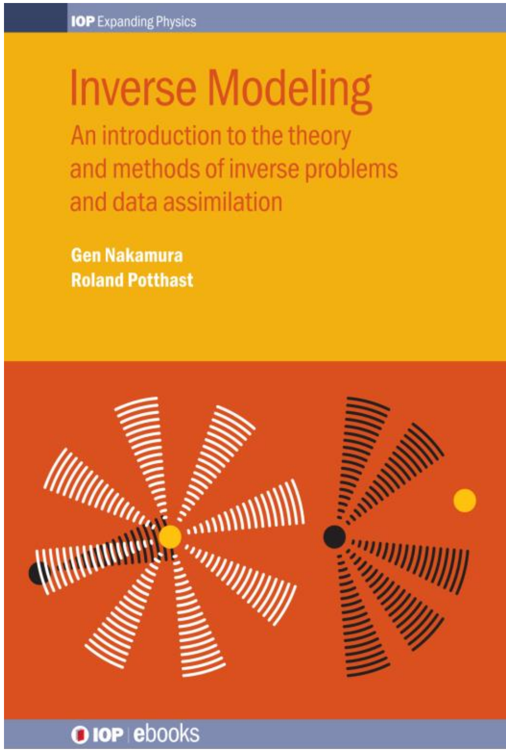
(4) More flexible than LETKF

(5) **Fully Non-Linear Filtering** by LAPF and LMCPF

(6) **Stable Particle Filters for global and regional NWP**

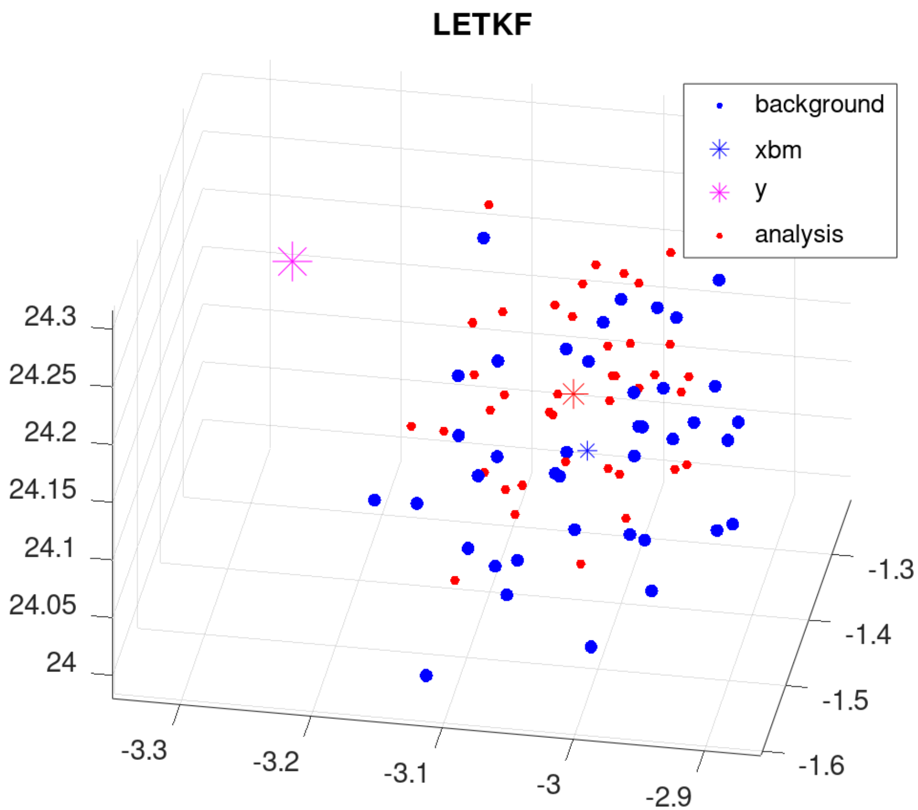
(7) Simple to Code following LETKF

(8) Promising Features for Cloud Assimilation



Thank You!

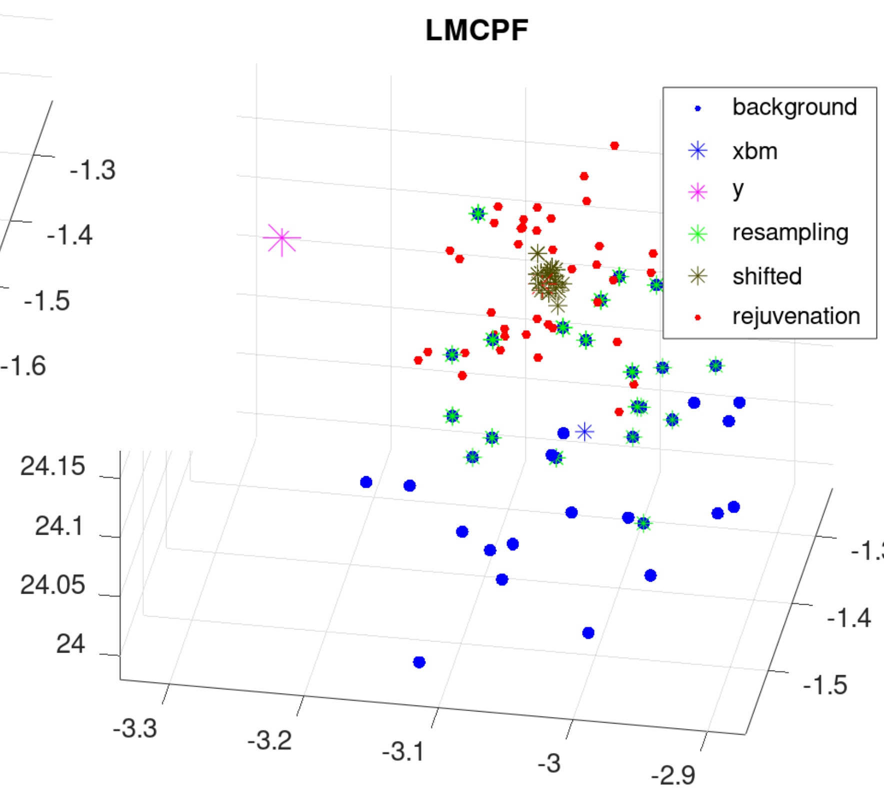
Deutscher Wetterdienst
Wetter und Klima aus einer Hand



What does a particle stand for?

Drawn from some distribution:

Representing the Distribution



Basics

- Background
- **Observation**
- Weights
- **Resampling**