Comparison of KENDA with nudging and impact of latent heat nudging

Hendrik Reich, Christoph Schraff, Andreas Rhodin, Klaus Stephan, Roland Potthast

DWD, Offenbach

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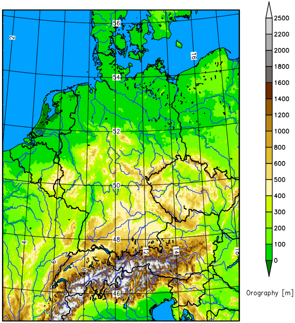
Outline

- General overview on experiments
- Results
- Remaining problems, next steps

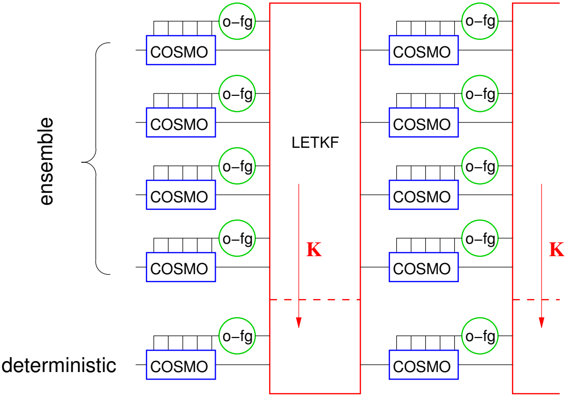
KENDA experiments: general overview

- **KENDA**: **K**ilometer Scale **En**semble **D**ata **A**ssimilation
- implementation of **LETKF** (**L**ocal **E**nsemble **T**ransform **K**alman **F**ilter) following Hunt et. al.

Orography of operational COSMO-DE domain used for KENDA-LETKF with 2.8 km horizontal resolution. The domain size is about 1170 km × 1280 km .Domain and resolution will be increased soon (COSMO-D2, 2.2.km resolution).



KENDA experiments: general overview



*KENDA system setup; 'o-fg' denotes observation minus first guess, '**K**' the Kalman Gain for the analysis mean.*

KENDA experiments: general overview

- first goal: replace (operational) nudging with deterministic LETKF analysis (second step: use as COSMO-DE EPS initial conditions)
- $\rightarrow$ focus on quality of deterministic analysis/forecast, compare with nudging (incl. LHN) as benchmark
- BACY (**ba**sic **cy**cling, bash script environment) for ICON-LETKF and KENDA
- KENDA-BACY:
  - analysis cycle: LETKF incl. det analysis, nudg cycle with same obs set; verify against obs (surface/upper air)
  - forecast cycle: nudgecast (nudg analysis), det LETKF, verify against obs (surface/upper air/radar precipitation)
- speed $\approx$ 2.0 for KENDA, but needs large hard disk storage

KENDA experiments: general overview

- BC for KENDA are taken from ICON-BACY, nudging and deterministic LETKF use same BC for analysis cycle and forecast
- ICON-BC (80 km resolution for ensemble members, 40 km for deterministic 3dVar-run):
  - 20120719-20120725,
    several experiments testing effect of soil moisture perturbations, latent heat nudging, RTPP
  - 20140517-20140615,
    compare LETKF/nudging within longer period
- preliminary tests with 20 km resolution BC from ICON-NEST; spread increased

KENDA setup for 2014 periods

variable / feature	**value**
ensemble size k	40
deterministic run	1
horiz. resolution ens. + det. run	2.8 km
forecast frequency / length	6 h / 24 h
analysis update frequency	1 h
vert. localis. length scale (ln p)	0.075 - 0.5
horizontal localisation	adaptive
→ target weighted no. obs. $N_{loc}^{o_{ef}}$	100
→ min. local. length scale r_{loc}^{min}	50 km
→ max. local. length scale r_{loc}^{max}	100 km
multiplicative covariance inflation	adaptive
→ lower / upper limit of ρ	0.5 / 3.0
RTPP relaxation weight α_p	0.75

model error: inflation/relaxation methods

- (1): compare "observed" with "expected" quantities:

$$\left\langle (y - H(x_b))(y - H(x_b))^T \right\rangle = \mathbf{R} + \rho \mathbf{H P_b H^T}$$
$$\left\langle (H(x_a) - H(x_b))(y - H(x_b))^T \right\rangle = \rho \mathbf{H P_b H^T}$$

- (2): "relaxation" methods: e.g. relaxation to prior spread (RTPS):

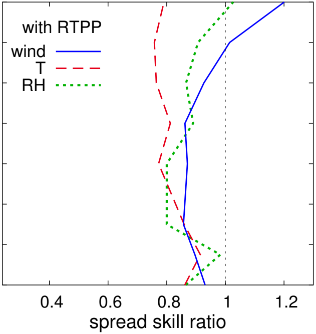
$$X_a^{i,infl} = \rho X_a^i, \; \rho = \sqrt{\alpha \frac{\sigma_b - \sigma_a}{\sigma_a} + 1}$$

or relaxation to prior perturbation (RTPP):

$$X_a^{i,infl} = (1-\alpha) X_a^i + \alpha X_b^i$$

- (1) works in observation space; tries to increase/decrease spread to fulfill statistical relations
- (2) works in model space; "corrects" reduction of spread due to assimilation of observations (RTPP: similar to additive pert., "directions" of fg pert partly remain; RTPS: inflates ana pert directions)

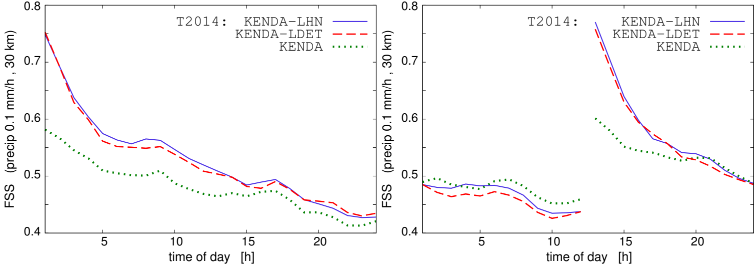
Spread-Skill Ratio (RTPP + mult. inflation)



Spread-skill ratio $r_s = \frac{\sigma_{f-\bar{f}}}{\sqrt{\sigma^2_{f_d-o} - \sigma^2_{od}}}$, where σ^2_{od} is the (diagnostic) observation error variance, $\sigma_{f-\bar{f}}$ the spread and $\sigma^2_{f_d-o}$ the RMSE.

→ With sufficient spread in the boundary conditions, RTPP (plus multiplicative inflation) gives reasonable spread-skill ratio

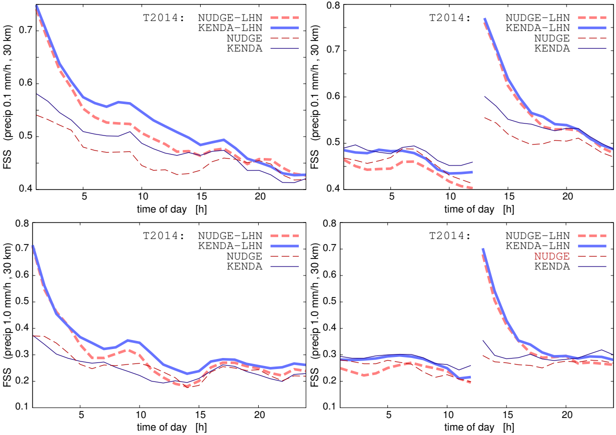
Effect of LHN on radar-derived precipitation rates



- Fraction Skill Score (FSS) of 1-hourly precipitation (11 grid points, ≈ 30 km, 0.1 mm/h threshold), 00/12-UTC forecast (left/right)
- KENDA without LHN
- KENDA-LDET with LHN only in the det run
- KENDA-LHN with LHN also in the LETKF ensemble

Similar results for all scales and forecast start times.

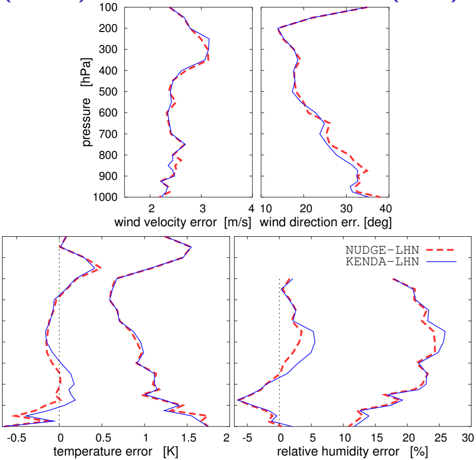
KENDA-LHN vs. NUDGE-LHN: precipitation



- FSS as before, 0.1 mm/h and 1.0 mm/h treshold (upper/lower row), 00/12-UTC forecast (left/right)
- KENDA-LHN (LETKF + LHN)
- NUDGE-LHN (nudging + LHN)
- KENDA (LETKF without LHN)
- NUDGE (nudging without LHN).

Similar results for all scales and forecast start times.

KENDA-LHN (blue) vs. NUDGE-LHN (red): 6h upper air



- Vertical profiles of bias and RMSE against radiosonde observations; 6-hour forecasts, wind speed and direction (upper row), temperature and relative humidity (lower row),) started from:
- KENDA-LHN analyses,
- NUDGE-LHN analyses

Surface verification results

experiment	PS [hPa]	T2M [K]	TD2M [K]
KENDA-LHN	.53	2.03	3.33
NUDGE-LHN	.55	2.06	3.54
KENDA	.56	2.10	3.55
NUDGE	.56	2.15	3.89

- Root mean square errors (RMSE) of surface pressure ('PS'), 2-m temperature ('T2M'), and 2-m dewpoint depression ('TD2M') against observations from surface stations.
- Each of the RMSE values shown is an average over the 21 RMSE values valid for the forecast lead times from 1 to 21 hours.

KENDA gives clearly better results for TD2M and slightly better results for T2M and PS (with LHN).

Soil moisture perturbations: Soil Moisture Index (SMI)

MeteoSwiss:

$$\mathrm{SMI} = \frac{\mathrm{WSO} - \mathrm{PWP}}{\mathrm{FC} - \mathrm{PWP}} \tag{1}$$

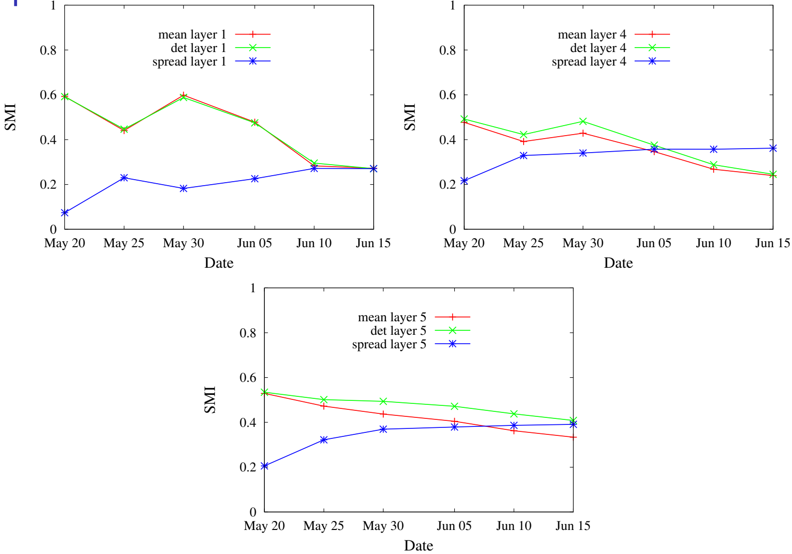
(PWP = Plant Wilting Point, FC = Field Capacity)

DWD:

$$\mathrm{SMI} = \frac{\mathrm{WSO} - \mathrm{ADP}}{\mathrm{PV} - \mathrm{ADP}} \tag{2}$$

(ADP = Air Dryness Point, PV = Pore Volume)

SMI plots



SMI (area mean of det run, ensemble mean and spread using Eq. (1) for layer 5 (54 cm), layer 4 (18 cm), layer 1 (0.5 cm)) → spread is too large, in layer 5 mean and det run diverge

Conclusions

- ICON-BC: sufficient amount of spread at boundaries, but still only 80 km resolution! → preliminary tests with 20 km resolution BC from ICON-NEST; spread increased
- 24 h forecast of det run, nudging: deterministic LETKF forecast overall similar /slightly better quality than nudging forecast (except relative humidity), especially better results for precipitation
- plots shown are for 6h forecasts, but results also hold for 12h, 18h forecasts (differences get smaller)
- LHN: nearly no influence on upper air verification (wind slightly better); better results for Radar verification (precipitation, 00 and 12 UTC runs)
- soil moisture perturbations: positive impact on spread/rmse close to surface; but seems to introduce bias!! → tune parameters

Next steps

- include SST, SNOW analysis
- compute winter period
- COSMO-D2 experiment, using ICON-NEST with 20 km resolution as BC
- tests with pattern generator
- use of additional observations, e.g. radar radial winds, SEVIRI, radar reflectivity (Theresa Bick, paper will be submitted soon)
- compute/investigate ensemble forecasts

LETKF basics

- Implementation following *Hunt et al., 2007*
- basic idea: do analysis in the space of the ensemble perturbations
  - computational efficient, but also restricts corrections to subspace spanned by the ensemble
  - explicit localization (doing separate analysis at every grid point, select only certain obs)
  - analysis ensemble members are locally linear combination of first guess ensemble members

LETKF Theory

- do analysis in the k-dimensional ensemble space

$$\bar{\mathbf{w}}^a = \tilde{\mathbf{P}}^a(\mathbf{Y}^b)^T\mathbf{R}^{-1}(\mathbf{y} - \bar{\mathbf{y}}^b)$$
$$\tilde{\mathbf{P}}^a = [(k-1)\mathbf{I} + (\mathbf{Y}^b)^T\mathbf{R}^{-1}\mathbf{Y}^b]^{-1}$$

- in model space we have

$$\bar{\mathbf{x}}^a = \bar{\mathbf{x}}^b + \mathbf{X}^b\bar{\mathbf{w}}^a$$
$$\mathbf{P}^a = \mathbf{X}^b\tilde{\mathbf{P}}^a(\mathbf{X}^b)^T$$

- Now the analysis ensemble perturbations - with $\mathbf{P}^a$ given above - are obtained via

$$\mathbf{X}^a = \mathbf{X}^b\mathbf{W}^a,$$

where $\mathbf{W}^a = [(k-1)\tilde{\mathbf{P}}^a]^{1/2}$

LETKF Theory

- it's possible to obtain a *deterministic run* via

$$\mathbf{x}_a^{det} = \mathbf{x}_b^{det} + \mathbf{K}\left[\mathbf{y} - H(\mathbf{x}_b^{det})\right]$$

with the *Kalman gain* **K**:

$$\mathbf{K} = \mathbf{X}_b\left[(k-1)\mathbf{I} + \mathbf{Y}_b^T\mathbf{R}^{-1}\mathbf{Y}_b\right]^{-1}\mathbf{Y}_b^T\mathbf{R}^{-1}$$

- the deterministic analysis is obtained on the same grid as the ensemble is running on; the *analysis increments* can be interpolated to a higher resolution

Assimilation of Radar-derived precipitation by LHN

Required relation:

precipitation rate $\leftrightarrow$ model variables

(observed) (info required by nudging)

precipitation $\leftrightarrow$ condensation $\leftrightarrow$ release of latent heat

$\rightarrow$ Assumption: vertically integrated latent heat release $\propto$ precipitation rate

Approach: modify latent heating rates such that the model responds by producing the observed precipitation rates $\rightarrow$ Latent Heat Nudging (LHN)

$$\frac{\partial T}{\partial t} = F(t) + \left.\frac{\partial T}{\partial t}\right|_{nudging} + \left.\frac{\partial T}{\partial t}\right|_{LHN}$$

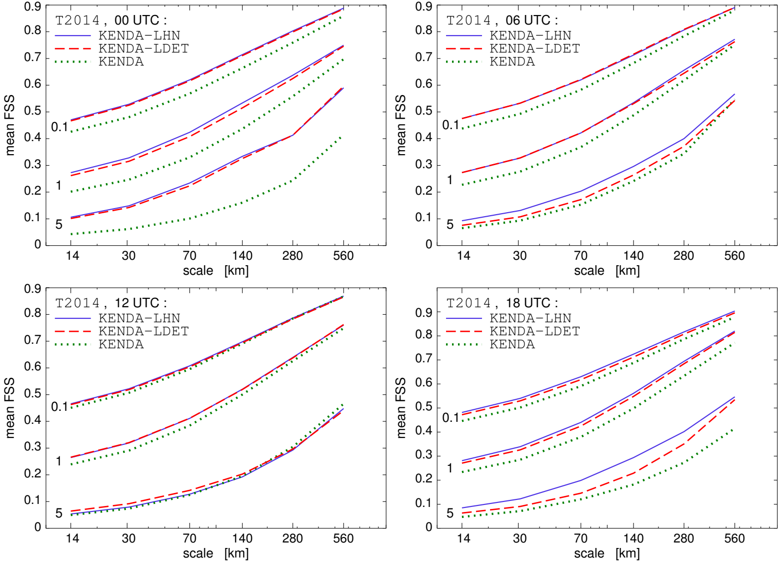
$$\Delta T_{LHN} = (\alpha - 1) \cdot \Delta T_{LH} \quad \text{with} \quad \alpha = \frac{RR_{obs}}{RR_{ref}}$$

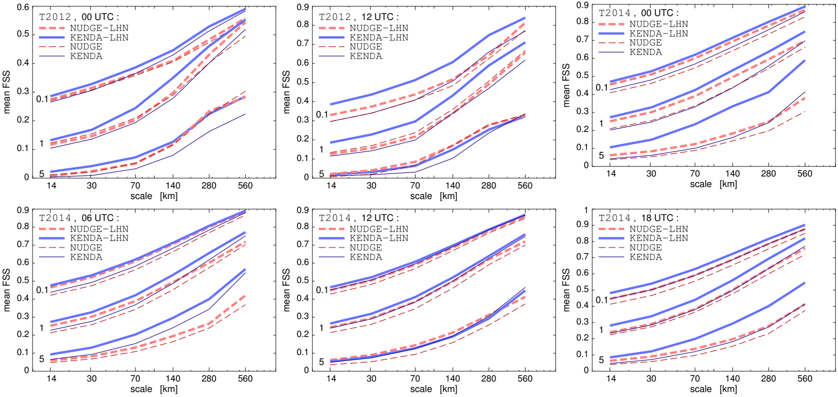
Use LHN in LETKF until assimilation of radar reflectivities is available

Soil moisture perturbations

- perturb soil moisture (and SST) with defined spatial and temporal length scales and amplitude
- soil moisture: 2 length scales, 100 km (synoptic), 10 km (convection)
- cut-off if moisture is below zero or above capacity ($\rightarrow$ bias)
- next step: for soil moisture, limit perturbation amplitude to "available capacity" (avoid bias)

```
name = 'W_SO'                ! disturb soil moisture
scales = 0.002 100 1 24 ! 0.004 of soil capacity, 100km,
                             ! 1m vertical, 24 hour
         0.002 10 1 24  ! 0.004 of soil capacity, 10km,
                             ! 1m vertical, 24 hour
name = 'SST'            ! disturb SST
scales = 1  100 0 24 ! 1K +  100 km length scale pattern,
                        ! 24 hour
```


T2014 , 00 UTC :
KENDA−LHN
KENDA−LDET
KENDA
T2014 , 06 UTC :
T2014 , 12 UTC :
T2014 , 18 UTC :
mean FSS
scale [km]
0.1
1
5
14
30
70
140
280
560


T2012 , 00 UTC :
T2012 , 12 UTC :
T2014 , 00 UTC :
T2014 , 06 UTC :
T2014 , 12 UTC :
T2014 , 18 UTC :
NUDGE-LHN
KENDA-LHN
NUDGE
KENDA
mean FSS
scale [km]
14
30
70
140
280
560
0.1
1
5