LETKF experiments: recent results on adaptive methods and other aspects

H. Reich, C. Schraff, A. Rhodin

DWD, Germany

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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 experiments

- technical implementation of experiments (up to now):
  - stand-alone LETKF script environment to run COSMO-DE LETKF + diagnostics / plotting
  - toy model (Lorenz-96,40 grid points) to test LETKF components
- experiments with successive LETKF assimilation cycles (32 ensemble members, drawn from 3dVar B-Matrix)
  - 3-hourly cycles, up to 2 days (7-8 Aug. 2009: quiet + convective day)
  - lateral boundary conditions (LBC) from COSMO-SREPS (3 * 4 members)
  - old experiments: use obs from GME NetCDF feedback files (sparse density)
  - new experiments: use obs from NetCDF files written by COSMO-model during integration (same obs set as nudging)
  - option for *deterministic analysis* has been implemented

LETKF experiments

- experimental settings:
  - 3h update (later $\approx$ 15 min)
  - observations used: TEMP, AIREP, PILOT, SYNOP
  - 2 day period
- $\rightarrow$ characteristics:
  - highly inhomogenous observation density
  - observation density $\approx$ 10 times larger as in old setup
- experience (GME): LETKF works best (in terms of rms/spread ratio) with low number of observations
- keep localization scales unchanged to test adaptive methods within a setup where problems can be expected

LETKF experiments

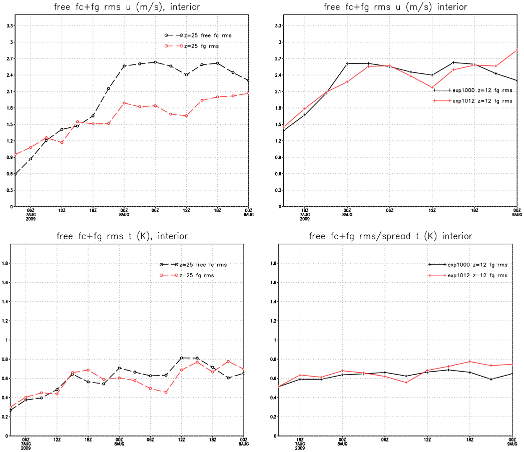
- analysed variables are $u, v, w, T, pp, qv, qcl, qci$
- analysed means that linear combination is applied to these variables (other variables taken from first guess ensemble / ensemble mean)
- verify LETKF *det run (mean)* against
  - nudging analysis (u, v, w, T, pp)
  - observations (u, v, T, rh)
- verification tool (deterministic/ensemble scores) is currently under development

comparison with free fc, old and new setup

free fc rmse

first guess rmse,

old setup



free fc rmse

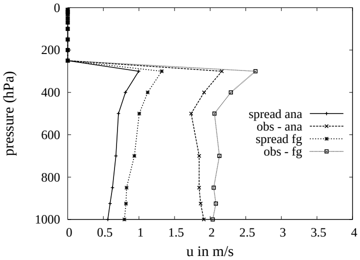
first guess rmse,

new setup

Fig.1: upper row: u (m/s) at 500 hPa; lower row: t (K) at 500 hPa.

more obs do not lead to better results...

u obs-fg/spread (time average, whole area)



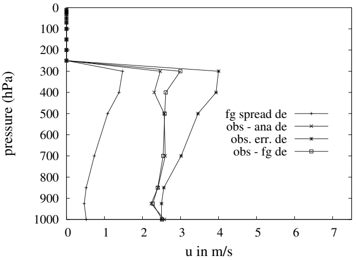


Fig.2: time average (20090807 15 UTC - 20090809 00 UTC) of obs-fg and spread of u (m/s), (whole area), AIREP; old setup (left), new setup (right)

new setup: small differences between fg/ana; ensemble is underdispersive.

→ using the same settings as in the old setup leads to worse results...

adaptive methods

- lack of spread is (partly) due to model error which is not accounted for so far
- one (simple) method to increase spread is multiplicative covariance inflation:
  - $X_{ens} \rightarrow \rho X_{ens}$ with $\rho > 1$
- adaptive method to estimate ρ preferable
  - (*Desroziers et al.*): describes methods to estimate (co)variance of background or analysis $\rightarrow$ estmation of ρ
  - (*Li et al.*) used two of these methods for online estimation of ρ within a toy model
  - (*Bonavita et al.*): ρ is computed at every gridpoint, tested in CNMCA LETKF

adaptive methods ctd.

two different ideas to estimate ρ have to be distinguished:

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

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

- idea (2): "relaxation" methods:
  - e.g. relaxation to prior spread (RTPS)
  - $\rho = \sqrt{\alpha \frac{\sigma_b - \sigma_a}{\sigma_a} + 1}, \, \alpha < 1$
- (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
- it is prefarable to compute ρ in *ensemble space* because this is where the LETKF works

adaptive methods ctd.

- obs errors / **R**-matrix probably assumed incorrectly, correction desirable
    - compare observed obs (co)variance with assumed one and correct **R** automatically if necessary
    - this is done in *ensemble space*
- both methods (est. of inflation factor / **R** matrix) have been tested with reasonable numerical cost and success within the toy model, and have been implemented in the LETKF (COSMO and GME)
- old setup: slightly postitive impact of inflation factor ρ, impact of estimation of **R** neutral
- new setup: much more observations, but worse results; can adaptive methods help?

comparison of adaptive ρ inflation methods

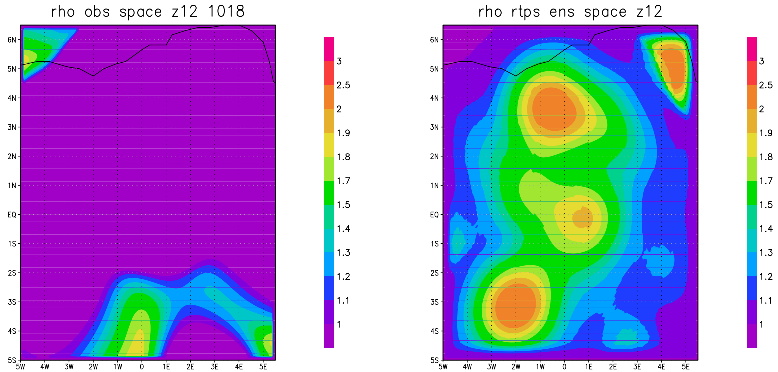


Fig.3: both plots: 2009080812 UTC, 500 *hPa*; ρ in obs space (left); ρ in ens space (RTPS) (right)

different spatial structures with obs-space/RTPS method!

adaptive **R** correction

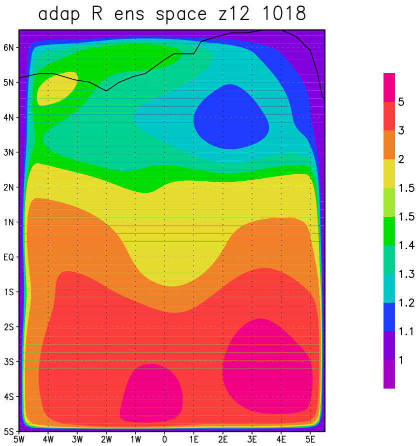


Fig.4: square root of adaptive **R**-correction factor; 2009080812 UTC, 500 *hPa*

large values in some areas → retuning of obs error necessary?

effect of adaptive observation error estimation

R const

R adap

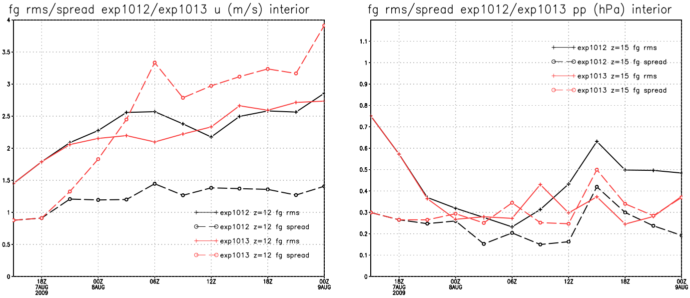


Fig.5: intercomparison of fg rms / spread with adaptive **R** estimation switched off/on(exp1012/exp1013); results for *u* in *m/s* at 500 *hPa* (left), *pp* in *hPa* at surface (right).

adaptive **R** estimation in general decreases rms, but spread is overestimated (adaptive ρ switched on in both experiments)

effect of adaptive observation error estimation

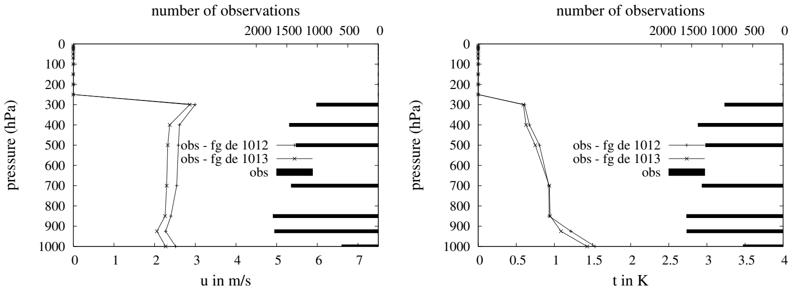


Fig.6: intercomparison of fg rmse with adaptive **R** estimation switched off/on(exp1012/exp1013); results for *u* (left), *t* (right), AIREPS

adaptive **R** estimation has slightly positive impact on first guess when comparing with observations

effect of adaptive covariance inflation

ρ const

ρ adap

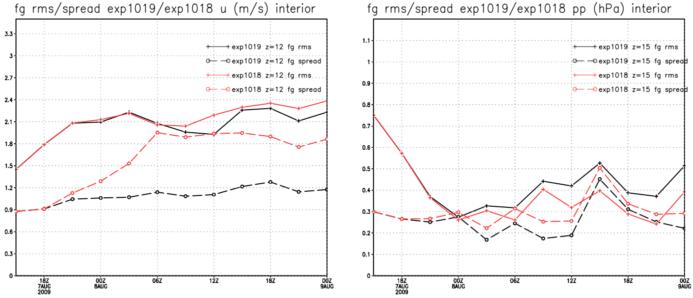


Fig.7: intercomparison of fg rms / spread with adaptive ρ estimation switched off/on(exp1019/exp1018); results for u in m/s at 500 hPa (left), pp in hPa at surface (right).

adaptive ρ inflation has positive impact on surface pressure, negative impact on u in terms of rms; spread is increased (adaptive **R** switched on in both experiments)

effect of adaptive covariance inflation

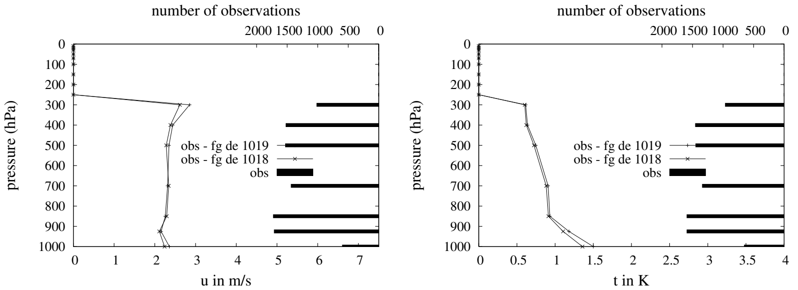


Fig.8: intercomparison of fg rms / spread with adaptive ρ estimation switched off/on(exp1019/exp1018); results for u (left), t (right), AIREPS

adaptive ρ estimation has slightly positive impact on first guess of t, neutral impact on u when comparing with observations

adaptive methods, ctd.

- ρ is computed in model space, **R** correction in ensemble space
- both methods don't take into account each other
- coupling of both methods desirable
- recompute ρ

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

$$\rho' = \rho \cdot \text{trace}\left((k-1)\mathbf{I} + \frac{\rho}{\alpha}(\alpha - 1)\mathbf{Y^T}\mathbf{R}^{-1}\mathbf{Y}\right)^{-1}$$

where α is the **R** correction factor, k number of ensemble members, **I** is the identity matrix and **Y** are the ensemble perturbations in observation space

effect of rho correction

ρ pure

ρ corrected

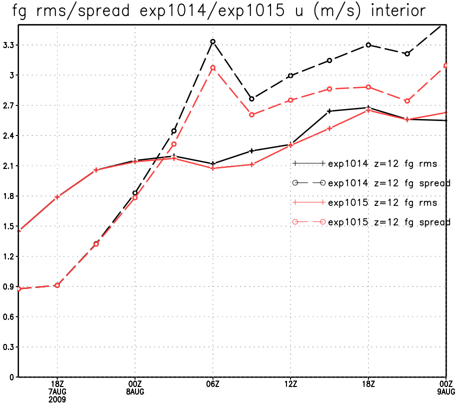


Fig.9: intercomparison of fg rms / spread with correction of adaptive ρ switched off/on(exp1014/exp1015); results for u in m/s at 500 hPa.

correction of adaptive ρ inflation has slightly positive impact on rms, spread is still too large

reason for overestimation of spread

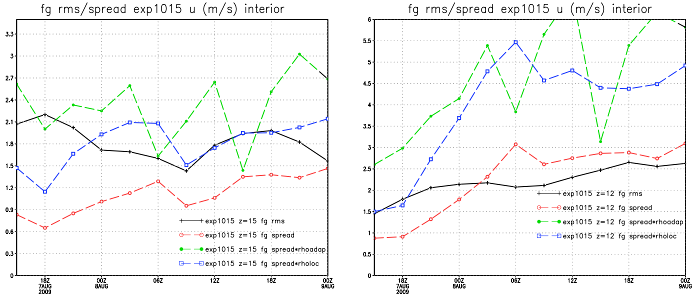


Fig.10: fg rms / spread (black/red) and spread times inflation factor ρ (green/blue); results for u in m/s at surface(left) and at 500 hPa (right).

adaptive ρ inflation factor is largely computed using surface observations $\rightarrow$ value appropiate for surface, but here too large at 500 hPa.

effect of using localization weights in ρ computation

ρ weights

ρ pure

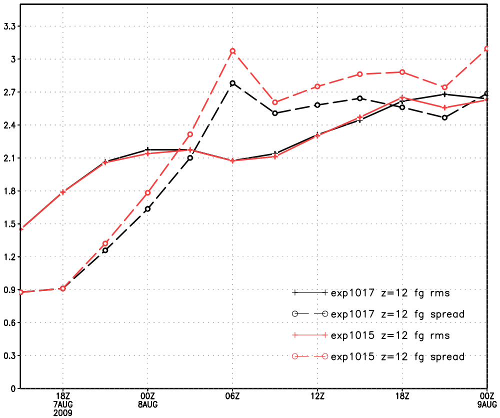


Fig.11: intercomparison of fg rms / spread with using localization weights to compute adaptive ρ switched off/on(exp1015/exp1017); results for u in m/s at 500 hPa.

using weights of adaptive has slightly negative impact on rms, but reduces overestimation of spread

effect of reducing vertical localization length scale

lv=0.3

lv=0.2

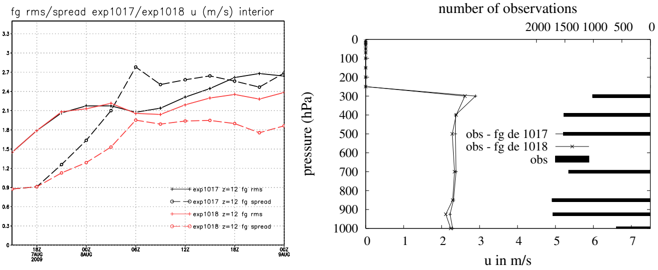


Fig.12: intercomparison of fg rms / spread with reduced vertical localization length scale; results for *u* in *m/s* at 500 *hPa* (left), verification against AIREPS (right)

in general positive impact, spread overestimation reduced

effect of preliminary retuned obs errors

old obs

errors

new obs

errors

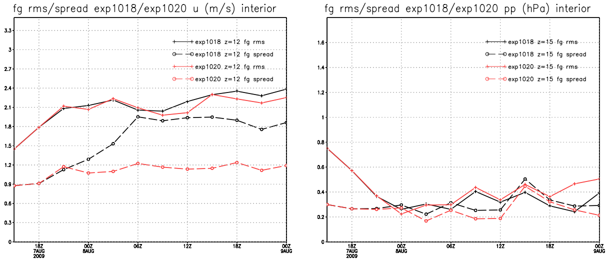


Fig.13: intercomparison of fg rms / spread with retuned specified observation errors; results for *u* in *m/s* at 500 *hPa* (left), *pp* at surface(right)

negative impact at surface, slightly positive impact at higher levels

effect of preliminary retuned obs errors

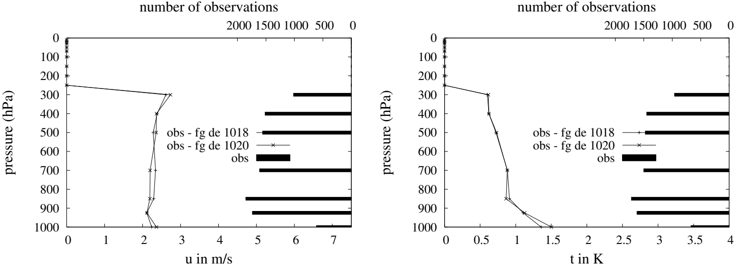


Fig.14: intercomparison of fg rms / spread with retuned observation errors; results for *u* (left), *t* (right), verification against AIREPS

negative impact at surface and higher levels, slightly positive impact at medium levels

effect of preliminary retuned obs errors

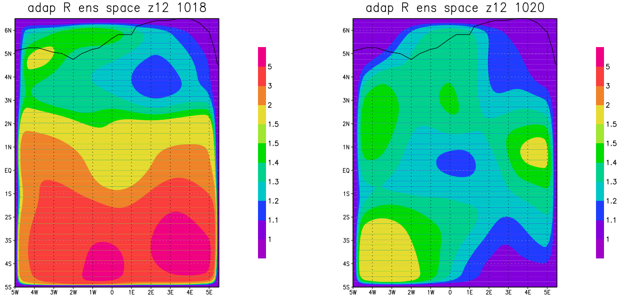


Fig.15: all plots: 2009080812 UTC, 500 *hPa*; left: adap **R**, old obs errors, right: new obs errors

large effect of specified obs errors; values decrease (closer to 1.0)

effect of preliminary retuned obs errors

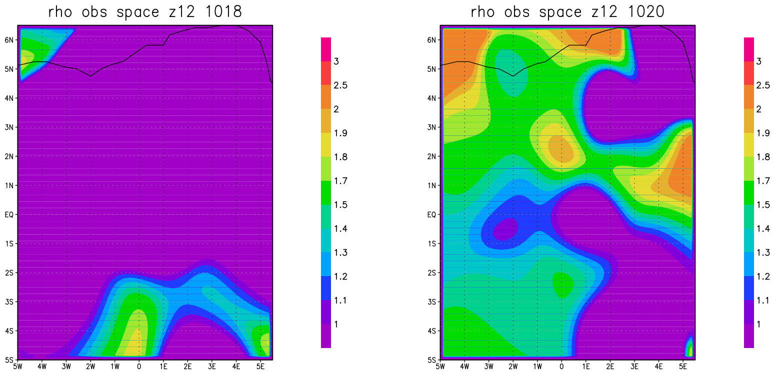


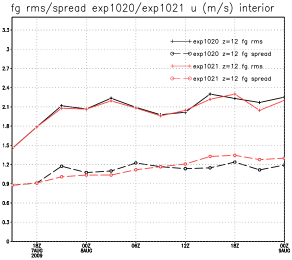
Fig.16: both plots: 2009080812 UTC, 500 *hPa*; ρ in obs space (left); ρ in obs space, specified obs errors changed (right)

obs-space method sensitive to (specified) obs errors changes

adaptive covariance inflation in ens space

ρ obs

ρ ens



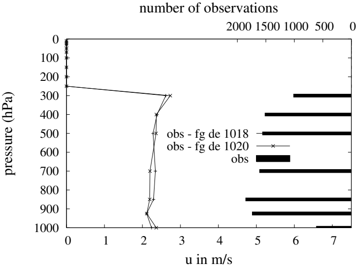


Fig.17: intercomparison of fg rms / spread with adaptive covariance inflation in ens space (RTPS); results for u at 500 hPa (left), u (right), AIREPS

neutral impact on rmse, spread increases slightly

impact of all methods

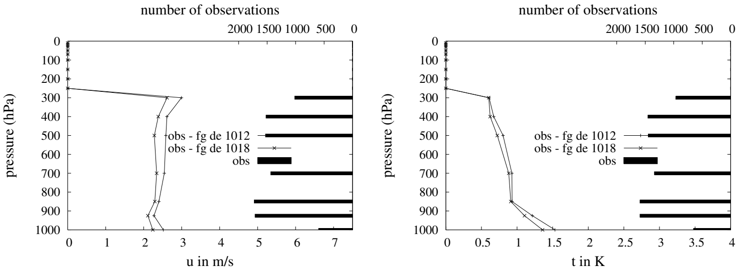


Fig.18: impact of all methods on fg rms / spread results for *u* (left), *t* (right), AIREPS

positive impact on all levels, but still not better than with old setup...

effect of new setup on noise

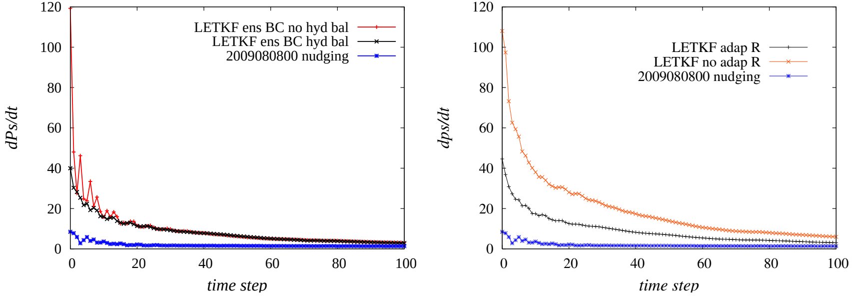


Fig.19: noise (dPs/dt in Pa/s, area mean) of one ensemble member with old obs setup at 20090808 00 UTC (left) and new setup (right)

without adaptive R correction: noise increases with new setup

comparison of det run and mean

det

mean

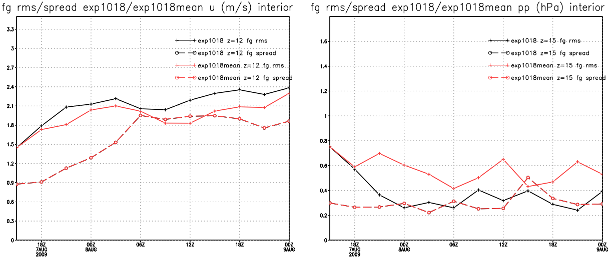


Fig.20: intercomparison of fg rms / spread for det run and mean results for *u* in *m/s* at 500 *hPa* (left), *pp* at surface(right)

mean for *u* better because of averaging at fc reference time; det run for *pp* better because of using same BC's as nudging

comparison of det run and mean

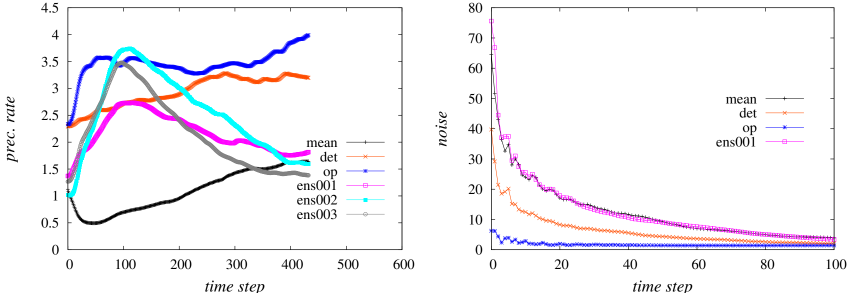


Fig.21: prec. rate (*mm*/*D*, left) and noise (*Pa*/*s*, right) for mean, det run, operational analysis (nudging) and ensemble member(s) at 20090808 12 UTC

prec. rate: mean, det run and ensemble members differ; noise: lowest noise for det run

Conclusions / open questions

- new observation setup:
  - number of obs increases by a factor of 10; but rms gets worse without changing settings
  - use of adaptive methods becomes essential
- adaptive methods:
  - adaptive correction of **R** reduces rms; in most cases, **R** is increased $\rightarrow$ reduces influence of obs
  - adaptive ρ inflation: different methods available, lead to different (spatial) structures, but relatively similar in terms of rmse
  - spread is sensitive to changes, rmse much less sensitive
- specified observation errors
  - need to be retuned, large influence on rmse/spread and results of adaptive methods
- status: all methods together reduce rmse, but still work to do on adaptive methods / observation errors

Outlook / next steps

next steps:

- increase update frequency, use NUMEX
- tuning of parameters , e.g. localization length scales
- compare det/mean run
- runs with BC from global LETKF

Outlook:

- model error (model perturbations): 2 projects within COSMO to account for model error; (stochastic) physics perturbations
- additional observations: radar data (radial winds, reflectivity), GPS, ...

LETKF Theory

- let $\mathbf{w}$ denote gaussian vector in k-dimensional ensemble space with mean 0 and covariance $\mathbf{I}/(k-1)$
- let $\mathbf{X}^b$ denote the (background) ensemble perturbations
- then $\mathbf{x} = \bar{\mathbf{x}}^b + \mathbf{X}^b\mathbf{w}$ is the corresponding model state with mean $\bar{\mathbf{x}}^b$ and covariance $\mathbf{P}^b = (k-1)^{-1}\mathbf{X}^b(\mathbf{X}^b)^T$
- let $\mathbf{Y}^b$ denote the ensemble perturbations in observation space and $\mathbf{R}$ the observation error covariance matrix

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