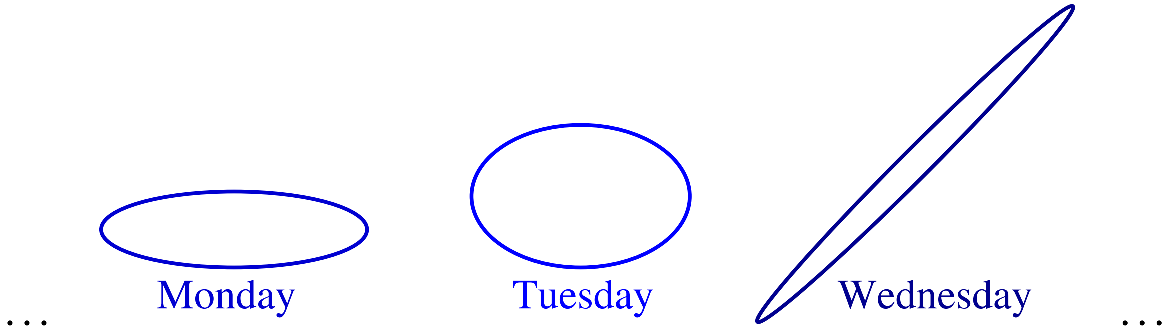
Ensemble forecasting and flow-dependent estimates of initial uncertainty

Martin Leutbecher

acknowledgements: Roberto Buizza, Lars Isaksen

• **Ensemble forecasting** aims at evolving a sample of the p.d.f. p_0 of the initial state to obtain a sample of the p.d.f. of the atmospheric state at a future time.

• In the real atmosphere, p_0 will be flow-dependent, i.e. it varies from day to day…



• Can data assimilation schemes provide flow-dependent estimates of p_0 that can be used to improve the current operational specification of initial uncertainty?

The operational ECMWF EPS specifies initial uncertainty by an isotropic Gaussian distribution in the space spanned by the leading singular vectors computed with a total energy norm.

• What are the improvements we can expect in ensemble forecasting when using more appropriate flow-dependent estimates in order to specify p_0?

Outline

1. a few simple experiments with the Lorenz-95 system
2. the operational EPS
3. some preliminary results from ensemble forecasting experiments that use ensemble data assimilation experiments (RB's and LI's experiments)
4. outlook
5. conclusions

Lorenz-95 system

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forecast model and
system (in perfect model setting)

$$\frac{dx_i}{dt} = -x_{i-2}x_{i-1} + x_{i-1}x_{i+1} - x_i + F$$

with $i = 1, 2 \ldots N$, cyclic boundary conditions
and a forcing of $F = 8$. Here, $N = 40$.

- nonlinear system of ODEs introduced by E. Lorenz in 1995
- allegorical for dynamics of “weather” at a fixed latitude
- a unit time $\Delta t = 1$ is associated with 5 days
- error doubling time of about 2 days.

L95: observations and data assimilation system

Observations:

- obs at every site $i = 1$–40, every 6 h
- uncorrelated, unbiased, normally distributed errors with standard deviation $\sigma_o = 0.15\,\sigma_{\text{clim}}$

Extended Kalman filter

$$\mathbf{x}^a = \mathbf{x}^b + \mathbf{K}(\mathbf{y} - \mathbf{H}\mathbf{x}^b) \tag{1}$$

$$\mathbf{x}^b = M(\mathbf{x}^a) \tag{2}$$

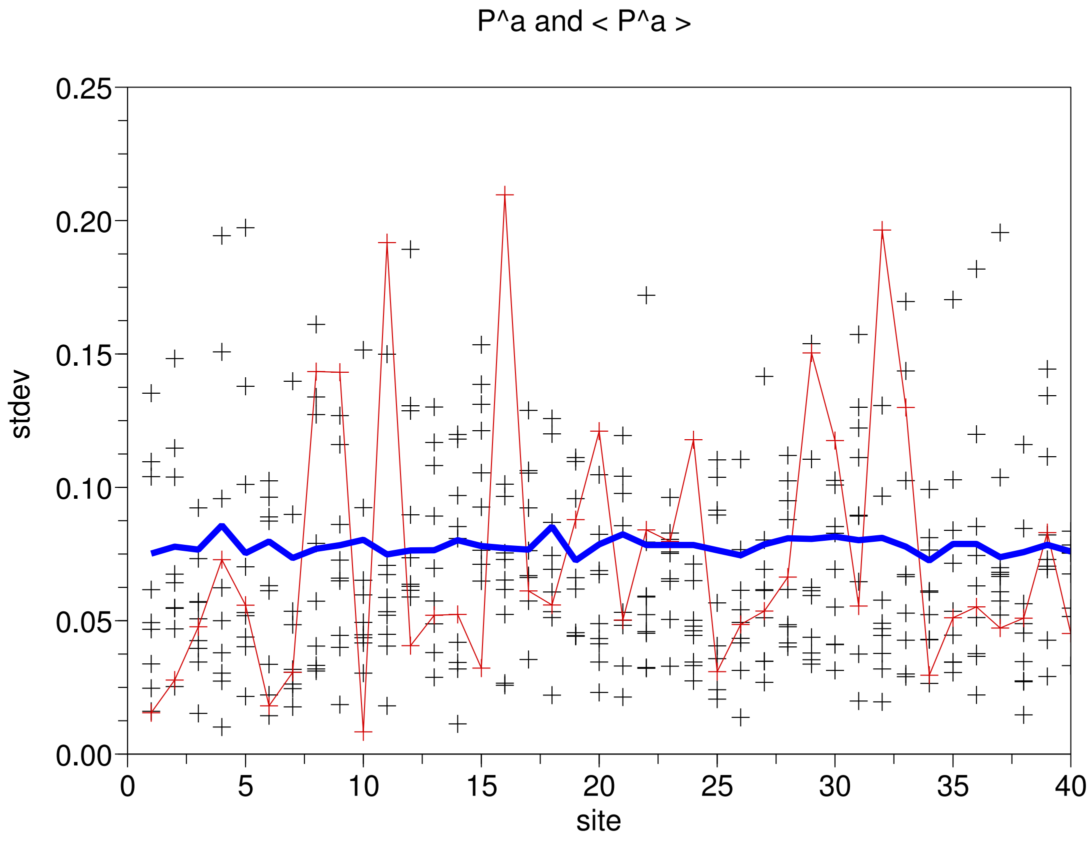
$$\mathbf{K} = \mathbf{P}^f\mathbf{H}^{\mathrm{T}}(\mathbf{R} + \mathbf{H}\mathbf{P}^f\mathbf{H}^{\mathrm{T}})^{-1} \tag{3}$$

$$\mathbf{P}^f = \mathbf{M}\,\mathbf{P}^a\,\mathbf{M}^{\mathrm{T}} + \mathbf{Q} \tag{4}$$

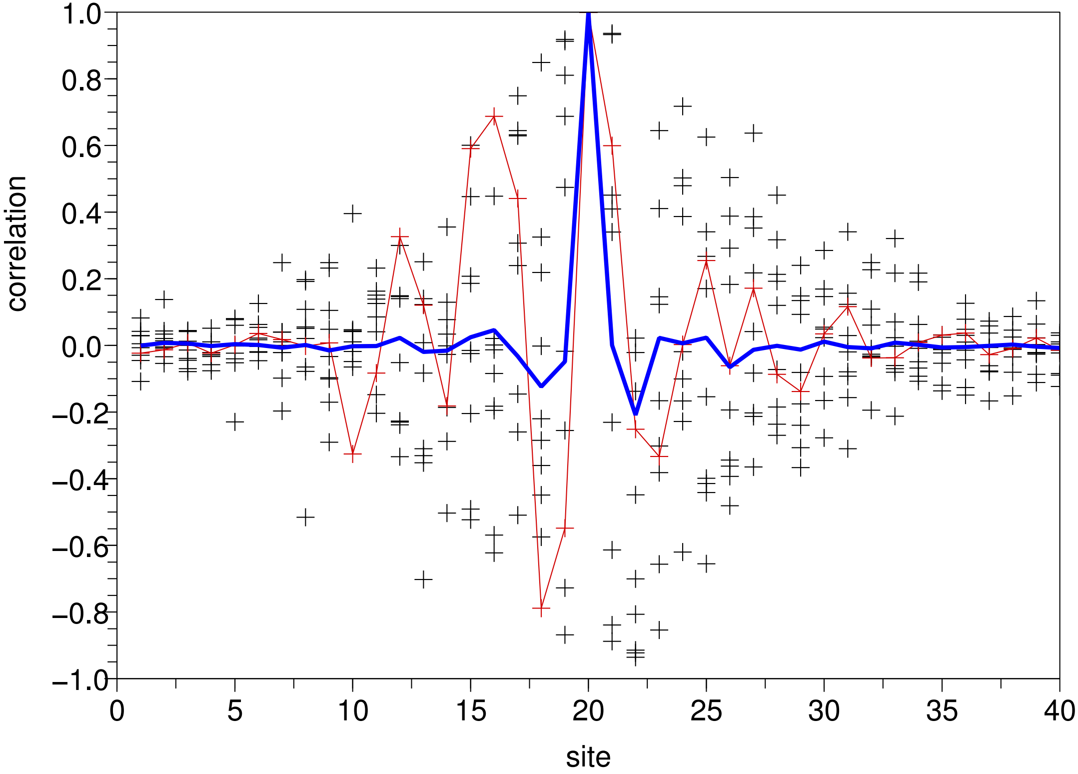
$$(\mathbf{P}^a)^{-1} = \left(\mathbf{P}^f\right)^{-1} + \mathbf{H}^{\mathrm{T}}\mathbf{R}^{-1}\mathbf{H} \tag{5}$$

Matrix **Q** is diagonal with variance tuned to avoid filter divergence and give best forecasts $\sigma_q = 0.001$ and 0.05 for perfect and imperfect model scenario, respectively ($\sigma_{\text{clim}} = 3.5$).

Flow-dependence of P^a: standard deviations



Flow-dependence of $\mathbf{P}^a$: correlations



L95: Ensemble forecasting

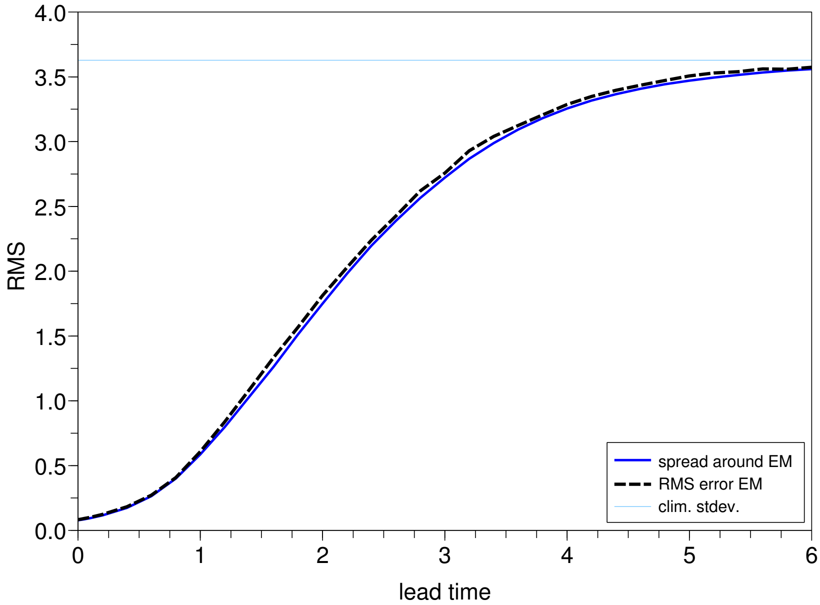
- 100 member
- initial conditions $\mathbf{x}_j(t=0), j=1,\ldots 100$ are sampled from a Gaussian distribution

$$\mathbf{x}_j(t=0) \sim N(\mathbf{x}^a, \mathbf{A}), \quad \text{where}$$

  - $\mathbf{A} = \mathbf{P}^a$, analysis err. cov. predicted by KF (i.e. valid for the start time of the forecast)
  - $\mathbf{A} = \langle \mathbf{P}^a \rangle$, time-average of $\mathbf{P}^a$
  - $\mathbf{A} \propto \mathbf{I}$, with same total variance as $\langle \mathbf{P}^a \rangle$
  - $\mathbf{A}$ a random draw from the sample of $\mathbf{P}^a$ predicted by the KF, i.e. the cov. from the wrong day.
  - some other choice of $\mathbf{A}$ that differs systematically from $\langle \mathbf{P}^a \rangle$.
- statistics are based on 180 cases; ensemble forecasts are started every 48 h (to avoid too much correlations).
- *perfect* model scenario (imperfect model: qualitatively similar results).

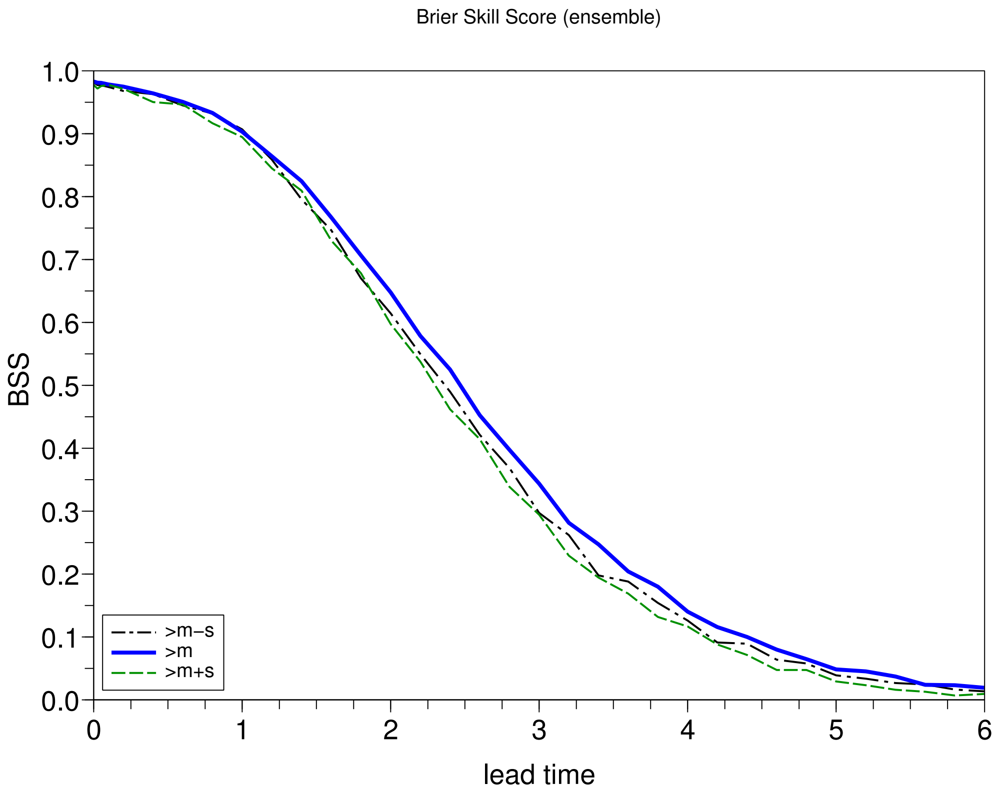
Spread and ensemble mean error

- initial conditions sample $N(\mathbf{x}^a(t), \mathbf{P}^a(t))$,
- forecast range $t = 6$ corresponds to 30 days
- doubling time of about $\Delta t = 0.4$ equivalent of 2 d

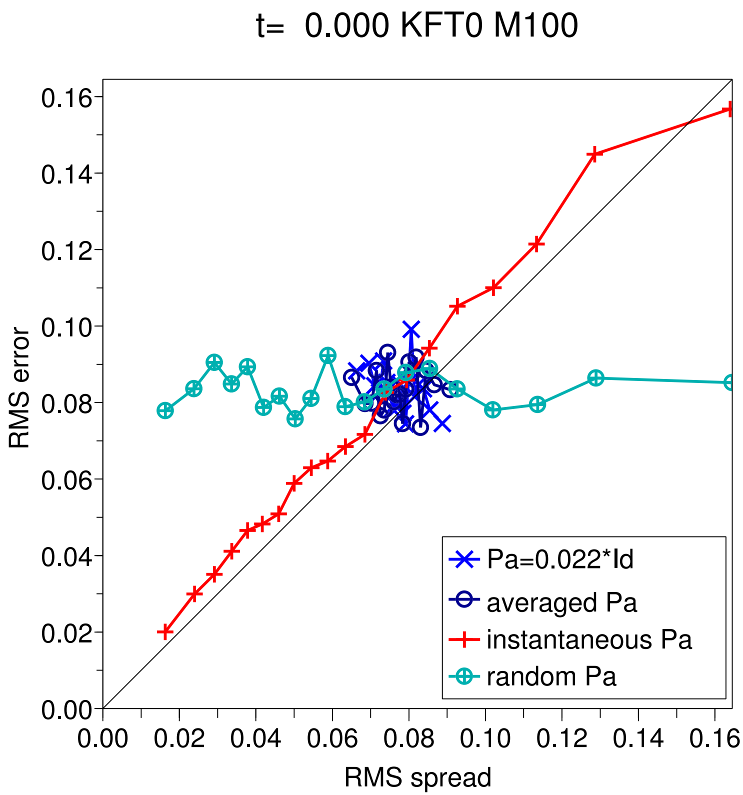


Brier skill score

for three events (positive anomalies, anomalies larger 1 stdev, anomalies larger −1 stdev)

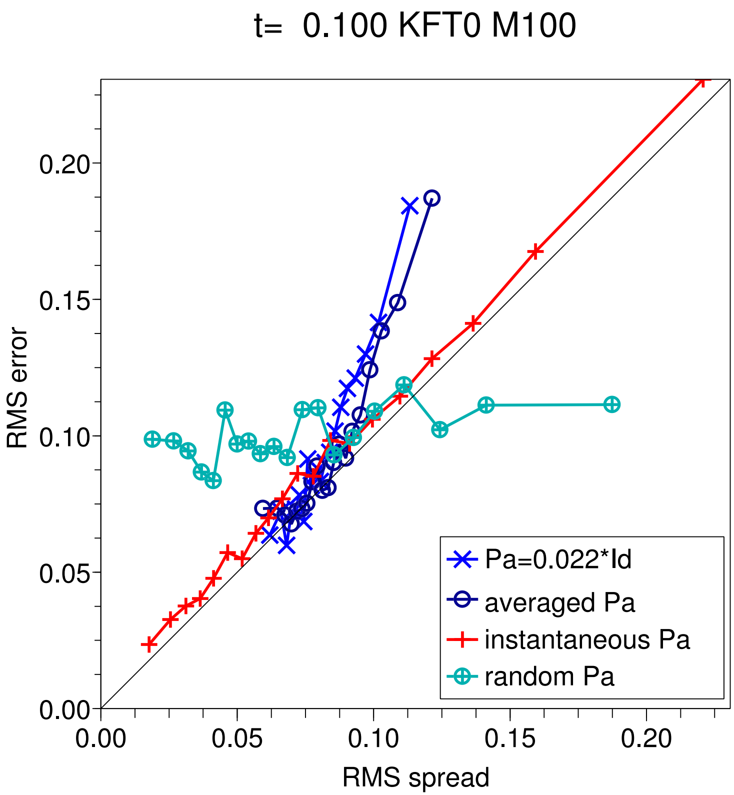


Spread and ensemble mean error: initial time

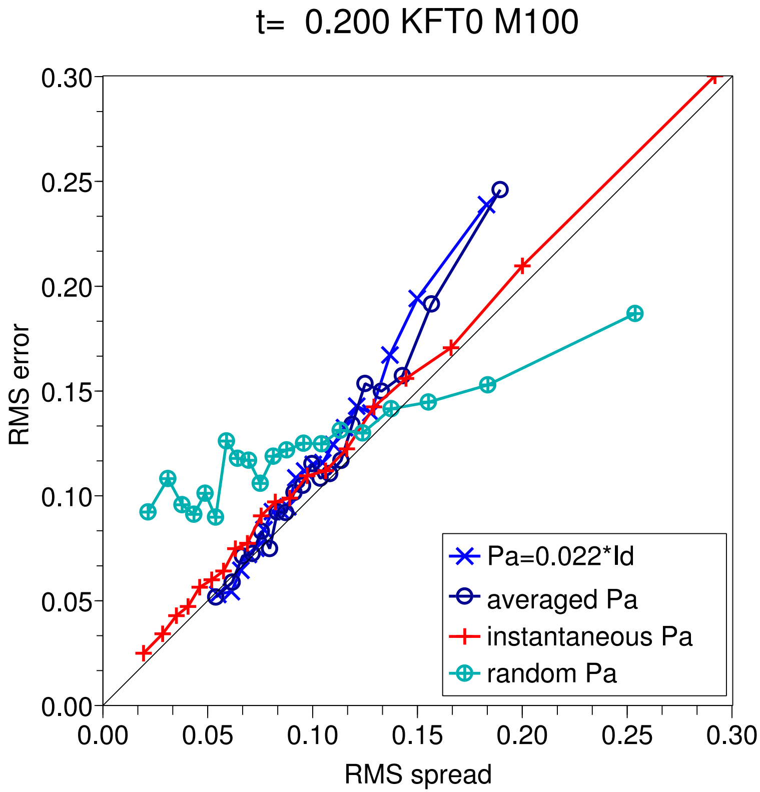


sample of sites $\times$ cases stratified by ensemble stdev; 20 bins with 360 values each.

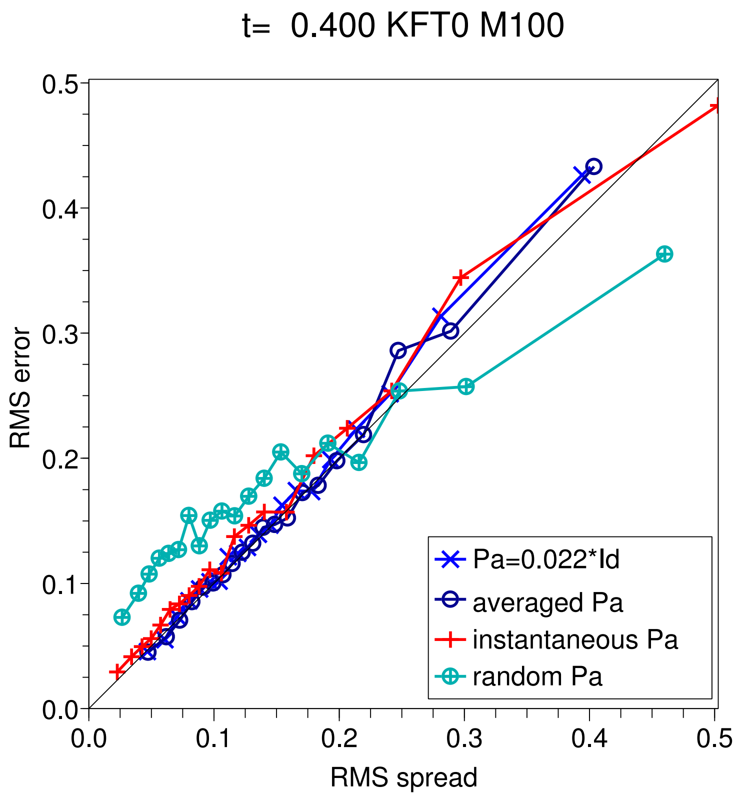
Spread and ensemble mean error: $t = 12$ h



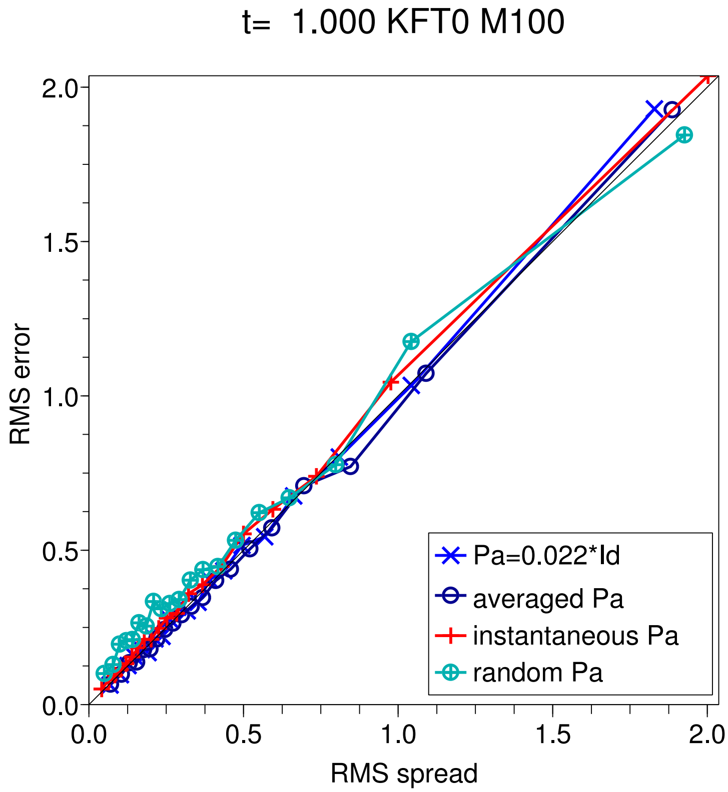
Spread and ensemble mean error: $t = 24$ h



Spread and ensemble mean error: $t = 48$ h

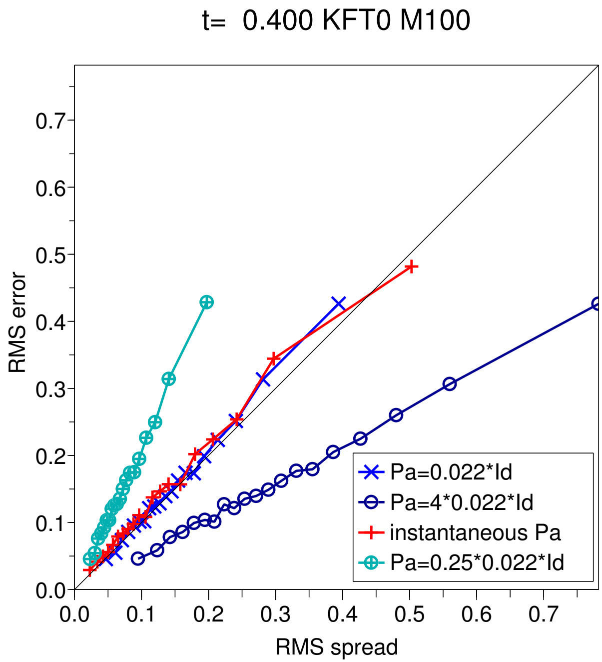


Spread and ensemble mean error: $t = 120$ h

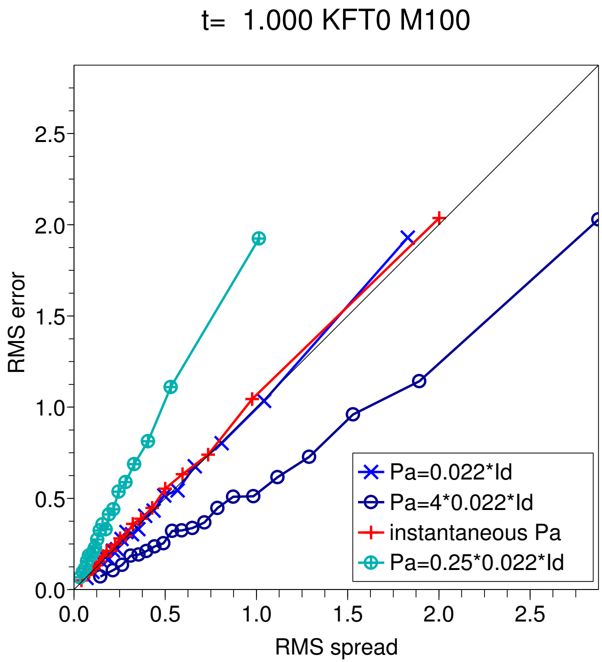


Over- and underdispersion

D+2

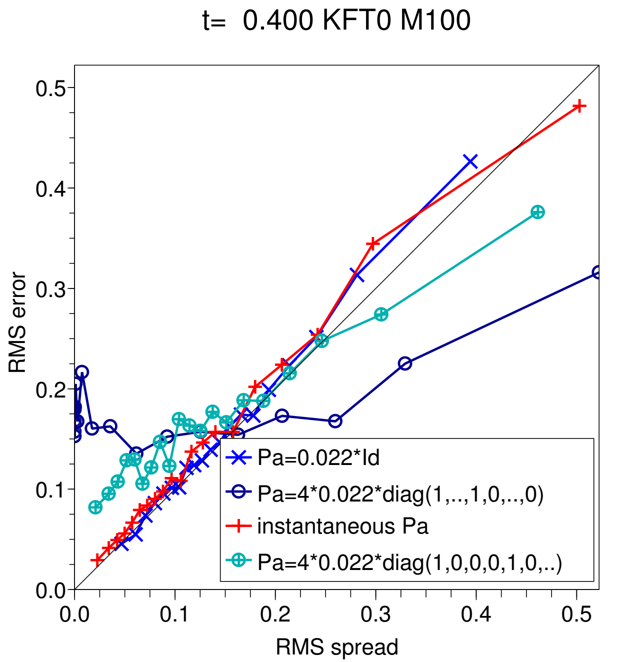


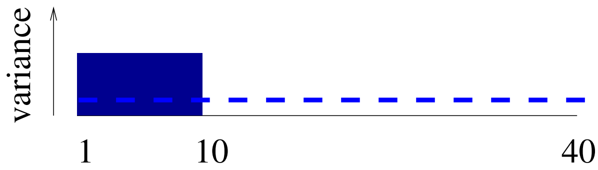
D+5



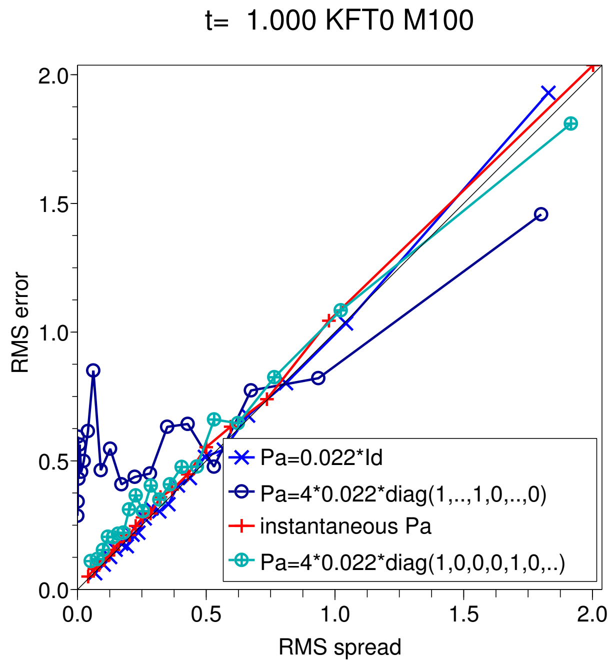
Erroneous distributions of variance

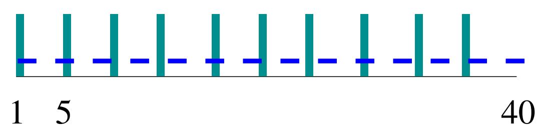
D+2



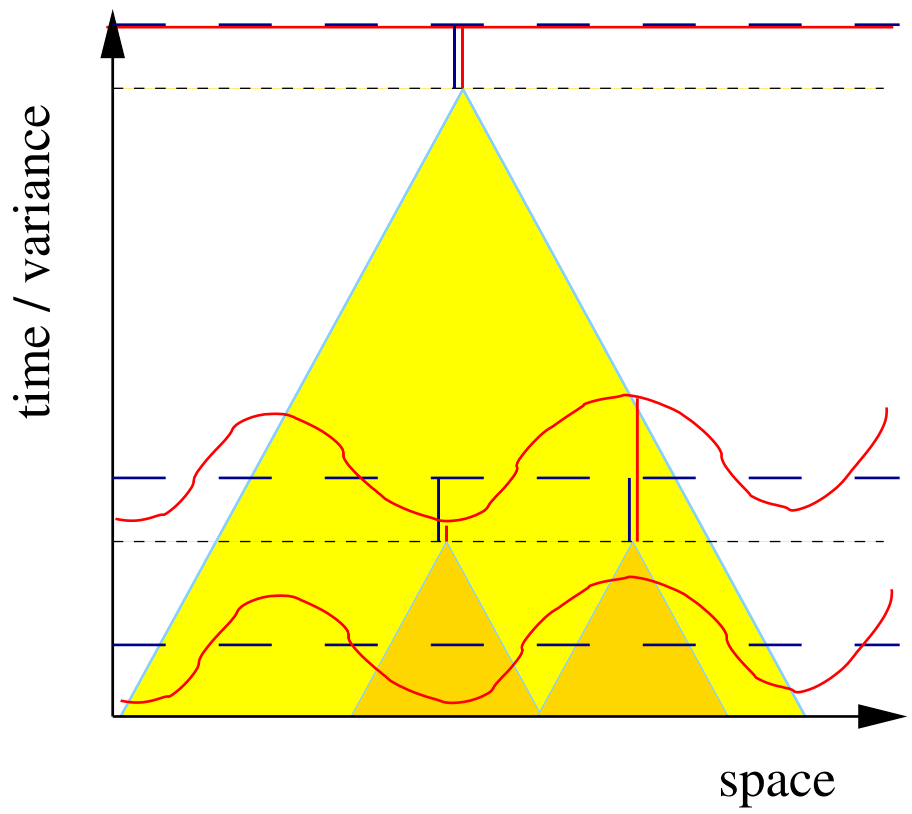


D+5





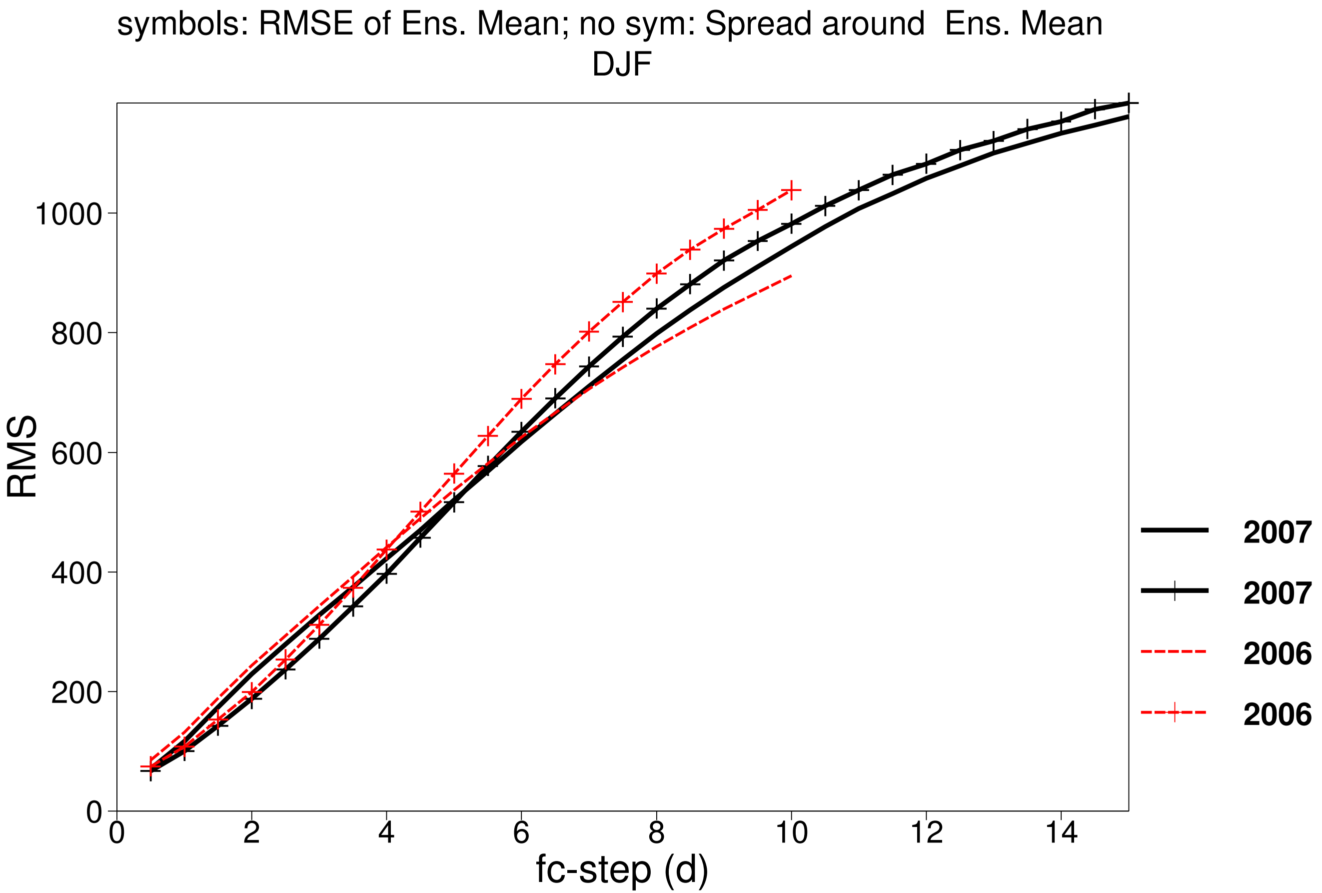
A tentative explanation



Operational ECMWF Ensemble Prediction System

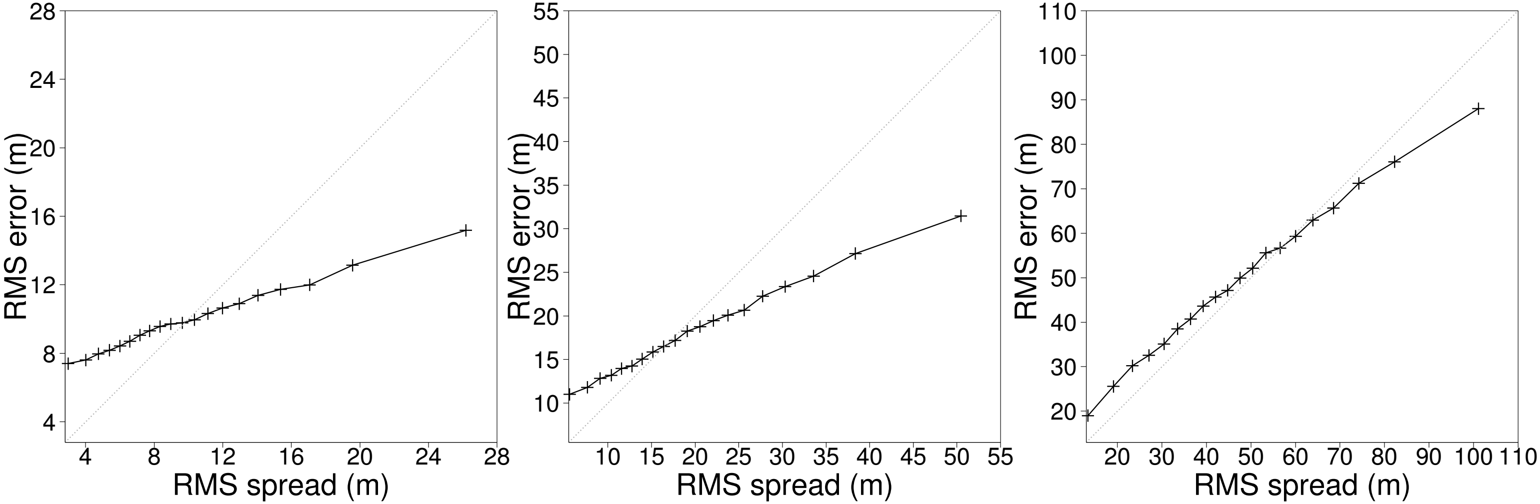
- 50 perturbed forecast, 1 (3) unperturbed forecasts
- initial perturbations based on the leading 50 singular vectors (2 sets of 50 for each hemisphere)
- perturbations in the tropics in the vicinity of active tropical cyclones based on the leading 5 singular vectors
- stochastic diabatic tendency perturbations (a.k.a. stochastic physics, uniform distr. between 0.5 and 1.5, random numbers change every 3 h and $10^\circ \times 10^\circ$)
- up to January 2006: T_L255L40
- from Feb 2006: T_L399L62 up to D+10, then T_L255L62 to D+15 (VAREPS)
- Feb 2006: reduction of amplitude assigned to evolved singular vectors by 33% because higher-resolution model is more active
  $\Rightarrow$ improved match between ens. dispersion and ens. mean error

Z500 spread and ens. mean error DJF 2006 vs 07, 35N–65N



Z500 Stdev and ens. mean RMSE, 35N–65N, DJF06/07

$t = 24$ h $\qquad t = 48$ h $\qquad t = 120$ h

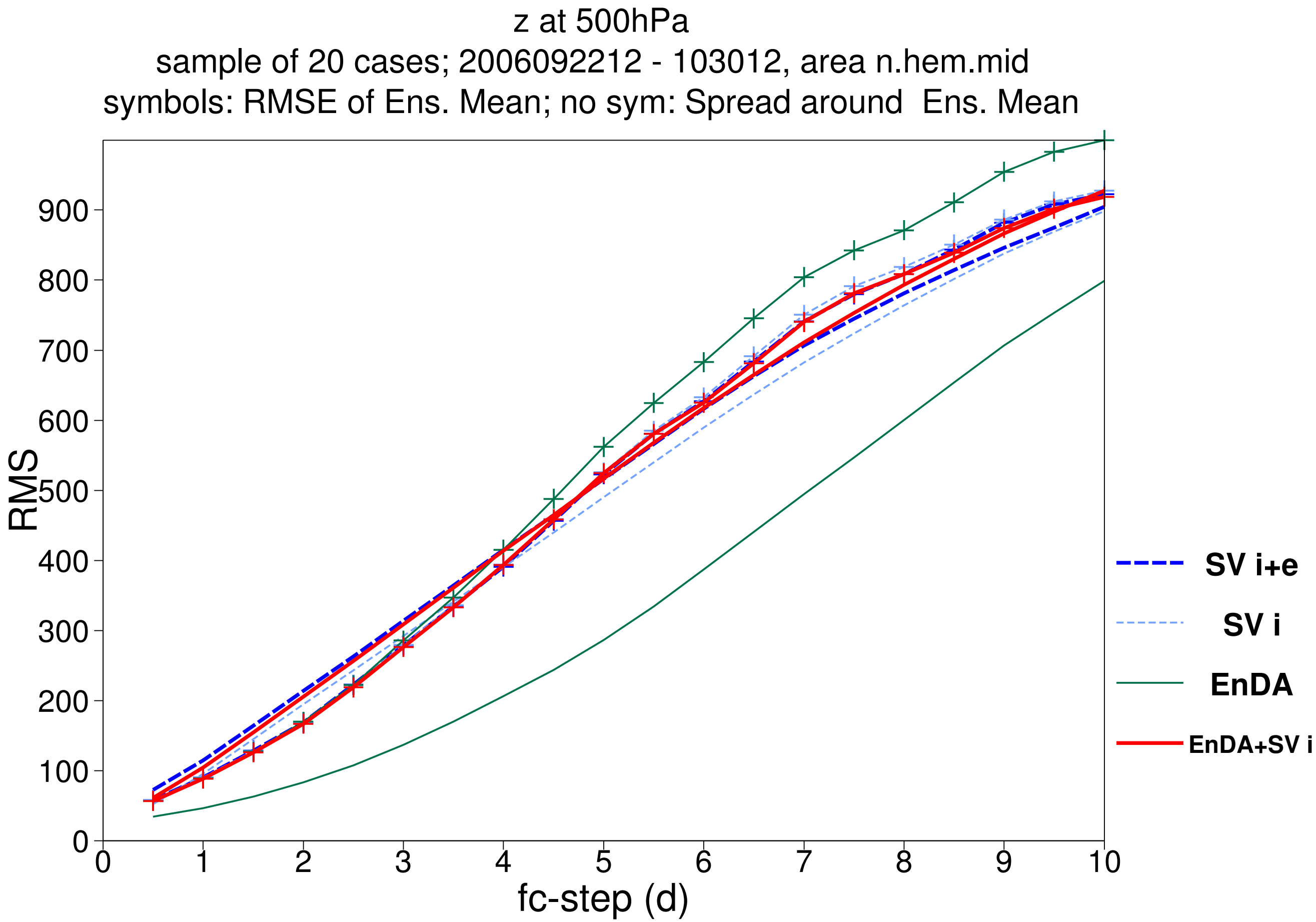


Flow-dependent initial uncertainty estimates in the ECMWF EPS

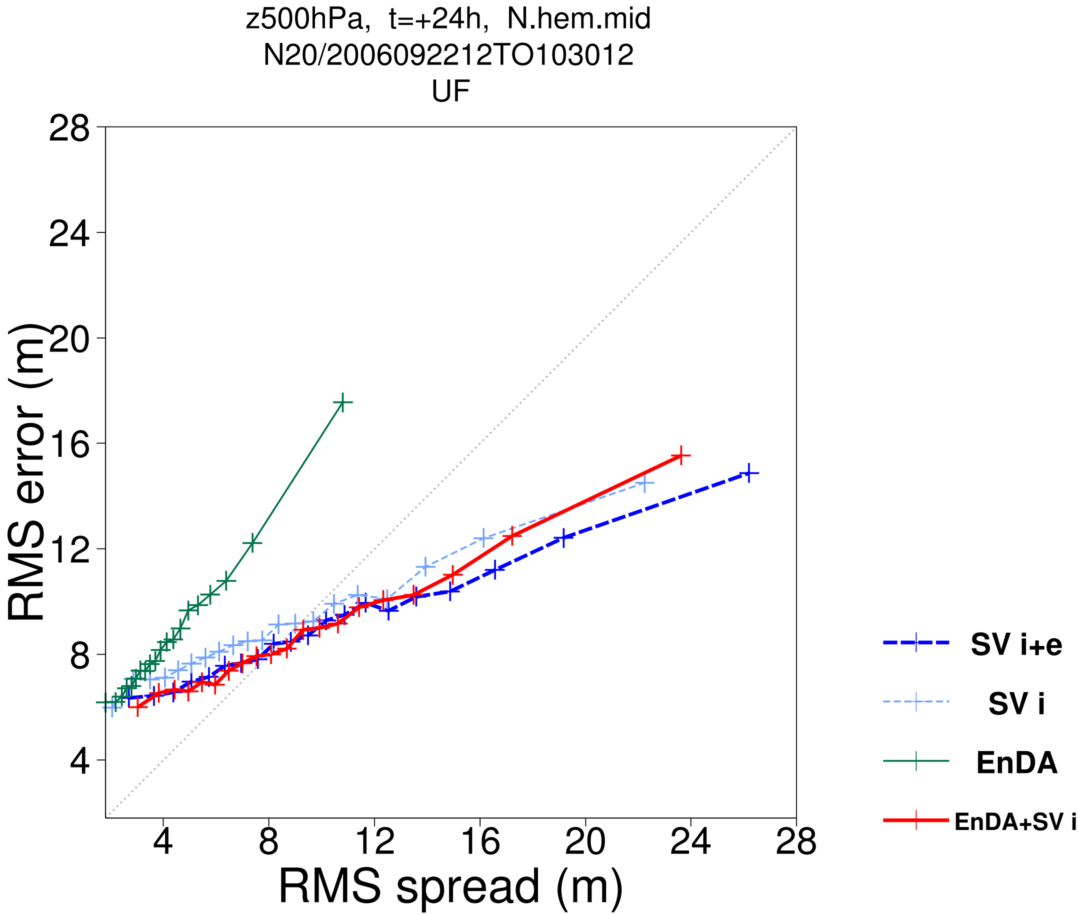
preliminary results from Roberto's + Lars' experiments (31R2):

- ensemble forecasts: TL255L62, 50 member
- ensemble data assimilation (EnDA): TL255L91, 10 member, 12-h 4D-Var
  - perturbed observations
  - model tendencies perturbed with backscatter scheme (Markov chain in spectral space for vorticity, vertical correlations from J_b, multi-variate through nonlinear balance + ω-equation)
- 4 configurations for initial perturbations (added to interpolated operational high-resolution analysis TL799L91):
  - initial singular vectors and evolved singular vectors (SV i+e)
  - initial singular vectors only (SV i)
  - perturbations of EnDA members about ens. mean (EnDA)
  - EnDA perturbations and initial singular vectors (EnDA+SV i)
- 20 cases in Sep/Oct 2006 (every other day)

Z500 Ensemble stdev and ensemble mean RMS error, 35N–65N

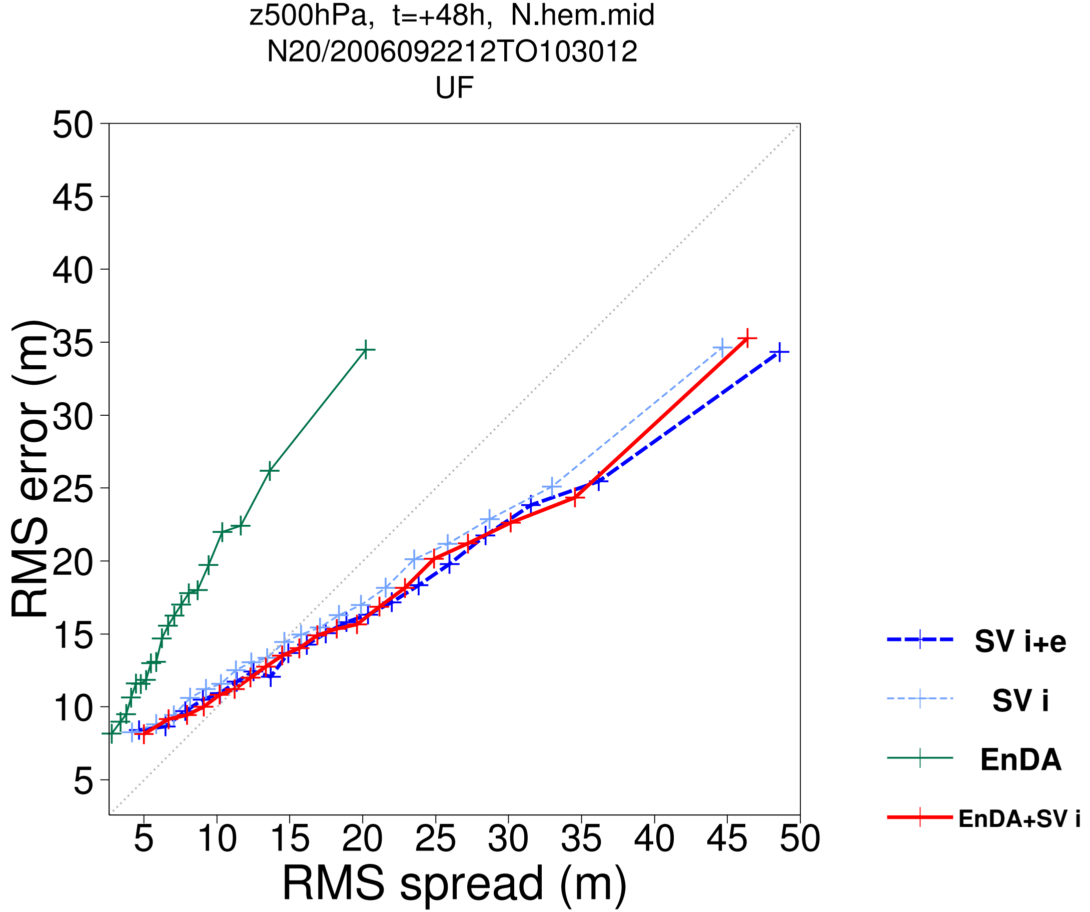


Ensemble stdev and ensemble mean RMS error: D+1



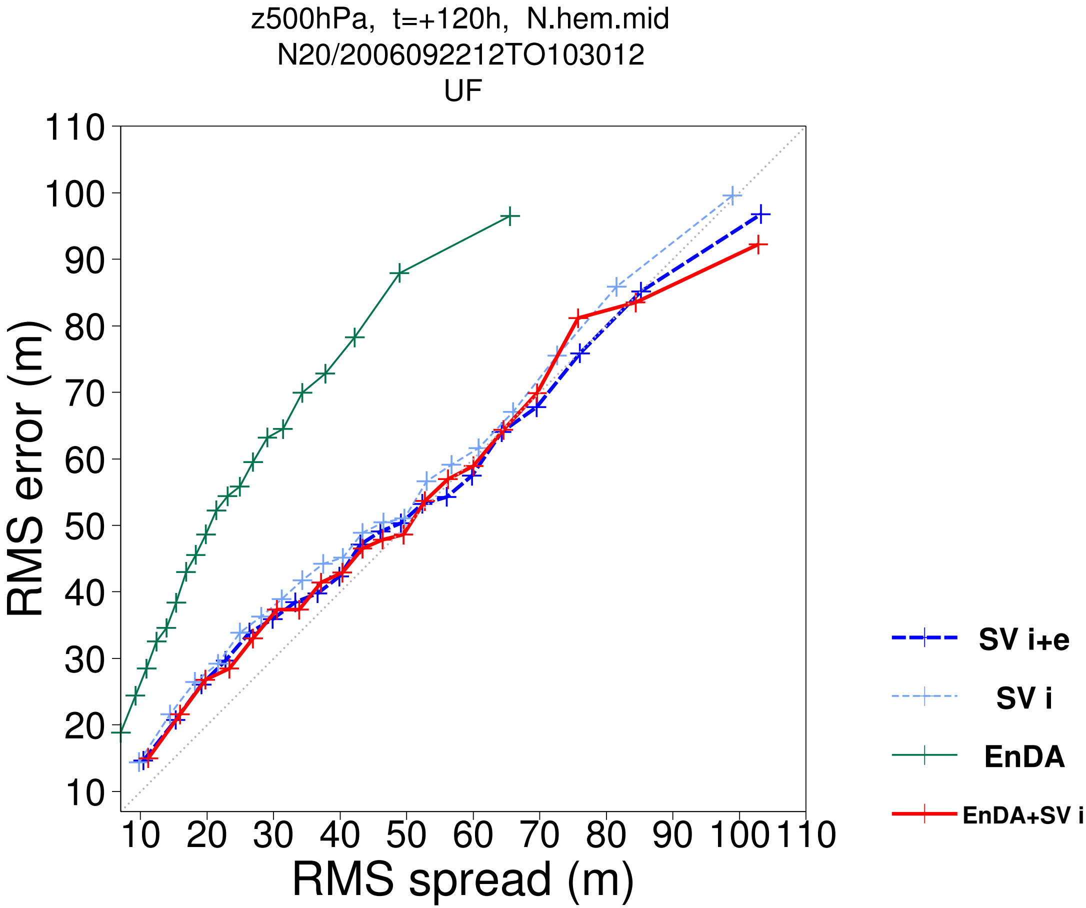
35N–65N

Z500 Ensemble stdev and ensemble mean RMS error: D+2



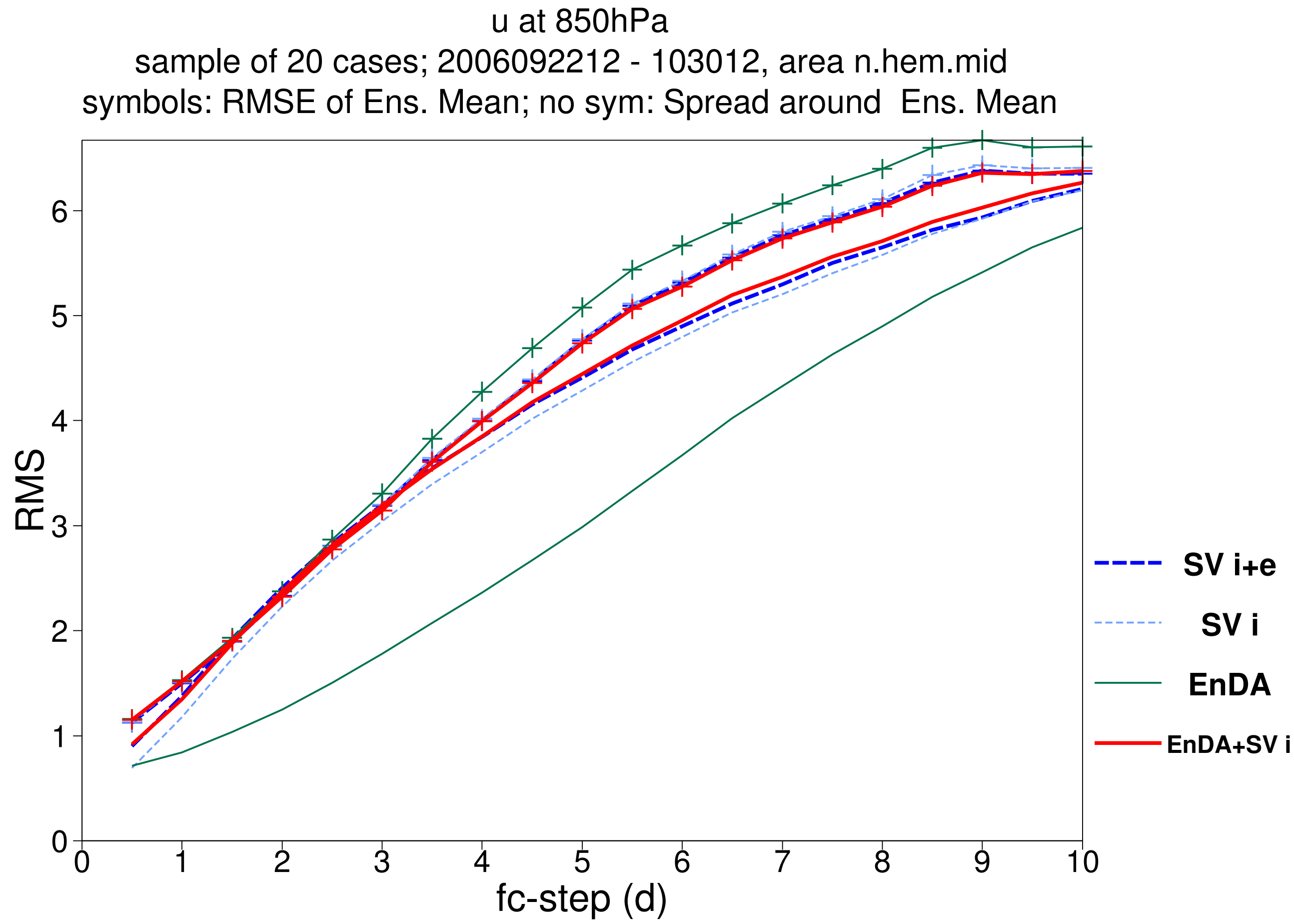
35N–65N

Z500 Ensemble stdev and ensemble mean RMS error: D+5

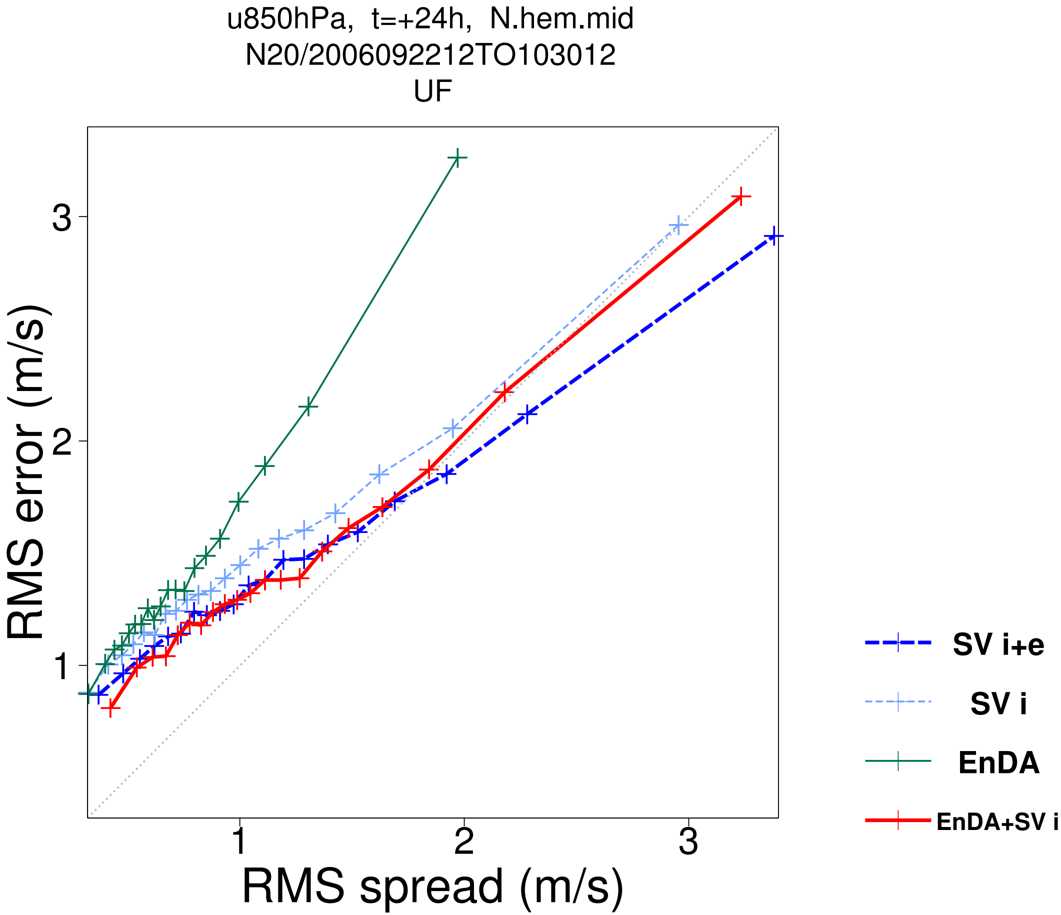


35N–65N

u850 Ensemble stdev and ensemble mean RMS error, 35N–65N

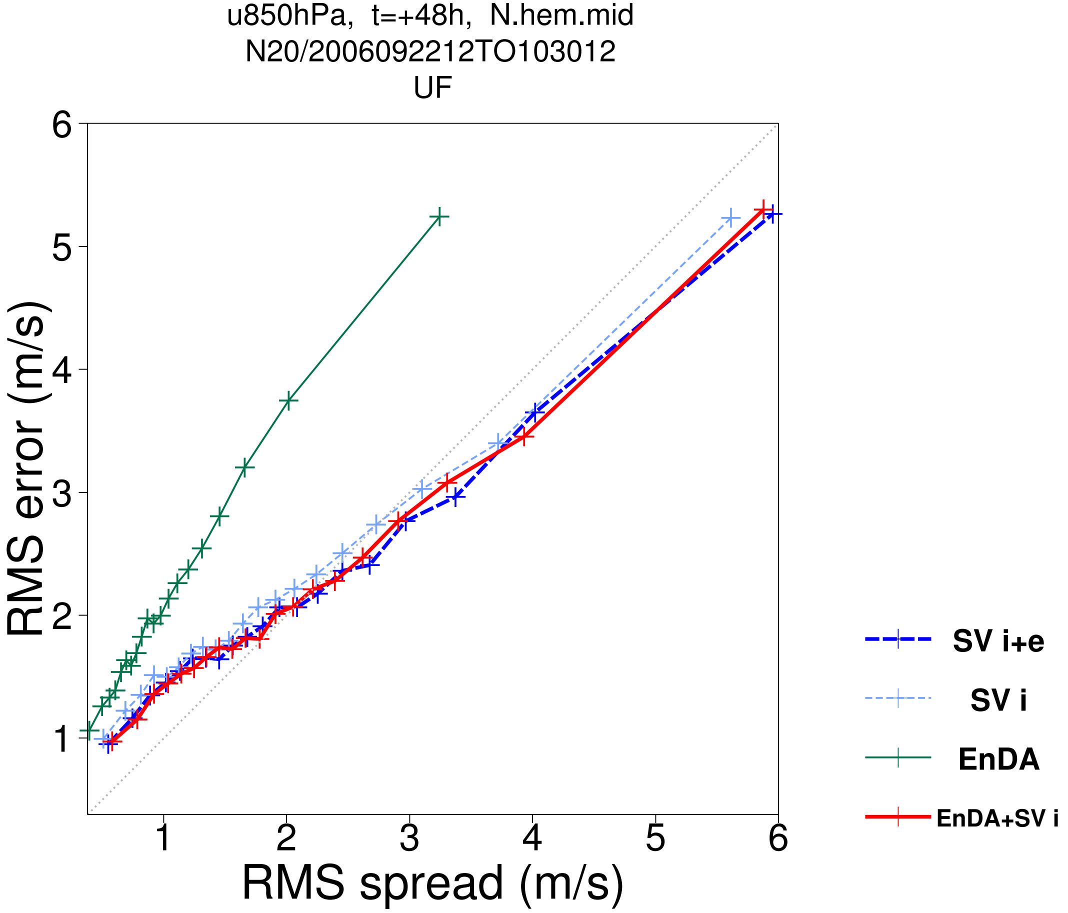


Ensemble stdev and ensemble mean RMS error: D+1



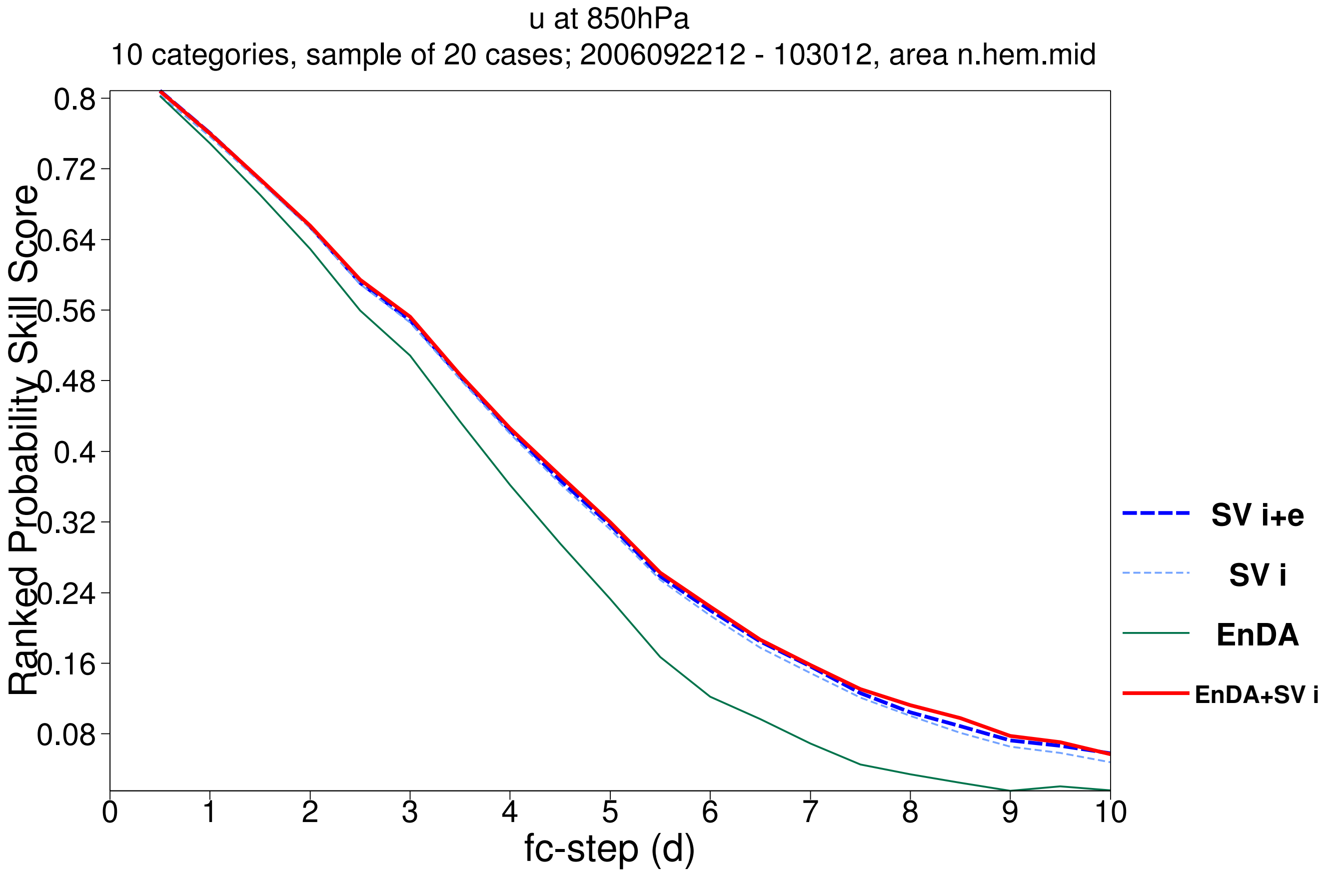
35N–65N

Ensemble stdev and ensemble mean RMS error: D+2

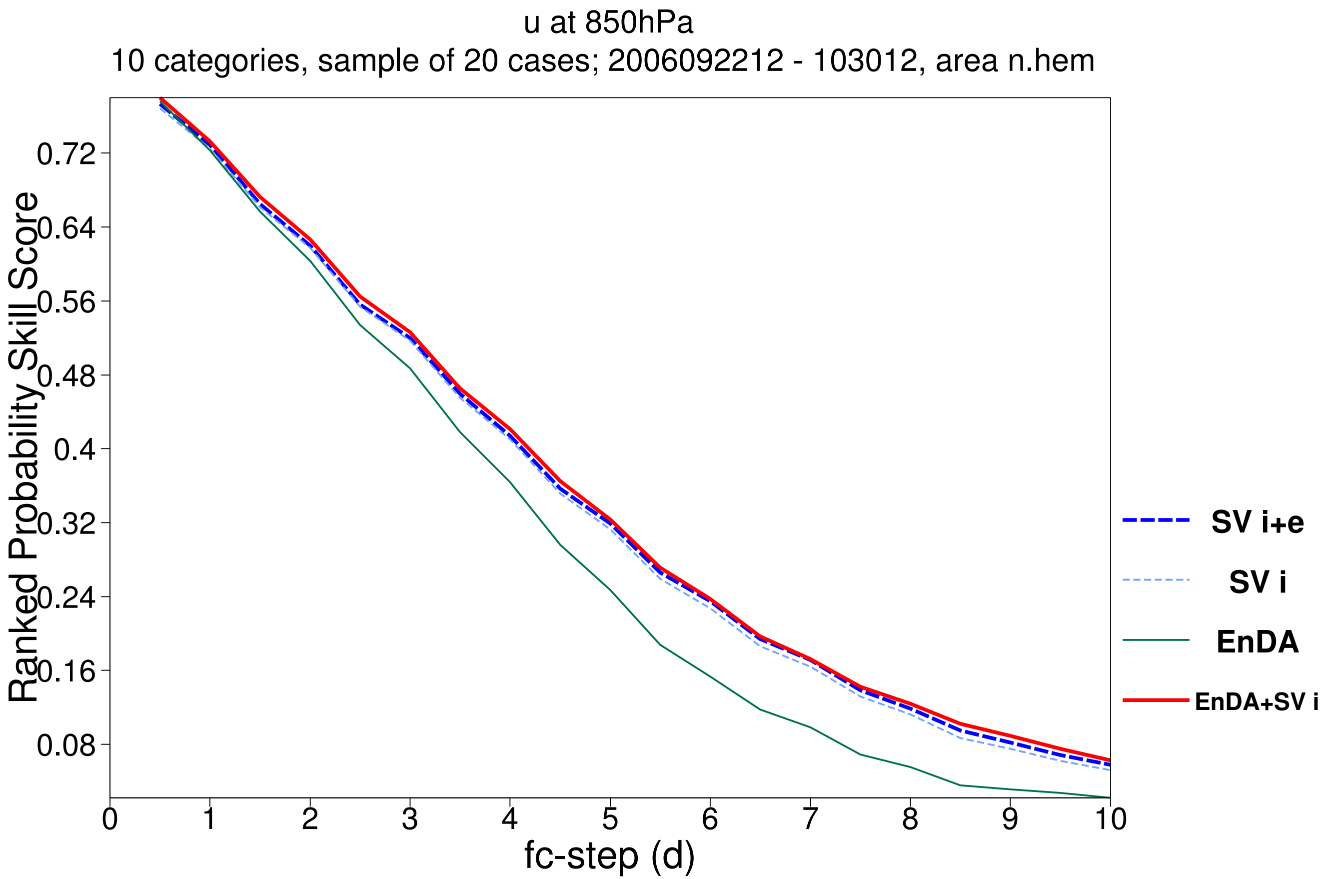


35N–65N

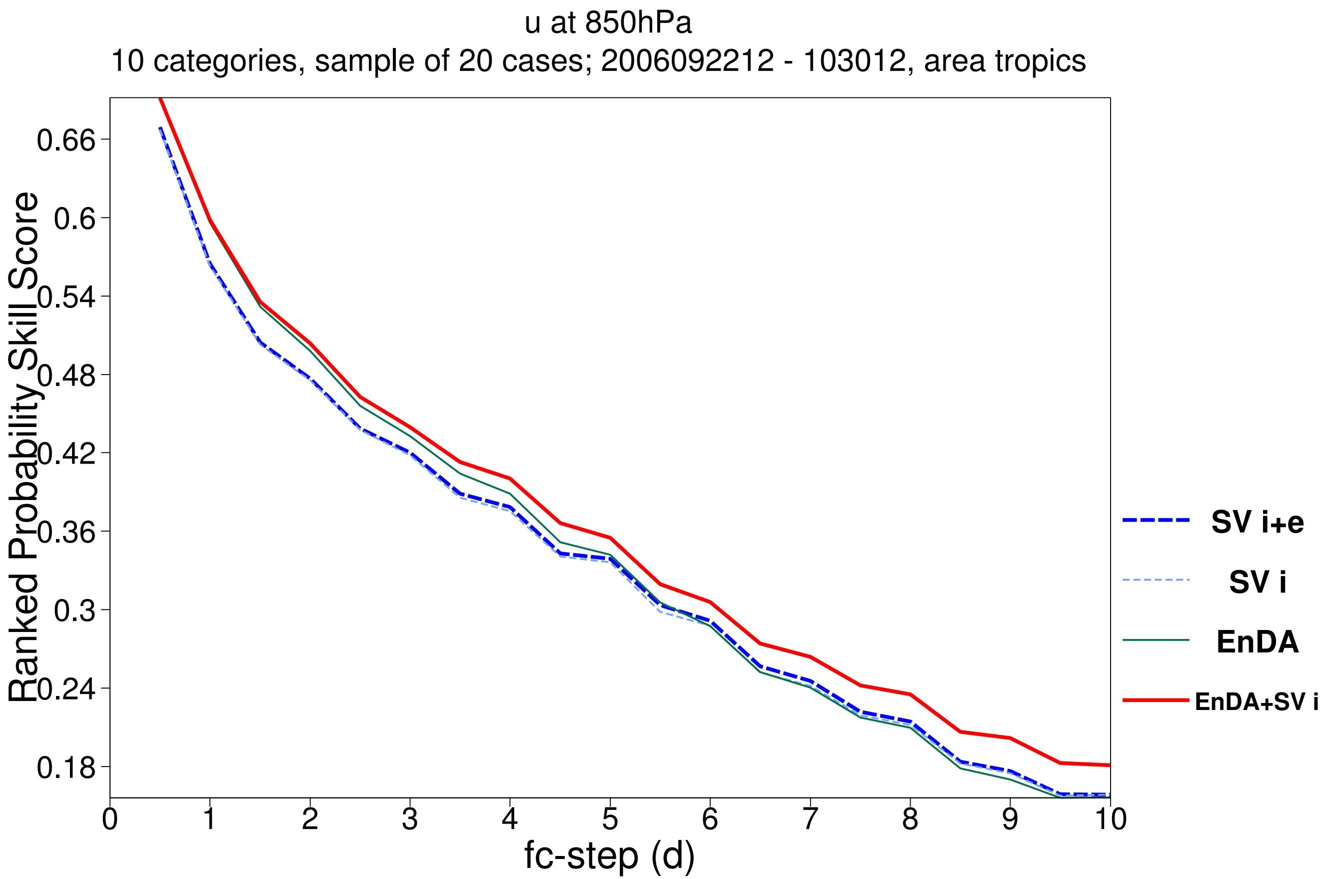
u850 Ranked Probability Skill Score, 35N–65N



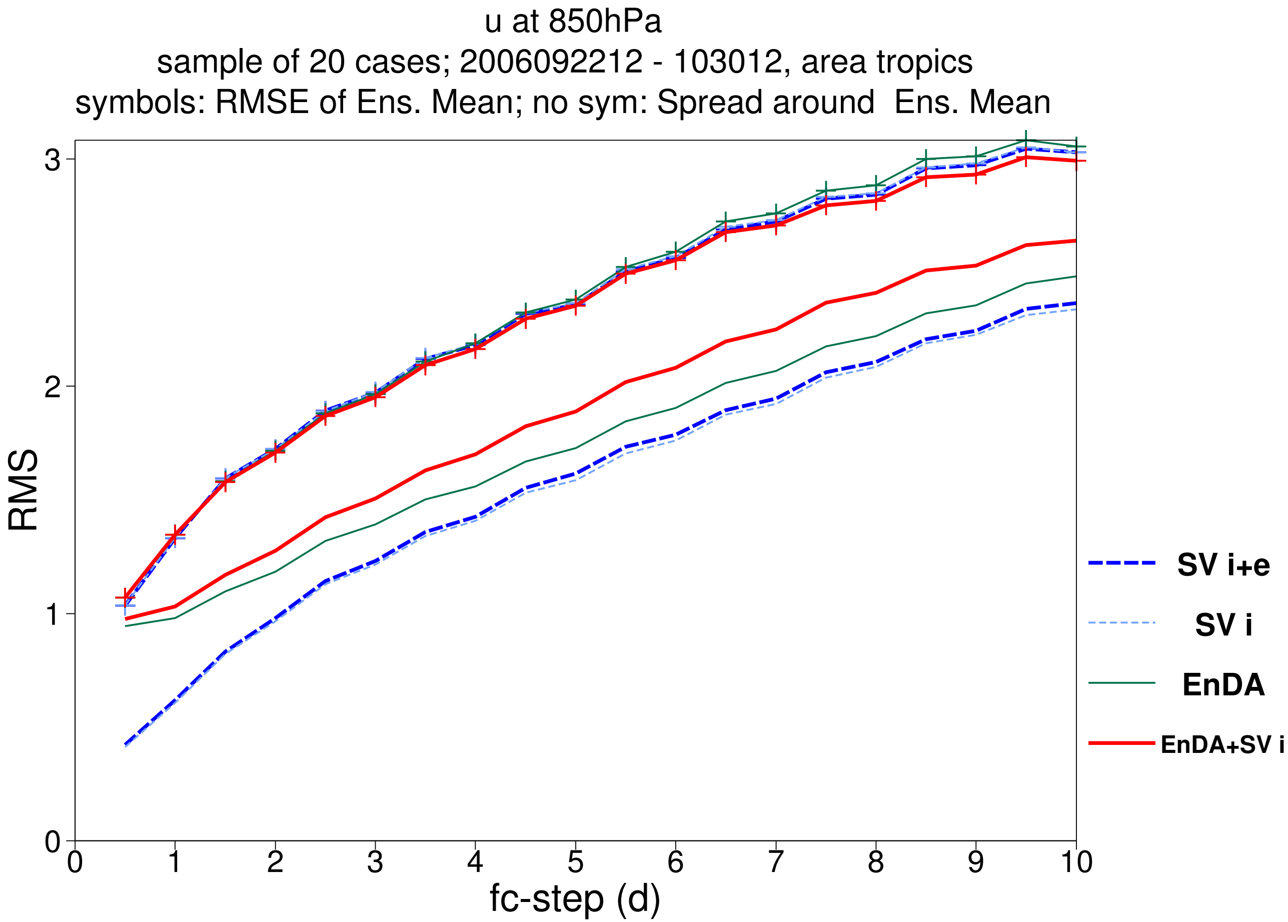
u850 Ranked Probability Skill Score, 20N–90N



u850 Ranked Probability Skill Score, 20S–20N



u850 Ensemble stdev and ensemble mean RMS error, 20S–20N



summary (1)

Experiments with the 40-variable Lorenz-95 system

• indicate that the skill of ensemble forecasts benefits from flow-dependent estimates of analysis error covariances at forecast lead times of up to $\sim$ 5 days.

• suggest that only gross systematic errors in representing initial uncertainty appear to be capable of deteriorating the ensemble forecasts at all lead times.

The operational ECMWF EPS (T_L399L62)

• shows a close match between ens. stdev.and ens. mean RMSE for 500 hPa geopotential during the last DJF overall, but

• exhibits over-dispersion for situations with large spread and under-dispersion for low spread in the early forecast ranges ($\leq$ D+3); the spread-skill relationship improves with lead time in a similar manner as in the L95-system (almost ideal relationship at D+5).

summary (2)

Experiments with the ECMWF EPS (T_L255L62)

- show that perturbations from current ensembles of data assimilations yield insufficient ensemble dispersion at all forecast ranges up to D+10;

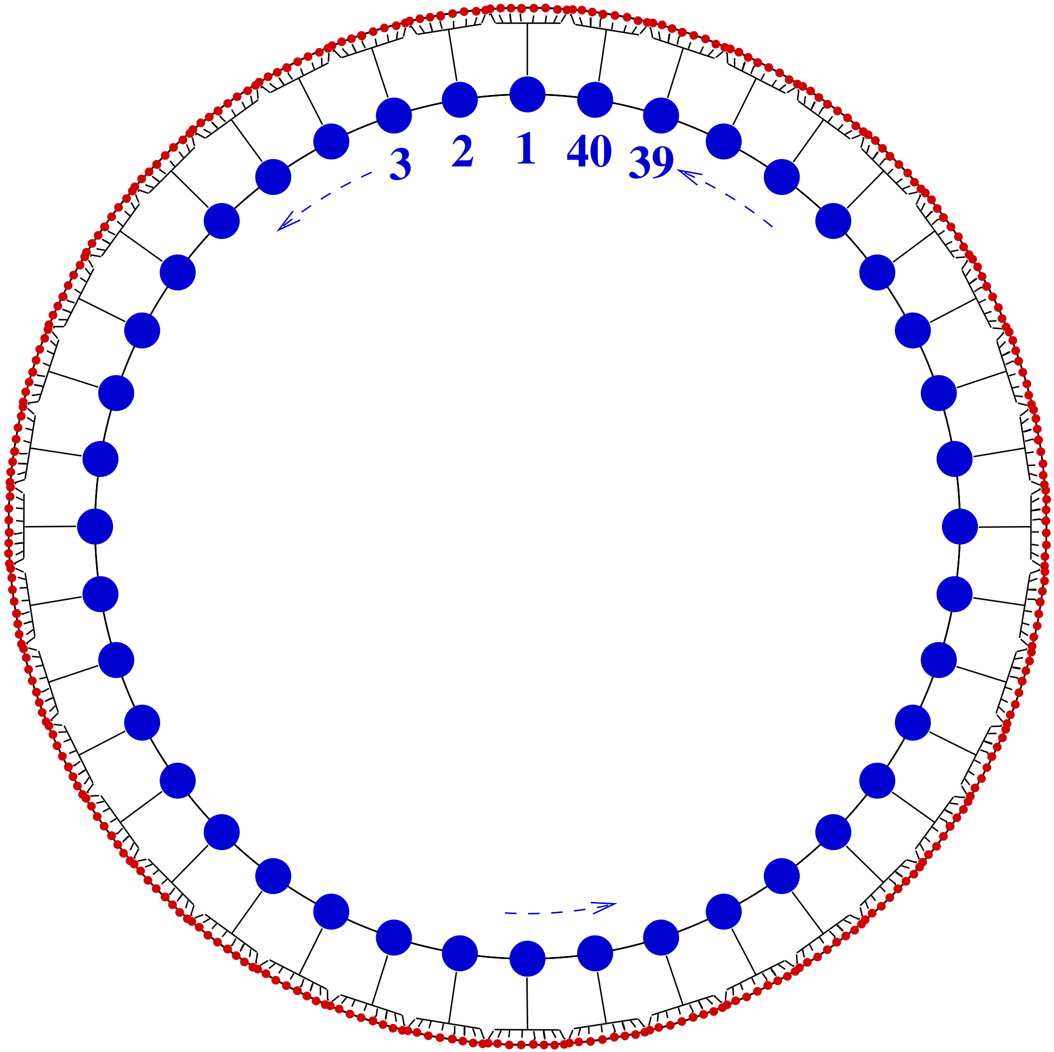
- indicate that it may be beneficial (tropics!) to replace evolved singular vectors by perturbations from an ensemble of data assimilations;

Outlook

It seems worth investigating the following aspects

- impact of EnDA configuration on EPS forecasts
  - EnDA resolution (inner/outer loop)
  - number of members
  - obs. selection, representation of obs. err. corr. ...
- test of improved versions of backscatter algorithm in EnDA and EPS
- representation of model error using forcing singular vectors in EnDA and in EPS
- use of singular vectors computed with analysis error (co-)variance metric based on statistics from EnDA (roughly same cost as total energy SVs and possibility of flow-dependent initial metric) — cf. Gelaro, Rosmond & Daley (2002); Buehner & Zadra (2006).
- impact of replacing evolved SVs by EnDA perturbations at operational EPS resolution (T_L399L62)

Imperfect model scenario



Imperfect model scenario: ODEs

The **system** is given by

$$\frac{\mathrm{d}x_k}{\mathrm{d}t} = -x_{k-1}(x_{k-2} - x_{k+1}) - x_k + F - \frac{hc}{b} \sum_{k=J(k-1)+1}^{Jk} y_j \qquad (6)$$

$$\frac{\mathrm{d}y_j}{\mathrm{d}t} = -cby_{j+1}(y_{j+2} - y_{j-1}) - cy_j + \frac{c}{b} F_y + \frac{hc}{b} x_{1+\lfloor \frac{j-1}{J} \rfloor} \qquad (7)$$

with $k = 1, \ldots, K$ and $j = 1, \ldots, JK$. The **forecast model** is given by

$$\frac{\mathrm{d}x_k}{\mathrm{d}t} = -x_{k-1}(x_{k-2} - x_{k+1}) - x_k + F - g_U(x_k). \qquad (8)$$

Here, $K = 40, J = 8$ and

$b = 10$	**amplitude ratio** between slow variables and fast variables
$c = 10$	**time-scale ratio** between slow and fast variables
$h = 1$	**coupling strength** between slow and fast variables
$F = F_y = 10$	**forcing amplitude**

see also Wilks (2005)