LETKF compared to 4DVAR for assimilation of surface pressure observations in IFS

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LETKF equations

- Description of method in (Hunt et al., 2007)
- Objective: minimization of *J* (as 4DVAR)

$$J(x) = (x - x^b)^T (P^b)^{-1} (x - x^b) + (y^o - H(x))^T R^{-1} (y^o - H(x))$$

- Ensemble prediction for background state and error estimation:

$$x^b \approx \overline{x^b} \qquad P^b \approx (k-1)^{-1} X^b (X^b)^T$$

- Analysis solved in the subspace *S*, space of ensemble perturbations (*w* € *S*):

$$x = \overline{x^b} + X^b w$$

ECMWF

LETKF equations

- Linearization of H assuming that perturbations are very small w.r.t the mean:

$$H(\overline{x^b} + X^b w) \approx H(\overline{x^b}) + \frac{\Delta H}{\Delta x} X^b w \approx \overline{y^b} + Y^b w$$

- Reformulation of *J* in S (now *J**):

$$J^*(w) = (k-1)w^T w + [y^o - \overline{y^b} - Y^b w]^T R^{-1} [y^o - \overline{y^b} - Y^b w]$$

- Minimization of *J** has analytical solution:

$$\overline{w^a} = P_w^a (Y^b)^T R^{-1} (y^o - \overline{y^b})$$

$$P_w^a = [(k-1)I + (Y^b)^T R^{-1} Y^b]^{-1}$$

LETKF equations

- The analysis state is:

$$\overline{x^a} = \overline{x^b} + X^b \overline{w^a}$$

- Analysis ensemble chosen using the Symmetric Square Root method:

$$X^a = X^b W^a \qquad W^a = [(k-1)P_w^a]^{1/2}$$

- Ensemble of analysis states is finally computed as:

$$x_i^a = \overline{x_b} + X^b (\overline{w_a} + w_i^a)$$

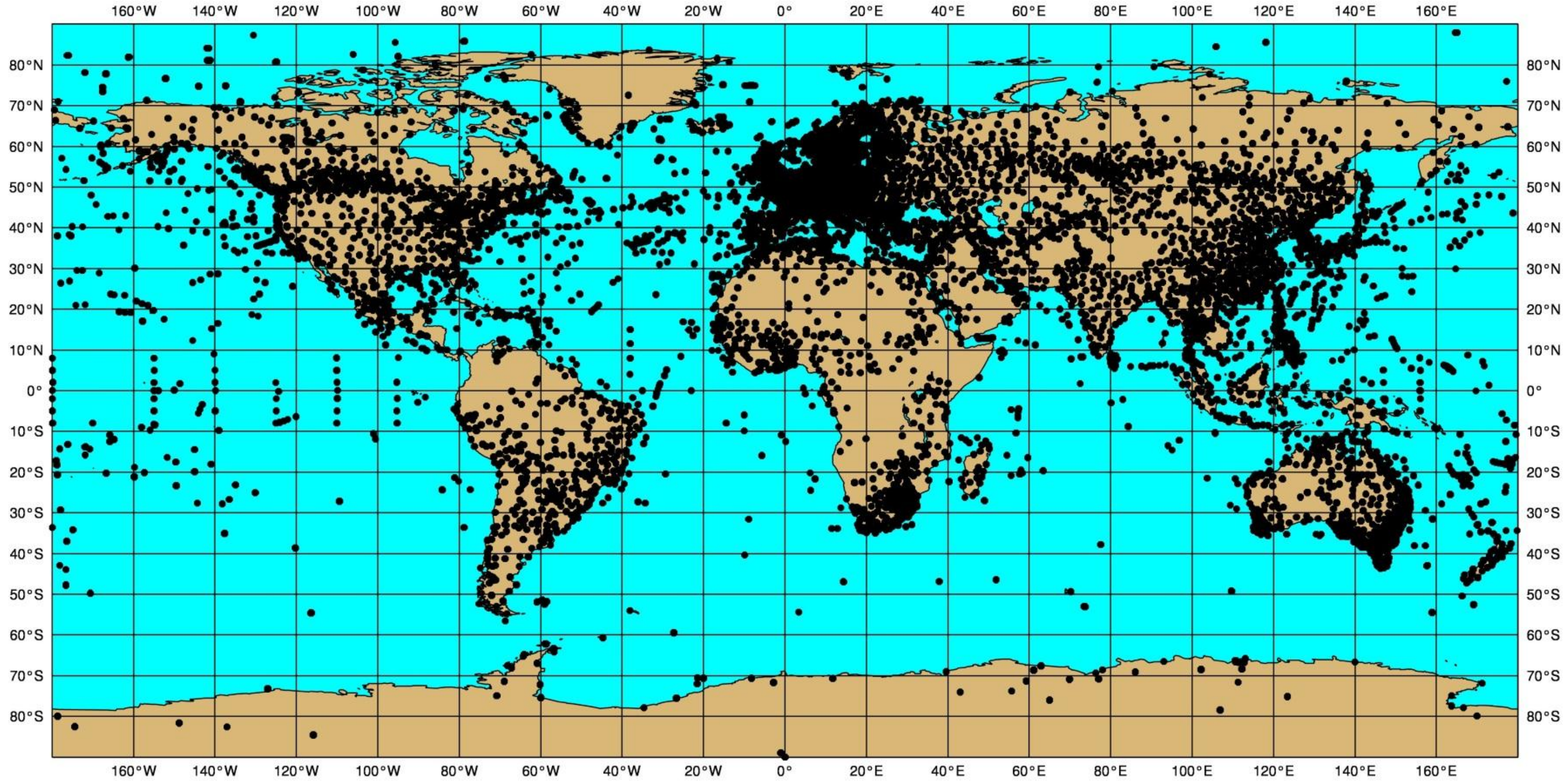
- Done independently for each grid point

Only Surface Pressure Data (PSFC) assimilated

- First check of performance of different schemes in a consistent environment
- A similar simplified configuration is used in the ERA-20C reanalysis
- Operational analysis can be used as *truth* (could favour 4DVAR scheme)
- It skips the (open) LETKF problems when assimilating all the observations:
  a) Localisation of satellite radiances
  b) B rank deficiency degrades fitting of observations when their number increases

Only Surface Pressure Data (PSFC) assimilated

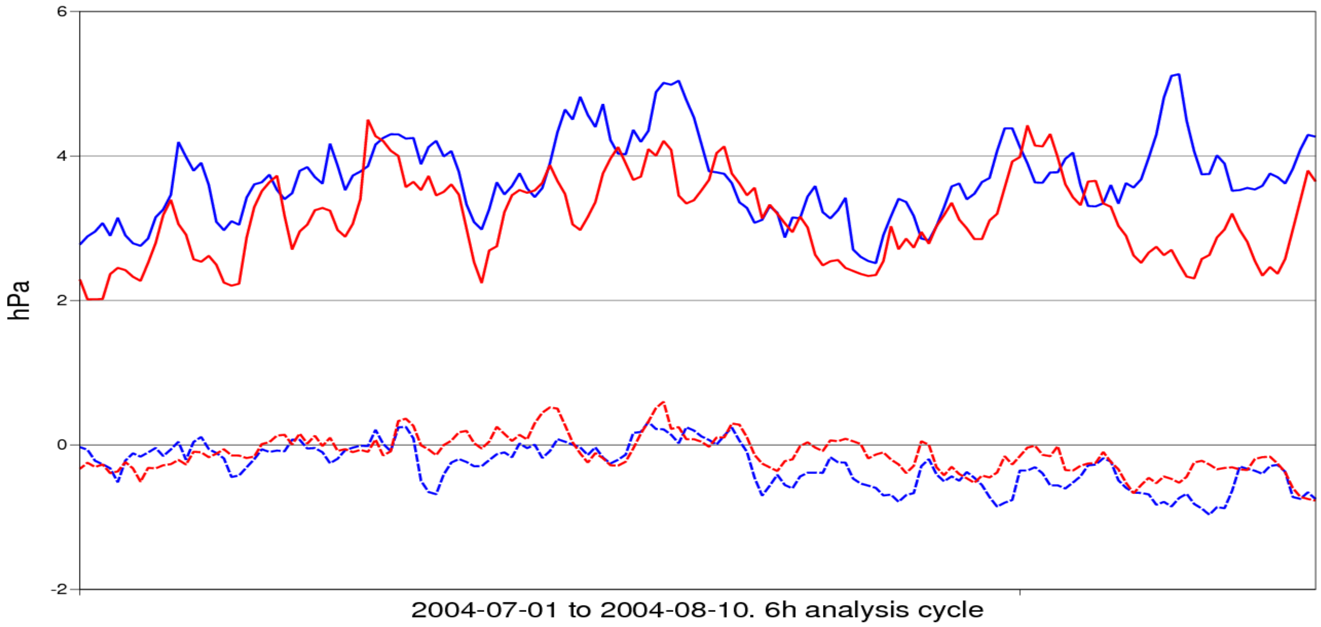
- ~ 100000 obs within a 12 hour assimlation window (all available types)



PSFC bias correction

- PSFC has been corrected by operational (Drasko's) bias correction scheme in LETKF (MSLP RMSE at SH with respect to operational analysis)

LETKF No BC LETKF BC



- Experimental results are very sensitive to PSFC bias correction

Inflation

- Ad hoc factor introduced in LETKF (and EnKF in general) because background error is known to be underestimated due to model and boundary condition errors, non-linearities, non-gaussianities, etc…
- Inflation applied in our EnKF is multiplicative and it is based on the “relaxation-to-prior spread” scheme (Whitaker, 2012):

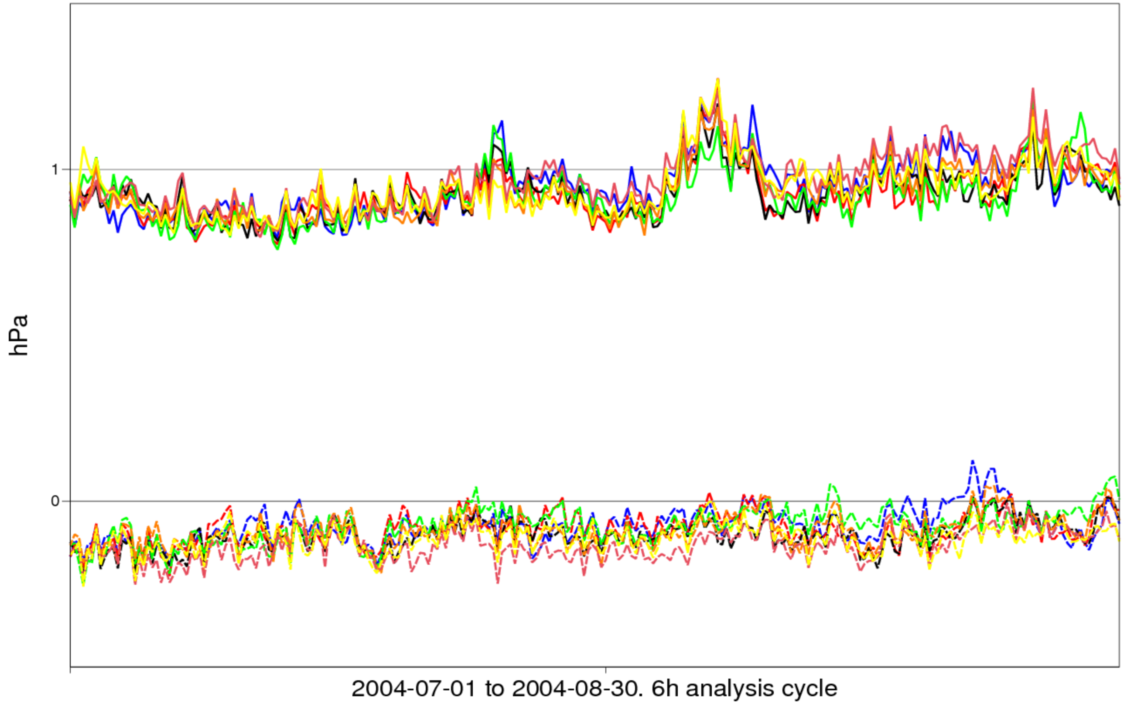
$$\sigma_a \leftarrow (1-\alpha)\sigma_a + \alpha\sigma_b$$

- Several schemes for additive and multiplicative inflation are implemented in IFS-EnKF

Inflation

- α = 0.90 good for surface and low troposphere (MSLP RMSE & BIAS at NH)

0.75 0.80 0.85 0.90 0.95 1.00 1.05

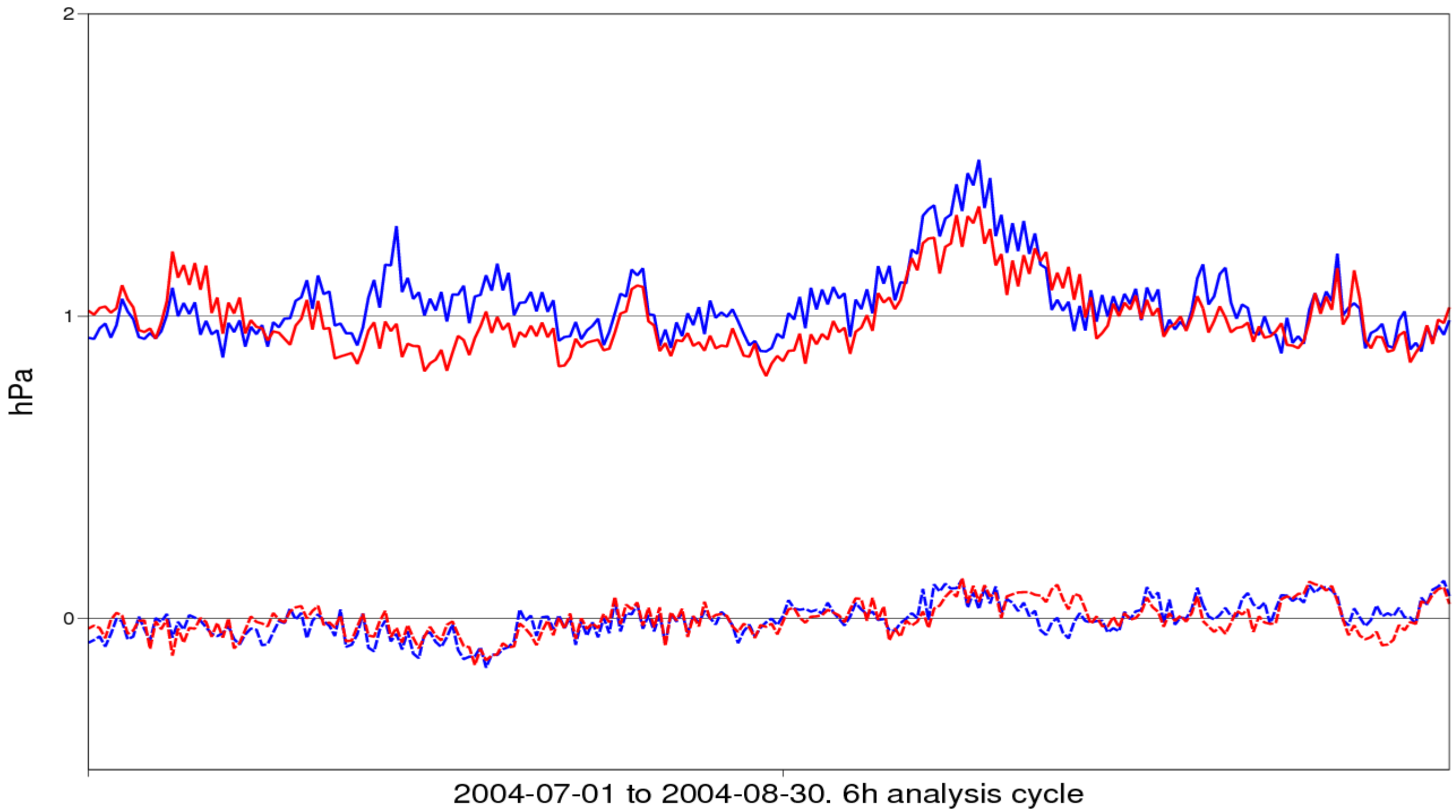


- Weak sensitivity to inflation factor

Inflation

- 4DVAR/EDA also benefits from inflation (here MSLP RMSE at NH)

EDA calibrated EDA no calibrated



ECMWF

Inflation

- REDNMC coefficient for 4DVAR experiments, α = 1.4

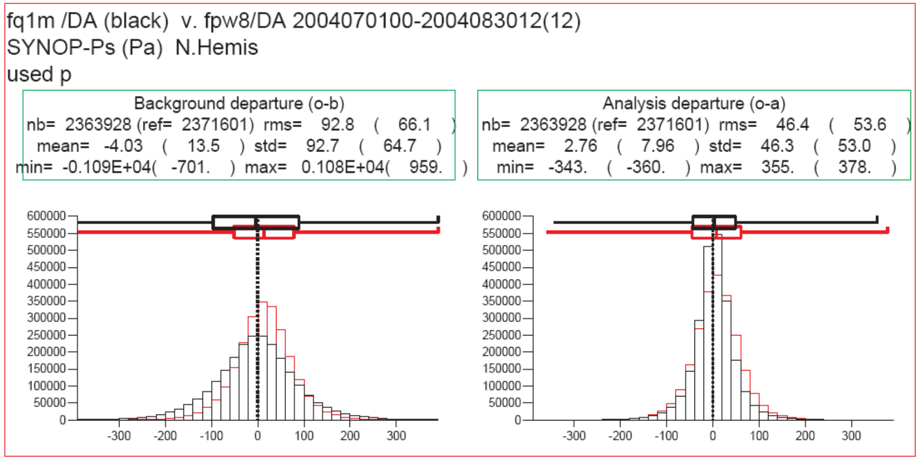
$$\sum_i (b_i - o_i)^2 = \sigma_o^2 + \alpha^2 \sigma_b^2$$

- After tuning (experiment fq1m):

NH, α = 1.04 Equilibrium

TR, α = 0.79 Overdispersion

SH, α = 1.32 Underdispersion



- Comparison well tuned for NH

LETKF against 4DVAR

- The aim is to compare LETKF, 4DVAR and hybrids in ERA-20C like surface pressure only assimilation (PSFC) experiments
- Verification metrics:
  - a) Analyses: Temporal series of MSLP, T2m, U10m, V10m and Z500 RMSE & BIAS

    Vertical profiles of T, Z, U and V RMSE (50 hPa top)

    MSLP RMSE spatial maps
  - b) Forecasts: MSLP and Z500 RMSE by forecast range
- All results are verified against operational analysis (truth)
- Verification for Northern Hemisphere (LAT > 20º N)

LETKF against 4DVAR

- Configuration of experiments

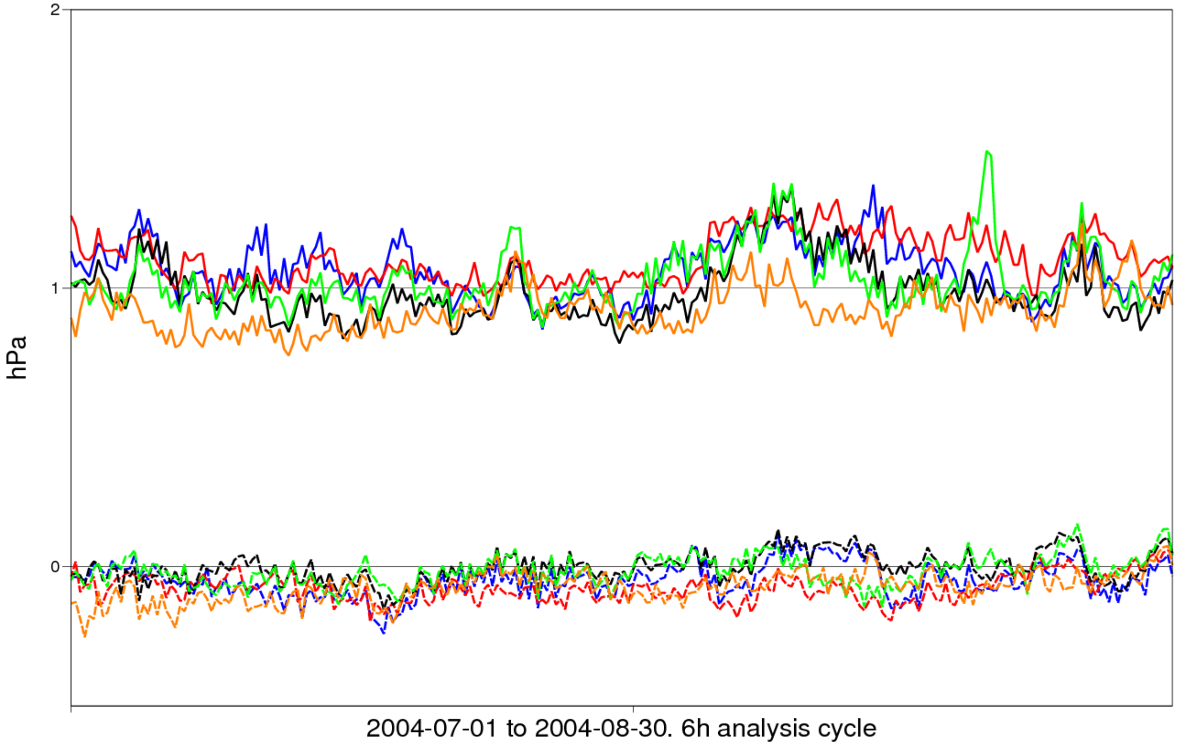
Name	Analysis Method	B matrix	Win leng	Initial Data	PSFC BC	Loop Trunc	Loop Iter	Ens memb	WallTime wrt fqi2
1549	4DVAR	Full Rank Static	12	ERA	Var	95/159	35/50	N/A	1
1580	4DVAR	Full Rank Static	24	ERA	Var	95/159	35/50	N/A	1
fq1m	4DVAR / EDA	Full Rank Dynamic Variance	12	ERA	Var	95/159	70/50	10	11
fr3m	4DVAR / LETKF	Full Rank Dynamic Variance	12	ERA	Var / Drasko's	95/159	70/50	60	2
fqi2	LETKF	Low Rank Full Dynamic	6	Cold	Drasko's	N/A	N/A	60	1

Obs assimilated	Resolution	Levels	Plotted Period
PSFC (Surface Pressure data)	T159 ~ 1.5 x 1.5 deg	91	20040701 - 20040830

LETKF against 4DVAR

- MSLP RMSE & BIAS of analyses at Northern Hemisphere

4DVAR-12 4DVAR-24 4DVAR/EDA 4DVAR/LETKF LETKF-6

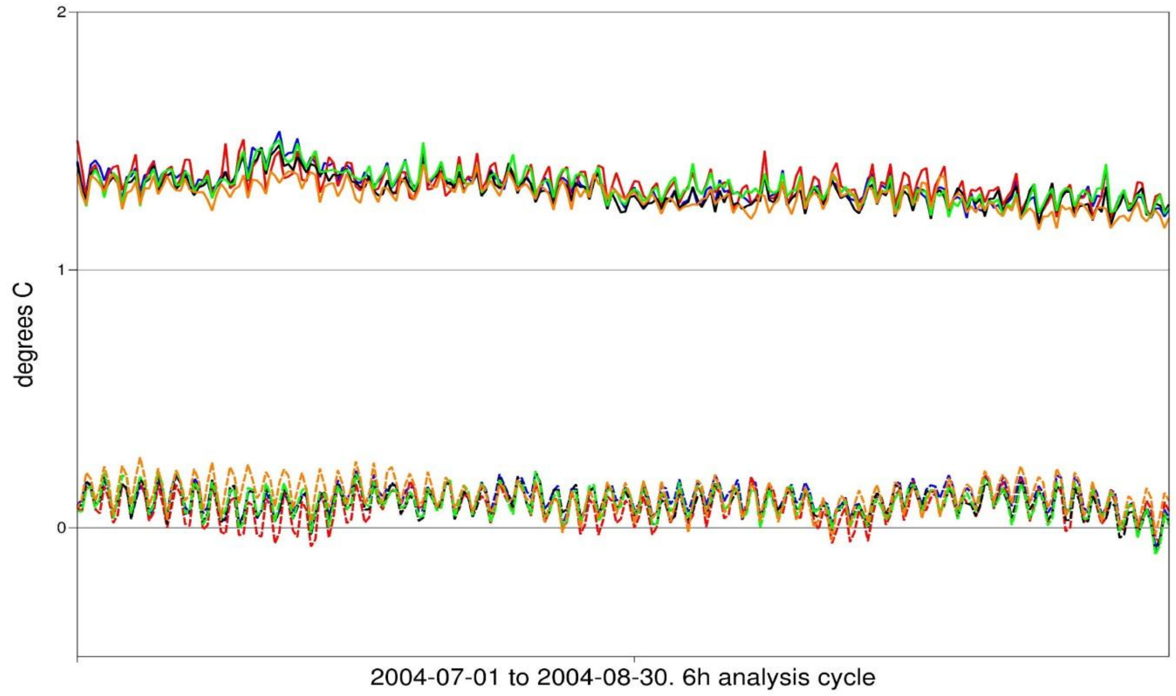


- LETKF performs generally better than any other scheme

LETKF against 4DVAR

- T2M RMSE & BIAS of analyses at Northern Hemisphere

4DVAR-12 4DVAR-24 4DVAR/EDA 4DVAR/LETKF LETKF-6

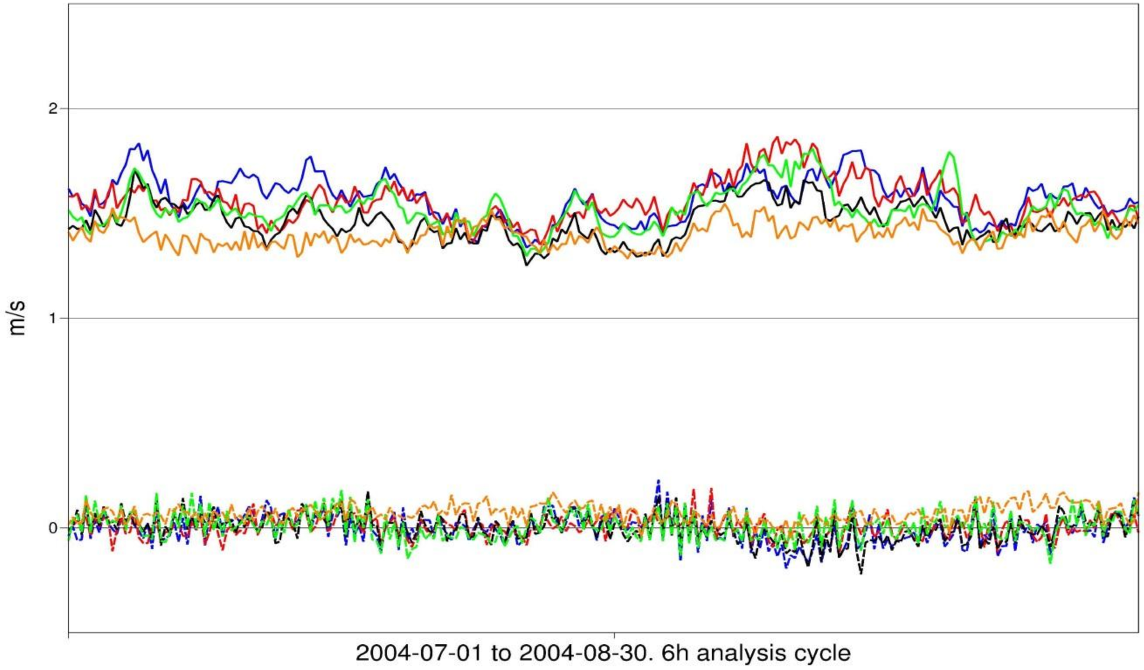


- LETKF performs generally better than any other scheme

LETKF against 4DVAR

- U10m RMSE & BIAS of analyses at Northern Hemisphere

  4DVAR-12 4DVAR-24 4DVAR/EDA 4DVAR/LETKF LETKF-6

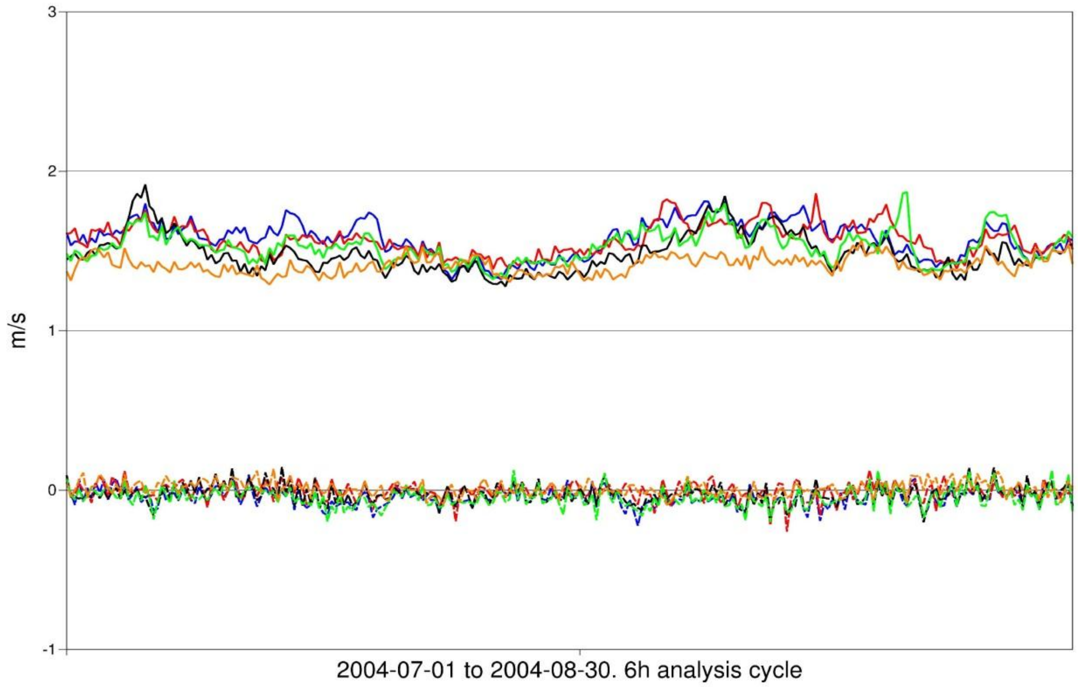


- LETKF performs generally better than any other scheme

LETKF against 4DVAR

- V10m RMSE & BIAS of analyses at Northern Hemisphere

4DVAR-12 4DVAR-24 4DVAR/EDA 4DVAR/LETKF LETKF-6

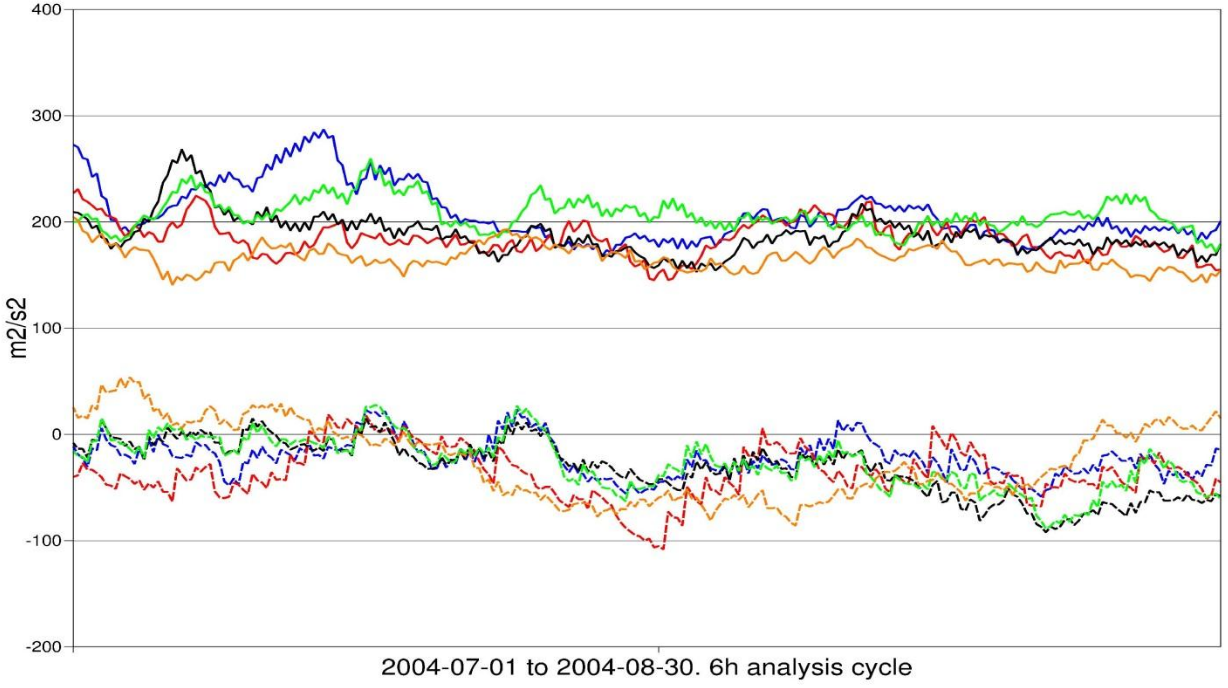


- LETKF performs generally better than any other scheme

LETKF against 4DVAR

- Z500 RMSE & BIAS of analyses at Northern Hemisphere

4DVAR-12 4DVAR-24 4DVAR/EDA 4DVAR/LETKF LETKF-6



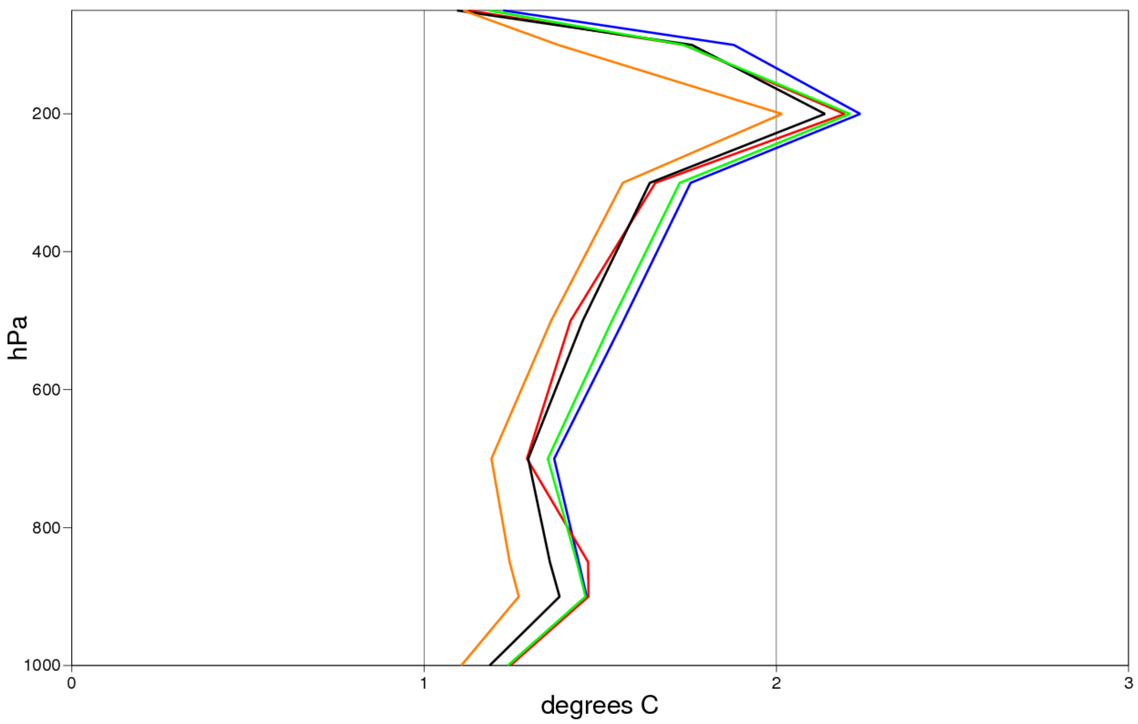
- LETKF performs generally better than any other scheme

ECMWF

LETKF against 4DVAR

- T RMSE profile of analyses at Northern Hemisphere

4DVAR-12 4DVAR-24 4DVAR/EDA 4DVAR/LETKF LETKF-6

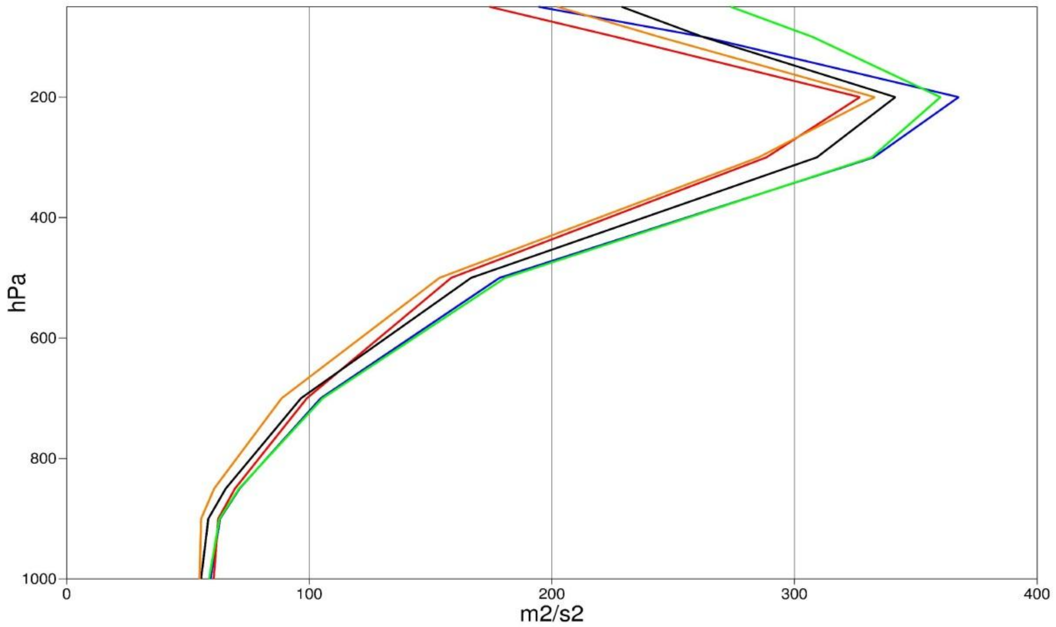


- LETKF best scheme (strong impact of B f-d in absence of observations?!)

LETKF against 4DVAR

- Z RMSE profile of analyses at Northern Hemisphere

4DVAR-12 4DVAR-24 4DVAR/EDA 4DVAR/LETKF LETKF-6



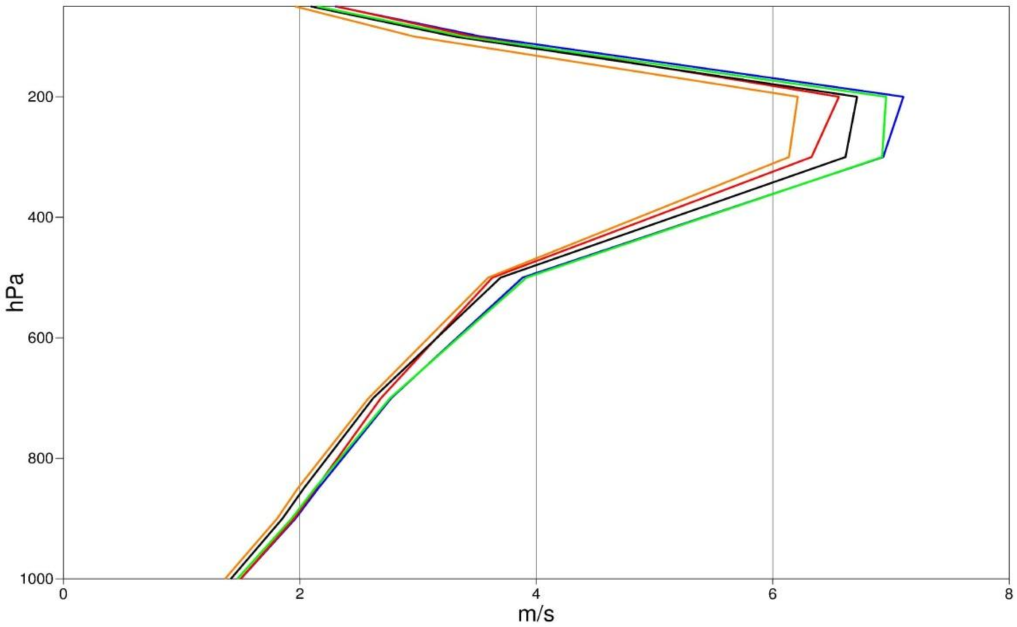
- LETKF best scheme

ECMWF

LETKF against 4DVAR

- U RMSE profile of analyses at Northern Hemisphere

4DVAR-12 4DVAR-24 4DVAR/EDA 4DVAR/LETKF LETKF-6

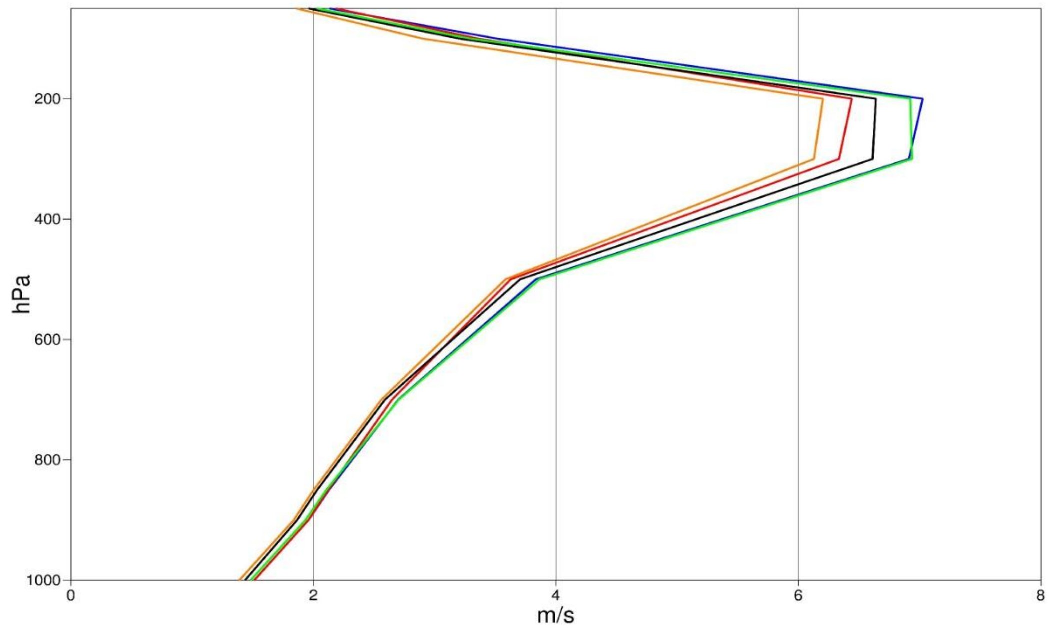


- LETKF best scheme

LETKF against 4DVAR

- V RMSE profile of analyses at Northern Hemisphere

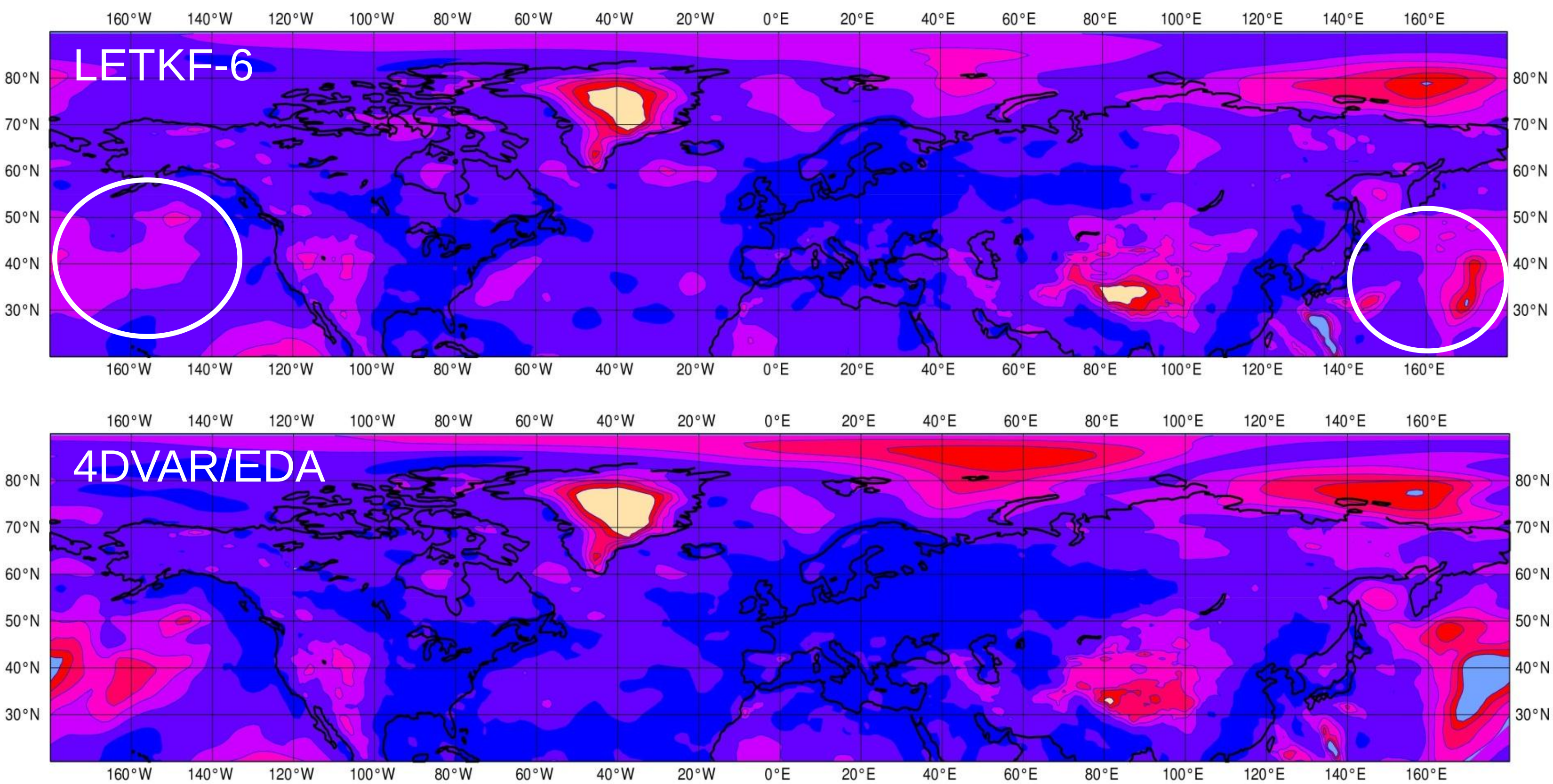
4DVAR-12 4DVAR-24 4DVAR/EDA 4DVAR/LETKF LETKF-6



- LETKF best scheme

LETKF against 4DVAR

- MSLP RMSE. LOW (0 hPa) HIGH (2.4 hPa)

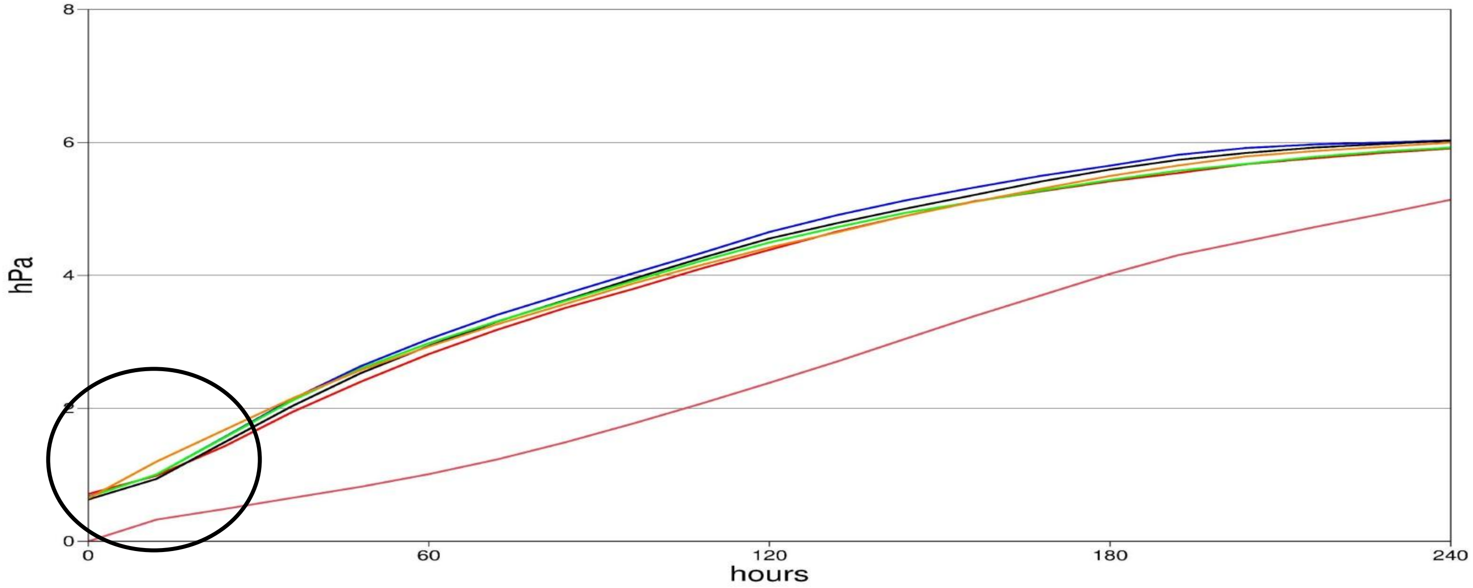


- In Pacific (few obs) LETKF positive impact (flow-dependency of B?!)

LETKF against 4DVAR

- MSLP RMSE of forecasts at Northern Hemisphere

4DVAR-12 4DVAR-24 4DVAR/EDA 4DVAR/LETKF LETKF-6 OPER

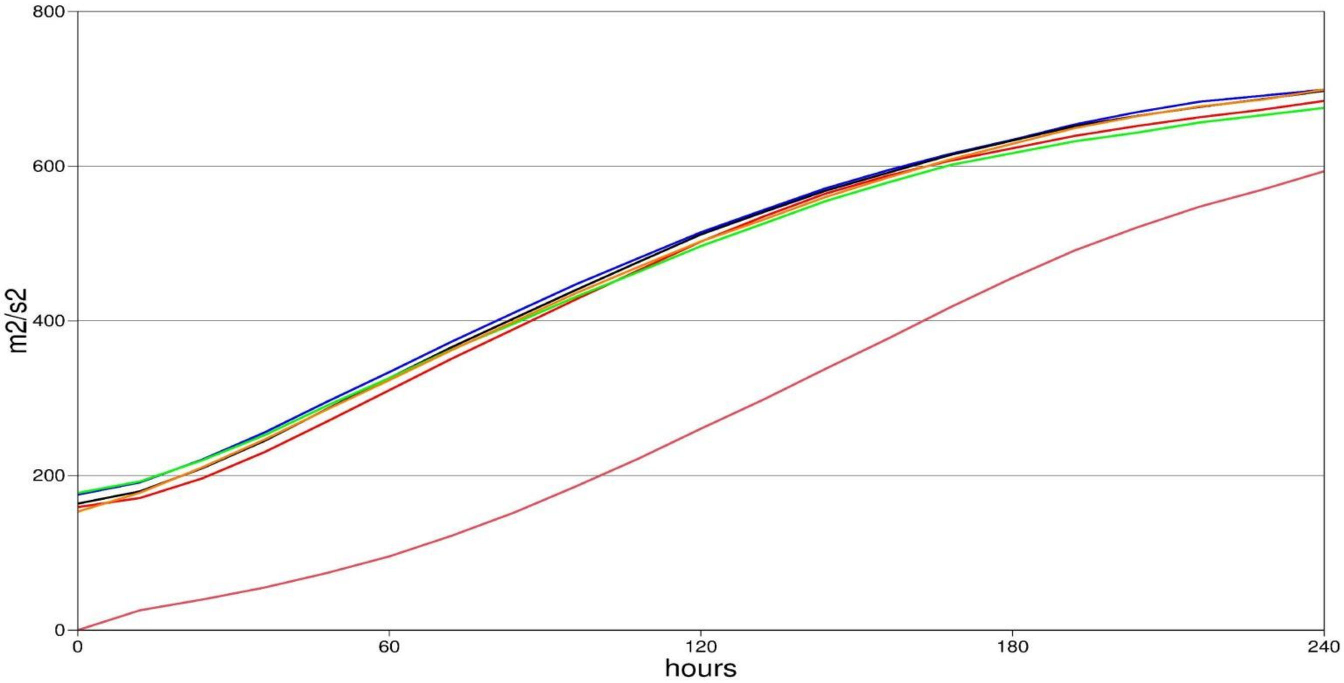


- LETKF analysis clear overperformance not in forecast (initial unbalance?!)
- 4DVAR-24 the best up to H+120 (beneficial enlarge window?!)

LETKF against 4DVAR

- Z500 RMSE of forecasts at Northern Hemisphere

4DVAR-12 4DVAR-24 4DVAR/EDA 4DVAR/LETKF LETKF-6 OPER



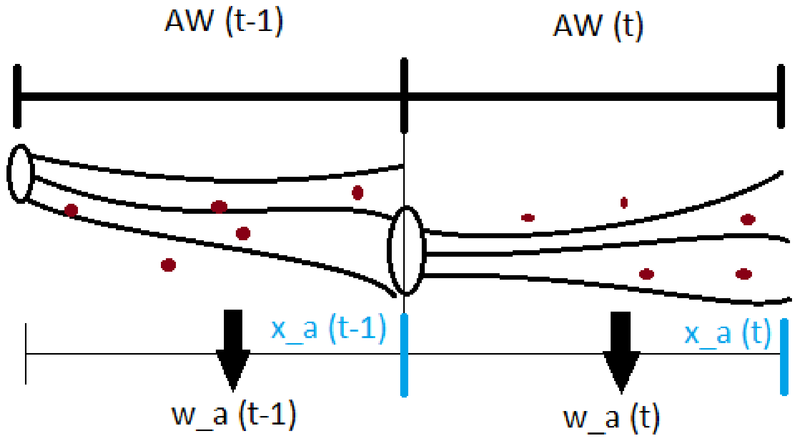
- 4DVAR/LETKF the best from H+120 on (B quality?!)

LETKF Smoother

- LETKF Smoother is a simple methodology for doubling the length of the assimilation window under the assumption of linearity in forecast error propagation (Yang et al., 2009)

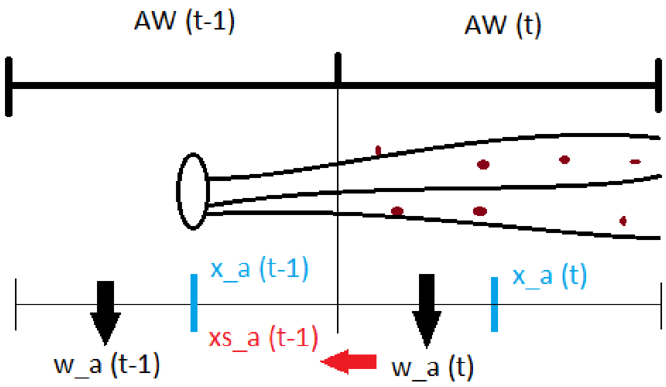
- As the weights w^a are valid in the whole assimilation window, in the beginning of the window, the current and the ones of the previous window are both valid. So one can apply the future weights to reconstruct the previous analysis:

$$\tilde{x}^a_{t-1} = \overline{x^a_{t-1}} + X^a_{t-1}\overline{w_t^{\ a}}$$



LETKF Smoother

- Due to technical implementation in IFS, future weights w^a_t are applied to a previous X^a_{t-1} out of the analysis window. However this should not affect the validity of Smoother due to linearity of first 3 hours forecast:

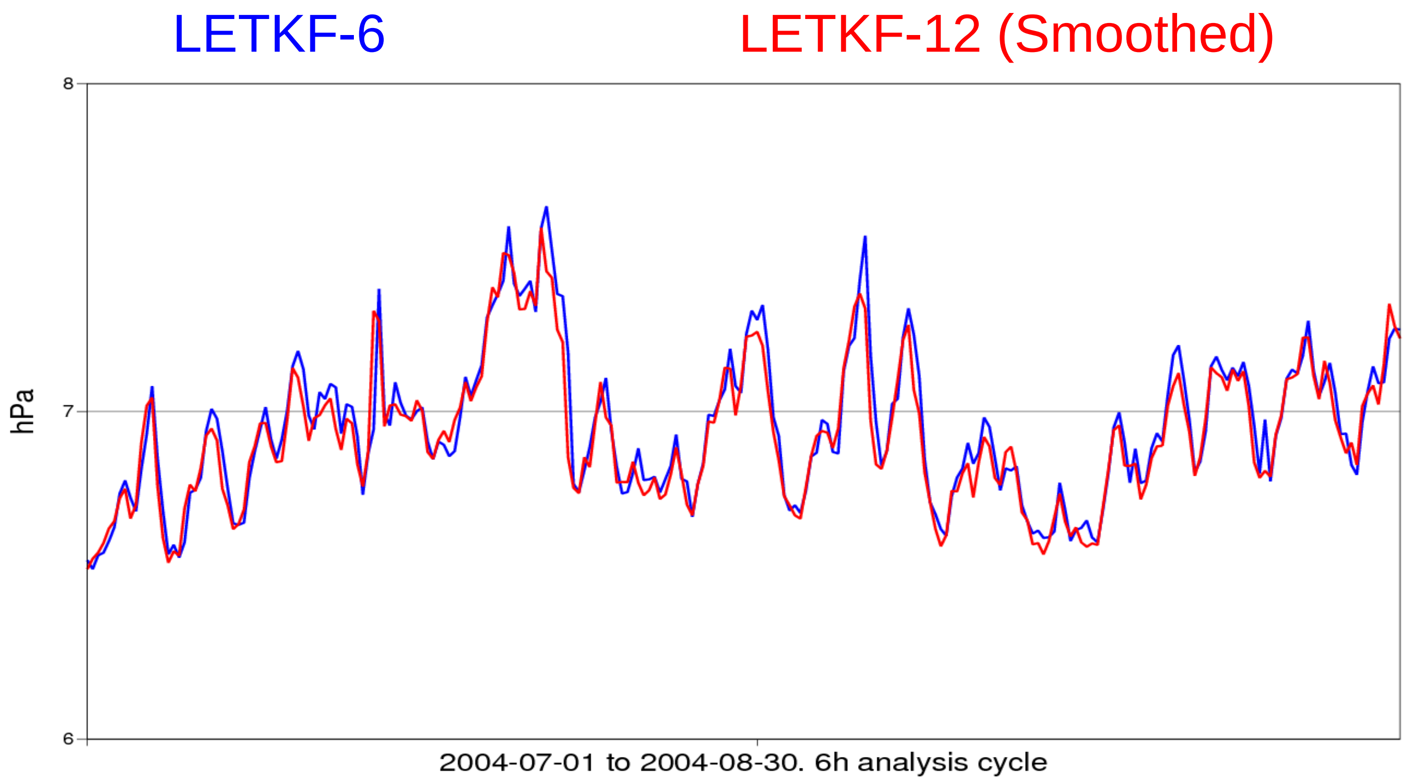


- A coherent Smoother should use the non-inflated ensemble of analysis (k=1), otherwise future observations would be weighted differently than previous:

$$x^a_{s,t-1} = x^a_{t-1} + X^a_{t-1} w^a_t = x^b_{t-1} + X^b_{t-1} w^a_{t-1} + kX^b_{t-1} W^a_{t-1} w^a_t = x^b_{t-1} + X^b_{t-1}\left(w^a_{t-1} + kW^a_{t-1} w^a_t\right)$$

LETKF Smoother

- PSFC RMSE of analyses at Southern Hemisphere

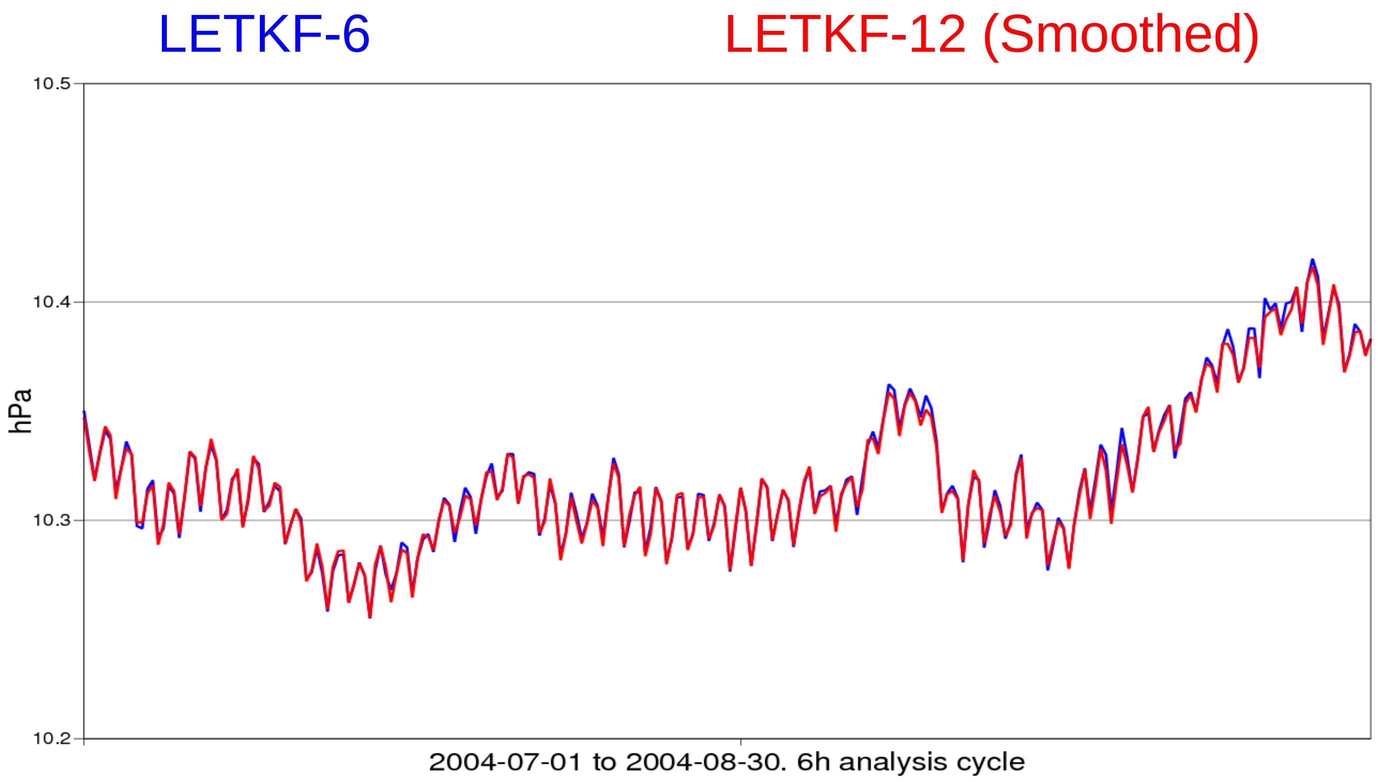


- Positive impact in presence of few observations

ECMWF

LETKF Smoother

- PSFC RMSE of analyses at Northern Hemisphere

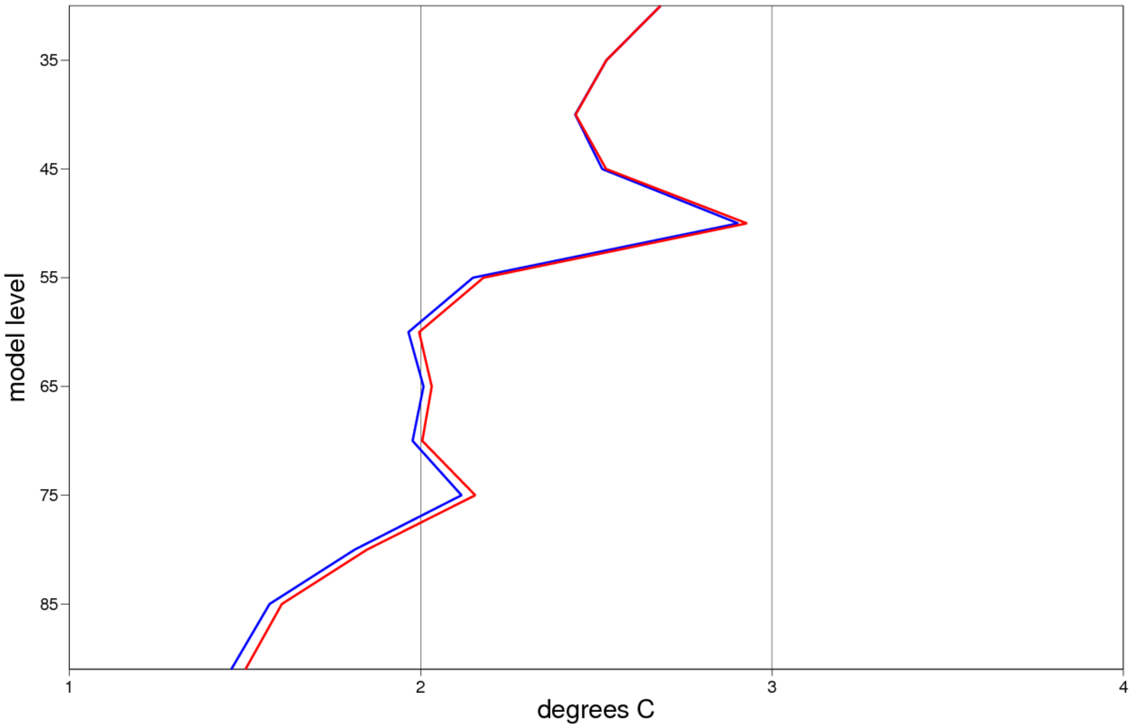


- No significant impact in presence of enough observations?!

LETKF Smoother

- T RMSE & BIAS profile of analyses at Southern Hemisphere

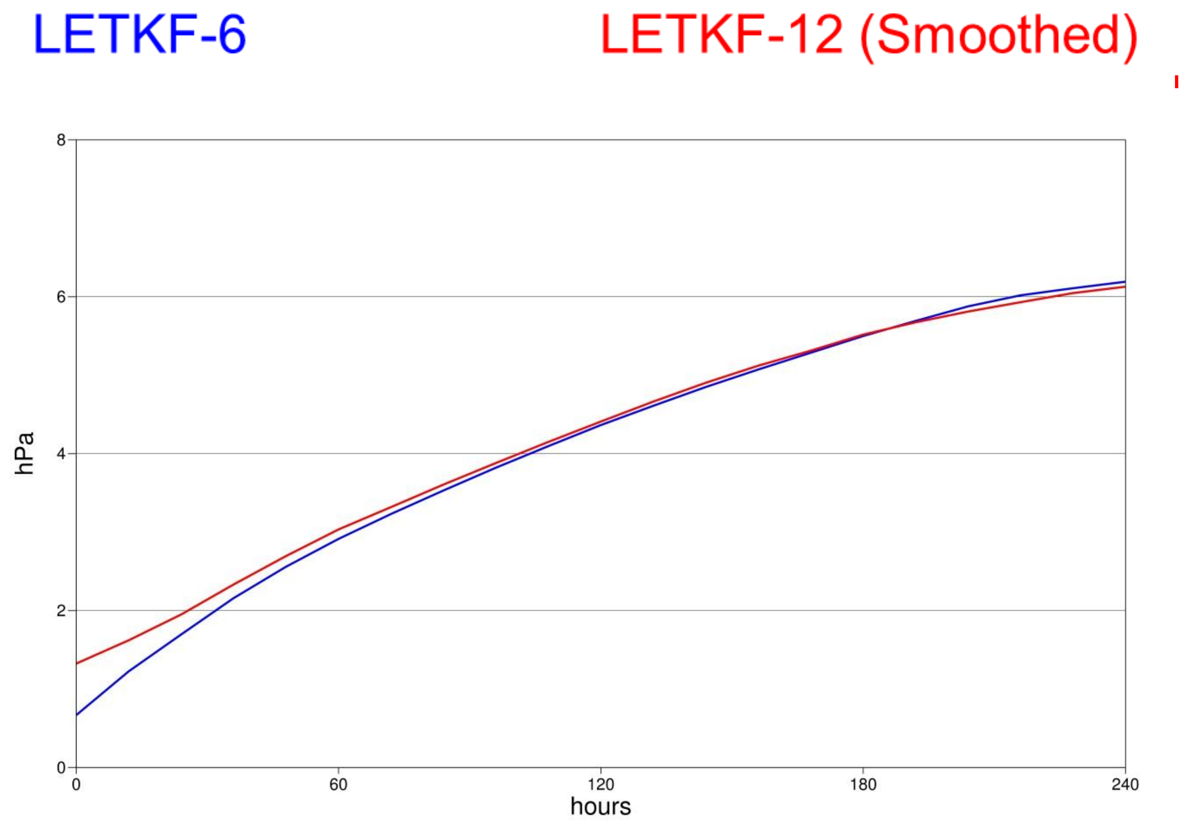
LETKF-6 LETKF-12 (Smoothed)



- Bad: Smoother worsens T in the vertical. Unbalanced analysis?

LETKF Smoother

- MSLP RMSE of forecasts at Northern Hemisphere



- Initial unbalance reduced with forecast range but an open issue

Summary

- This study compares performances of LETKF, 4DVAR and hybrids in a simplified environment only assimilating PSFC and low resolution T159
- In this configuration LETKF analysis performs generally the best at NH (comparison well tuned) assuming the same computational cost
- Flow-dependent estimation of B seems to have specially positive impact over Pacific and in the vertical, where few and no observations are available
- LETKF analyses clear overperformance is not observed in forecasts probably due to initial unbalance
- 4DVAR-24 forecast is the best up to H+120 whereas from then on is 4DVAR/LETKF. This suggests is beneficial enlarging window and increasing flow-dependent signal in B estimation
- LETKF smoother has positive impact in analysis skill specially in presence of few observations but at the same time it creates important unbalances in the vertical

Discussion

- LETKF seems to be a powerful assimilation tool when only PSFC is assimilated. Could it be extended to other poor observed systems such as ocean or pollution modelling?
- However, work must be done in removing LETKF initial unbalance and trying other methodologies for covariance inflation
- LETKF Smoother seems to take less profit of doubling assimilation window than 4DVAR and it is still an open issue with respect to vertical unbalances
- Conclusions of comparison can not be directly extended to all observations assimilated simulations. Work on this comparison is going on for all the Globe

A ECMWF technical memorandum on this study is going to appear soon. For more discussions:

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