HIRLAM 4DEnsVar – discussion and first results

Nils Gustafsson and
Jelena Bojarova

4DEnsVar: Issues

- **Avoid use of TL and AD models (difficult to scale on thousands of processors) => Cheaper than 4DVar**
- **Utilize ensemble perturbations based on the non-linear model.**
- **Ensemle generation: Perturbed observations? ETKF re-scaling? Stochastic physics?**
- **Need for many EPS members (~100?); can lagged ensembles be used?**
- **Easy to implement with existing 4DVar Hybrid**
- **4DEnsVar similar to 4D-En-KF in its simplest form with possibilities to treat non-linearities better (outer loops)**

Incremental 4DVar

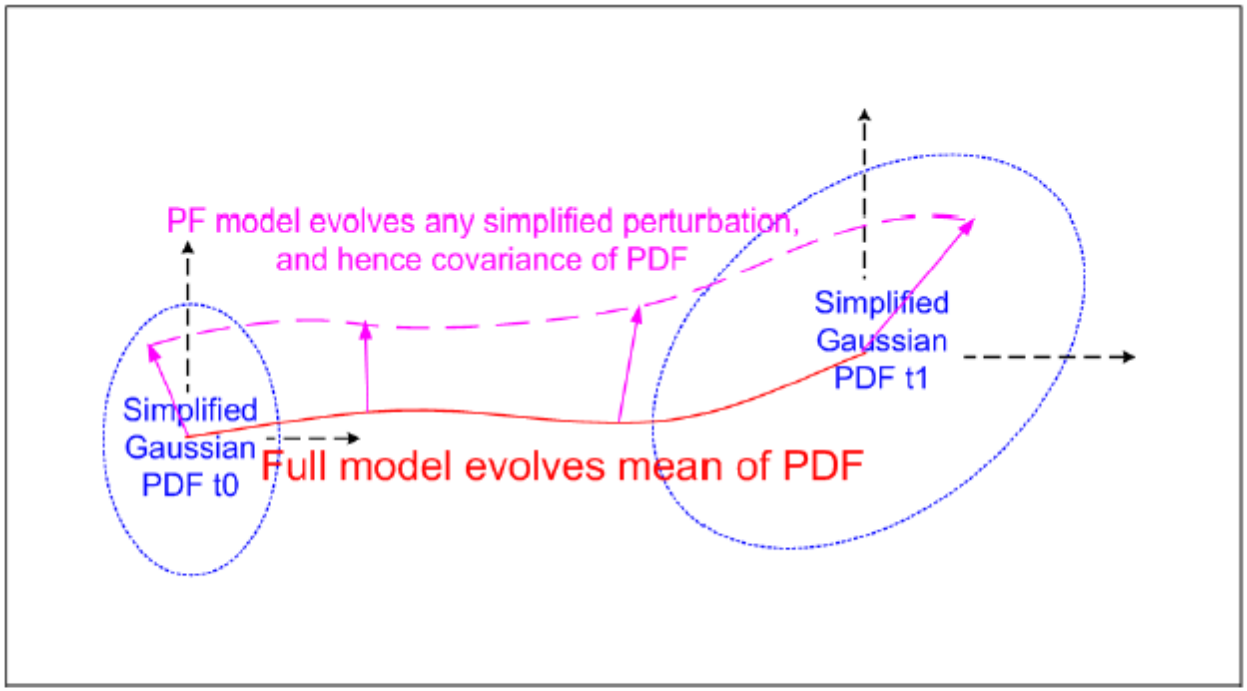


Figure 3: Statistical, incremental, 4D-Var approximates entire PDF by a Gaussian. The 4D analysis increment is a trajectory of the PF model, optionally augmented by a model error correction term.

From Lorenc (2011)

4DEnsVar

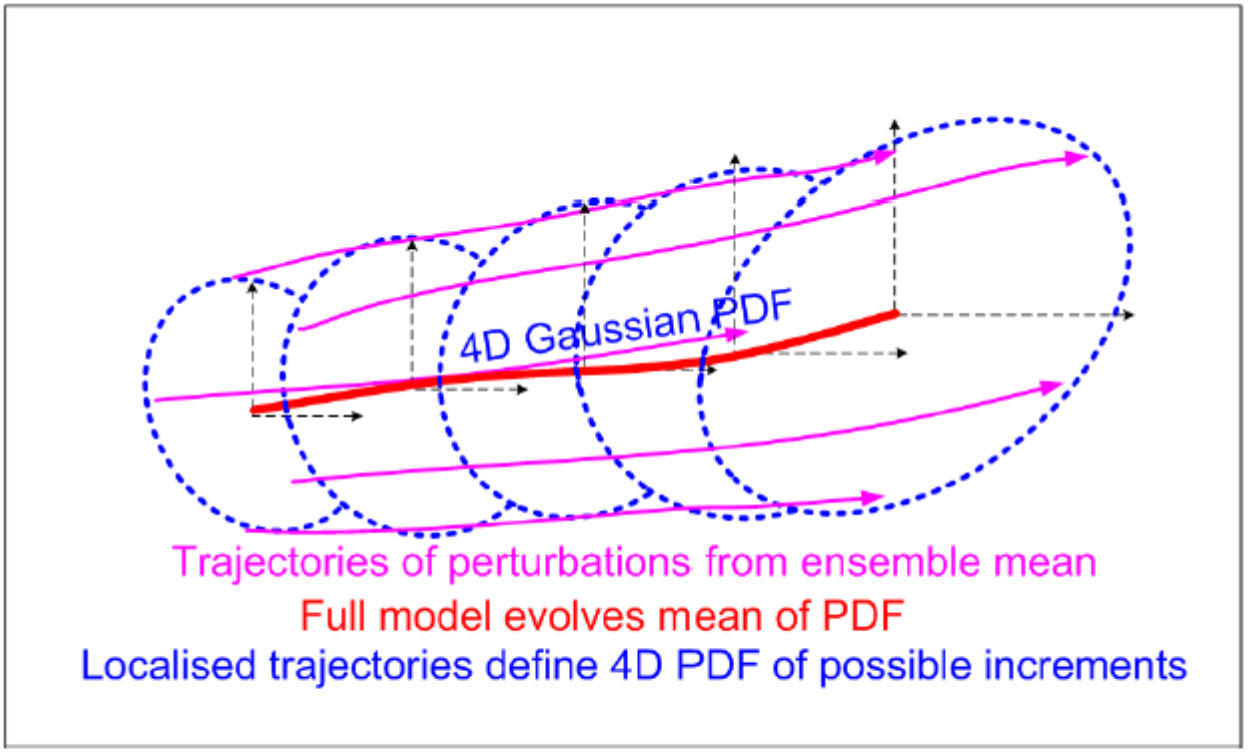


Figure 6: A schematic diagram of 4D-En-Var, for comparison with figure 3. The 4D analysis is a localised linear combination of model trajectories – it is not itself a model trajectory.

From Lorenc (2011)

4DEnsVar - literature and status

- Liu et al. 2008, MWR
- Buener et al. 2010, MWR
- UK MetOffice: Bowler, strategy paper; Lorenc, design paper;
- To replace 4DVar in Canada in 2013; 4DEnsVar as good as 4DVar in trial runs
- **Very first** results at Met.Office: 4DVar better than 4DEnsVar
- Applied at SMHI for Sea ice model (Axell)

Lorenc (2003) augmentation of the control vector space:

spectral space

$$J(\delta x_{3D-Var}, \alpha) = \beta_{3D-Var} J_{3D-Var}(\delta x_{3D-Var}) + \beta_{ens} J_{ens}(\alpha) + J_o$$

- Spatial mean of $\alpha_k = 0$;
- Spatial variance of $\alpha_k = 1/K$ is constant and controls amplitude;
- Horizontal auto-correlation controls smoothness of α_k fields

$$\frac{1}{\beta_{3D-Var}} + \frac{1}{\beta_{ens}} = 1 \qquad J_{ens} = \frac{1}{2}\alpha^T \mathbf{A}^{-1} \alpha$$

The same α_k fields for vertical levels and all types of model state components

grid-point space

$$\delta x = \delta x_{3D-Var} + \sum_{k=1}^{K} (\alpha_k \circ \delta x_k^{ens})$$

Empirical matrix A contains spectral density of the horizontal auto-correlation of α_k fields

Spatial averaging is applied on vorticity, divergence, temperature, specific humidity and log of surface pressure in order to preserve a geostophic balance.

Different HIRLAM Hybrid variational ensemble schemes

Assimilation window $t_0 \leq t \leq t_1$
$t_* = (t_0 + t_1)/2$

$d_t = y_t - M(t_0, t)(x(t_0))$
M Non-linear model

$J_o = \sum (d_t - \delta x_t)^T R^{-1} (d_t - \delta x_t)$

3D-Var (FGAT) : $\delta x_{t_*} = \delta x^B_{t_*}$

3D-Var FGAT Hybrid:
$\delta x_{t_*} = \delta x^B_{t_*} + \sum_{k=1}^{K} \alpha_k \circ \delta x^{EPS}_k(t_*)$

4D-Var :

$\delta x_t = \mathbf{M}(t_0, t)\delta x^B_{t_0}$

$\mathbf{M}$ Tangent-linear model

4D-Var Hybrid:

$\delta x_t = \mathbf{M}(t_0, t)\left(\delta x^B_{t_0} + \sum_{k=1}^{K} \alpha_k \circ \delta x^{EPS}_k(t_0)\right)$

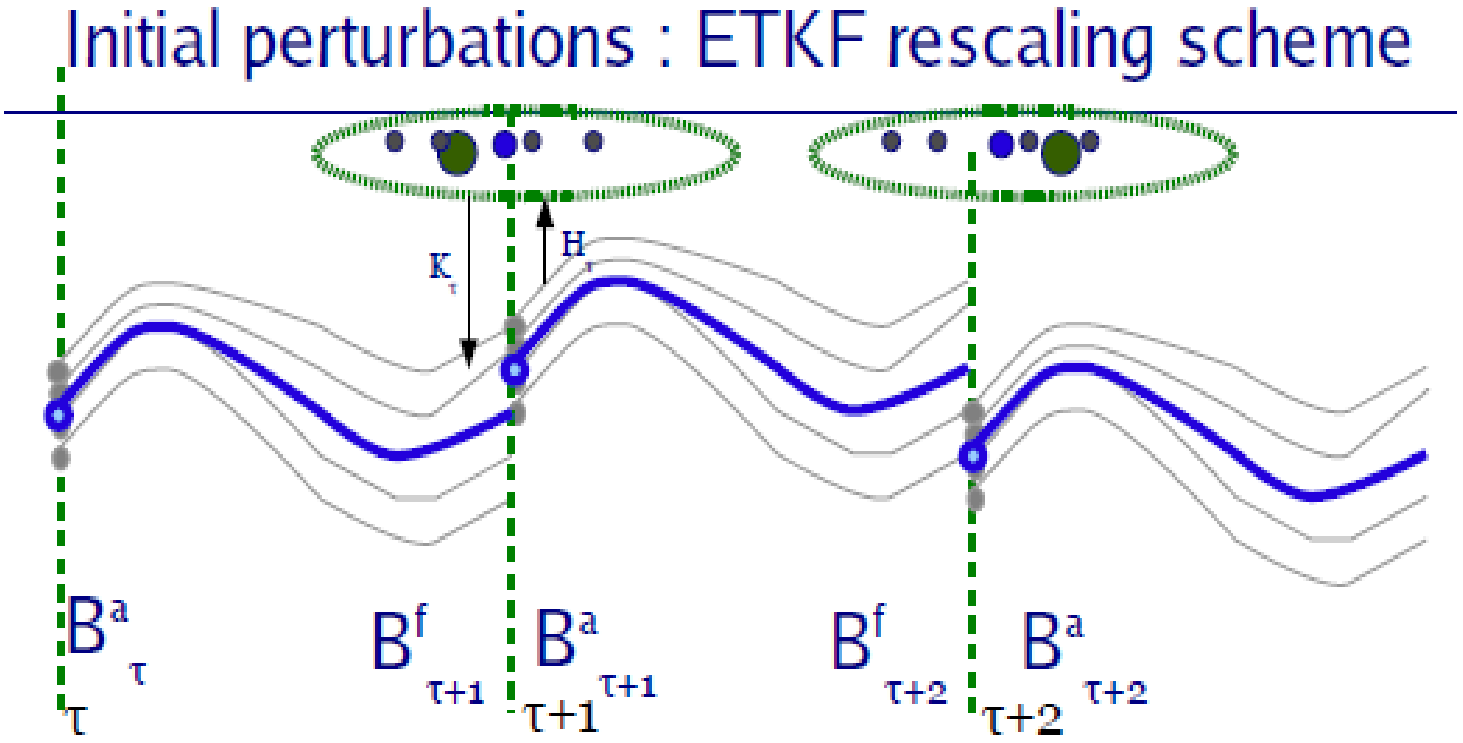
4DEnsVar (strong constraint):

$\delta x_t = \sum_{k=1}^{K} \alpha_k \circ \delta x^{EPS}_k(t)$

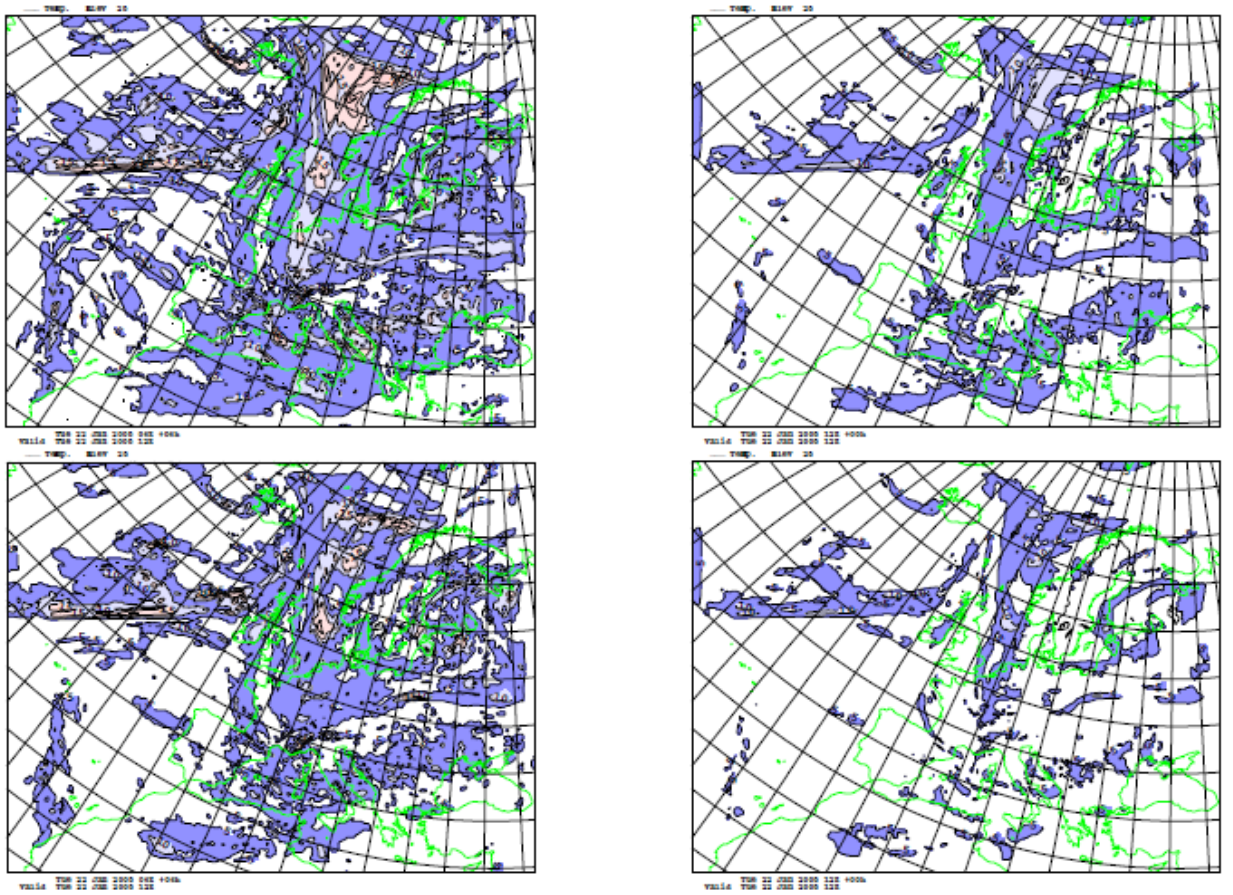
$+\delta x^B_{t_*}$ (optional term)

With time-variable localization α_k we will have Weak constraint 4DEnsVar!

ETKF rescaling scheme:
sequential low-rank estimation of covariance evolution



Examples of ensemble spread (standard deviation) for temperature at model level 28 (~800 hPa)



3D-Var

4D-Var

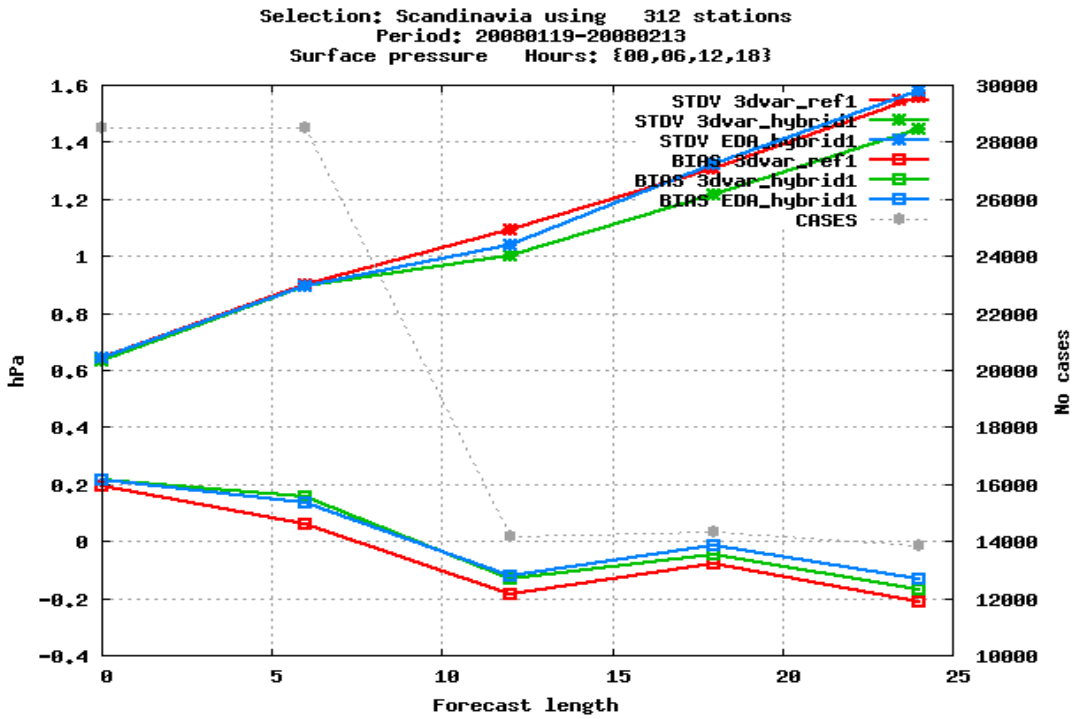
Figure 12. Temperature level 28 spread (rms), 3dvar (top), 4dvar(bottom), before etkf re-scaling (left), after etkf re-scaling (right), 22

Before ETKF re-scaling

After ETKF re-scaling

Which ensemble generation technique is better?

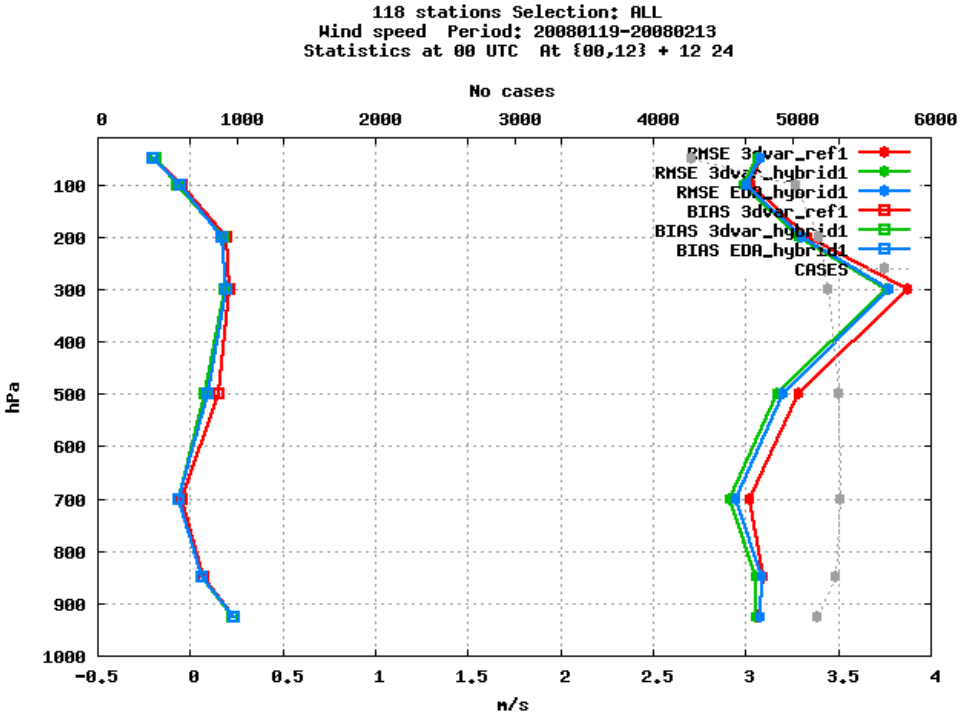
ETKF or EDA (perturbed observations)

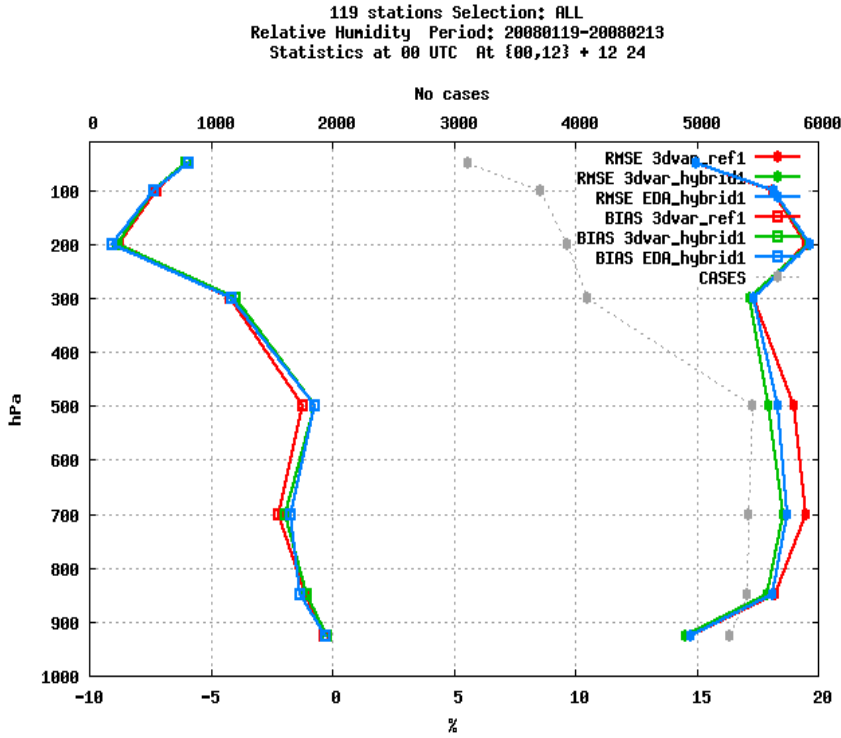


3DVAR-ETKF outperforms both ***3DVAR*** and ***3DVAR_EDA***

Dynamically consistent structures are important

EDA or ETKF perturbations – verification of upper air profiles



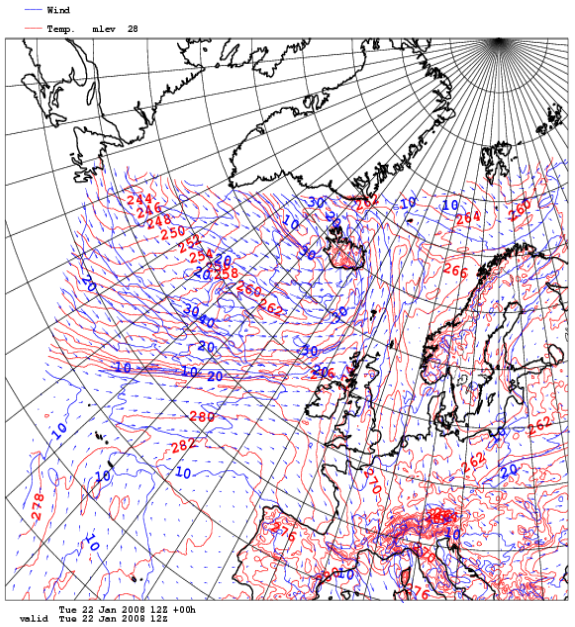


---- 3D-Var

---- 3D-Var EDA hybrid

---- 3D-Var ETKF hybrid

EnsDA: analysis at 22 Jan 2008 12 UTC & mbr005



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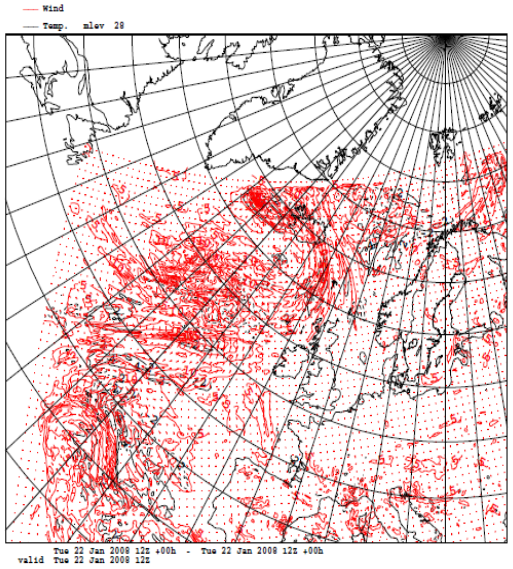

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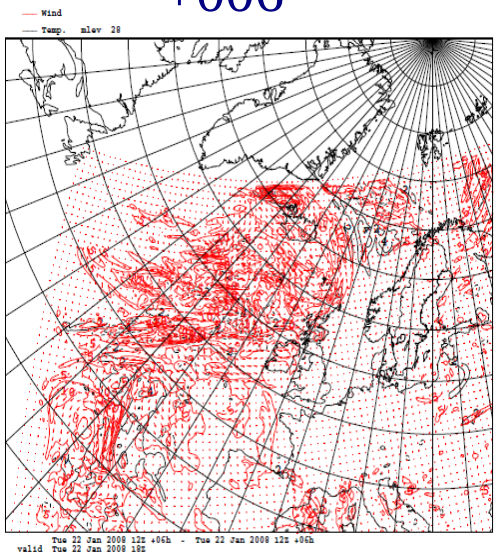

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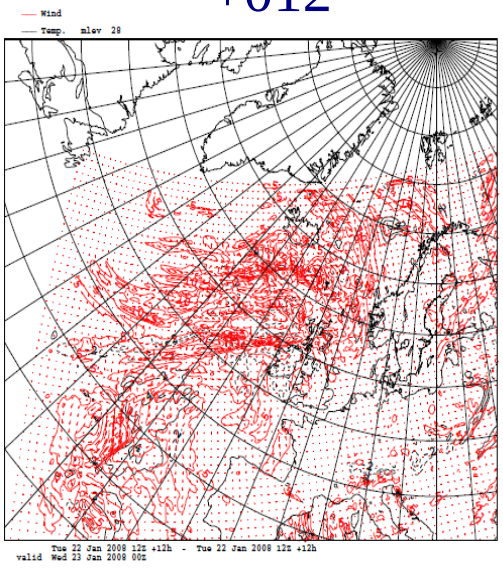

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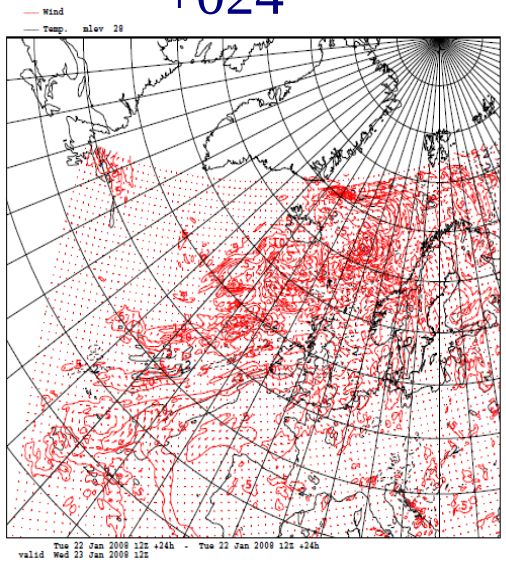
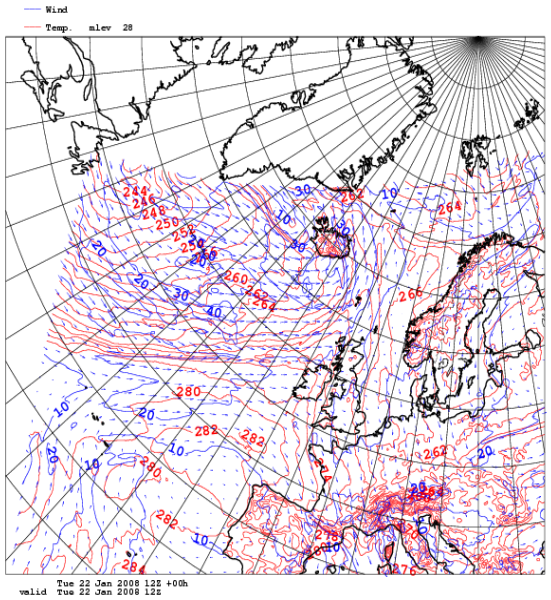
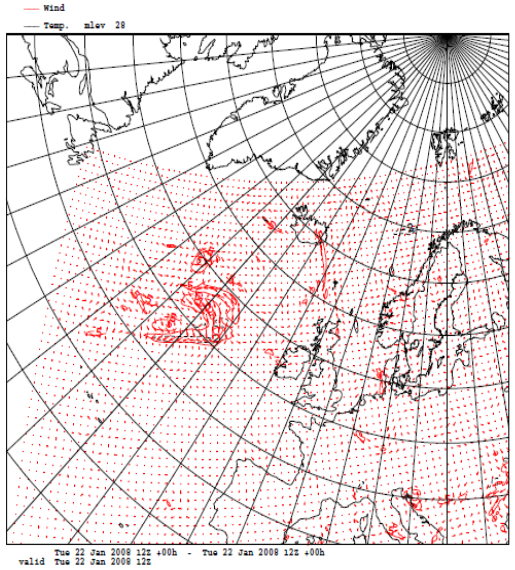


ETKF: analysis at 22 Jan 2008 12 UTC & mbr005

+000





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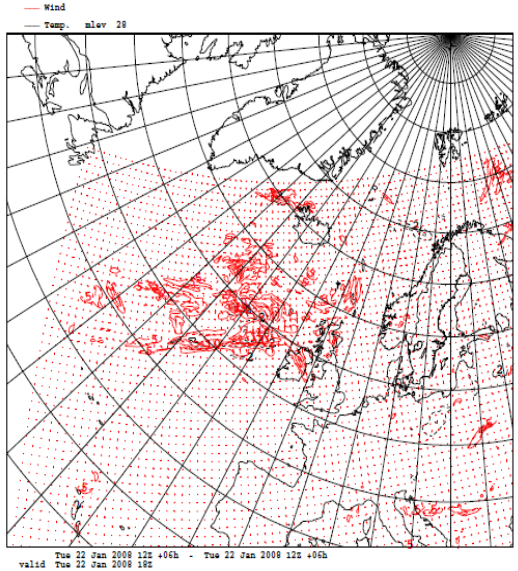

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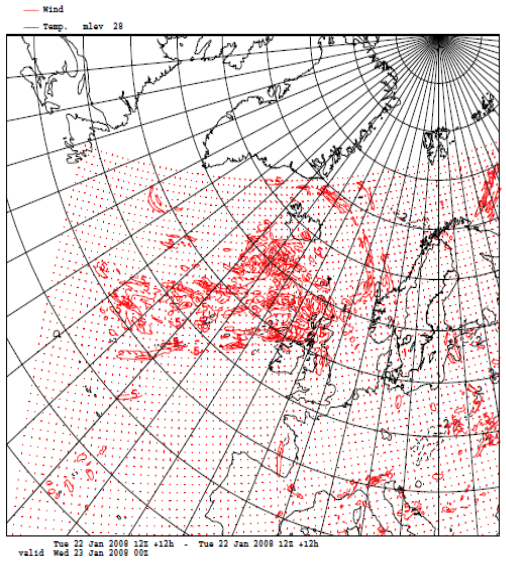

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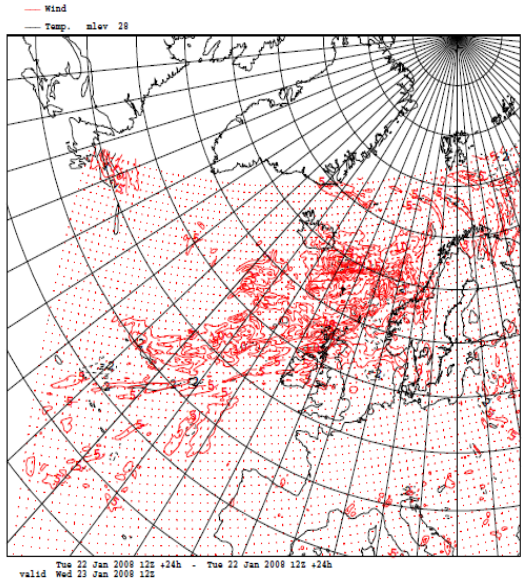
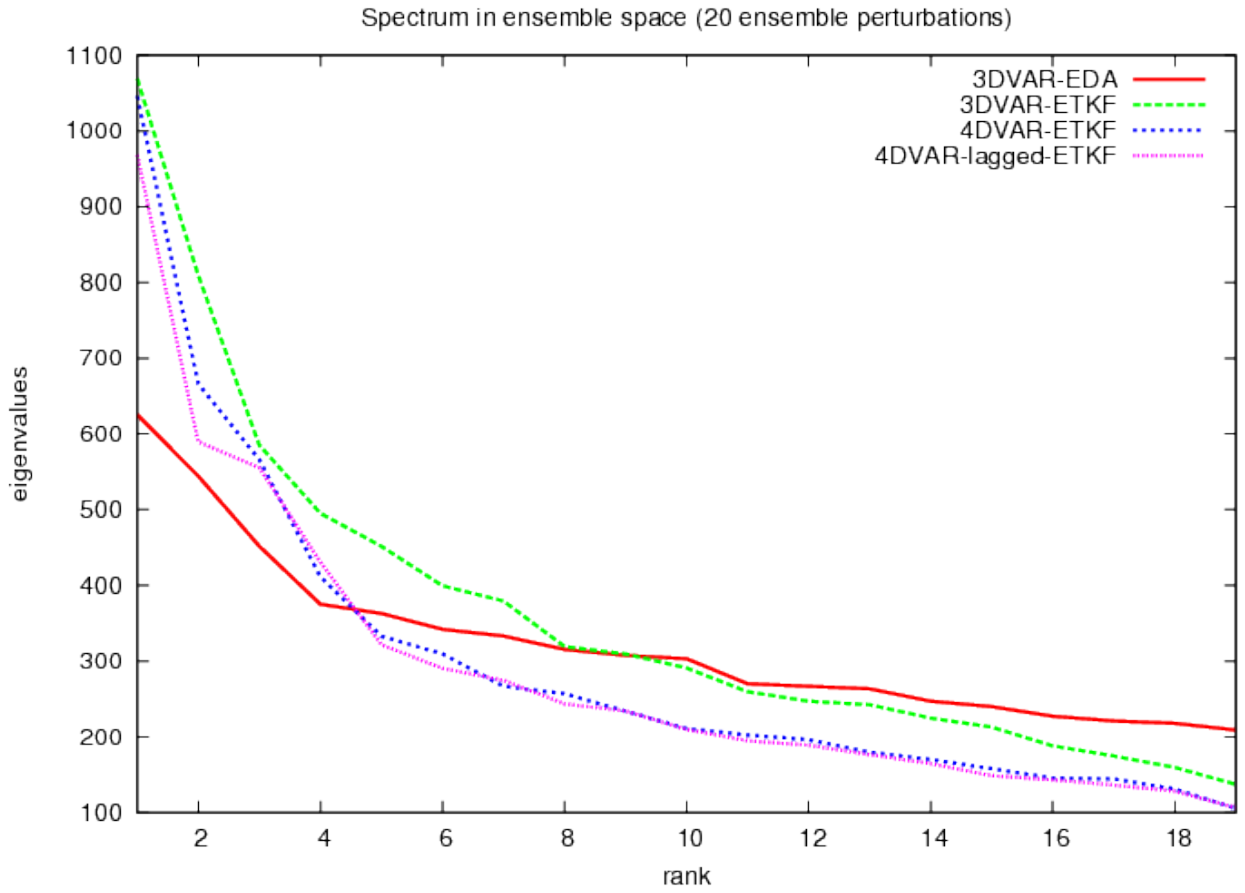


Spectra in ensemble space of different ensemble perturbations (22 January 2008 06UTC +06h)

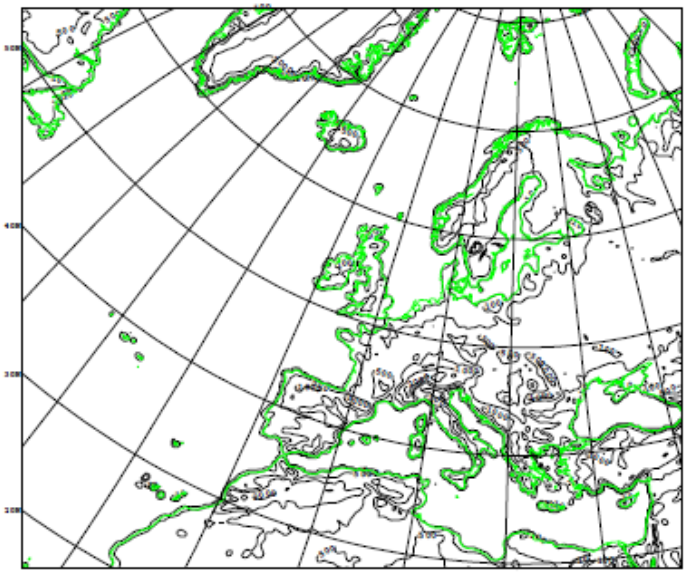


Experiments over 17 January – 29 February 2008

4dvar_ref1: 4D-Var, 2 outer loops (6 h window, 20 iter. at 66 km and 40 iter. at 44 km incr. resol.), simple TL physics (vertical diffusion only), J_c DFI

4dvar_hybrid1: As 4dvar_ref1 with hybrid ensemble constraint, 20 members, ETKF perturb., 75% static and 25% ensemble variance, ens. perturbations inflated by a factor 4 in hybrid.

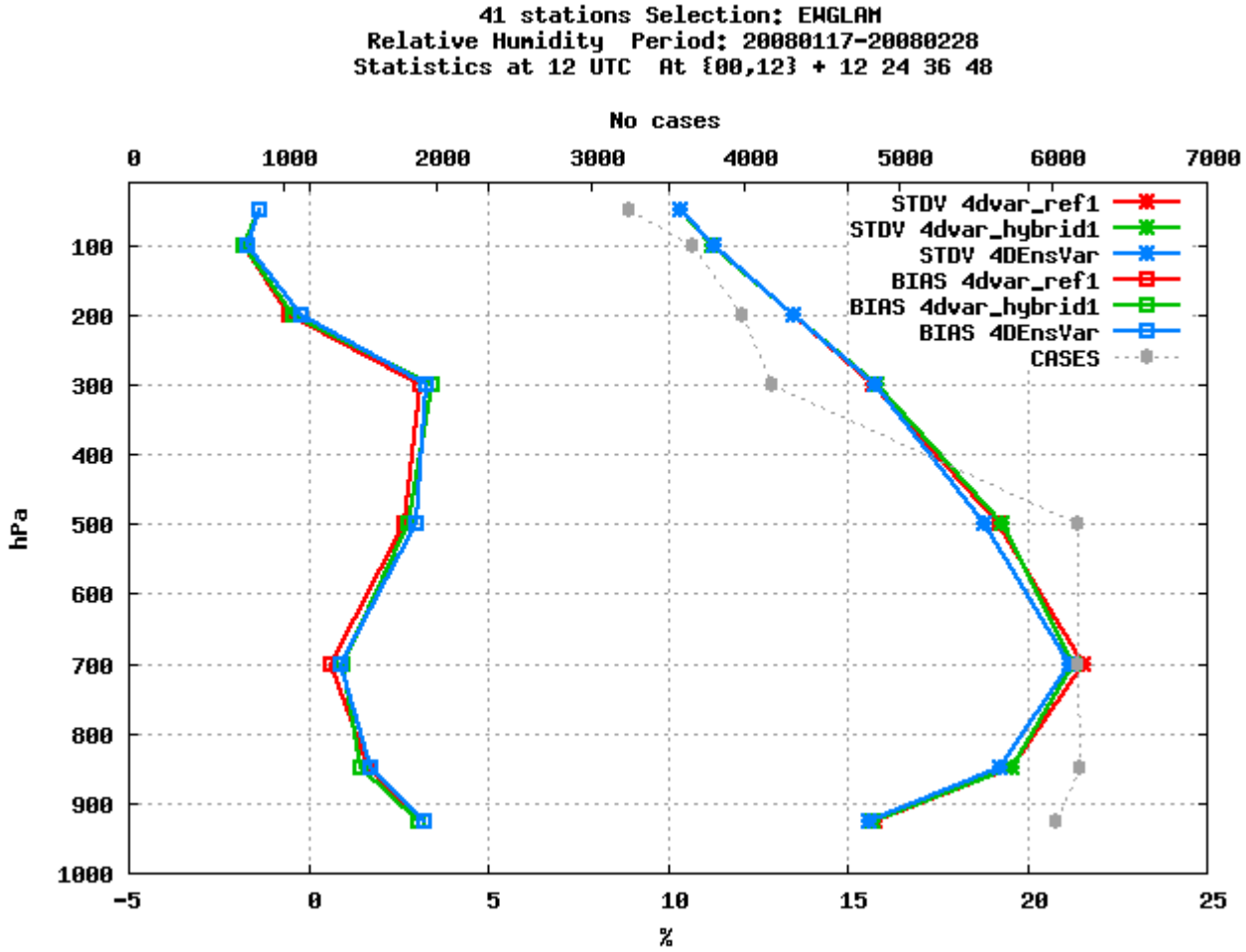
4DEnsVar: 6 h window, 1 outer loop (60 iter. at 33 km incr. resol.). 50% static and 50% ens. variance, no ens. perturb. inflation, 3D-Var constraint in the middle of the window (<=> FGAT).



Model grid res. 11 km
40 levels
20 members

Verification of relative humidity profiles against EWGLAM radiosonde stations; average over +12h, +24h, +36h and +48h

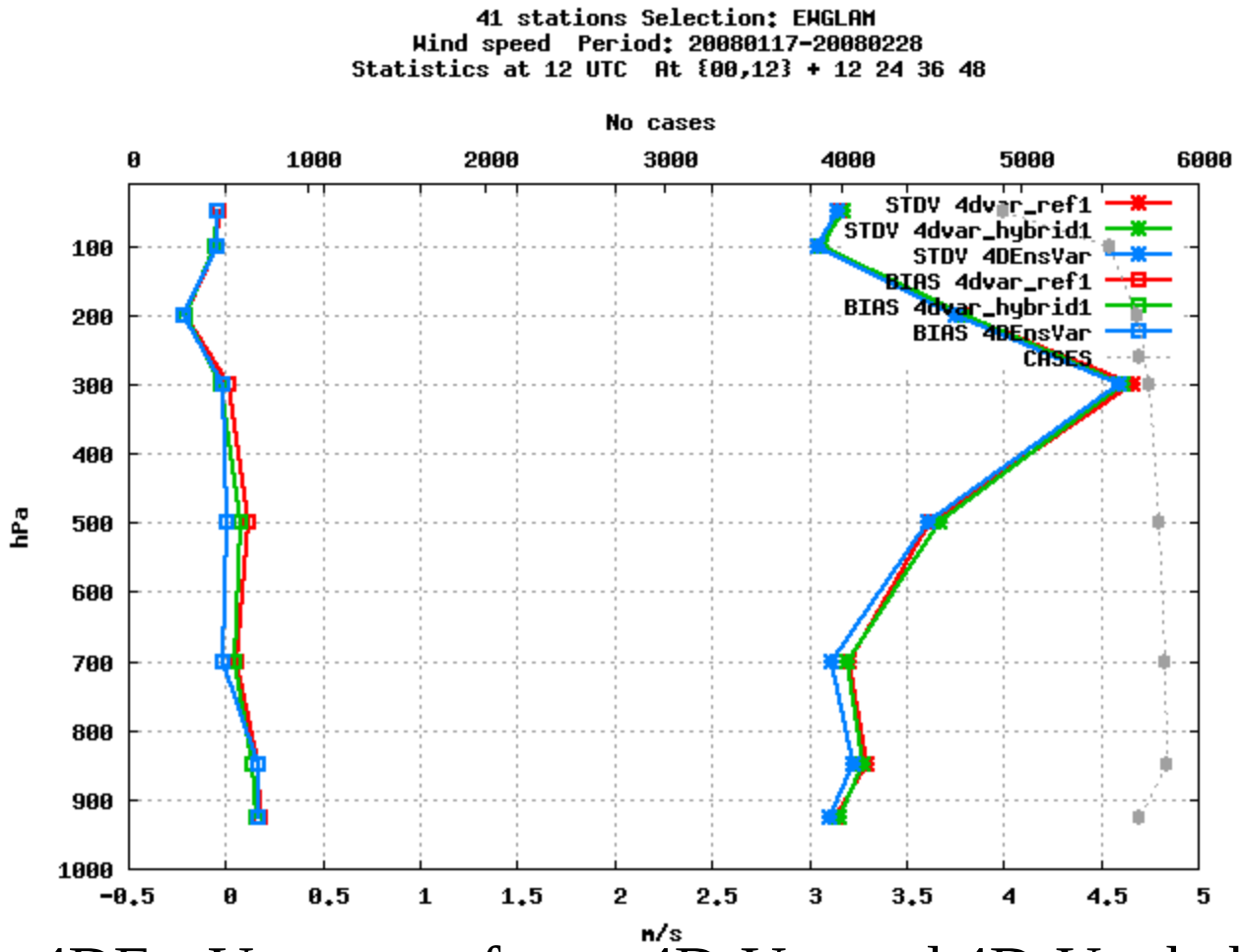
------ 4D-Var, ----- 4D-Var Hybrid, -----4DEnsVar



Comments:
- 4DEnsVar outperforms 4D-Var and 4D-Var hybrid; this is probably due to the poor HIRLAM 4D-Var moist physics
- 4D-Var hybrid slightly better than 4D-Var

Verification of wind speed profiles against EWGLAM radiosonde stations; average over +12h, +24h, +36h and +48h

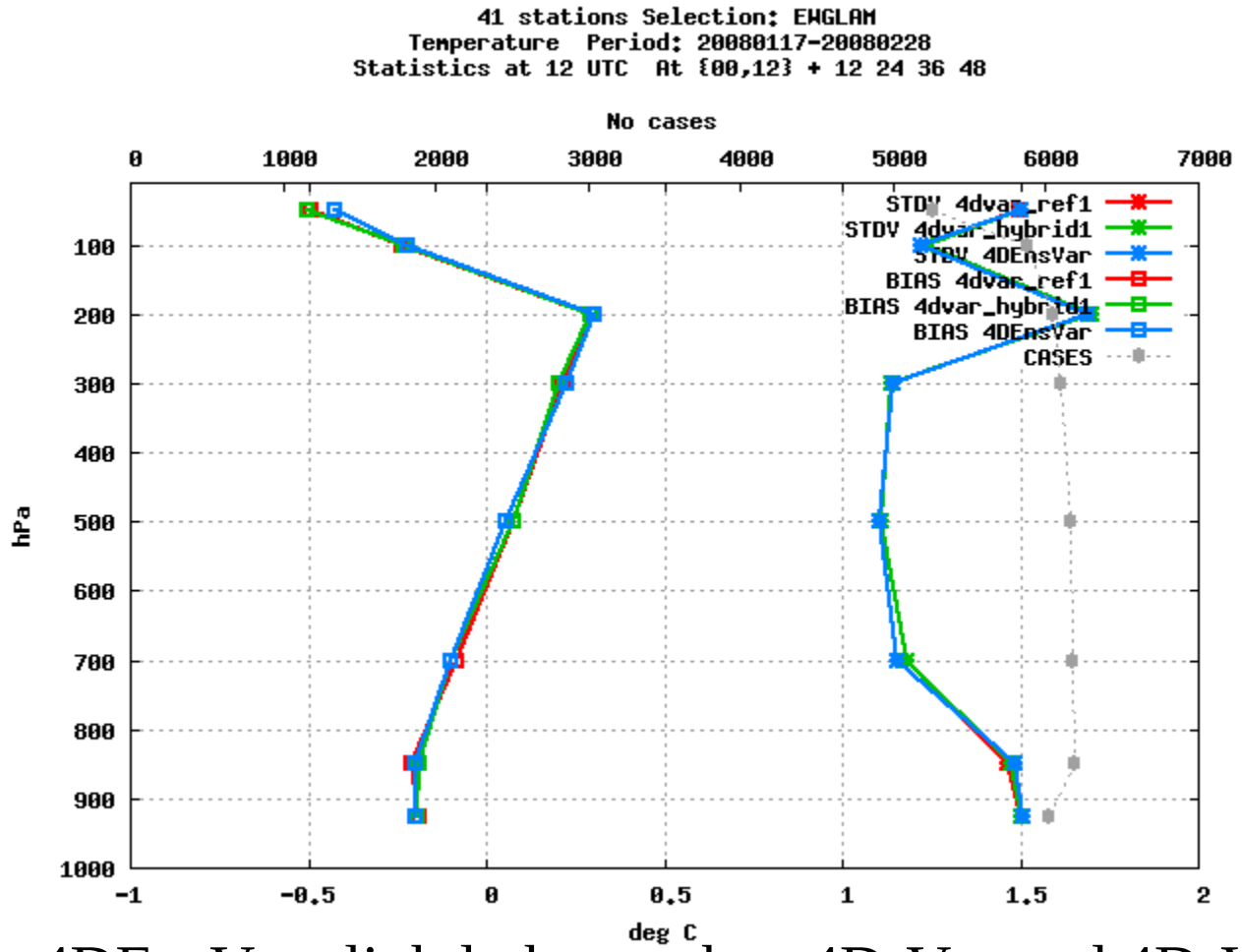
------ 4D-Var, ----- 4D-Var Hybrid, -----4DEnsVar



Comment: 4DEnsVar outperforms 4D-Var and 4D-Var hybrid in the troposphere

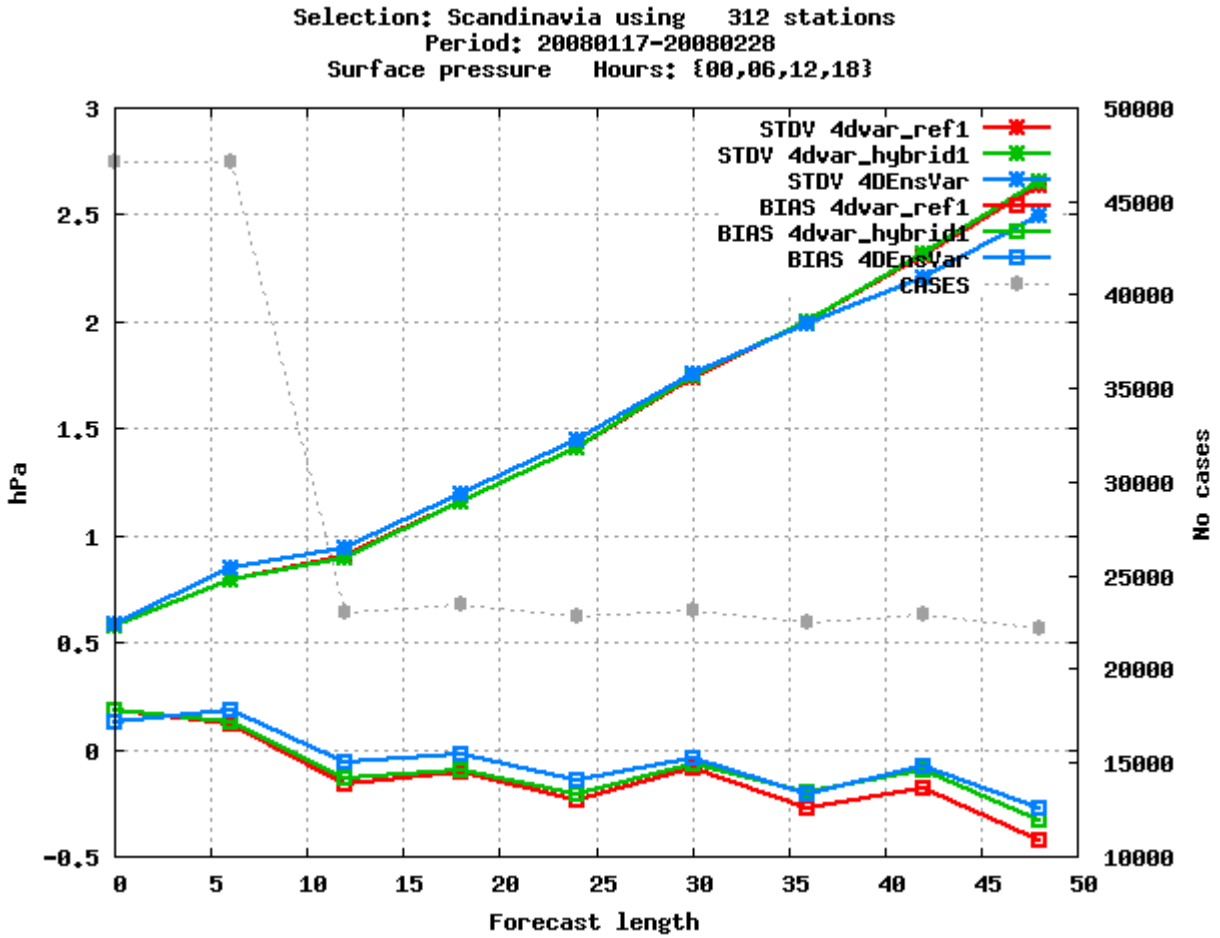
Verification of temperature profiles against EWGLAM radiosonde stations; average over +12h, +24h, +36h and +48h

------ 4D-Var, ----- 4D-Var Hybrid, -----4DEnsVar



Comment: 4DEnsVar slightly better than 4D-Var and 4D-Var hybrid in the mid troposphere

Verification of surface pressure forecasts against Scandinavian SYNOP stations:---- 4D-Var, --- 4D-Var Hybrid, ---4DEnsVar



Comments: - 4D-Var and 4D-Var Hybrid better than 4DEnsVar at very short range. Overfit of hourly observations in 4D-Var??
- 4DEnsVar better at +48 h (3D-Var similar, not shown)

Related problems?

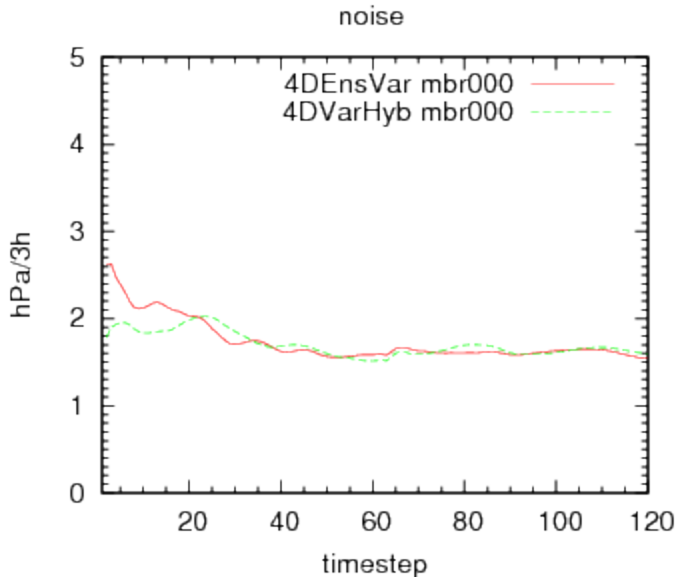
Is noise a potential problem for 4DEnsVar (and ETKF re-scaling)?

- **Incremental DFI is applied in 3D-Var (FGAT) and 3D-Var (FGAT) Hybrid for the control forecast.**
- **A weak digital filter constraint is applied in HIRLAM 4D-Var and HIRLAM 4D-Var Hybrid for the control forecast – no explicit initialization is applied.**
- **Do we need to apply initialization (incremental DFI) after ETKF re-scaling for ensemble members other than the control ?**
- **Do we need to apply initialization after 4D-EnsVar, which is mixture of 3D-Var FGAT increment and localized ETKF non-linear model perturbations ?**

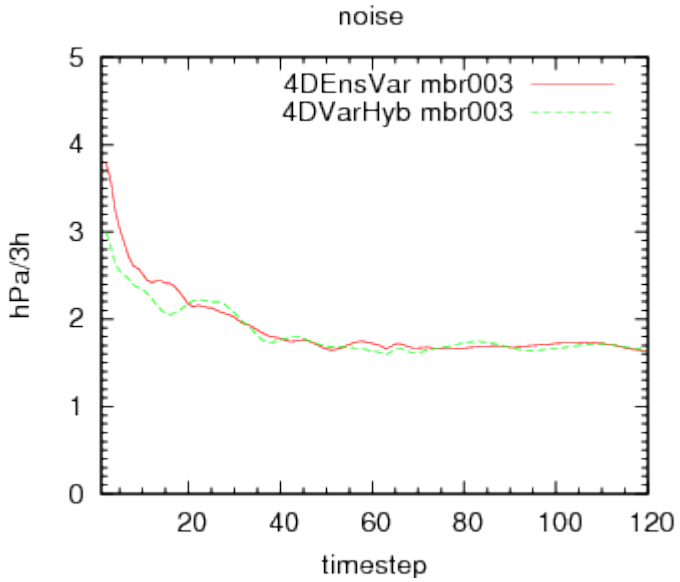
Average absolute surface pressure tendecies (hPa/3h) for forecasts starting from the main observation hour 22 February 2008 12UTC:

-------- 4D-Var Hybrid ------- 4DEnsVar

Member 0 (Control)



Member 3



- 4D-Var Hybrid Control is essentially noise-free

- 4dEnsVar control has a slightly incresed noise level

- Noise based on 4DEnsVar control increments and ETKF re-scaling of ensemble perturbations adds up

Examle of analysis fit to observations over the assimilation time window (22 Feb 2008 12UTC)

	4dvarhyb	4densvar
Window 1 (-3h)		
RTM	244 (3390)	309 (3760)
fis	306 (1940)	404 (1938)
Window 2 (-2h)		
RTM	318 (2350)	300 (2635)
fis	184 (1318)	311 (1317)
Window 3 (-1h)		
RTM	141 (710)	98 (735)
fis	190 (1312)	289 (1305)
Window 4 (0h)		
RTM	383 (3685)	344 (3780)
fis	398 (2054)	403 (2059)
Window 5 (+1h)		
RTM	637 (5080)	655 (5520)
fis	250 (1313)	371 (1311)
Window 6 (+2h)		
RTM	360 (3530)	289 (3560)
fis	252 (1277)	438 (1273)

Remarks: Fit to observations over the assimilation time window (22 Feb 2008 12UTC)

- The 4D-Var hybrid surface pressure analysis fits observations much tighter than the 4DEnsVar analysis for all observation windows except in the middle of the assimilation window. This is (probably) a matter of tuning the weight of the 3D-Var FGAT background constraint !
- The 4DEnsVar analysis seems to fit AMSU data better than the 4D-Var Hybrid analysis. Why?

IO and memory are problems!

486 x 378 x 40 gridpoints; 10 km resolution; 30 km increments; 32 processors IBM-ECMWF

- Total time 536 s.
- GRIB input 255 s. (includes reading of 120 ensemble member model states in GRIB)
- GRIB output 90 s.
- CMA input/output 42 s.
- Create low resolution ens. perturbations 54 s.

  (includes reading of 120 models states from distributed direct access files)
- Minimization calculations 80 s.

Issues – short term

- Resolution of increments ? 2 ds, 3 ds, 4 ds and 6 ds have been tested. Improved algorithm för change of resolution?
- Vertical localization (2-3 vertical modes?)
- Contribute to the IFS OOPS framework such that Hybrid, ETKF and 4DEnsVar can be included.
- Need and weight for the climatological B term?
- Outer loops (re-linearization for observation operators)
- Iitialization

Issues – long term

- Can 4DEnsVar be applied successfully with one resolution for the control (e.g. 2.5 km) and a coarser resolution for the ensemble (e.g. 5 km) ?
- More efficient IO is needed and possibly also packing of the ensemble perturbations in memory.!
- Weak constraint 4DEnsVar – correlation in time for the localization weights?