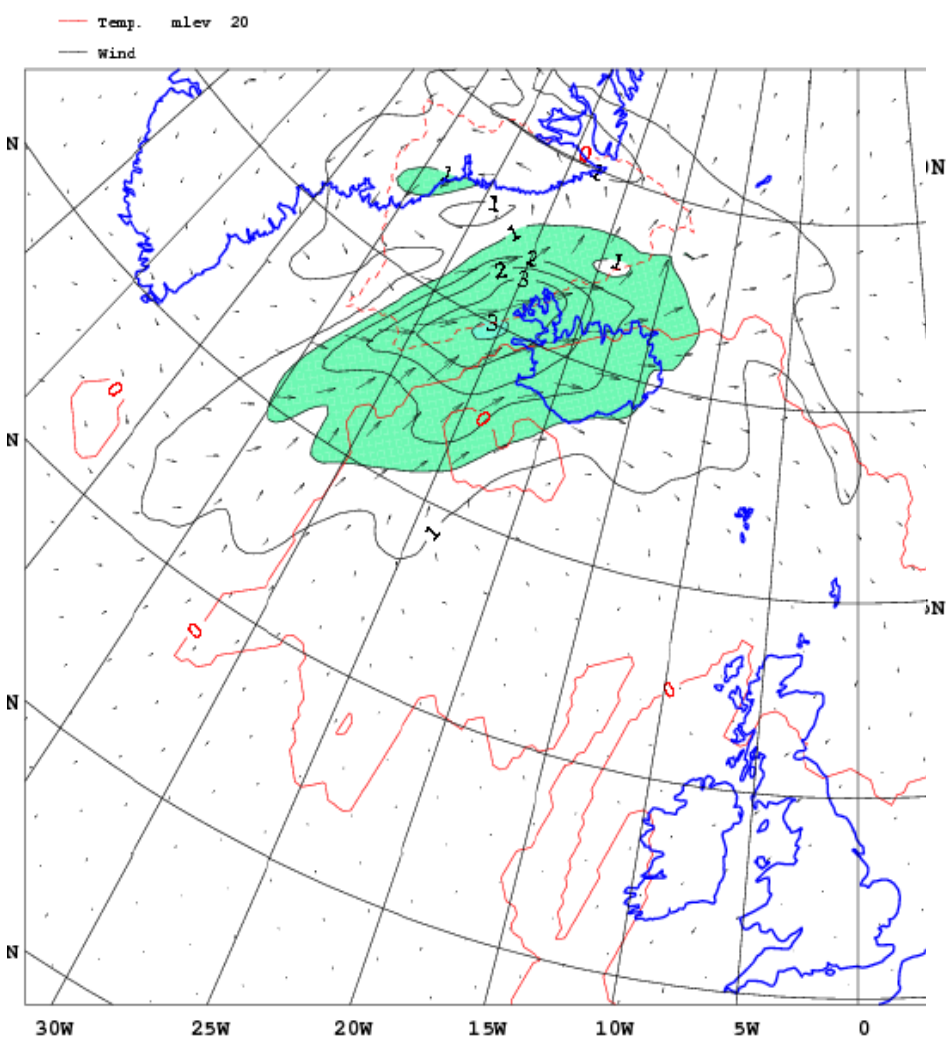
Sensitivity of hybrid variational ensemble data assimilation to the ensemble generation

Nils Gustafsson SMHI
and
Jelena Bojarova met.no

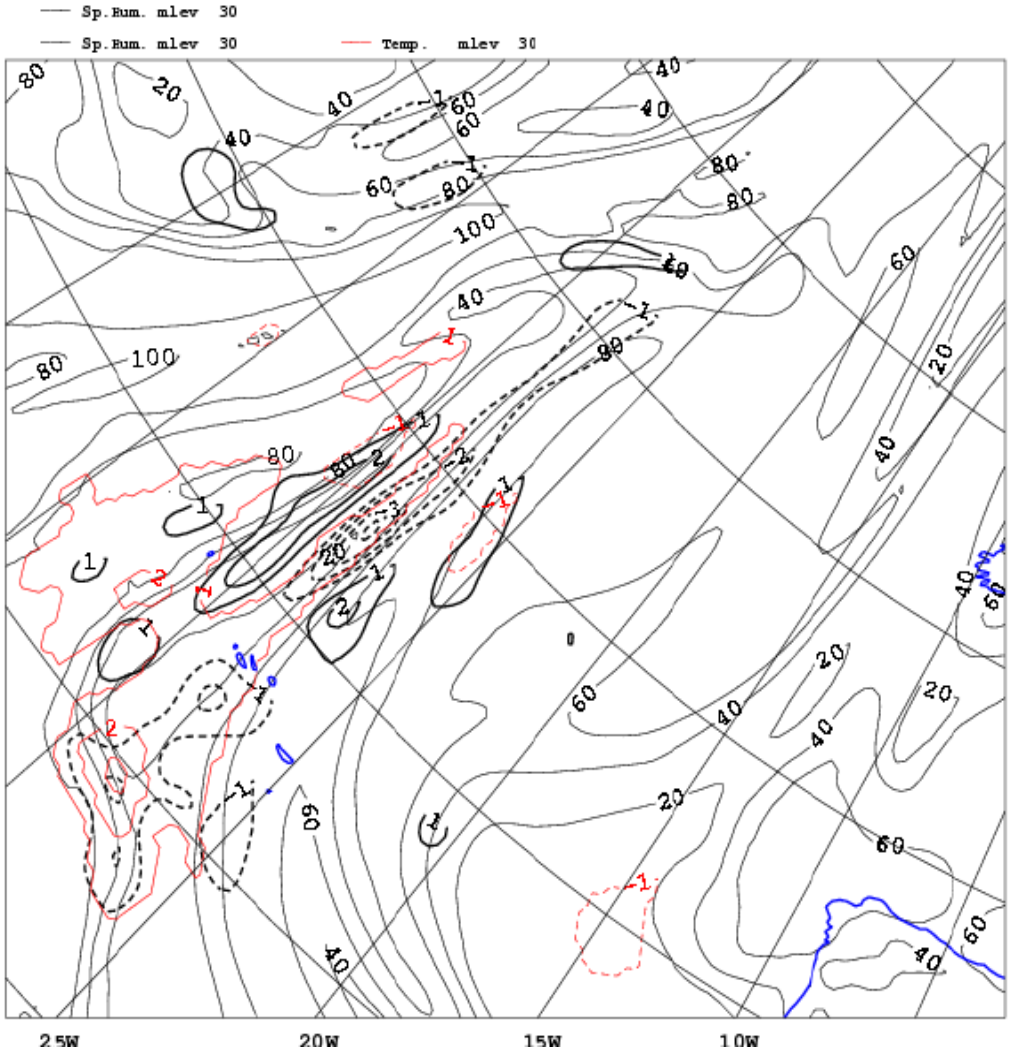
Motivation 1:
Flow-dependent background error statistics

Single observation experiments

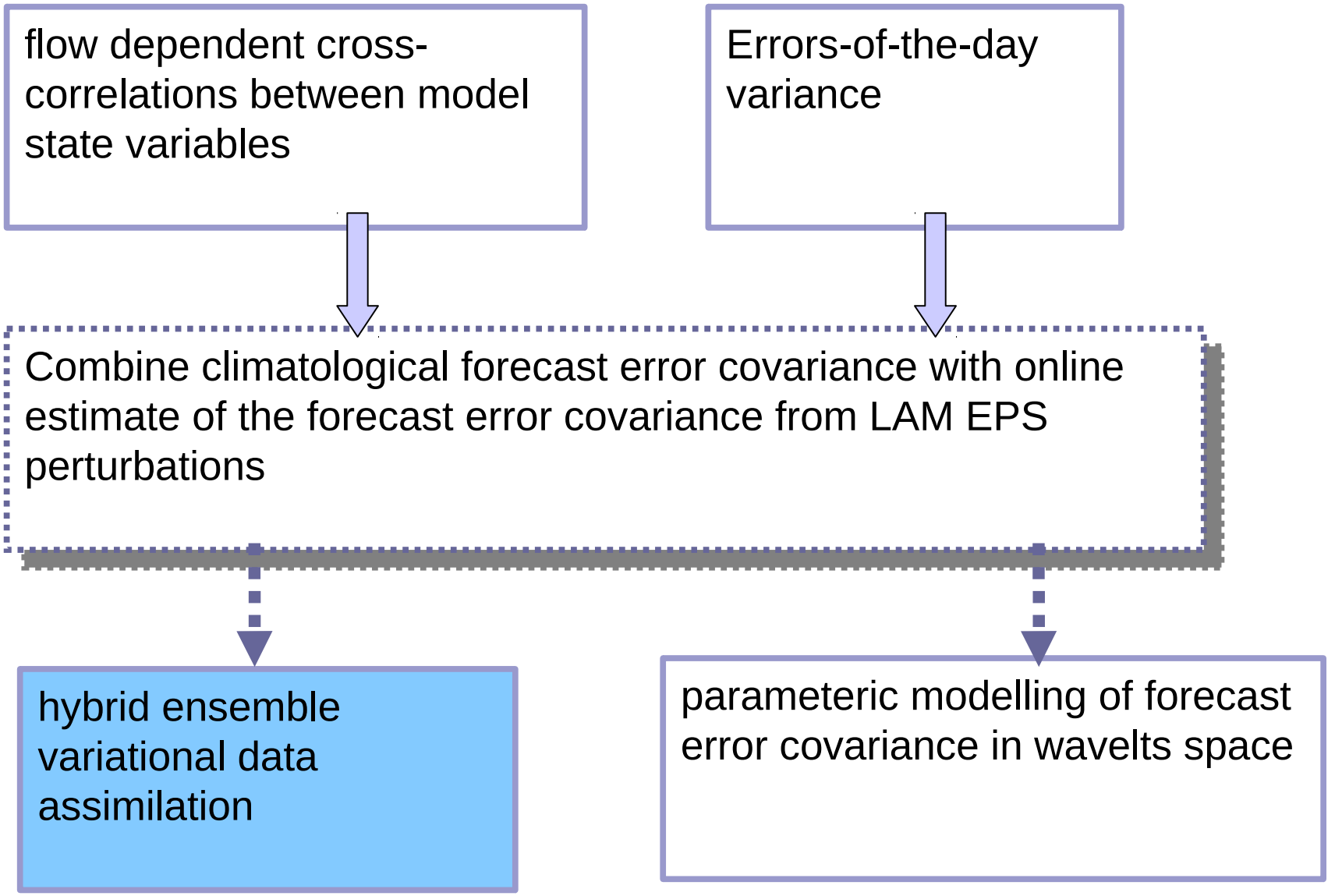
Wind increment (65N,25W)
300 hPa



Temperature increment
(40N,30W) 850 hPa



Motivation 2:
Merging EPS&DA...



HIRLAM variational data assimilation (HIRVDA)

- LAM 3D-Var & 4D-Var
- Background error constraint in spectral space (Berre, 2000)
- B based on the NMC-method or ensemble assimilations
- FGAT in 3D-Var
- TL and AD model based on spectral version of HIRLAM
- Very simple TL and AD physics
- Weak digital filter constraint in 4D-Var, incremental digital filter initialization with 3D-Var
- Applied at model resolutions 5-20 km
- 6 hour assimilation window

HIRLAM first approach to use ensembles in 3D-Var and 4D-Var

- **Use the ETKF algorithm for re-scaling of a 6h forecast ensemble to an analysis ensemble (estimation of the analysis error covariance).**
- **Use ensemble of 3h (4D-Var) or 6h (3D-Var) forecasts to estimate the background error covariance and blend it with the static background error covariance.**
- **Lateral boundary conditions in the first version are based on Euro-TEPS (later on ECMWP EPS based on EDA).**

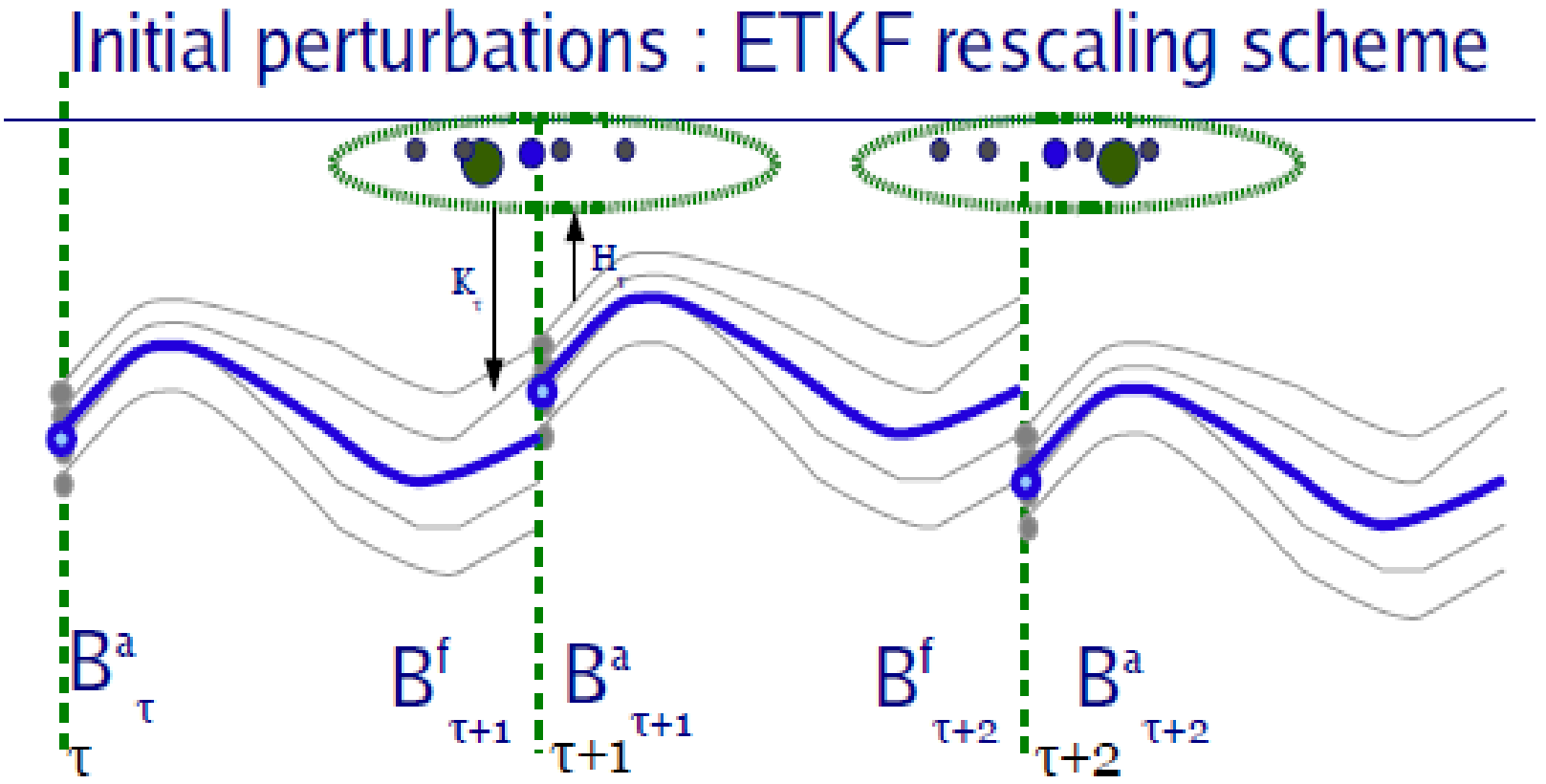
ETKF based rescaling of perturbations: properties

- The ETKF perturbation resembles structures of the analysis error covariance
- The ETKF based perturbations samples leading eigenvectors

$$B^a = R^{-1/2} H E[(X_\tau - E(X_\tau))(X_\tau - E(X_\tau))^T] H^T R^{-1/2}$$

- The ETKF based rescaling scheme can be viewed as Generalized Breeding
- A matrix of ensemble size is constructed to downscale the perturbations
- Both quality and density of observation network is used to construct the matrix
- Both adaptive multiplicative and additative inflation (from the B matrix) are applied

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



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

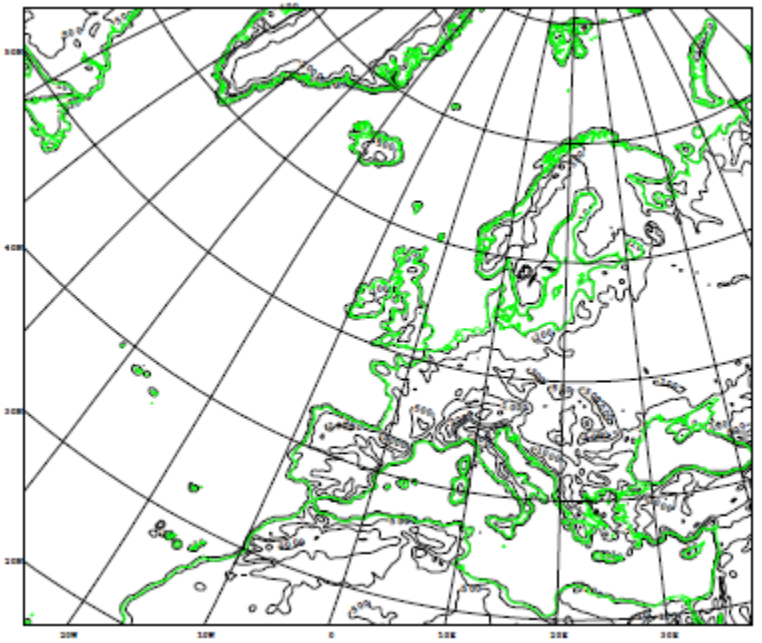
$$\delta x = \delta x_{3D-Var} + \sum_{k=1}^{K} (\alpha_k \circ \delta x_k^{ens})$$

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.

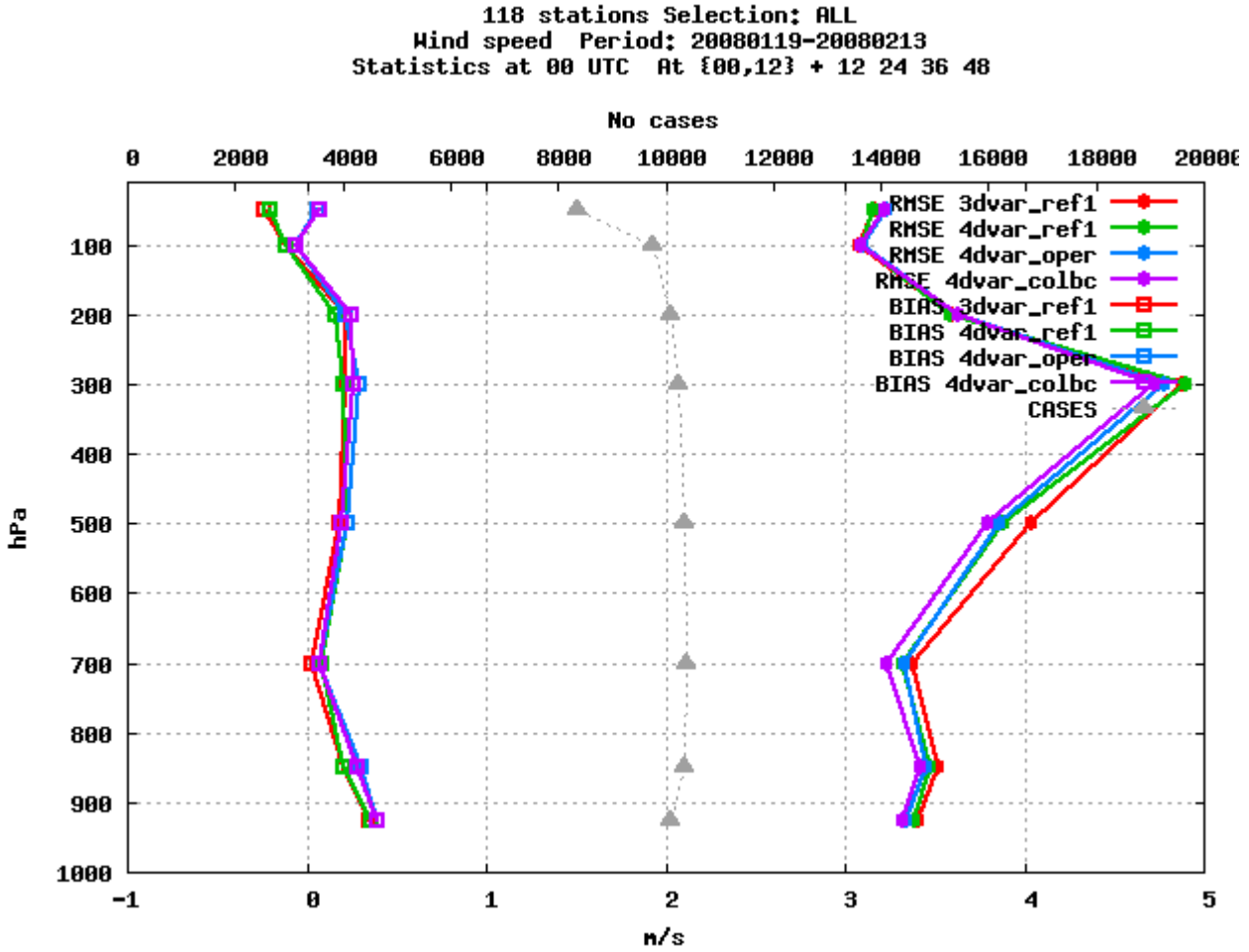
Experiments over 17 January – 29 February 2008

3dvar_ref1	3D-Var, no ensemble constraint.
3Dvar_hybrid1	3D-Var Hybrid, $\beta_{var} = 2$ (50% ensemble, 50% static cov.), Ensemble perturbations inflated by a factor 2 in Hybrid.
4dvar_ref1	4D-Var, no ensemble constraint.
4dvar_oper	4D-Var, no ensemble constraint. Lateral boundary conditions from a deterministic ECMWF operational forecast based on 6 h earlier initial data.
4dvar_colbc	as 4dvar_oper but with control of of lateral boundary conditions at start of assimilation window
4dvar_hybrid1	4D-Var Hybrid, $\beta_{var} = 4$ (25% ensemble, 75% static cov.), Ensemble perturbations inflated by a factor 4 in Hybrid.
4dvar_hybrid2	4D-Var Hybrid, $\beta_{var} = 4$ (25% ensemble, 75% static cov.), Ensemble perturbations inflated by a factor 4 in Hybrid, Ensemble perturbations for Hybrid complemented with perturbations with a +2 h lagged valid time.
EDA_hybrid1	3D-Var, , $\beta_{var} = 2$ (50% ensemble, 50% static cov.). Generation of ensemble perturbations through an ensemble of 3D-Var assimilations with perturbed observations. Ensemble perturbations inflated by a factor 2 in Hybrid.



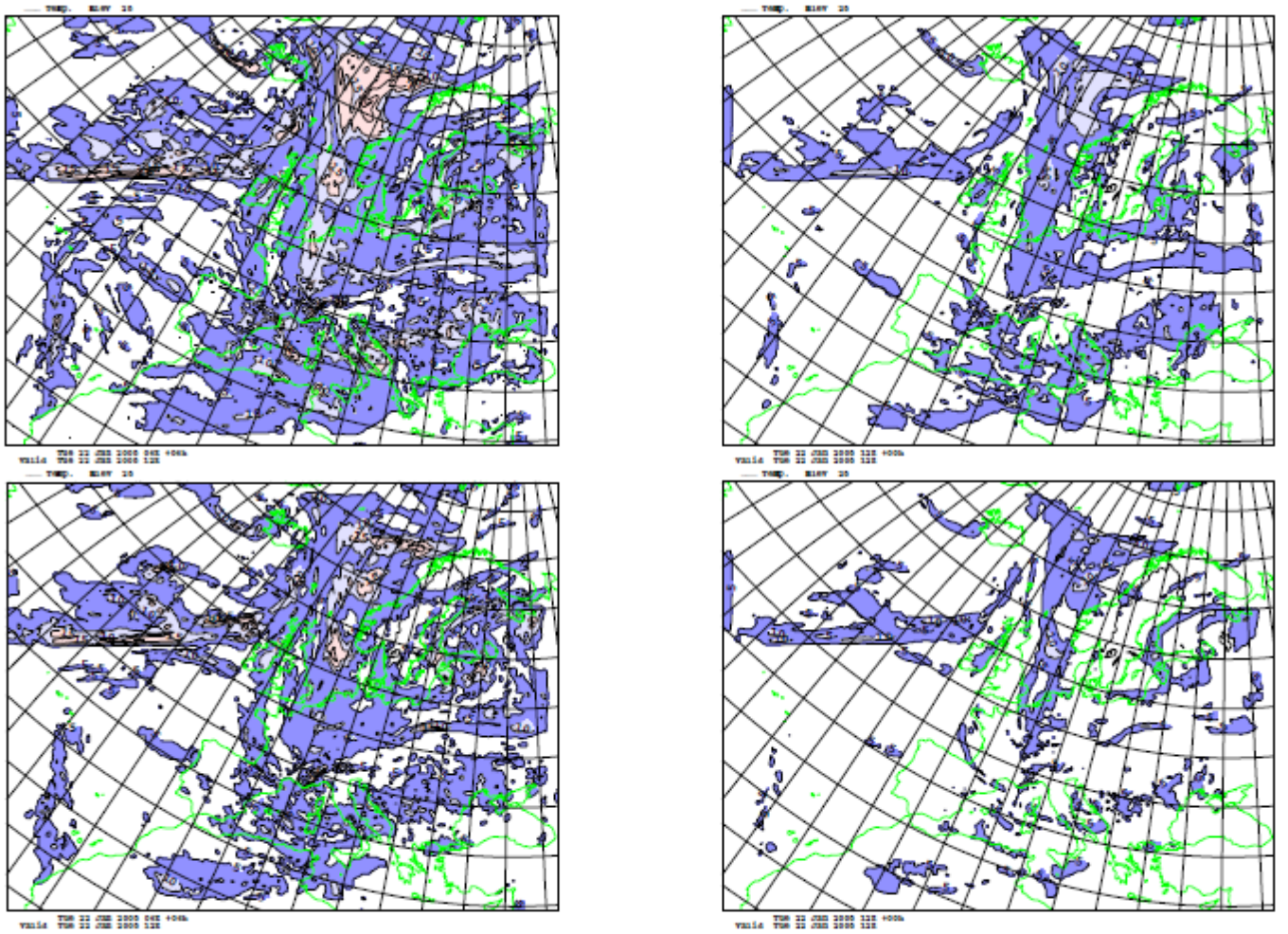
Model grid res. 11 km
40 levels
20 members

Verification of wind speed forecast with different treatment of lateral boundary conditions



----- 3D-Var with EuroTEPS Control LBC; --------- 4D-Var with EuroTEPS CONTROL LBC
----- 4D-Var with ECMWF high res. LBC;
------4D-Var with ECMWF high res. LBC + control of LBC at start od assimilation window

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

Examples of assimilation increments

Standard 3D-Var

3D-Var hybrid

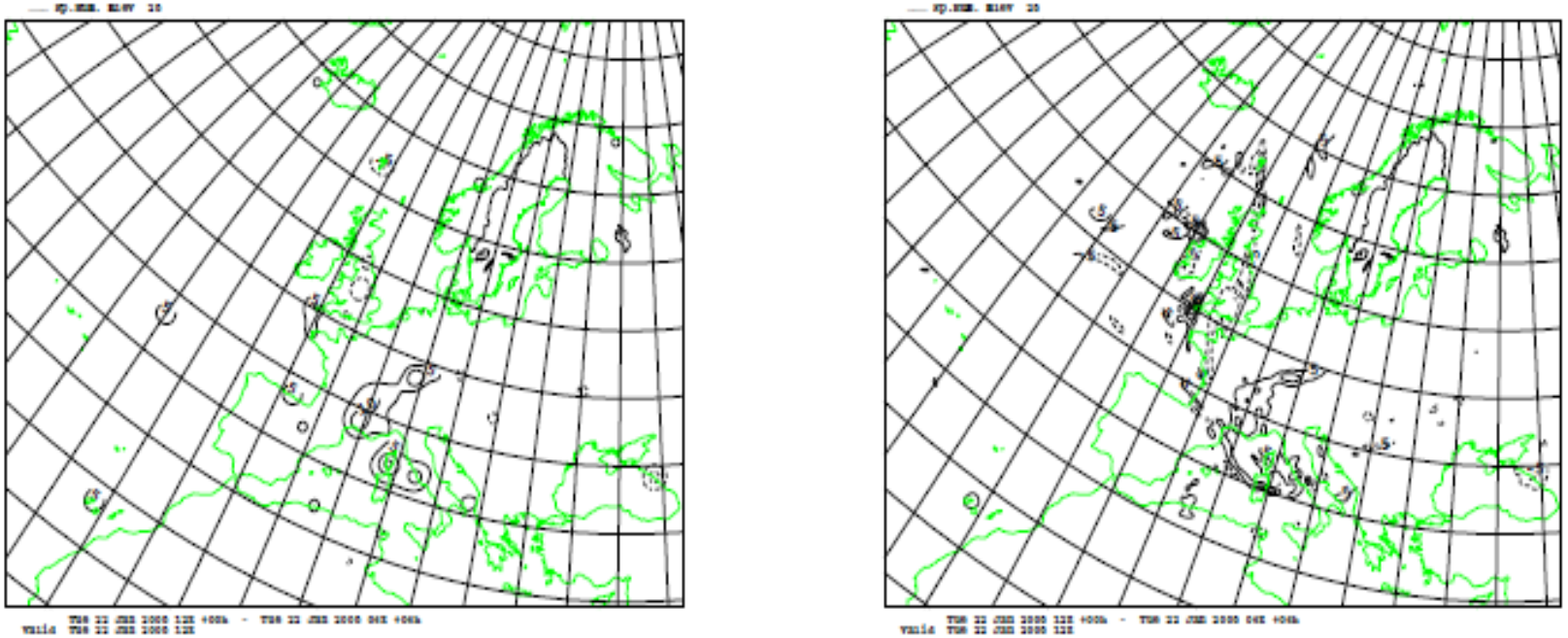
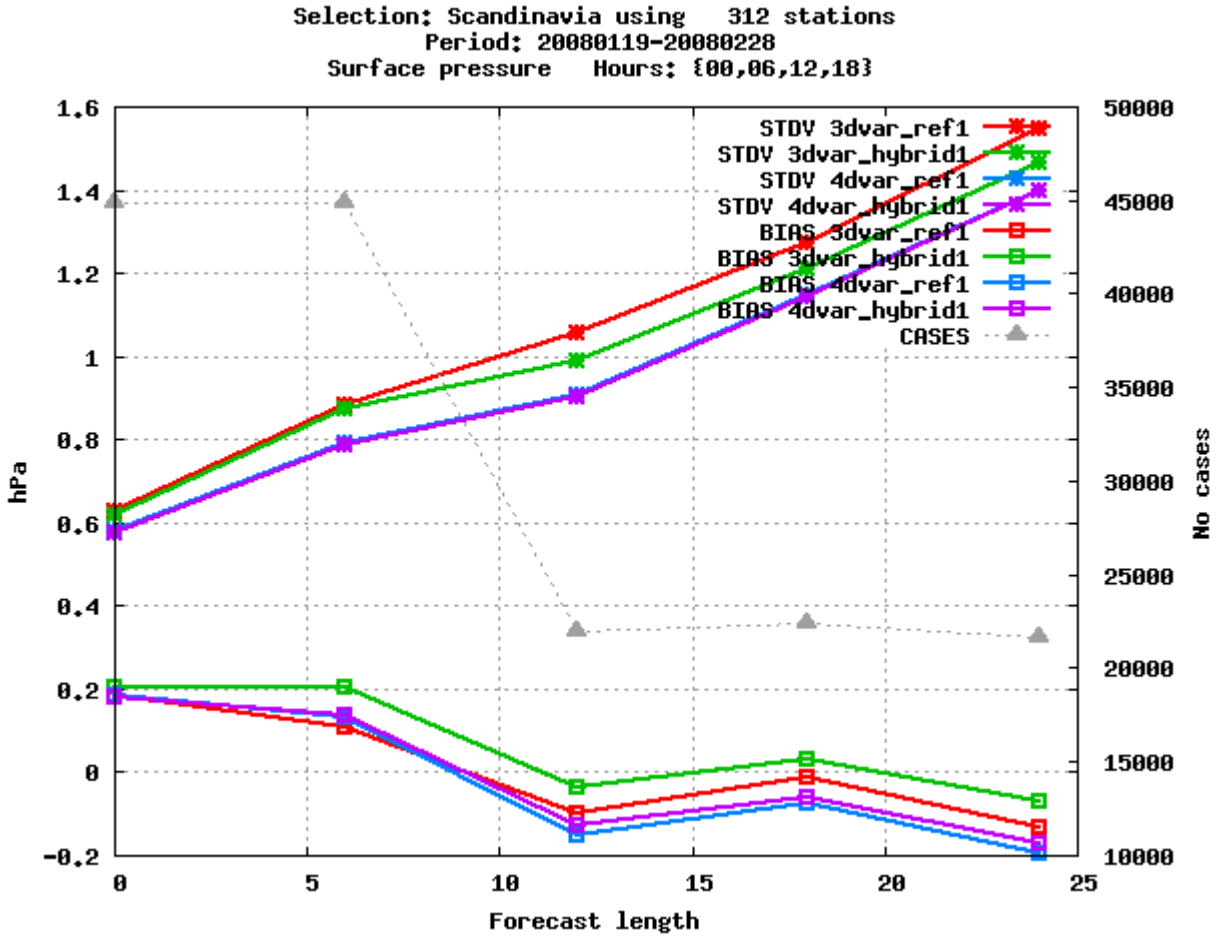


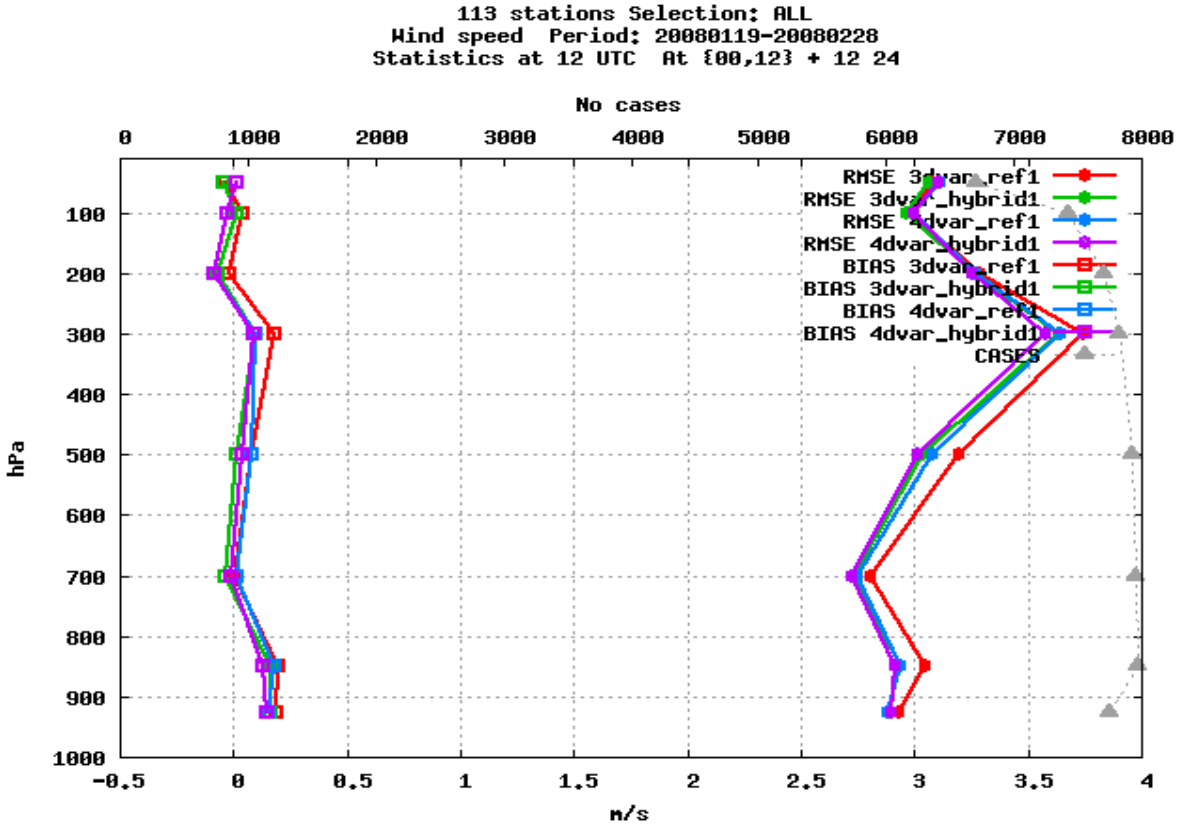
Figure 13. Specific humidity assimialtion increment at model level 30 with 3D-Var (left) and with 3D-Var Hybrid (right). 22 January 2008 12 UTC

Hybrid impact on forecast verification scores – mean sea level pressure



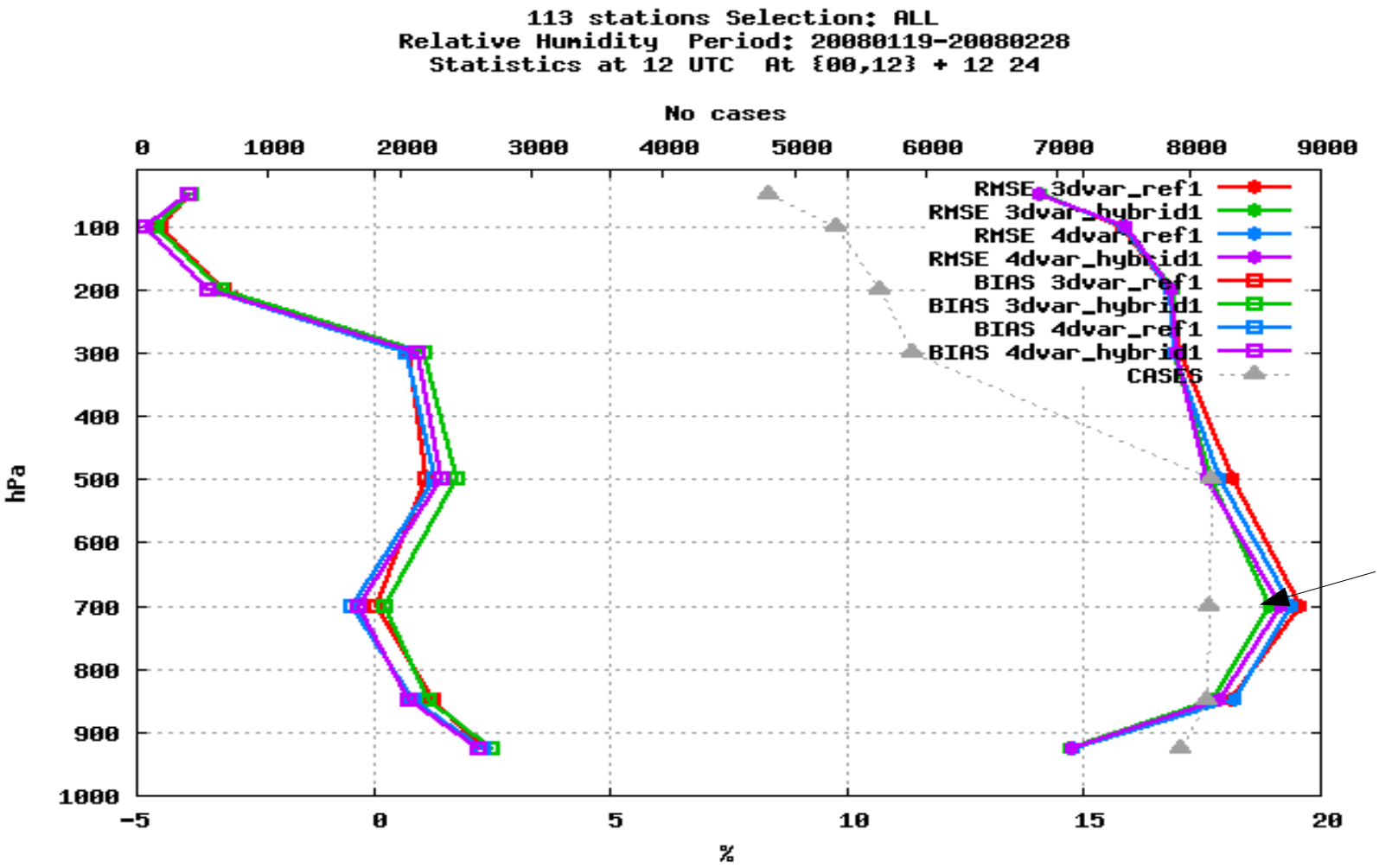
---- 3D-Var; **---- 3D-Var hybrid; ---- 4D-Var; ---- 4D-Var hybrid**

Hybrid impact on forecast verification scores – wind speed profiles



---- 3D-Var; **---- 3D-Var hybrid; ---- 4D-Var; ---- 4D-Var hybrid**

Hybrid impact on forecast verification scores – relative humidity profiles

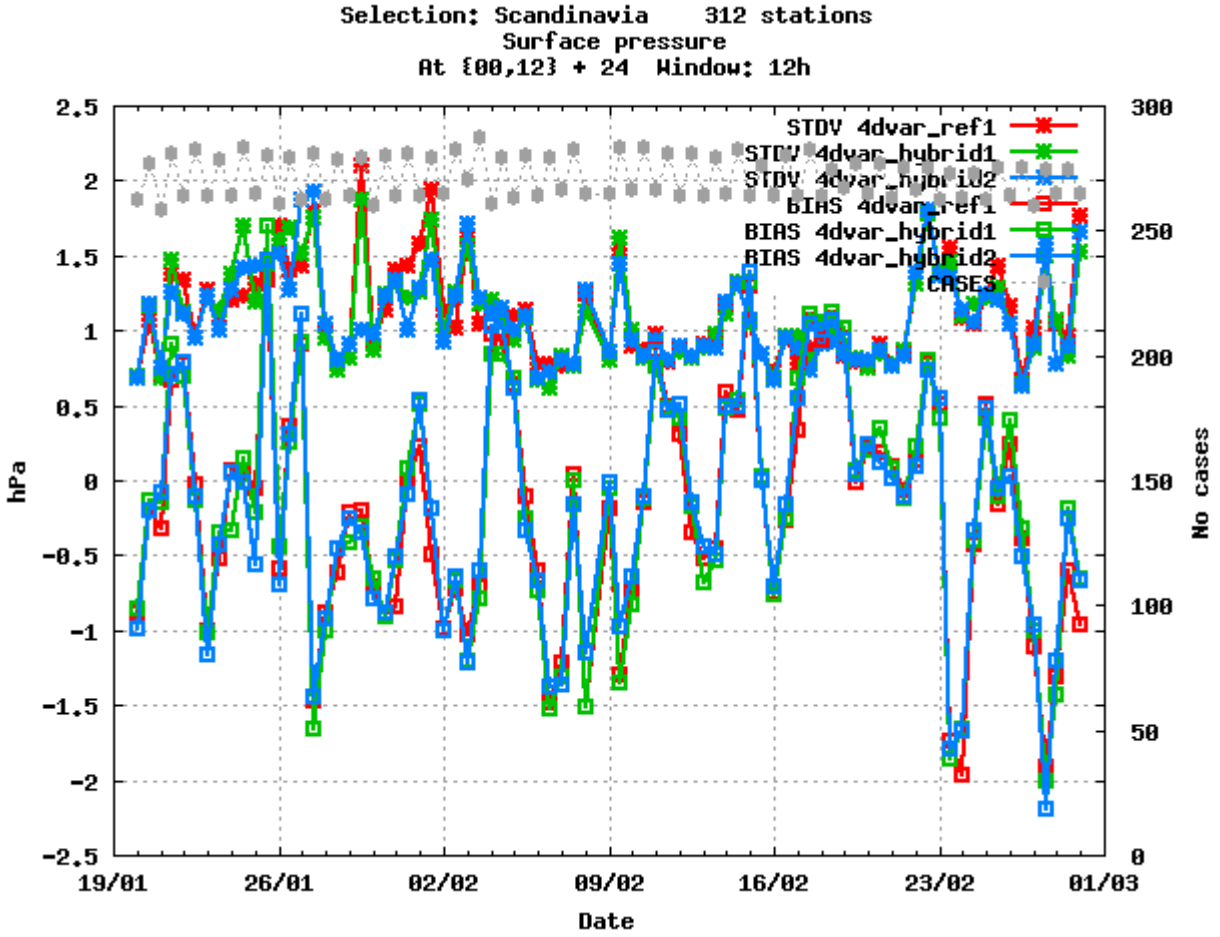


Note large impact of 3D-Var hybrid!

---- 3D-Var; ---- 3D-Var hybrid; ---- 4D-Var; ---- 4D-Var hybrid

“Correcting phase errors”

4dvar_hyb1: the 4DVAR hybrid (ETKF with 20 members)
4dvar_hyb2: the 4DVAR hybrid (ETKF with 40 members:
20 members: fc20080122_06+003
20 members: fc20080122_06+005)



Example of surface pressure forcast differences with and without the lagged valid time ensemble applied in the 4D-Var hybrid assimilation

+12h

+24h

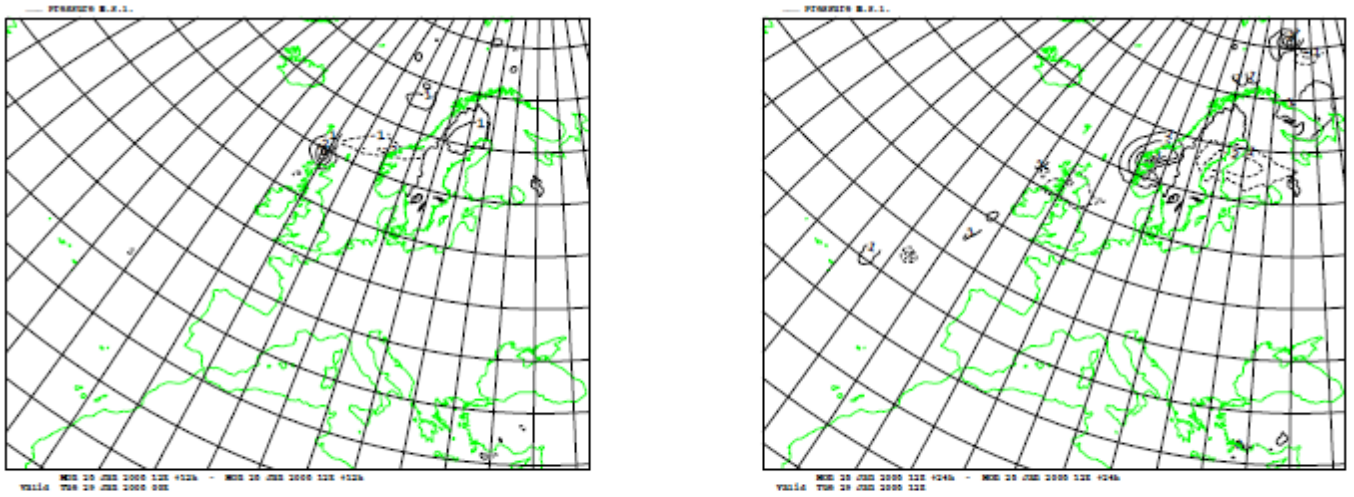


Figure 17. Differences between mean sea level pressure forecasts from the 4*dvar_hybrid*1 and the 4*dvar_hybrid*2 experiments. 27 January 2008 +12h (left) and +24h (right). The difference between the two experiments is that 4*dvar_hybrid*2 uses an additional valid time lagged (+2h) ensemble in the 4D-Var hybrid ensemble covariance.

EnsDA estimation of analysis uncertainty

1) ***Perturb*** observations $N(0, \sigma_o)$

2) ***Assimilate*** perturbed obs. around perturbed background

3) ***Assimilate*** unperturbed obs. around control

4) ***Calculate*** multiplicative inflation α to account for the model errors

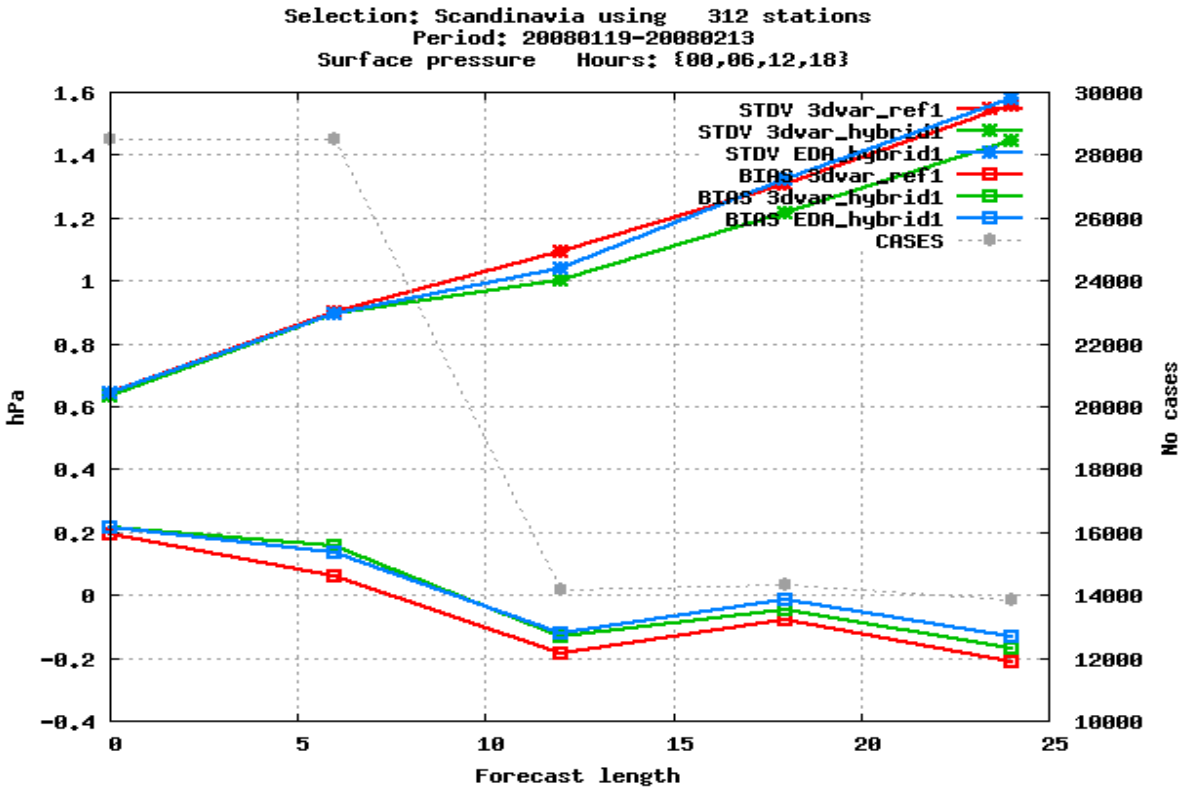
5) ***Analysis perturbation***:

(perturbed analysis-unperturbed analysis) x α

6) ***The consistency*** between the spread of 6h forecast length ensemble perturbations and the observation innovations is used to determine the inflation α

Which ensemble generation technique is better?

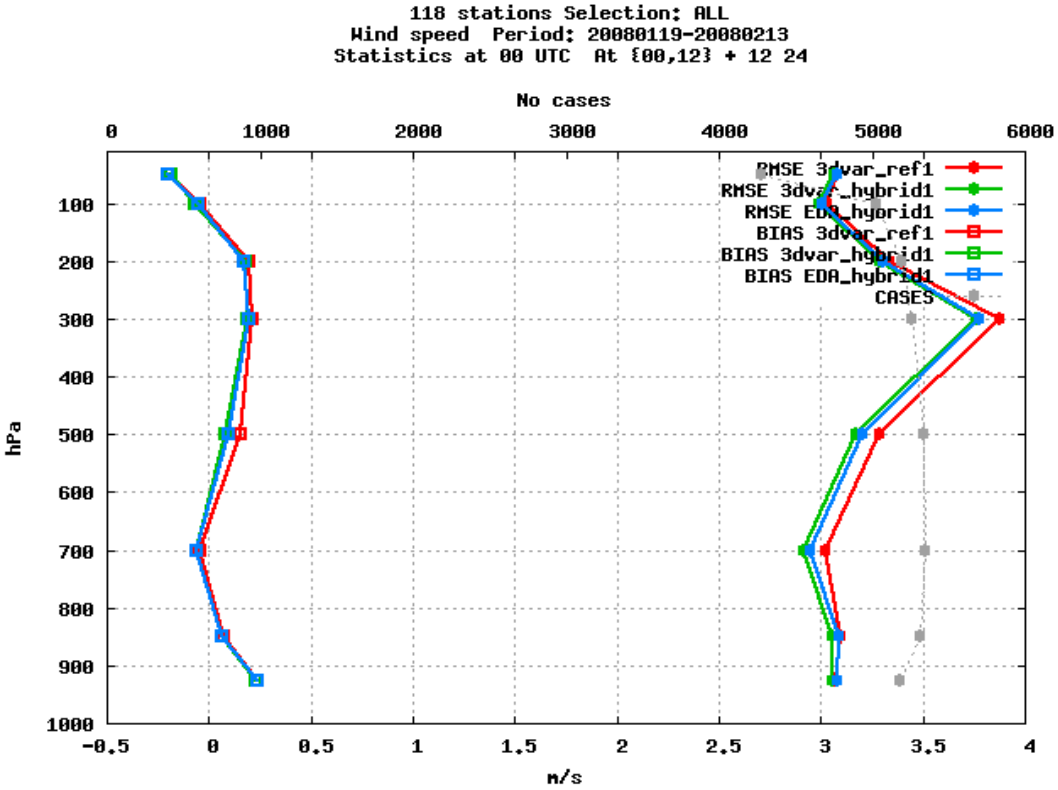
ETKF or EnsDA

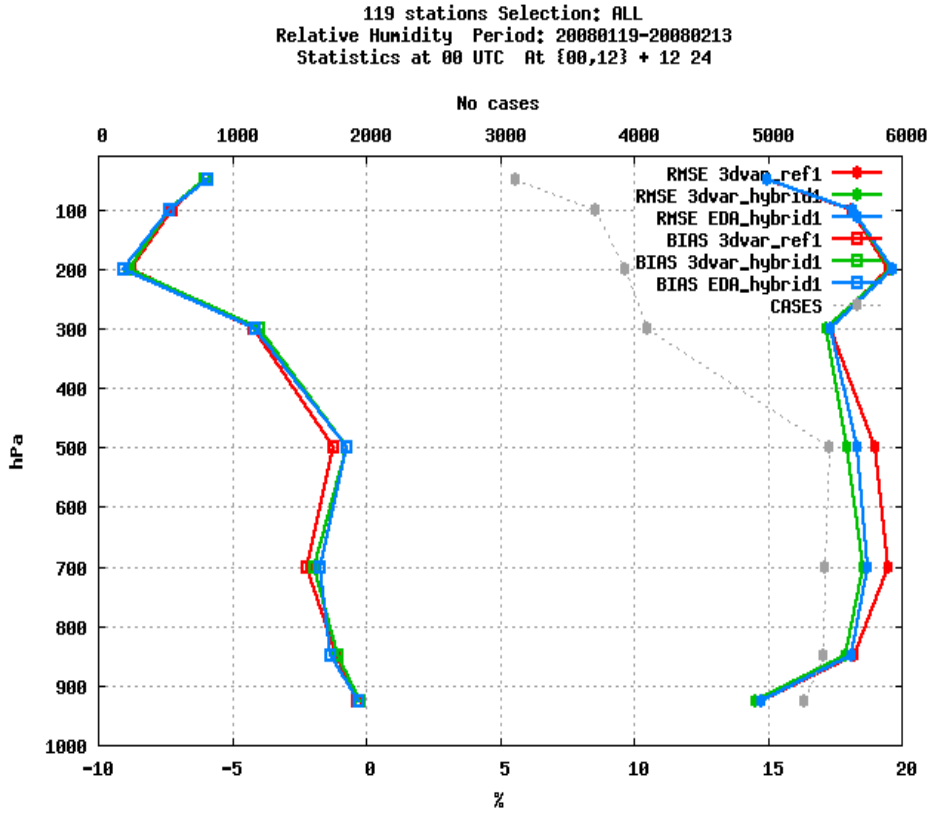


3DVAR-ETKF outperforms both ***3DVAR*** and ***3DVAR_EDA***

Dynamically consistent structures are important

EDA or ETKF perturbations – verification of upper air profiles



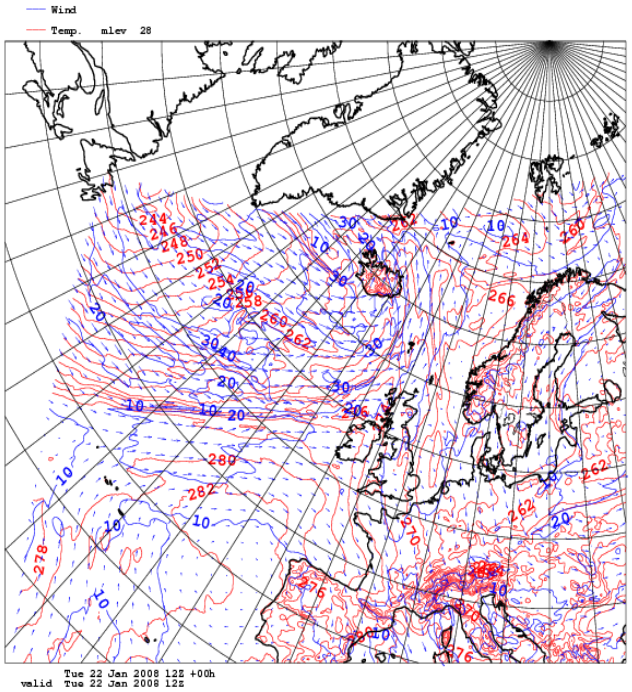


---- 3D-Var

---- 3D-Var EDA hybrid

---- 3D-Var ETKF hybrid

EnsDA: analysis at 22 Jan 2008 12 UTC & mbr005



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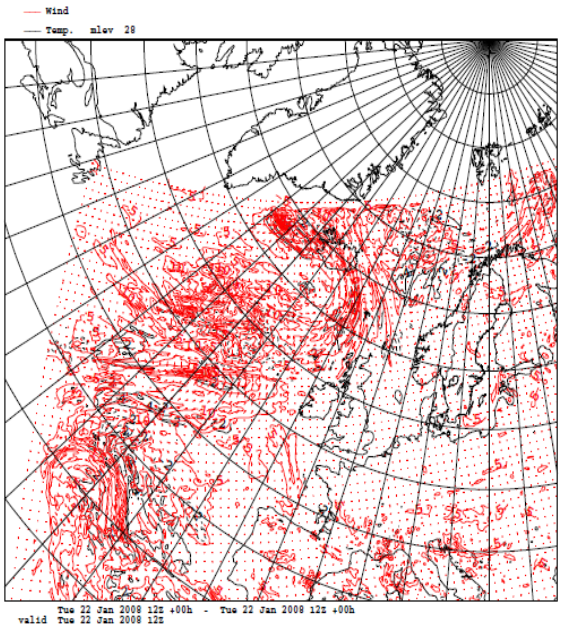

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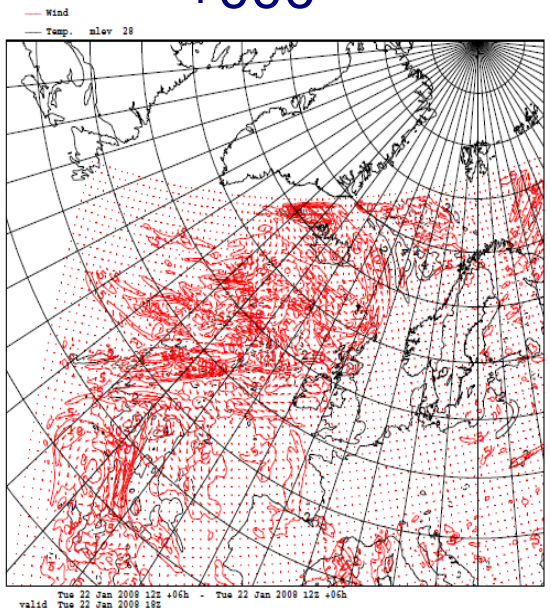

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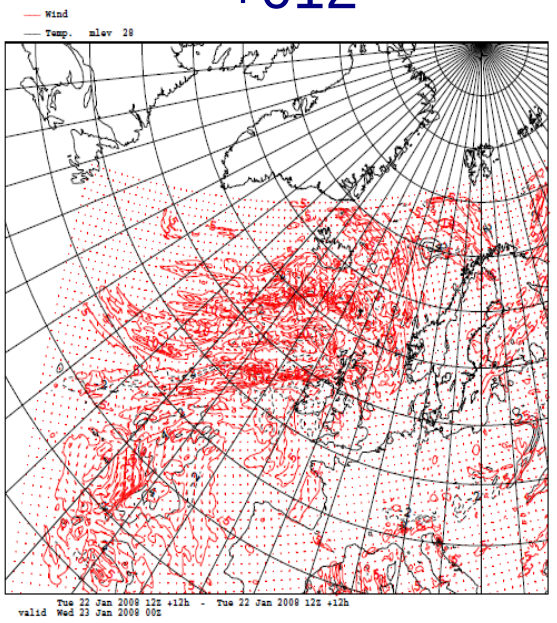

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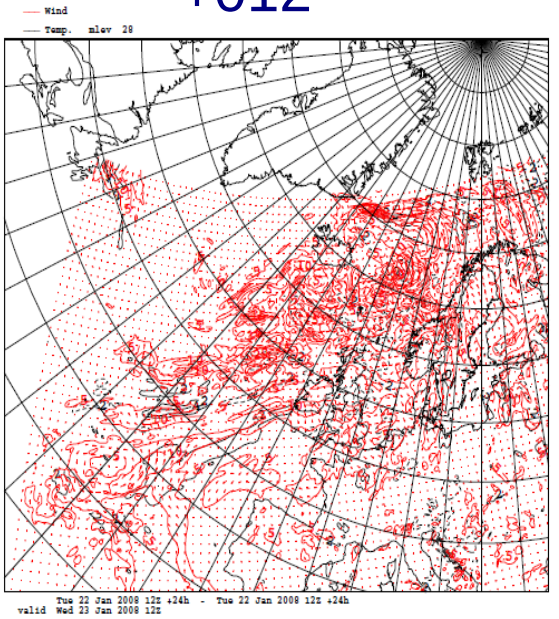
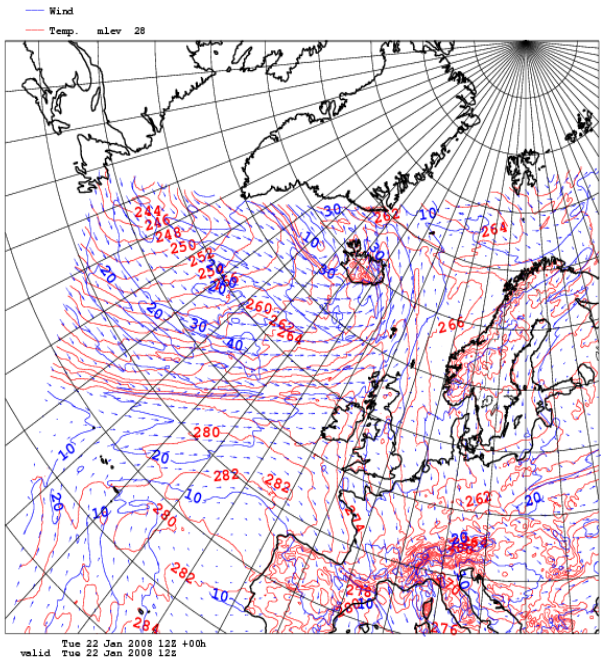


ETKF: analysis at 22 Jan 2008 12 UTC & mbr005



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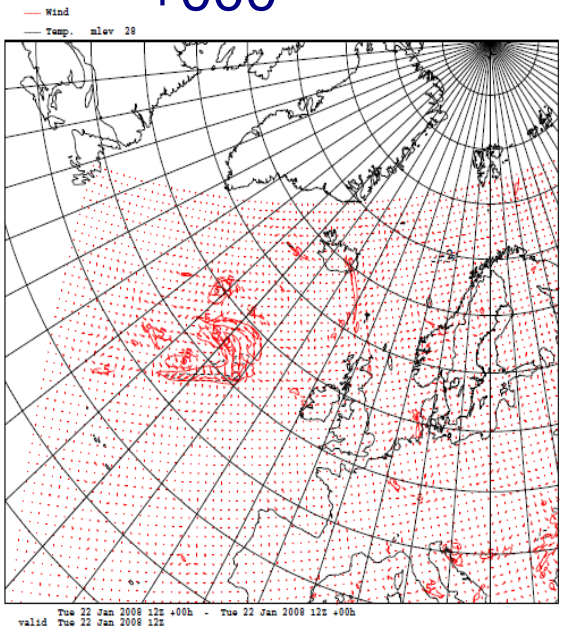

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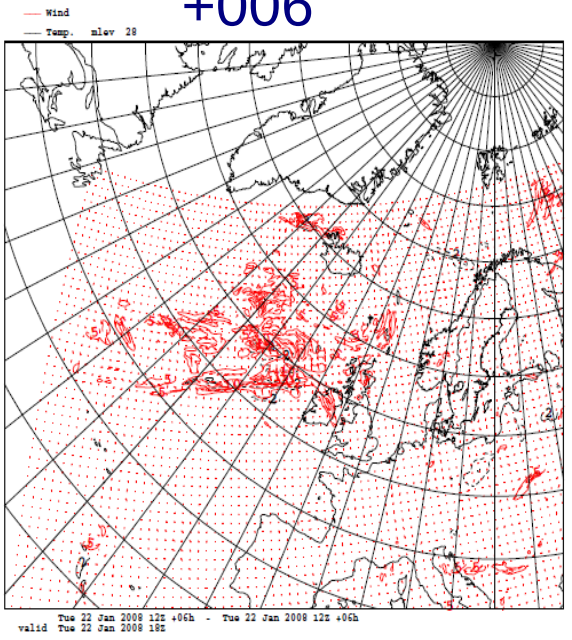

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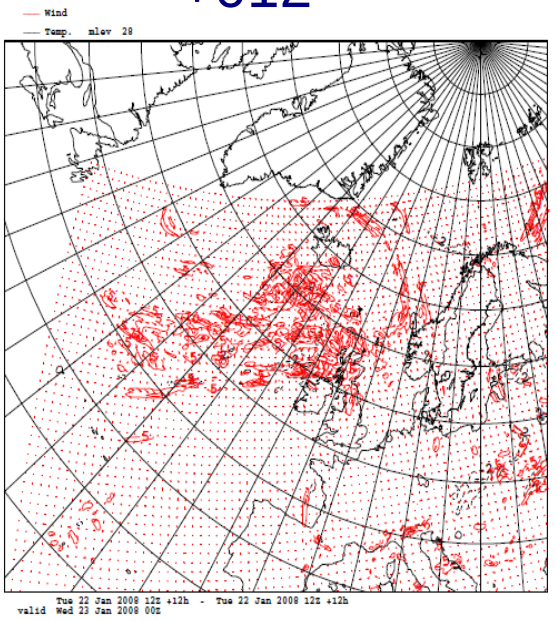

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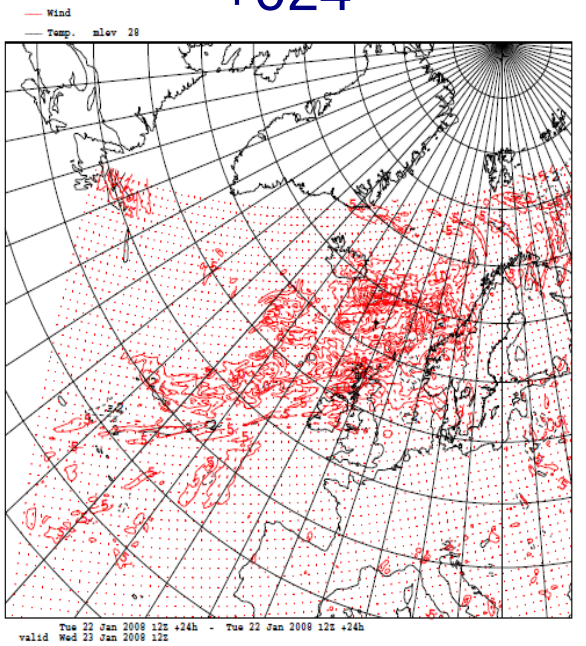
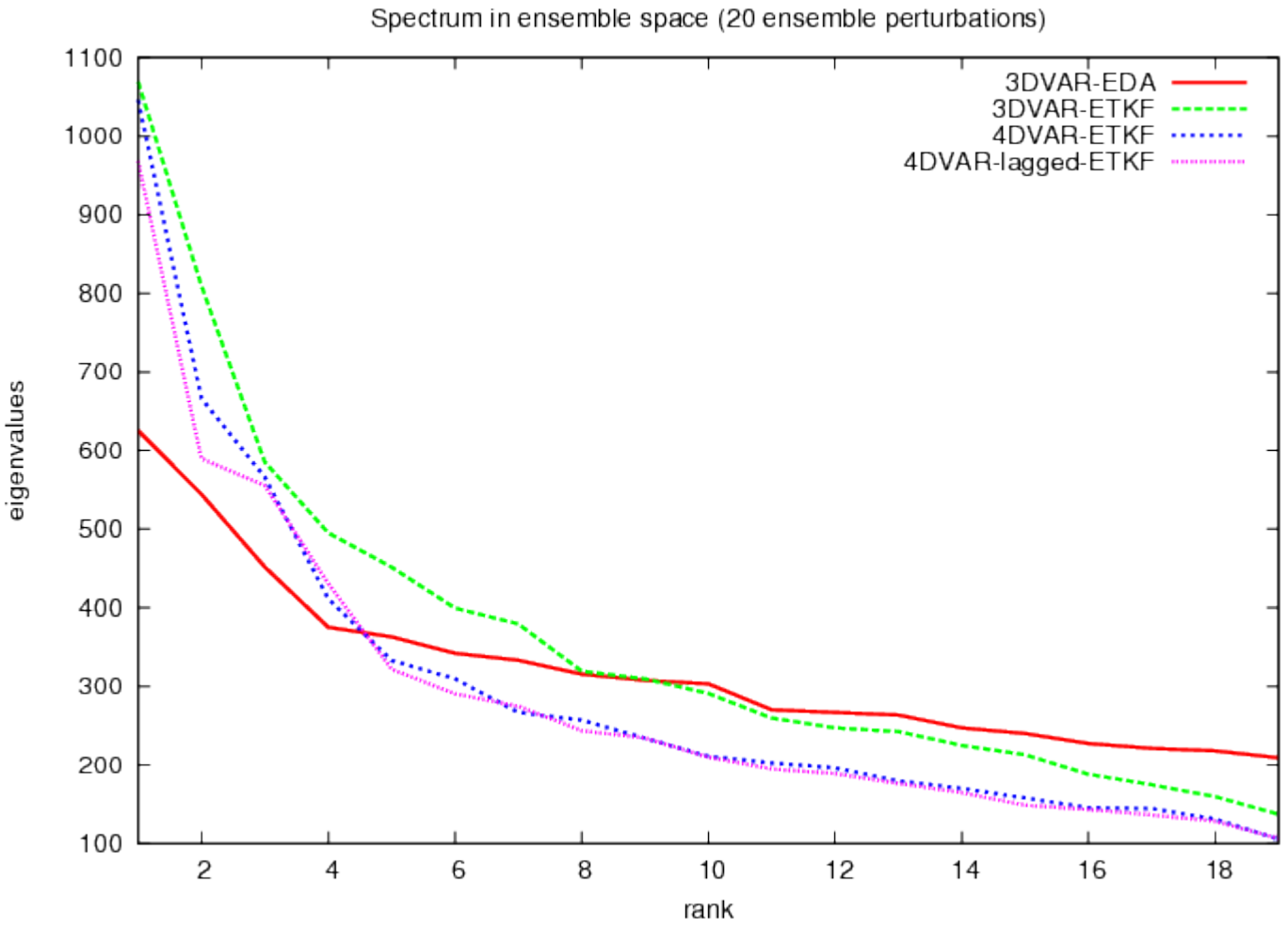
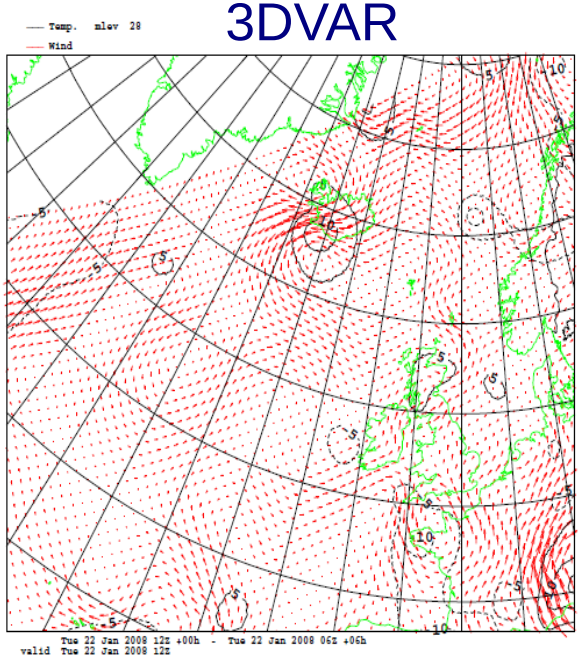


Spectra in ensemble space of different ensemble perturbations (22 January 2008 06UTC +06h)

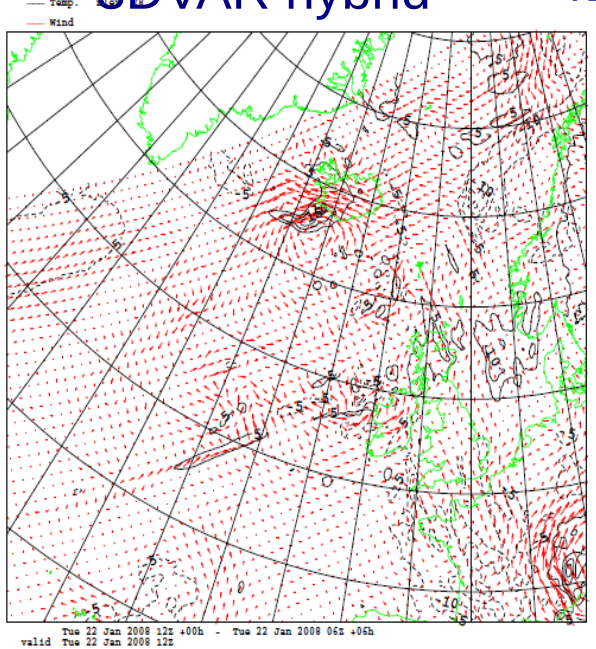


Analysis increment along front

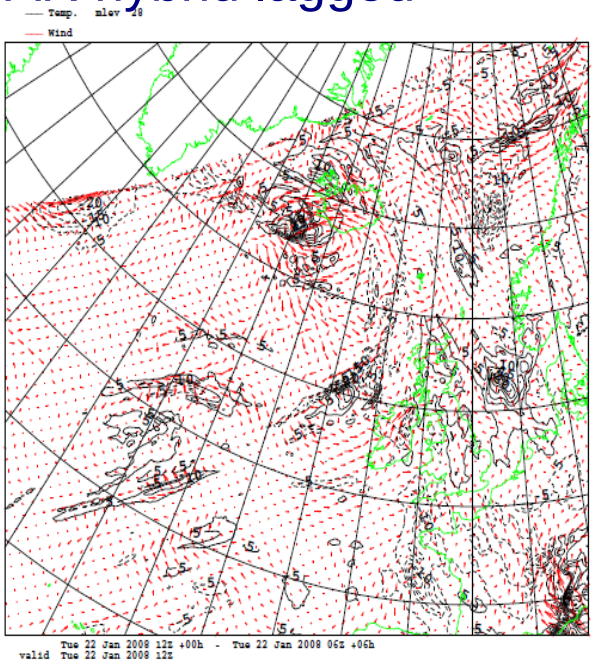
3DVAR



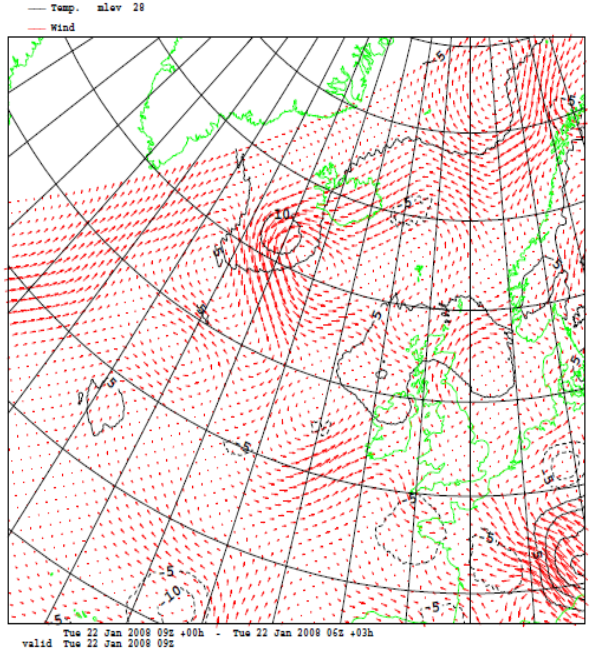
3DVAR hybrid



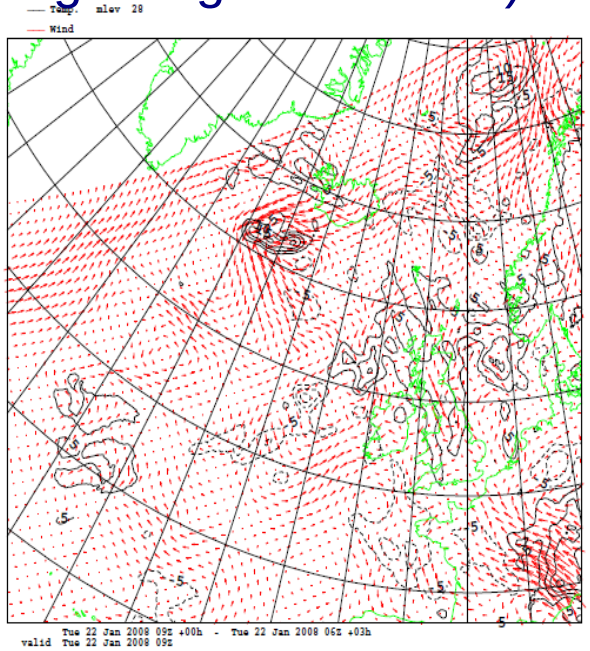
4DVAR hybrid lagged



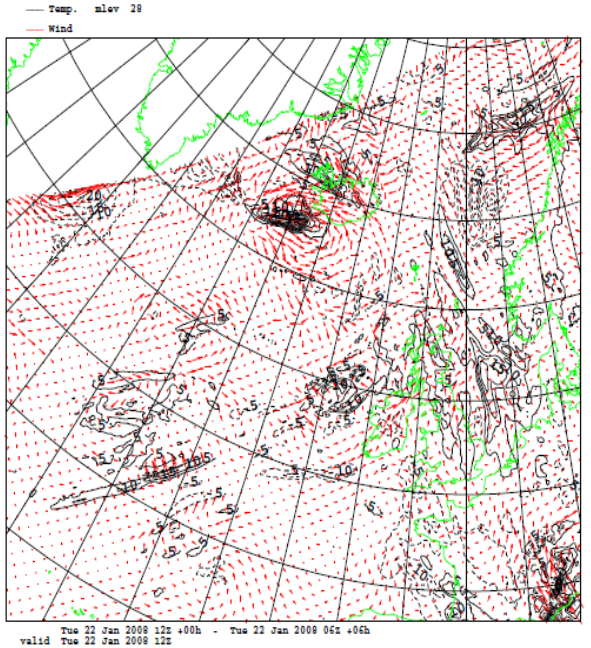
4DVAR
(beginning DA window)



4DVAR hybrid
(beginning DA window)



4DVAR hybrid
(middle DA window)



Concluding remarks

- The hybrid variational ensemble assimilation has been introduced for HIRLAM 3D-Var and 4D-Var with good results
- Emphasis on preservation of dynamical structures – “Hybrid ETKF” better than “Hybrid EDA with perturbed observations”
- Possibility to apply ensembles with lagged valid time – seem to perform better than lagged initial time ensemble

Plans in the HIRLAM community:

- Last step with HIRLAM : 4DEnsVar as an extension of the Hybrid 3-4D-Var hybrid (proof of the concept)
- 4DEnsVar framework for the HARMONIE cloud permitting model (hybrid as one possible realization) – Must start with design within the OOPS (Object Oriented Prediction System) for IFS

Questions, please....