

Balancing and data assimilation – a review

Nils Gustafsson, SMHI

- **Brief historical review**
- **Balancing in HIRLAM 4D-Var**
- **Hybrid variational ensemble DA and balancing**
- **Problems at convection permitting scales**

Aims of balancing in data assimilation

- Utilize dependencies between different model variables for mutual improvements, mass-wind for example
- Avoid high frequency oscillations and drift away from the observed state due to adjustment processes

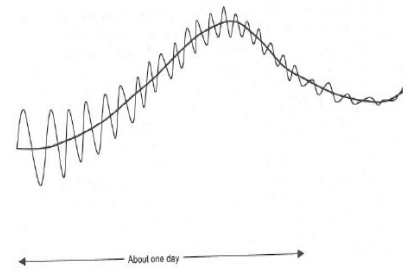
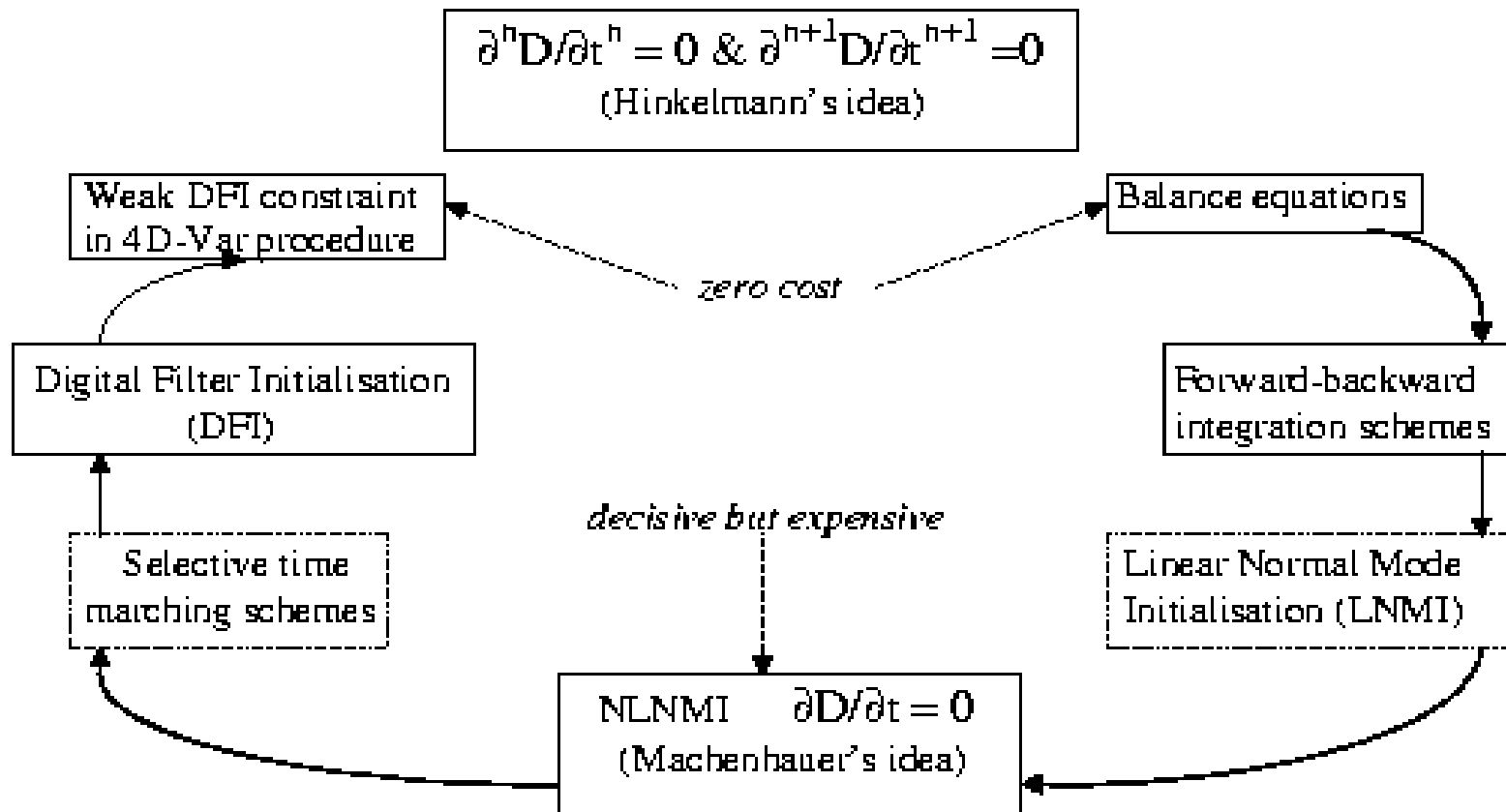


Figure 1.2.1: Schematic of a forecast with slowly varying weather-related variations and superimposed high-frequency gravity waves. Note that even though the forecast of the slow waves is essentially unaffected by the presence of gravity waves, the initial time derivative is much larger in magnitude, as obtained in the Richardson (1922) experiment.

- Ideally these two aims should be handled simultaneously (initialization and analysis in one go)

History of “initialization procedures” (in memory of Jean-Francois Geleyn)



How did we start?

Example – Sweden in the 1960's

QG models; Successive corrections analysis (Bergthorsson and Döös, 1955):

- Geopotential analysis only; Use wind observations to estimate geopotential gradients between stations and gridpoints
- Separate analysis of wind and geopotential in successive scans, variational blending with assumption on gradient or geostrophic wind (Sasaki, 1958)

In collaboration with Stockholm University (Sundqvist, Lejenäs) the SMHI analyses data were also tried as initial data for the primitive equation model of Hinkelmann (1959). Initialization by the non-linear balance equation on sigma-levels – no data assimilation cycling.

OI developments 1970-1987

3-dimensional multivariate OI (Rutherford, 1976, Lorenc, 1981)

- Used successfully by ECMWF together with non-linear normal mode initialization for operational global NWP
- Multivariate co-variances could include separation into divergent and rotational winds, latitude dependent geostrophy and frictional effects

3-dimensional uni-variate OI with variational blending of mass- and wind-fields

- (1) Used together with the non-linear balance equation and the ECMWF LAM for operational LAM NWP; High frequency oscillations in the +6h forecasts made “finalization” necessary
- (2) Non-linear normal mode initialization solved the problem + ECMWF OI => HIRLAM (1985) ; Digital filter initialization added later (Lynch and Huang, 1992)

Other early assimilation schemes:

- 1) The Hough mode spectral analysis (Flattery)
- 2) Time continuous data assimilation or nudging

Example of 2); Impact of aircraft data in two very different data assimilation system (Barwell and Lorenc,1985)

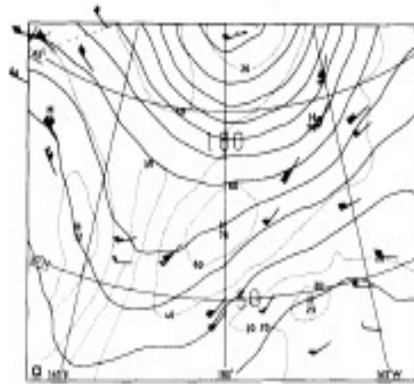
ECMWF

- Multivariate, wind influences mass, and vice versa (dominance by non-divergence)
- 3D, one wind observations influences several model levels
- Assimilation every 6 h
- Normal mode initialization

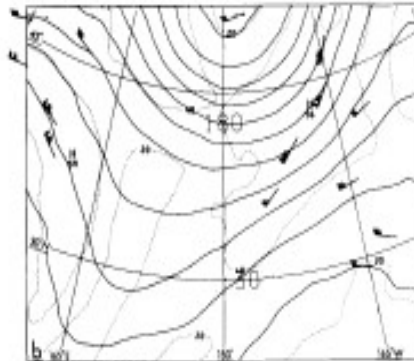
UKMO

- Univariate, wind influences only wind, mass only mass (u and v separately => 50 % divergence)
- 2D, only level closest to the observation is influenced
- Continuous with nudging
- Divergence damping

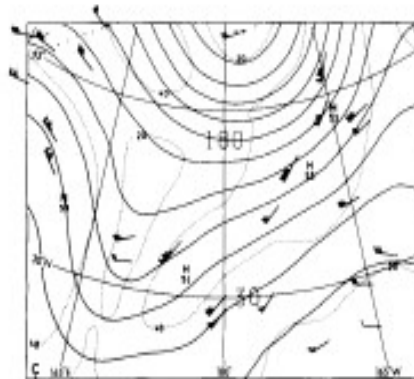
Analysis fields at 250 hPa
over the Pacific
11 November 1979 00UTC



UKMO with
aircraft winds



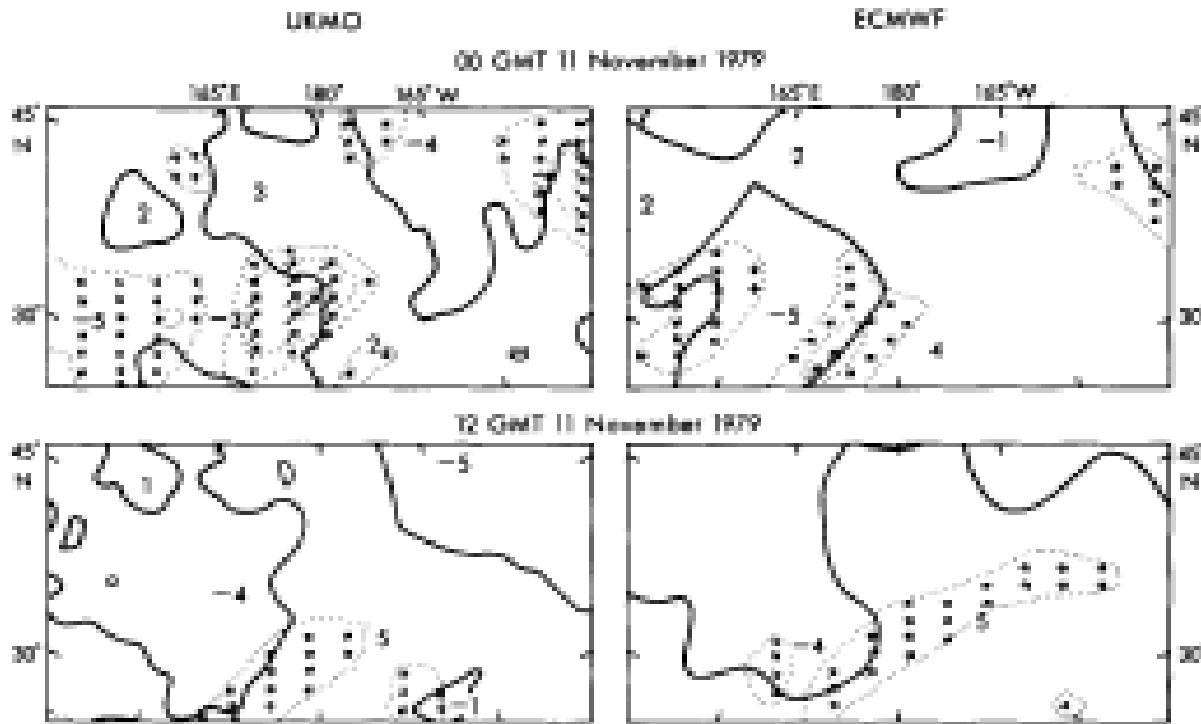
UKMO without
aircraft winds



ECMWF with
aircraft winds

Figure 5. More detailed charts of 250 mb analyses over the central North Pacific, 00 UTC 11 November 1979, showing contours at 10 dm intervals, isobars and wind observations. Charts are for with-aircraft analysis (a), without-aircraft analysis (b) and ECMWF IIIb analysis (c).

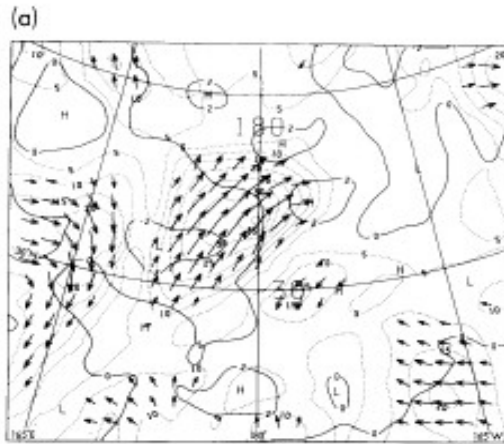
Differences between analyses with and without aircraft data



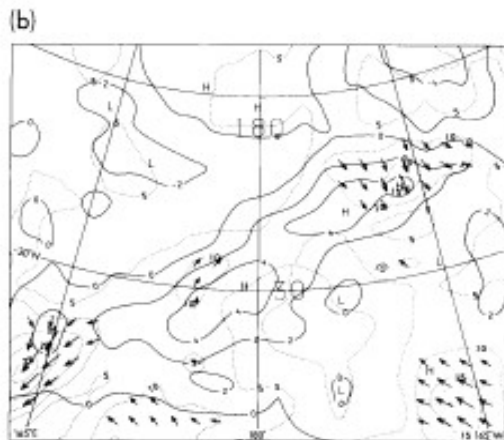
11 November
1979 00 UTC

11 November
1979 12 UTC

Differences between analyses and forecasts from these analyses with and without aircraft data



UKMO analysis
11 November 1979 00UTC



UKMO forecast
11 November 1979 00UTC + 6h

Figure 9. Impact of aircraft observations over the Pacific Ocean. (a) Close-up of part of Fig. 4(b); (b) same after 6-hour forecast.

UK Met Office used this example to improve their assimilation!

3D-Var: Statistical balance background constraint (Berre, 2000)

Spatial covariances between forecast errors are estimated thanks to multiple linear regressions (Parrish and Derber, 1992):

$$\begin{aligned}\zeta &= \zeta \\ \eta &= MH\zeta + \eta_u \\ (T, P_s) &= NH\zeta + P\eta_u + (T, P_s)_u \\ q &= QH\zeta + R\eta_u + S(T, P_s)_u\end{aligned}$$

where $\zeta, \eta, (T, P_s), q$ are respectively the forecast errors on vorticity, divergence, temperature, the logarithm of surface pressure and specific humidity. M, N, P, Q, R, S are matrices containing the linear regression coefficients. $\eta_u, (T, P_s)_u, q_u$ are the residual fields of the respective regressions.

Refinements:

- Take spatial variations of the Coriolis parameter into account.
- Non-linear balance equation
- Tropical mode structure functions (Zagar et al., 2004)

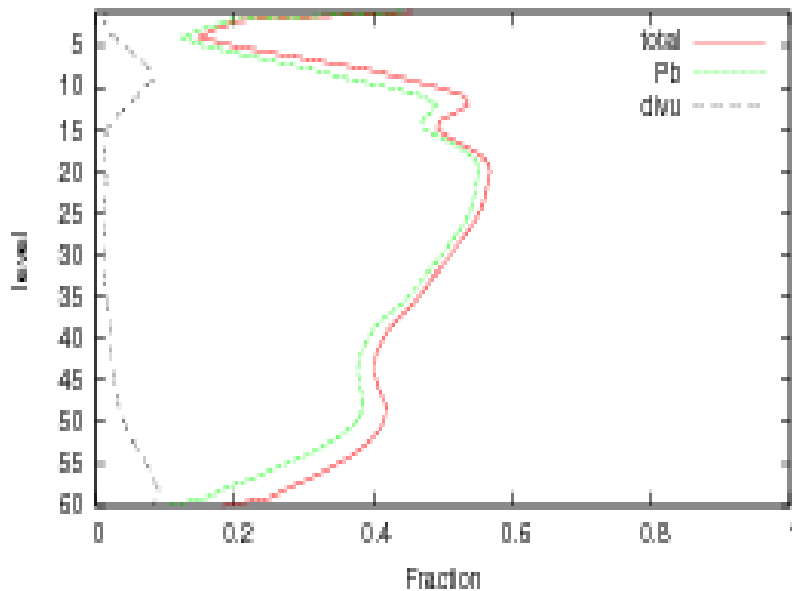
ECMWF: Similar balance in global geometry!

Example of statistical balance background error statistics

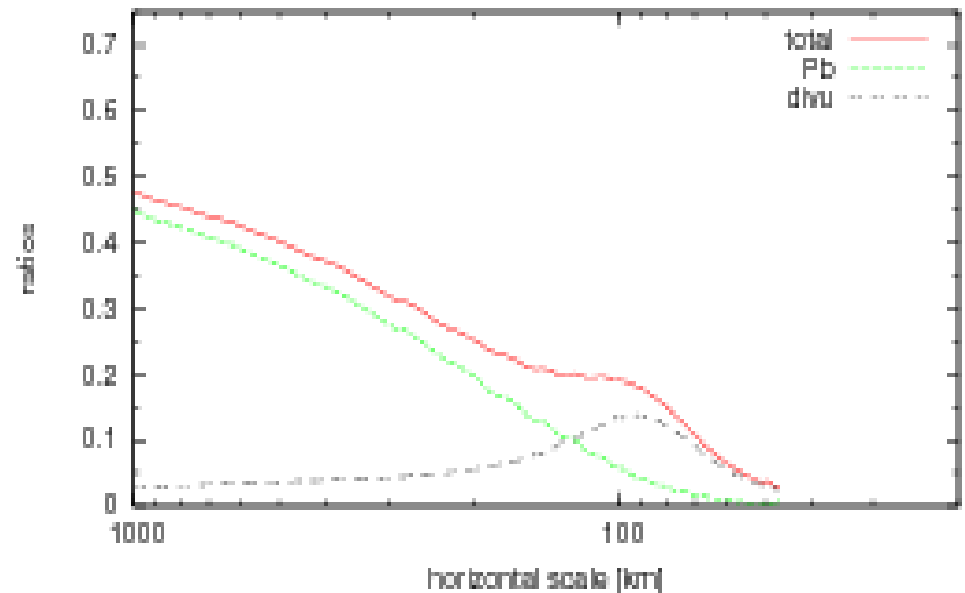
**HIRLAM RCR version 15 km resolution with 4D-Var
September-November 2008 36h – 12h forecasts valid at the
same time**

**Temperature variance explained by vorticity and un-
balanced divergence**

Vertical variation of explained temperature variance



Horizontal scale variation of explained temperature variance



**“Noise” level from
OI and 3D-Var -
The “Sundquist”
parameter
mean abs (dpsdt)
hPa/3h**

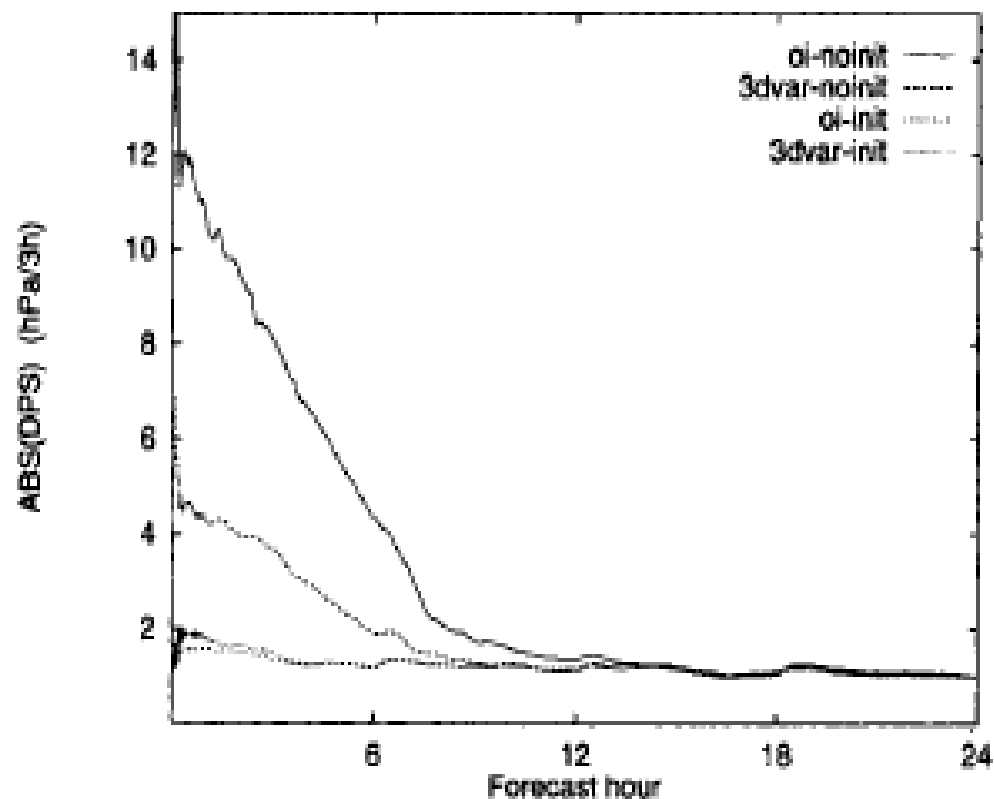


Fig. 18. Model area average of the absolute surface pressure tendency as a function of forecast length with the grid point HIRLAM model. Initial time is 5 March 1998 12 UTC. Statistical interpolation without initialization (curve marked oi-noinit) and with initialization (oi-init); 3D-Var without initialization (3dvar-noinit) and with initialization (3dvar-init).

Basic HIRLAM 4D-Var components:

- Tangent linear and adjoint of the semi-Lagrangian spectral HIRLAM.
- Simplified physics packages: Meteo France (Janiskova) package (vertical diffusion only).
- Multi-incremental minimization (gridpoint HIRLAM in outer loops).
- Tangent linear normal mode initialization (talks by Kleist and Parrish)
- Weak digital filter constraint.

(Gustafsson, et al., 2012)

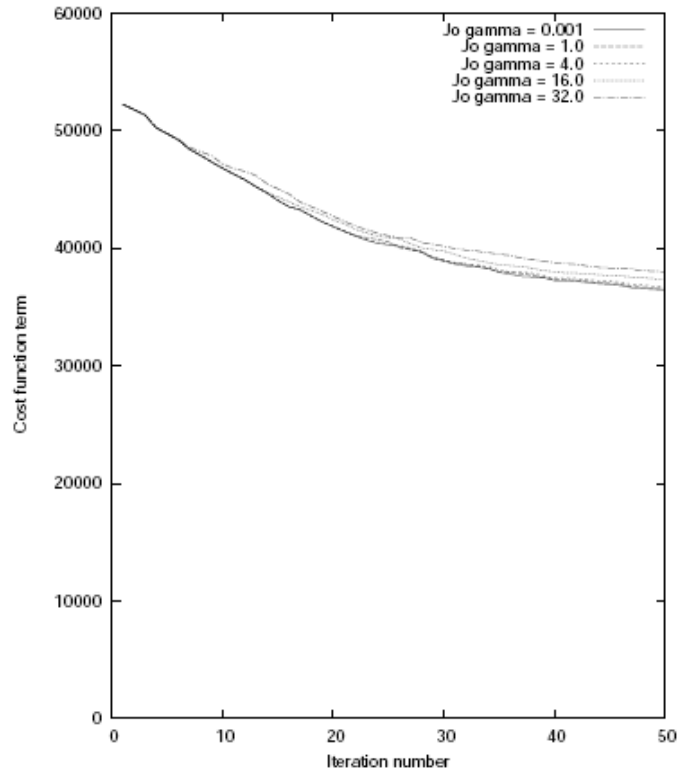
Weak digital filter constraint

$$J_c = \frac{\gamma_{df}}{2.0} (\delta X_{N/2} - \delta X_{N/2}^{df})^T C^{-1} (\delta X_{N/2} - \delta X_{N/2}^{df})$$

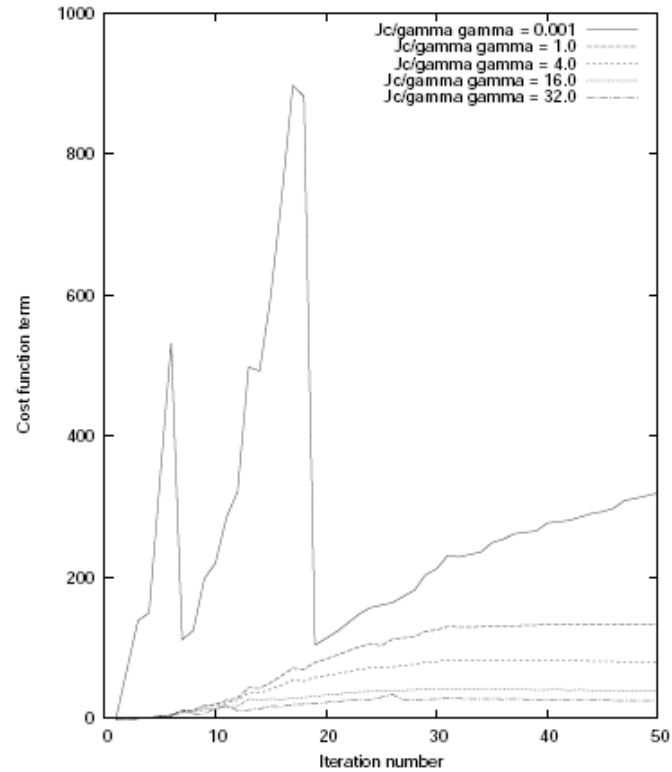
$$\delta X_{N/2} - \delta X_{N/2}^{df} = \delta X_{N/2} - \sum_{n=0}^N f_n \delta X_n = \sum_{n=0}^N h_n \delta X_n$$

Try to come close to the “slow manifold” at the same time as minimization of J_0 helps us to come close to the observations!
Note the un-known coefficient γ_{df} .

Tuning of the weak digital filter constraint by testing different values of γ_{DFI}

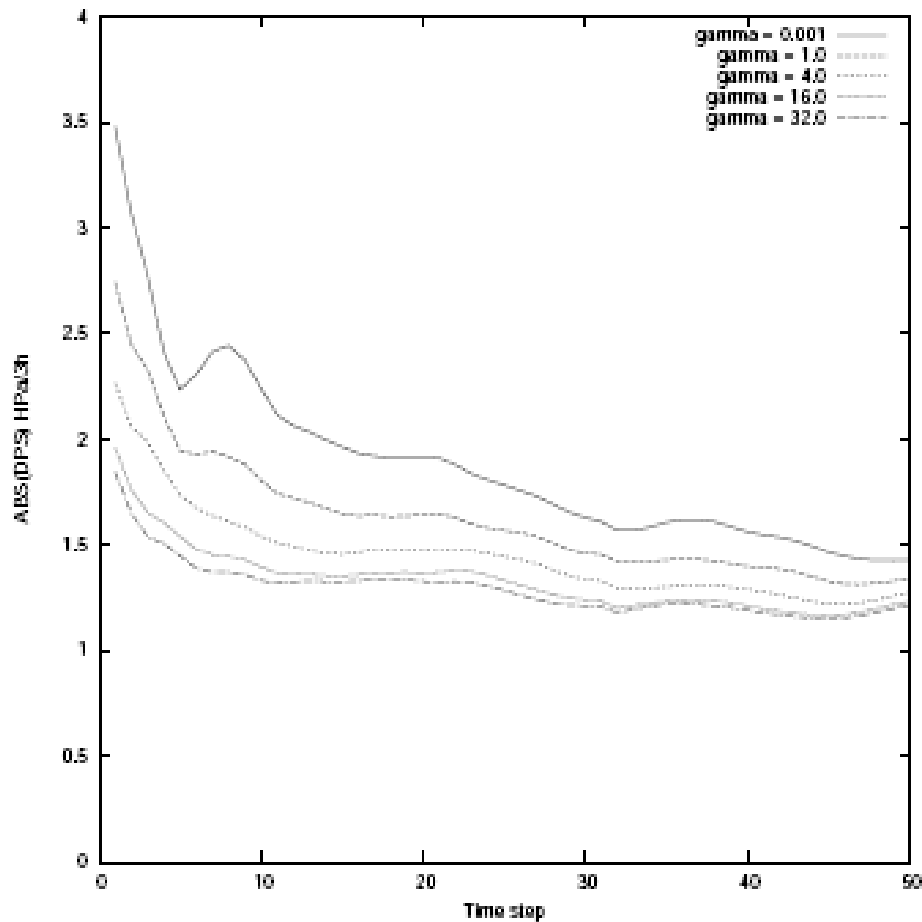


J_0



J_{DFI} / γ_{DFI}

Does this help to prevent “noise” in the non-linear model integration?



**Horizontal average
of the absolute
value of the surface
pressure tendency.**

Versions of Hybrid 4D-Var ensemble data assimilation

$$J = \frac{1}{\beta_{3dvar}} J_{3dvar} + \frac{1}{\beta_{ens}} J_{ens} + J_o + J_{dfi}$$

$$\text{4D-Var: } \delta x(t_k) = M_k \delta x(t_0)$$

$$\text{4D-Var Hybrid: } \delta x(t_k) = M_k (\delta x_{3dvar}(t_0) + \sum_{l=1}^N \alpha_l \delta x_l^{ens}(t_0))$$

$$\text{4D-En-Var Hybrid: } \delta x(t_k) = \delta x_{3dvar}(t_*) + \sum_{l=1}^N \alpha_l \delta x_l^{ens}(t_k)$$

N = number of ensemble members

δx_l^{ens} Ensemble perturbations, generated by ETKF for example

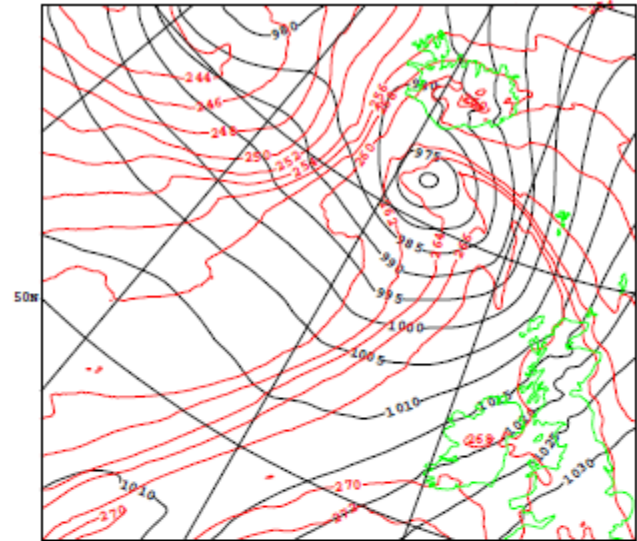
α_l Localized ensemble weights

$t_0 \leq t_k, t_* \leq t_K$ assimilation time window

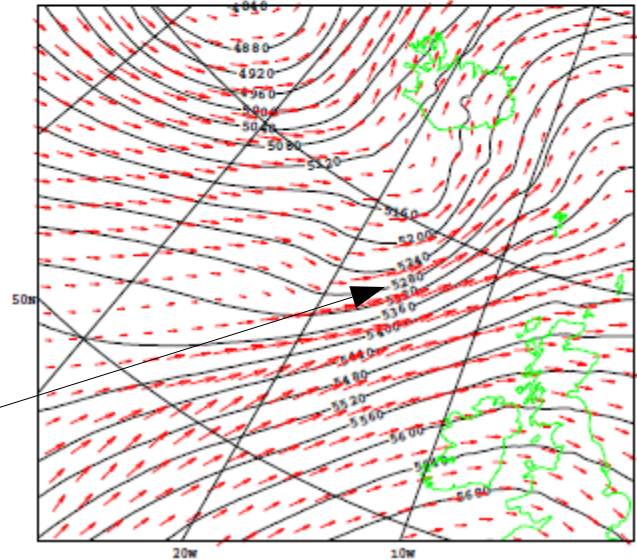
(Gustafsson and Bojarova, 2014)

Example of single observation experiments with 4D-Var, 4D-Var Hybrid and 4D-En-Var

Background states



PMSL
T700

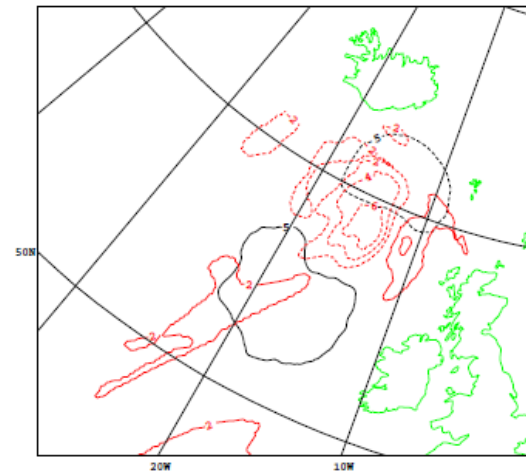
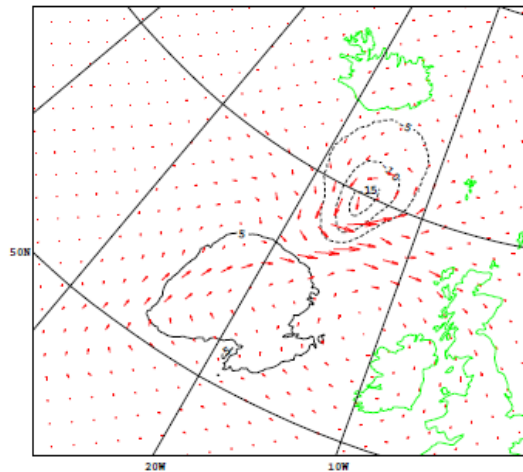


Z500
V500

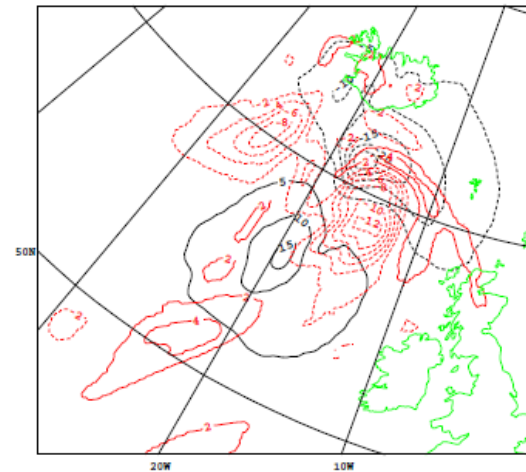
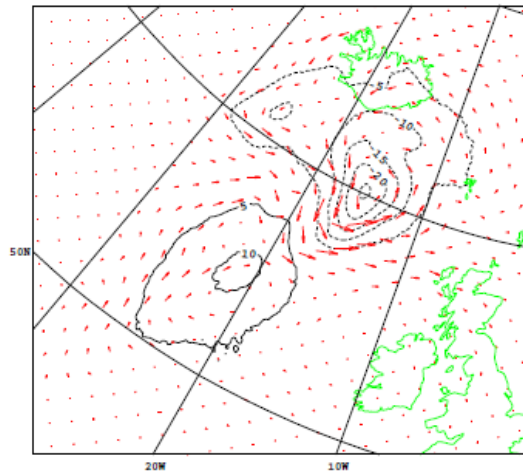
Position of simulated observation V500

Single observation assimilation increments

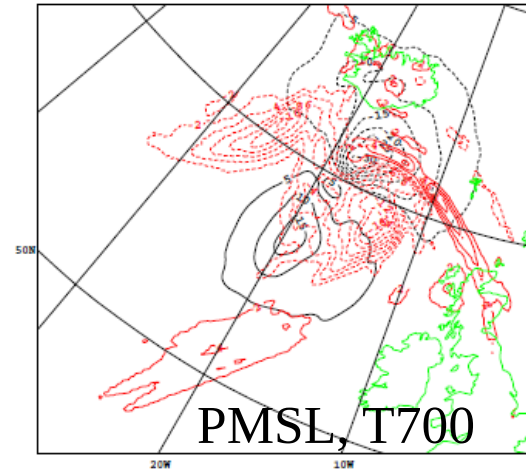
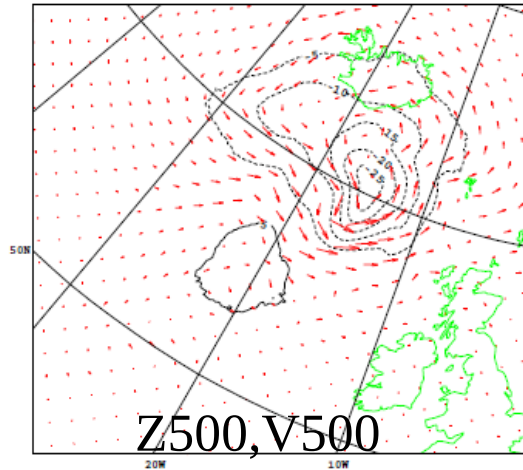
4D-Var



4D-Var
Hybrid



4D-En-Var



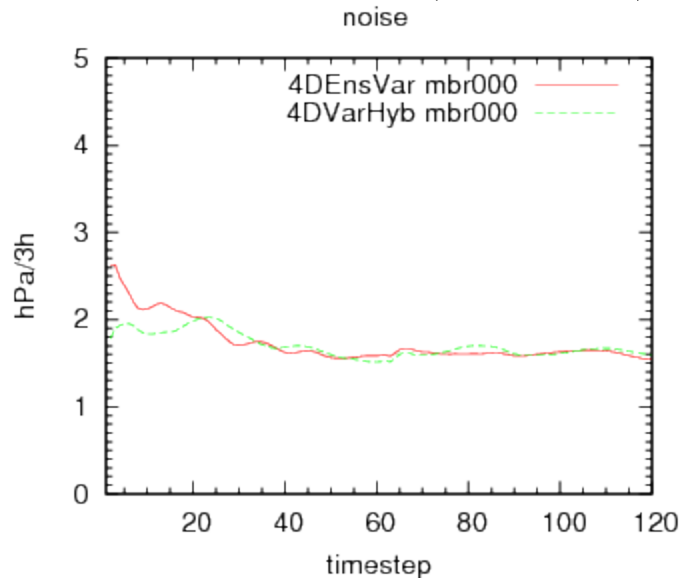
Z500, V500

PMSL, T700

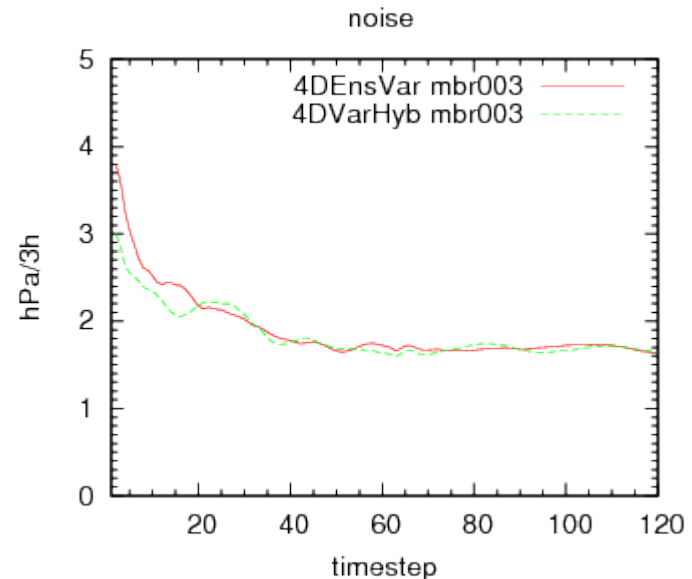
Average absolute surface pressure tendencies (hPa/3h) for forecasts starting from the main observation hour 22 February 2008 12UTC:

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

Member 0 (Control)



Member 3

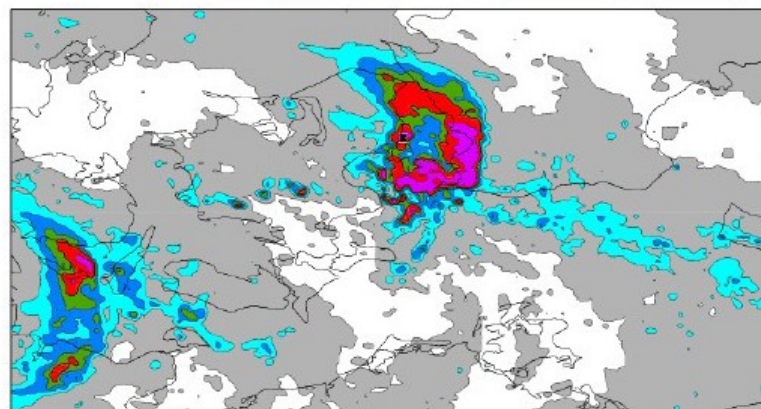


- 4D-Var Hybrid Control is essentially noise-free
- 4D-En-Var control has a slightly increased noise level
- Noise based on 4D-En-Var control increments and ETKF re-scaling of ensemble perturbations adds up

Verification of the HARMONIE AROME 2.5km forecasts for extreme weather event

(from Xiaohua Yang (DMI) & Lisa Bengtsson et al (SMHI))

Radar data 31.08 00UTC - 12UTC

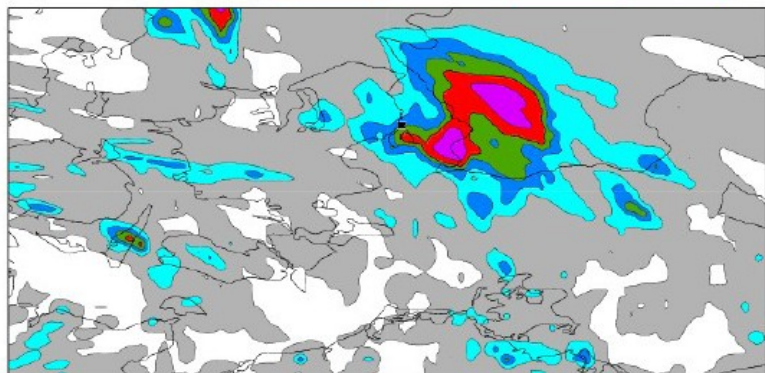


The HARMONIE AROME **is capable** in many cases to predict convective precipitation events (severe high impact weather events);

Stochastic nature of the convective phenomena should be taken into account both for verification and in post-processing (timing and location uncertainty);

The quality of the short-term forecasts in the operational runs is not satisfactory: **3D-Var data assimilation partly to be blamed – 4D-Var in progress**

HARMONIE AROME + 30h (MetCoOp)



12 h accumulated rainfall

HARMONIE 3D-Var - (potential) problems

- **Background error (BGE) statistics (spectra and balances) based on down-scaling of ECMWF ensembles => spectral spin-up problems !**
- **Very “noisy” forecasts; One reason is that horizontal diffusion has been re-tuned to avoid aliasing of explicit convection on larger scale super-cells**
- **Significant model surface pressure bias => difficult to assimilate surface pressure observations.**
- **Assumptions on stationarity, homogeneity and isotropy of BGE are less valid at the meso scale**

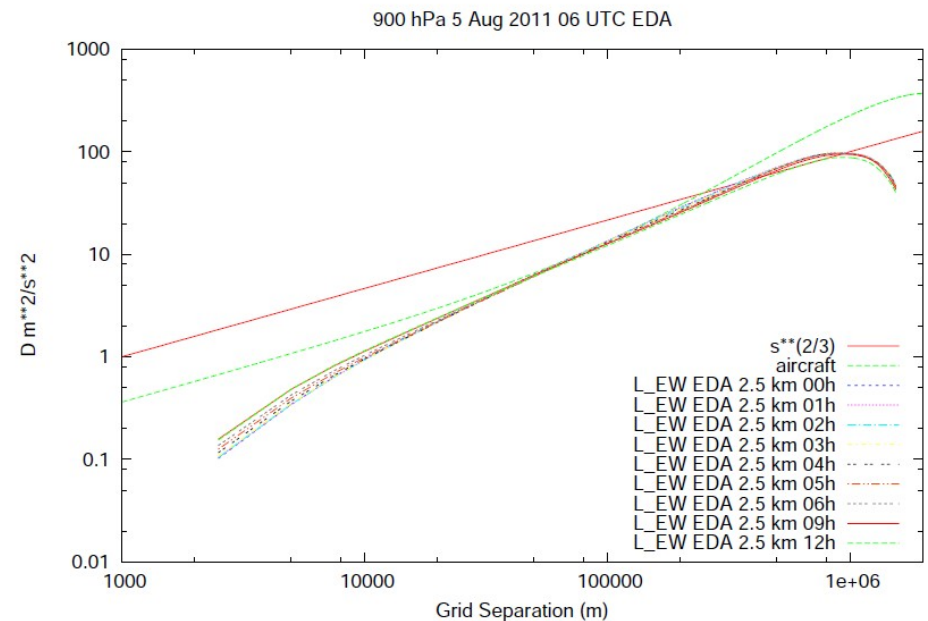
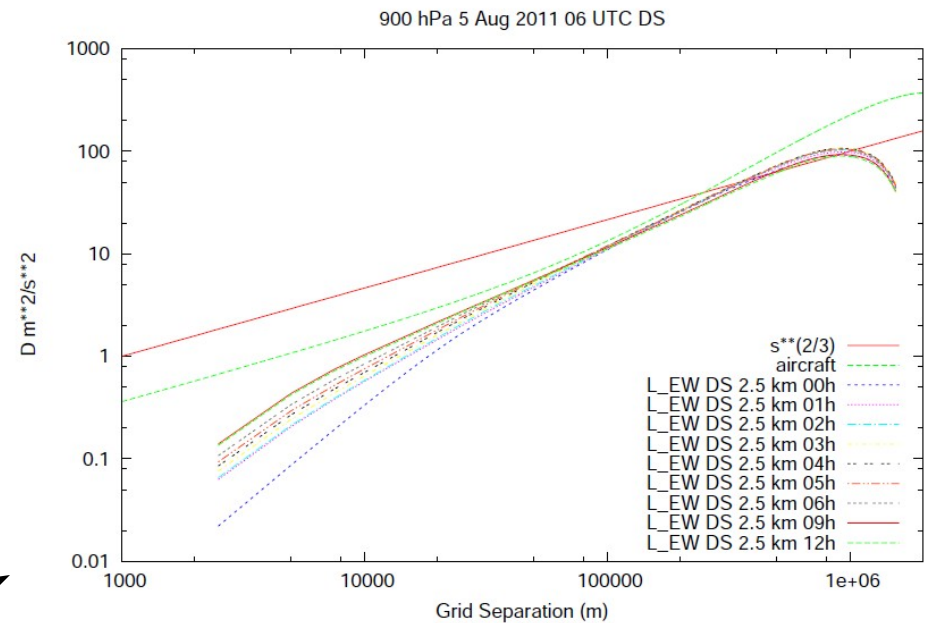
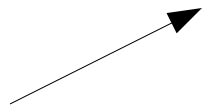
**Thanks to Jelena Bjarova, Nedjeljka Zagar
and Magnus Lindskog!**

Structure functions for the longitudinal comp. in the east-west direction, 900 hPa

(Frelich and Sharman, 2004)

Down-scaling

Ensemble Data Assimilation (EDA)

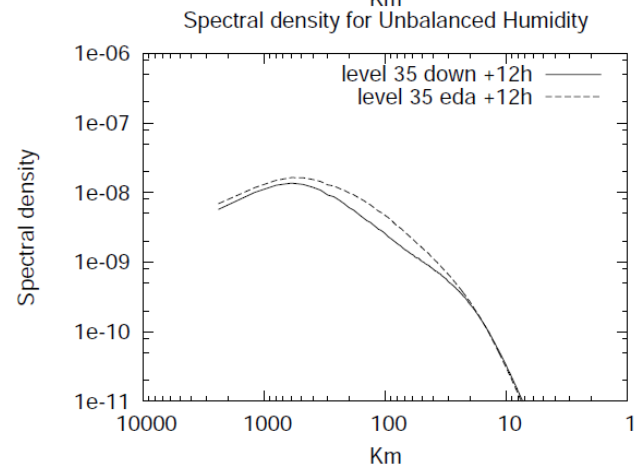
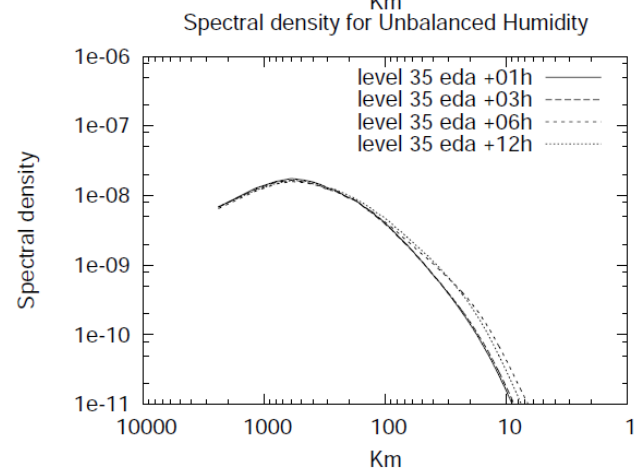
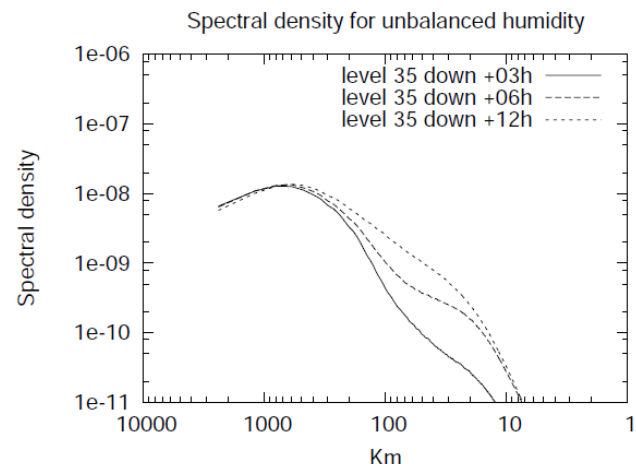


Spectral densities for unbalanced humidity, August 2011, 10 ensemble members

Downscaling +3h, +6h, +12h

EDA +3h, +6h, +12h

Downscaling +12h – EDA 12h

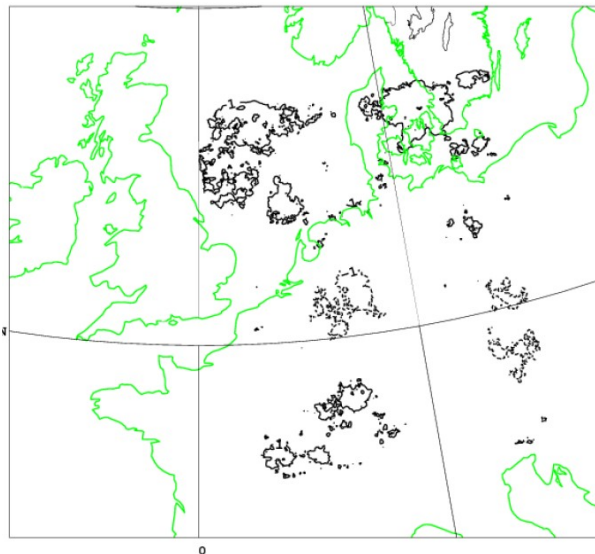


Sensitivity to perturbations in different initial state variables (inspired by Fabry and Sun, 2010)

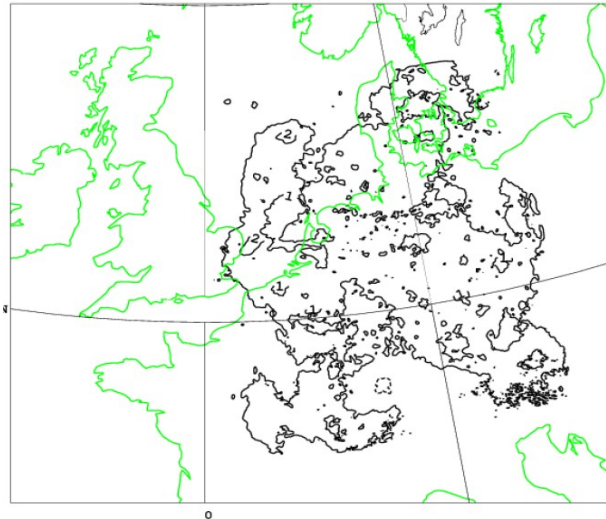
Evolution of random perturbations generated from the structure of B-matrix covariance.

Surface pressure, Member 1 – Control, 13 08 2012 03UTC

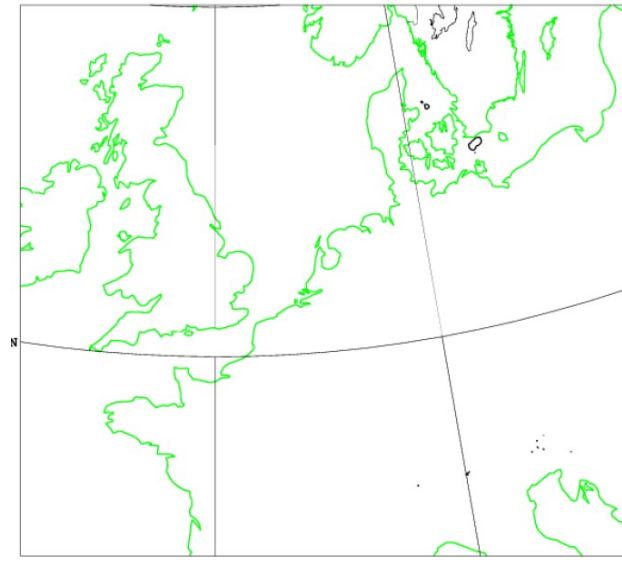
+0 h



+1 h

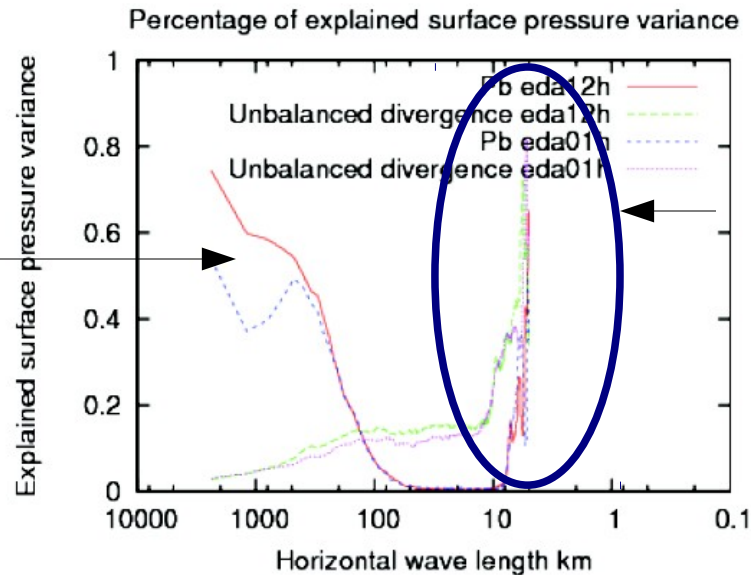


+5 h



Percentage of surface pressure variations explained by vorticity and unbalanced divergence

+12 h better balanced with vorticity than +1h

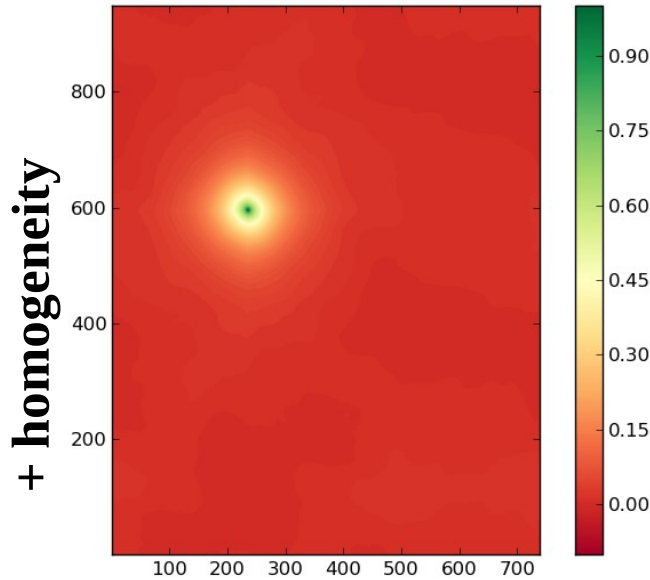
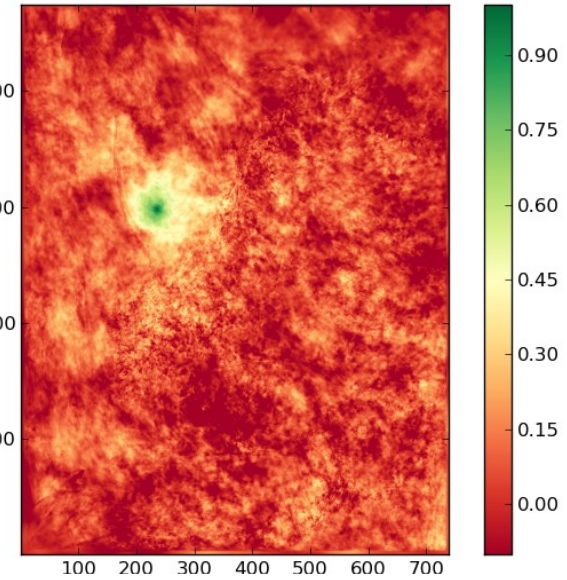
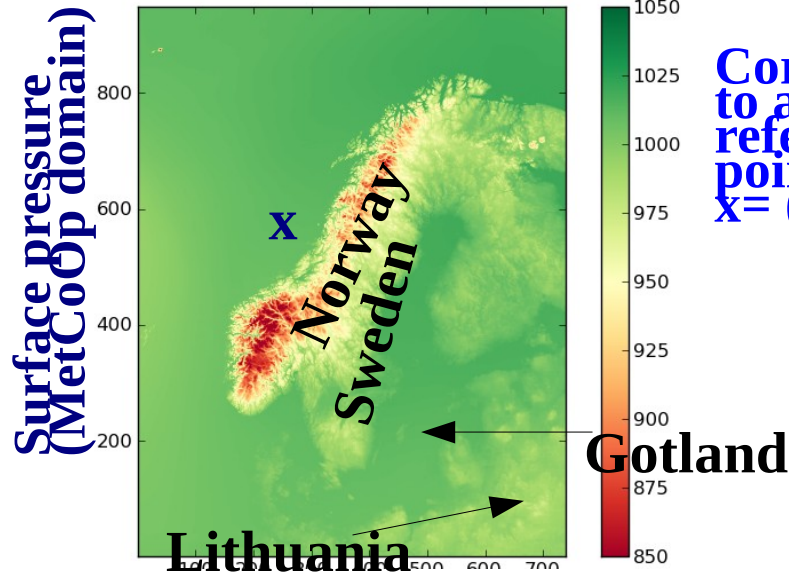


*Small scale noise:
Aliasing of high-order terms on $2\Delta x$, $3\Delta x$, $4\Delta x$, $5\Delta x$ waves?*

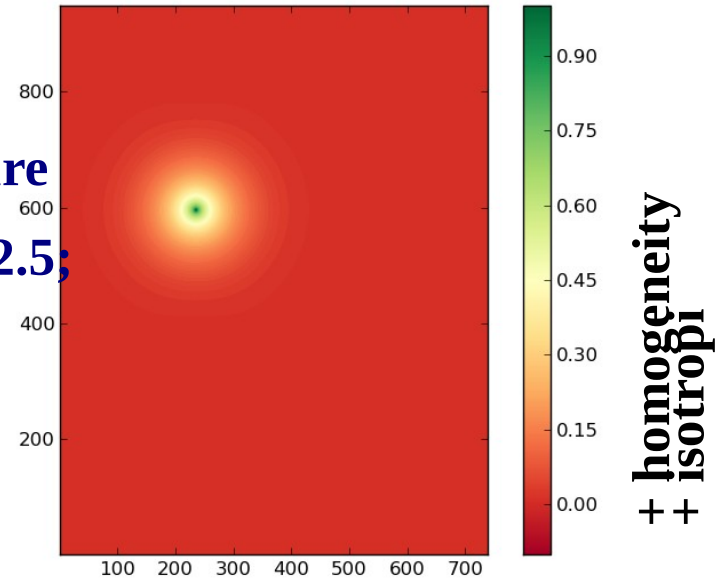
Preliminary results using **cubic grid truncation** (Mariano Hortal) show encouraging results : **increased numerical stability of the scheme and longer time stepping in the semi-Lagrangian forward propagation**. Processes are resolved in the grid-point space and smoothed in the spectral space.

Climatological structure functions

(6 EDA based HarmonEPS perturbations; 06UTC +12h)



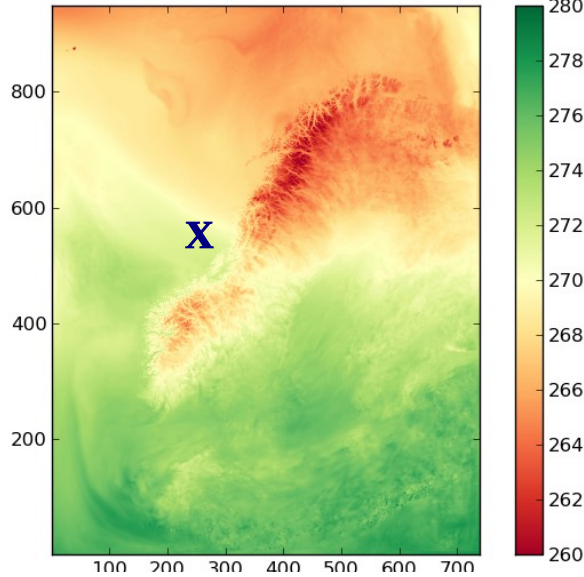
Temperature $\approx 500\text{hPa}$ (AROME 2.5; 65 vert.l)



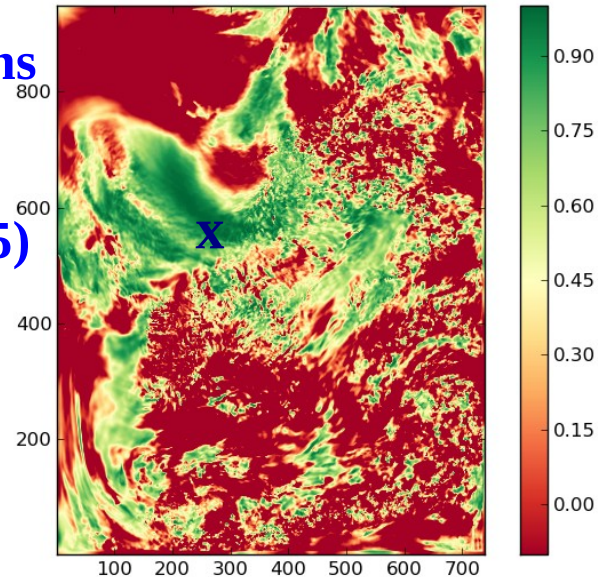
Climatological structure functions

(6 EDA based HarmonEPS perturbations; 06UTC + 12h)

Temperature (control)
(12 08 2008)

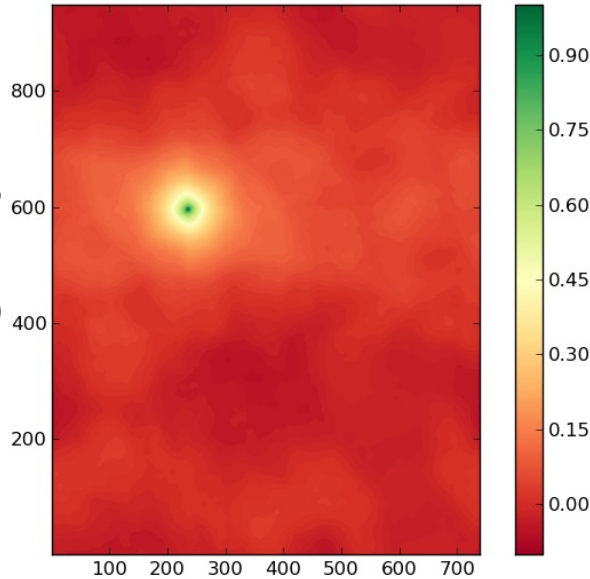


Correlations
to a single
reference
point
 $x = (235, 595)$

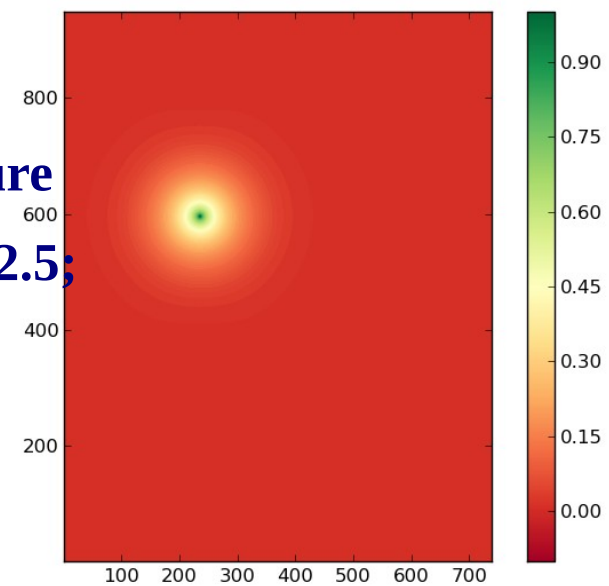


Single case

+ homogeneity



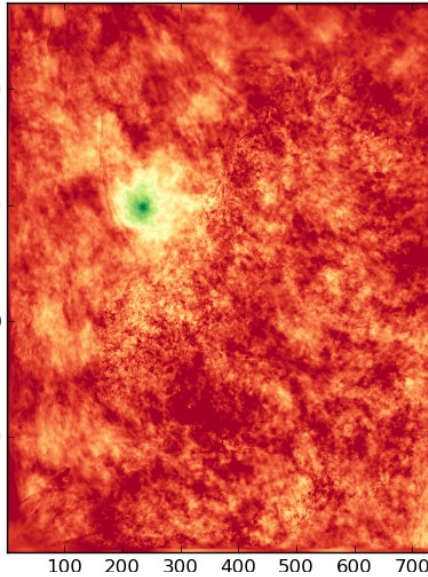
Temperature
 $\approx 500\text{hPa}$
(AROME 2.5;
65 vert.l)



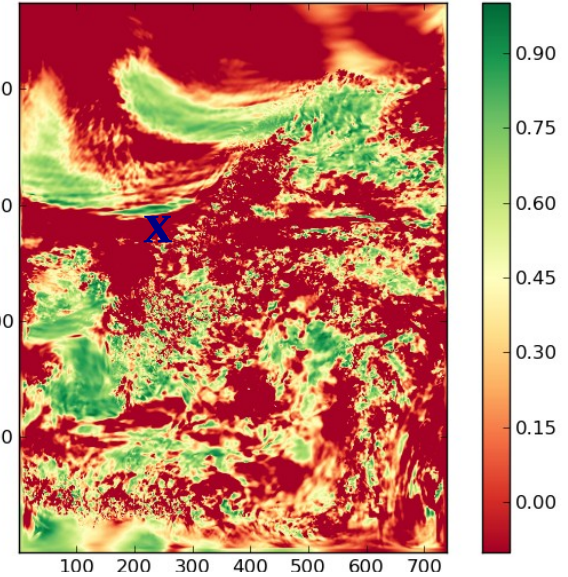
+ homogeneity
+ isotropy

Climatological structure functions (6 EDA based HarmonEPS perturbations; 06UTC + 12h)

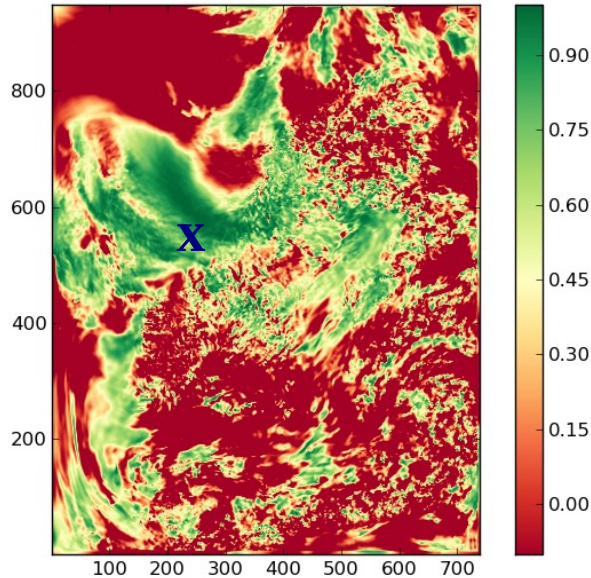
Average in time (25 cases)



Correlations
to a single
reference
point
 $x = (235, 595)$

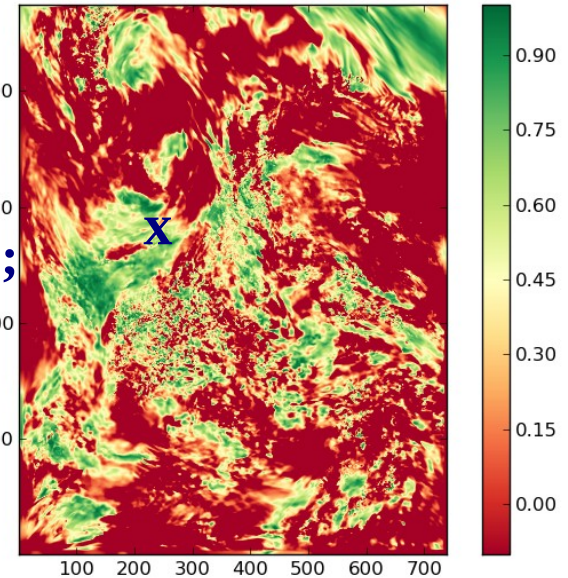


06 08 2008



12 08 2008

Temperature
 $\approx 500\text{hPa}$
(AROME 2.5;
65 vert.l)

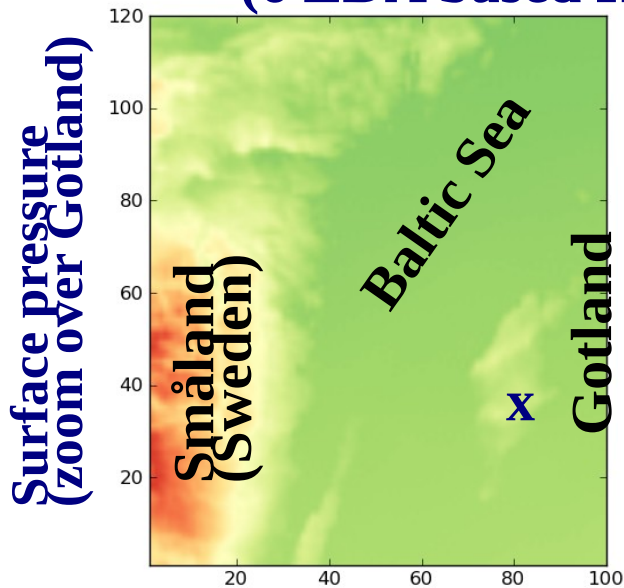


18 08 2008

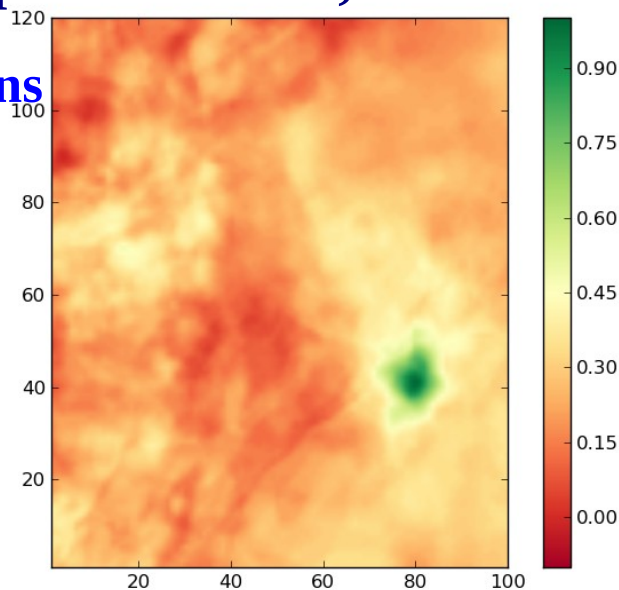
Allow flow-dependency,
Avoid homogeneity & isotropi

Climatological structure functions

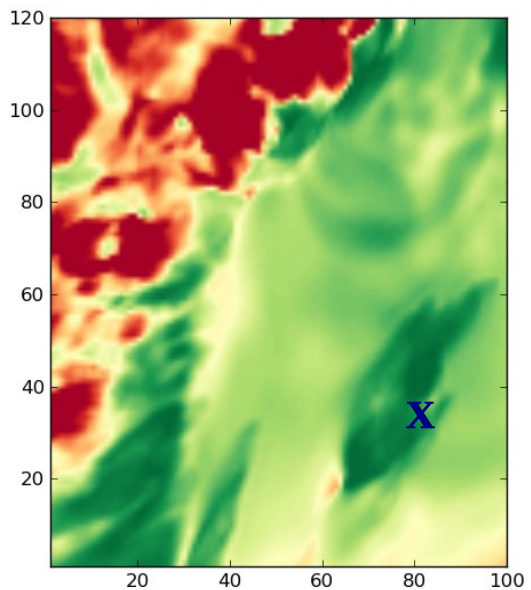
(6 EDA based Harmony EPS perturbations; 06UTC + 12h)



Correlations
to a single
reference
point
 $x = (80, 40)$

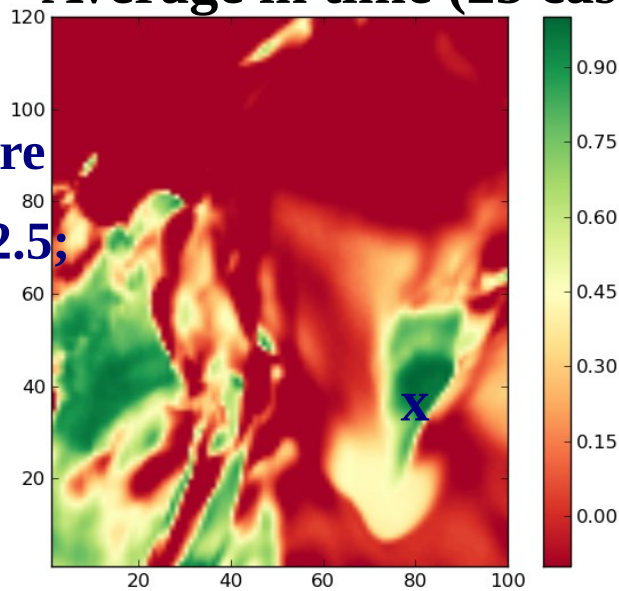


Big potential of HarmonEPS ensemble
for convective scale phenomena (surface
& PBL)



Temperature
level 62
(AROME 2.5;
65 vert.l)

Average in time (25 cases)



12 08 2008

21 08 2008

Concluding remarks on the mesoscale

- **Balancing continues to be crucial also on the convective scale.**
- **We cannot come much further forward without flow-dependent structure functions! => Stationarity, homogeneity and isotropy assumptions about the forecast error statistics do not hold for the convective scale phenomena.**
- **Small scales structures and noise is a poor combination => Go for “cubic grid” truncation, possibly low-resolution orography; We need to rethink about initialisation on convective scales**
- **Ensembles have potential for data assimilation on convective scales (processes driven by surface and PBL conditions) => Go for Ensemble Variational techniques using convection permitting ensembles**