Scale-dependent localization in ensemble-variational data assimilation: Application in global and convective-scale systems

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Outline

1. An approach to improve spatial covariance localization in EnVar: scale-dependent localization (SDL)

2. Application in two EnVar-based DA systems
   a) A simplified version of ECCC’s global operational system
   b) Meteo-France AROME convective-scale system (R&D version)
Scale-dependent localisation (SDL)

Definition: Simultaneously apply appropriate (i.e. different) localization to different range of scales.

• The approach can be applied to both horizontal and vertical localization but this presentation will only focus on horizontal-scale-dependent horizontal localization.

• Pros:
  • Seems appropriated for multi-scale analysis.
  • In limited-area: Could avoid the need of multi-step or large-scale blending approaches.

• Cons:
  • Adds more parameters to tuned.
  • Increases the cost of the analysis step (at least in our formulation).
EnVar with $B^{1/2}$ preconditioning (ECCC)

Current (one-size-fits-all) Approach

- Analysis increment computed from control vector ($B^{1/2}$ preconditioning) using:

$$\Delta x = \sum_{k} e_k \circ \left( L^{1/2} \xi_k \right)$$

k: member index

Scale-dependent Approach (as in Buehner and Shlyaeva, 2015, Tellus)

- Varying amounts of smoothing applied to same set of amplitudes for a given member

$$\Delta x = \sum_{k} \sum_{j} e_{k,j} \circ \left( L^{1/2}_{j} \xi_k \right)$$

k: member index

j: scale index

where $e_{k,j}$ is scale $j$ of normalized member $k$ perturbation
EnVar with B preconditioning (Meteo-France)

Current (one-size-fits-all) Approach

- Analysis increment computed from control vector (B preconditioning) using:

\[
\Delta x_o = \sum_k e_k \circ (L(e_k \circ \Delta x_i))
\]

Scale-dependent Approach

- Direct application to the above formulation

\[
\Delta x_o = \sum_{j1} \sum_{j2} \sum_k e_{k,j1} \circ (L_{j1,j2}(e_{k,j2} \circ \Delta x_i))
\]

- Reformulation using \(B^{1/2} B^{T/2}\)

\[
\Delta x_o = \sum_k \sum_j e_{k,j} \circ \left( L_{j}^{1/2} \xi_k \right)
\]

\[
\xi_k = \sum_j L_{j}^{T/2}(e_{k,j} \circ \Delta x_i)
\]
Application in a global EnVar system:

ECCC’s Global Deterministic Prediction System

- 256 ensemble member @ 50km
- Localization in spectral space
- Deterministic forecast @ 25 km
Horizontal Scale Decomposition

Perturbations for ensemble member #001 – Temperature at ~700hPa
Scale-dependent covariance localization

Impact in single observation DA experiments

700 hPa T observation at the center of Hurricane Gonzalo (October 2014)

Normalized temperature increments (correlation-like) at 700 hPa resulting from various B matrices.

- $B_{ens} \text{ Std hLoc}$
- $B_{ens} \text{ No hLoc}$
- $B_{ens} \text{ SD hLoc}$
- $B_{nmc}$

Locations:
- hLoc: 2800km
- hLoc: 1500km / 4000km / 10000km
Scale-dependent covariance localization

Impact in single observation DA experiments

700 hPa T observation at the center of a High Pressure

Normalized temperature increments (correlation-like) at 700 hPa resulting from various B matrices.

- $B_{\text{ens}}$ Std hLoc
- $B_{\text{ens}}$ No hLoc
- $B_{\text{ens}}$ SD hLoc
- $B_{\text{nmc}}$

- hLoc: 2800km
- hLoc: 1500km / 4000km / 10000km
Scale-dependent covariance localization

Forecast impact

• 2.5-month trialling (June-August 2014) in our global NWP system.

• 3DEnVar with 100% $B_{ens}$ used in both experiments

  1) **Control experiment** with $h_{Loc} = 2800$ km, $v_{Loc} = 2$ units of $\ln(p)$

  2) **Scale-Dependent experiment** with a 3 horizontal-scale decomposition
     
     I. Small scale uses $h_{Loc} = 1500$ km
     II. Medium scale uses $h_{Loc} = 2400$ km
     III. Large scale with uses $= 3300$ km

     Ad hoc values!

     Same $v_{Loc}$ (2 units of $\ln(p)$) for every horizontal-scale

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[Environnement et Changement climatique Canada]  [Environment and Climate Change Canada]  [METEO FRANCE]
Scale-dependent covariance localization

Forecast impact

**Time series Northern E-T**

- Std Dev for U at 250 hPa

**Time series Southern E-T**

- Std Dev for U at 250 hPa

➢ Control  ➢ Scale-Dependent
Scale-dependent covariance localization

Forecast impact

Is it possible to do as good as SDL with a single localization approach?

After all, perhaps our one-size-fits-all horizontal localization radius of 2800 km is not optimal...

- 2 new 1.5-month trialling (June-July 2014) with a single localization approach (still using 3DEnVar with 100% $B_{ens}$)

1) $h_{Loc} = 2400$ km (the value used for medium scale in SD $h_{Loc}$)

2) $h_{Loc} = 3300$ km (the value used for large scale in SD $h_{Loc}$)
Scale-dependent covariance localization

Forecast impact

Time series Northern E-T

Std Dev for U at 250 hPa

Time series Southern E-T

Std Dev for U at 250 hPa

➢ Control (hLoc = 2800 km)

➢ hLoc = 2400 km

Environnement et Changement climatique Canada

Environment and Climate Change Canada
Scale-dependent covariance localization

Forecast impact

Time series Northern E-T

Std Dev for U at 250 hPa

Time series Southern E-T

Std Dev for U at 250 hPa

➢ Control (hLoc = 2800 km)

➢ hLoc = 3300 km
Application in a convective-scale EnVar system:
Meteo-France’s AROME R&D version

- 25 ensemble member @ 3.8km
- Localization in spectral or gridpoint space
- Deterministic forecast @ 3.8 km
(Adhoc) scale-decomposition for AROME

Temperature perturbations at ~950 hPa for member #1. 3h forecast valid on 06 February 2016 at 00 UTC.
Pseudo-single obs - Frontal case

SP 250km
Pseudo-single obs - Frontal case

SP-SDL 080/250/500km
Pseudo-single obs - Convective case

SP 250km
Pseudo-single obs - Convective case

SP-SDL 080/250/500km
Performed DA and forecast cycles

- 2 weeks trialling (February 2016) were used testing many horizontal localization lengthscale for both SDL and ‘one-size-fits-all’ approaches.
- Extension to 1 month for both the control experiment and the best performing SDL configurations.
- Spectral and gridpoint (recursive filter) localization were used/compared.
- The same horizontal-scale decomposition (3 wave band) was used in all the SDL experiments.
- 3-hourly DA cycle
- 30-hour forecasts issued from 00, 06, 12 and 18 UTC
Verification against aircraft (+3 to +30h, 3h)

SP 075/150/300km

VS

SP 250km
Verification against aircraft (+1 to +10h, 1h)

SP 075/150/300km

VS

SP 250km

2 weeks
Verification against aircraft (+3 to +30h, 3h)

SP 300km

VS

SP 250km

2 weeks
Verification against aircraft (+3 to +30h, 3h)

SP 200km

VS

SP 250km
Verification against aircraft (+3 to +30h, 3h)

SP 150km

VS

SP 250km
Full verification (+3 to +30h, 3h)

SP 075/150/300km vs SP 250km

ScoreCard B6W9 vs B6PM
20160206-20160309: HHALL

T (ALT)

T (2M)

HU (ALT)

HU (2M)

U/V (ALT)

U/V (10M)

MSLP

Total NWP index change (altitude) : +0.39 %
Total NWP index change (surface) : +0.23 %
Summary and conclusion

• SDL is feasible and straightforward to implement in EnVar, but more expensive than using single-scale localization.
  – In the SDL experiments reported here: 3x to 3.5x more expensive

• Results using a horizontal-scale-dependent horizontal localization indicate small forecast improvements in both systems examined. However, the time-scales over which the SDL method impacted the forecasts are completely different:
  – Improvements up to day 5 were noticed in the global system,
  – In the convective-scale system, they were limited mostly in the first 9 hours of the forecasts

• In terms of dynamical balance, SDL seems to alleviate somewhat the imbalance generated by the localization (not shown).

• Finding the optimal SDL setup is not straightforward.
  – No objective approach has been found useful so far.
Spatial covariance localization is essential to obtain useful analyses with “small” ensembles (a 256-member ensemble is still "small"!).

Currently, ECCC's EnVar uses simple localization of ensemble covariances, similar to EnKF: single length scale in both horizontal and vertical localizations based on Gaspari and Cohn (1999) 5th order piecewise rational function.

Comparing various NWP studies, seems that the best amount of horizontal localization depends on application/resolution:

- convective-scale assimilation: \(\sim 10\)km
- mesoscale assimilation: \(\sim 100\)km
- global-scale assimilation: \(\sim 1000\)km – 3000km (2800km at ECCC)

A one-size-fits-all approach for localization does not seem appropriate for analysing a wide range of scales.
Scale-dependent localisation (SDL)

The basic idea (from Buehner and Shlyaeva, 2015, Tellus)

- The original ensemble covariances with localization
  \[ B_L = \sum_{k} e_k e_k^T \circ L \]
  \( k: \) member index

- With a scale-decompose ensemble
  \[ e_{k,j} = F_{j} e_k \]
  \[ e_k = \sum_{j} e_{k,j} \]
  \[ B_L = \sum_{j1} \sum_{j2} \sum_{k} e_{k,j1} e_{k,j2}^T \circ L \]
  \( F: \) filtering step
  \( j: \) scale index

- With scale-dependent localization
  \[ B_{SDL} = \sum_{j1} \sum_{j2} \sum_{k} e_{k,j1} e_{k,j2}^T \circ L_{j1,j2} \]
Horizontal Scale Decomposition: Global

Filter response functions for decomposing with respect to 3 horizontal scale ranges

- Large scale
- Medium scale
- Small scale
Horizontal Scale Decomposition: Global

Homogeneous horizontal correlation length scales

6-h temperature perturbation from 256-member EnKF

Horizontal scale-dependent localization leads to (implicit)...
vertical-level-dependent horizontal localization

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- Large scale
- Medium scale
- Small scale

Full
Horizontal Scale Decomposition: Global

Waveband integrated variances
- Large scale
- Medium scale
- Small scale
- All the scales

Horizontal scale-dependent localization leads to (implicit)... variable-dependent horizontal localization

6-h perturbation from 256-member EnKF
Impact on Balance: Global

Impact on Rotational Part

It is well known that localization can disrupt the dynamical balance of the analysis increments.

Does the SDL increase or decrease this problem?

Balance diagnostics as in Caron and Fillion (2010; MWR)

• Rotational part: Charney’s (1955) nonlinear balance equation

\[
\nabla^2 \Phi' = f \zeta' + 2 \left[ \left( \frac{\partial u'_r}{\partial x} \frac{\partial v'_r}{\partial y} - \frac{\partial u'_r}{\partial y} \frac{\partial v'_r}{\partial x} \right) + \left( \frac{\partial u'_r}{\partial x} \frac{\partial v'_r}{\partial y} - \frac{\partial u'_r}{\partial y} \frac{\partial v'_r}{\partial x} \right) + \left( \frac{\partial u'_r}{\partial x} \frac{\partial v'_r}{\partial y} - \frac{\partial u'_r}{\partial y} \frac{\partial v'_r}{\partial x} \right) \right] - \frac{\partial f}{\partial y} u'_r
\]

One conclusion from Caron and Fillion: Both horizontal and vertical localization have significant deleterious effect on the rotational balance with the largest detrimental impact coming from the vertical localization.
Impact on Balance: Global

Impact on Rotational Part

Vertical profile of average normalized departure from (n-l) balance
Impact on balance: Convective Scale

RMS of the Ps tendency

\[
\text{dPs/dt (hPa/h)}
\]

- RF-SDL
- RF
- SP-SDL
- SP

forecast time (min)
Full verification (+3 to +30h, 3h)

RF 075/150/300km

VS

RF 250km

ScoreCard B7AL vs B6TW
20160206-20160309: HHALL

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