Four-dimensional Ensemble-Variational data assimilation for global deterministic NWP

Mark Buehner¹, Josée Morneau², Cecilien Charette¹ and Ron McTaggart-Cowan³

¹Data Assimilation and Satellite Meteorology Research Section
²Data Assimilation and Quality Control Development Section
³Numerical Weather Prediction Research Section

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Background

• Environment Canada currently has 2 relatively independent state-of-the-art global data assimilation systems
  
• 4D-Var (Gauthier et al 2007) and EnKF (Houtekamer et al 2009):
  – both operational since 2005
  – both use GEM forecast model and assimilate similar set of observations
  – current effort towards unifying fortran code of the two systems

• 4D-Var is used to initialize medium range global deterministic forecasts (GDPS)

• EnKF is used to initialize global ensemble forecasts (GEPS)

• Intercomparison of approaches and various hybrid configurations was performed in carefully controlled context: similar medium-range forecast quality from EnKF and 4D-Var analyses, 4D-Var-Ben best (Buehner et al 2010, MWR)
Ensemble-Variational assimilation: EnVar

- Planning to replace 4D-Var with 4D-EnVar
- EnVar uses a variational assimilation approach in combination with the already available 4D ensemble covariances from the EnKF
- By making use of the 4D ensembles, EnVar performs a 4D analysis without the need of the tangent-linear and adjoint of forecast model
- Consequently, it is more computationally efficient and easier to maintain/adapt than 4D-Var
- Hybrid covariances can be used in EnVar by averaging the ensemble covariances with the static covariances
Current systems

- **Global EnKF**
  - Perturbed members of the global ensemble prediction system (GEPS)

- **Global 4D-Var**
  - Global deterministic prediction system (GDPS)

- **Regional 4D-Var**
  - Regional deterministic prediction system (RDPS)

- **Perturbed members of the regional ensemble prediction system (REPS)**
2013-2017: Toward a Reorganization of the NWP Suites at Environment Canada

Increasing role of global ensembles… in 2014

- Global EnKF
- Global EnVar
- Background error covariances

Perturbed members of the regional prediction system (RPS)
Control member of the regional prediction system (RPS)
Regional EnVar

Global EnKF

Perturbed members of the global prediction system (GPS)
Control member of the global prediction system (GPS)

global system  

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Global and regional ensembles...

Global EnKF → Perturbed members of the global prediction system (GPS)

Global EnVar → Background error covariances

Regional EnKF → Perturbed members of the regional prediction system (RPS)

Regional EnVar → Background error covariances

High-res EnVar → High-resolution deterministic prediction system (HRDPS)

Control member of the regional prediction system (RPS)

Control member of the global prediction system (GPS)
EnVar formulation: Preconditioning

- Limited-memory estimate of Hessian initialized with estimate from previous analysis
- With quasi-Newton algorithm, convergence accelerated with negligible computational cost
- Same strategy used with 3D-Var and 4D-Var, also effective for EnVar
Experimental results: Configuration

EnVar tested in comparison with version of forecast system implemented in operations in Feb, 2013:
• model top at 0.1hPa, 80 levels
• model has ~25km grid spacing
• 4D-Var analysis increments with ~100km grid spacing

EnVar experiments use ensemble members from new configuration of EnKF:
• 192 members every 60min in 6-hour window
• model top at 2hPa, 75 levels
• model ~66km grid spacing → EnVar increments ~66km
EnVar uses Hybrid Covariance Matrix
Model top of EnKF is lower than GDPS

Bens and Bnmc are averaged in troposphere $\frac{1}{2}$ & $\frac{1}{2}$, tapering to 100% Bnmc at and above 6hPa (EnKF model top at 2hPa)

Therefore, EnVar not expected to be better than 3D-Var above ~10-20hPa

Also tested 75% Bens and 25% Bnmc in troposphere, but results slightly worse

Also did preliminary tests with a full outer loop, but degraded the results
Forecast Results: EnVar vs. 4D-Var
Radiosonde verification scores – 6 weeks, Feb/Mar 2011

6h Forecast

**North Tropics**

(a) NH-X

(b) TR

(c) SH-X

**South**

(d) NH-X

(e) TR

(f) SH-X
Forecast Results: EnVar vs. 4D-Var
Radiosonde verification scores – 6 weeks, Feb/Mar 2011

EnVar vs. 4D-Var
120h forecast
North extra-tropics

EnVar vs. 4D-Var
24h forecast
Tropics
Forecast Results: EnVar vs. 3D-Var and 4D-Var
Verification against ERA-Interim analyses – 6 weeks, Feb/Mar 2011

EnVar vs. 3D-Var
120h forecast, global domain

EnVar vs. 4D-Var

- No EnKF covariances transition zone
- ½ EnKF and ½ NMC covariances

U GZ RH T

U GZ RH T

U GZ RH T

U GZ RH T

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Experimental results:
4D-EnVar vs. 3D-EnVar

3D version of EnVar also tested:
only uses EnKF flow-dependent ensembles valid at the centre of the 6h assimilation window, instead of every 60 minutes throughout the window
(both still use $\frac{1}{2}$ & $\frac{1}{2}$ hybrid covariances in the troposphere)

3D-EnVar compared with:
• 4D-EnVar: impact of 4D vs 3D covariances, and
• 3D-Var: impact of using flow dependent vs purely stationary (NMC) covariances (both 3D)
Forecast Results: 4D-EnVar vs. 3D-EnVar
Verification against ERA-Interim analyses – 4 weeks, Feb 2011

North extra-tropics
500hPa GZ correlation anomaly

4D-EnVar vs. 3D-EnVar

3D-EnVar vs. 3D-Var
Forecast Results: 4D-EnVar vs. 3D-EnVar
Verification against ERA-Interim analyses – 4 weeks, Feb 2011

South extra-tropics
500hPa GZ correlation anomaly

4D-EnVar vs. 3D-EnVar

3D-EnVar vs. 3D-Var
Forecast Results: 4D-EnVar vs. 3D-En-Var
Verification against ERA-Interim analyses – 4 weeks, Feb 2011

Tropics 250hPa U-wind STDDEV

STD and Mean errors against analyses
Variable: UU
Level: 250 hPa
Region: tropiques
2011020100-2011030100
KEH125G
KEH125_G
Against ecmwf

4D-EnVar vs. 3D-EnVar

STD and Mean errors against analyses
Variable: UU
Level: 250 hPa
Region: tropiques
2011020100-2011030100
K3H125 J
KEH125G
Against ecmwf

3D-EnVar vs. 3D-Var

Change in STD error
000 024 048 072 096 120
0.00 0.05 0.10 0.15 0.20 0.25
0.00 0.05 0.10 0.15 0.20 0.25
Forecast Lead Time (hr)

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Relative fit to observations: Aircraft T and U obs in 4D-EnVar, 4D-Var, 3D-Var

• Compute stddev of $y - H(x_b)$ and $y - H(x_a)$ and relative fit of each analysis:

$$D = \frac{\text{var} \left( y - H(x_b) \right)}{\text{var} \left( y - H(x_a) \right)}\frac{\text{var} \left( y - H(x_b) \right)}{\text{var} \left( y - H(x_a) \right)}$$

![Graphs showing relative standard deviation of temperature and wind speed over relative time for different analysis methods.](image)
Conclusions

• Comparison of EnVar with 3D-Var and 4D-Var:
  – EnVar produces similar quality forecasts as 4D-Var below ~20hPa in extra-tropics, except southern extra-tropical summer, significantly improved in tropics
  – above ~20hPa, scores similar to 3D-Var, worse than 4D-Var; potential benefit from raising EnKF model top to 0.1hPa

• EnVar as an alternative to 4D-Var:
  – like EnKF, uses full nonlinear model dynamics/physics to evolve covariances; no need to maintain TL/AD version of model
  – makes use of already available 4D EnKF ensembles, improvements to EnKF will benefit all systems
  – more computationally efficient and easier to parallelize than 4D-Var for high spatial resolution and large data volumes
  – computational saving allows increase in analysis resolution and volume of assimilated observations
Next Steps

• Finalize testing EnVar with goal of replacing 4D-Var in global and regional systems early 2014 in combination with:
  – GEM global model: 25km lat-lon grid → 15km Yin-Yang grid
  – CALDAS: new surface analysis system based on an EnKF (see talk by Bernard Bilodeau)
  – EnKF: increased resolution 66km → 50km and ensemble size 192 → 256 members
  – modified satellite radiance bias correction scheme that gives conventional observations more influence on correction
  – improved use of radiosonde (4D) and aircraft data
  – additional AIRS/IASI channels and modified observation error
  – replace digital filter with (4D) incremental analysis update

• Early results from using EnVar in regional prediction system to replace 4D-Var look very promising (see poster by Jean-Francois Caron)
Experimental results:
4D-IAU vs. non-incremental Digital Filter

Preliminary results from testing Incremental Analysis Update (IAU) instead of non-incremental digital filter

4D-EnVar facilitates modified IAU approach using 4D analysis increments

IAU also gives natural way for cycling clouds, turbulence fields, etc. within assimilation cycle (previously not done)

Preliminary results look promising
Forecast Results: 4D-IAU vs. DF (non-incremental)

Radiosonde verification scores – 4 weeks, Feb 2011

120h global forecasts
Forecast Results: 4D-IAU vs. DF (non-incremental)

Verification against ERA-Interim analyses – 1 week, Feb 2011

24h forecasts, tropics
Large improvement in surface pressure

Wave-2 difference in mean surface pressure in the tropics likely related to impact of DF on semi-diurnal tide.
Extra Slides Follow
EnVar: a possible replacement of 4D-Var

Overall, EnVar analysis ~6X faster than 4D-Var on half as many cpus, even though higher resolution increments Wall-clock time of 4D-Var already close to allowable time limit; increasing number of processors has negligible impact To progress with 4D-Var, significant work would be required to improve scalability of TL/AD versions of forecast model at resolutions and grid configuration used in 4D-Var Current focus for model is on development of higher-resolution global Yin-Yang configuration that scales well Decision made to try to replace 4D-Var with more efficient EnVar → if EnVar is at least as good as current 4D-Var
EnVar formulation

- In 4D-Var the 3D analysis increment is evolved in time using the TL/AD forecast model (here included in $H_{4D}$):

$$J(\Delta x) = \frac{1}{2}(H_{4D}[x_b] + H_{4D}\Delta x - y)^T R^{-1}(H_{4D}[x_b] + H_{4D}\Delta x - y) + \frac{1}{2}\Delta x^T B^{-1}\Delta x$$

- In EnVar the background-error covariances and analysed state are explicitly 4-dimensional, resulting in cost function:

$$J(\Delta x_{4D}) = \frac{1}{2}(H_{4D}[x_b] + H\Delta x_{4D} - y)^T R^{-1}(H_{4D}[x_b] + H\Delta x_{4D} - y) + \frac{1}{2}\Delta x_{4D}^T B_{4D}^{-1}\Delta x_{4D}$$
4D error covariances
Temporal covariance evolution (explicit vs. implicit evolution)

EnKF and EnVar (4D B matrix):

192 NLM integrations provide 4D background-error covariances

4D-Var:

TL/AD inner loop integrations,
2 outer loop iterations,
then 3h NLM forecast

↑ “analysis time”
Forecast Results: EnVar vs. 4D-Var
Radiosonde verification scores – 6 weeks, Jul/Aug 2011

North

6h forecast

Tropics

South

6h forecast

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<th>Temperature (°C)</th>
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<table>
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North extra-tropics
500hPa GZ correlation anomaly

EnVar vs. 3D-Var

EnVar vs. 4D-Var
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Verification against ERA-Interim analyses – 6 weeks, Feb/Mar 2011

South extra-tropics
500hPa GZ correlation anomaly

EnVar vs. 3D-Var
This is the only significant degradation seen vs. 4D-Var in troposphere;
Not in radiosonde scores because it originates from south of 45°S

EnVar vs. 4D-Var
Forecast Results: EnVar vs. 3D-Var and 4D-Var

Verification against ERA-Interim analyses – 6 weeks, Feb/Mar 2011

Tropics
250hPa U-wind STDDEV

Variable : UU
Level : 250 hPa
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Verification against ERA-Interim analyses – 6 weeks, July-Aug 2011

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500hPa GZ correlation anomaly

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Verification against ERA-Interim analyses – 6 weeks, July-Aug 2011

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Tropics
250hPa U-wind STDDEV
Relative fit to observations:
AMSU-A obs in 4D-EnVar, 4D-Var, 3D-Var

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