Intercomparison of variational, EnKF, and ensemble-4D-Var data assimilation approaches in the context of deterministic NWP

Project Team:
Mark Buehner
Cecilien Charette
Bin He
Peter Houtekamer
Herschel Mitchell

Mark Buehner
Data Assimilation and Satellite Meteorology Section
Meteorological Research Division
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Introduction

• **Goal**: compare 4D-Var and EnKF approaches in the context of producing *global deterministic analyses for operational NWP*

• 4D-Var and EnKF:
  – both operational at CMC since 2005
  – both use GEM forecast model
  – both assimilate similar set of observations using mostly the same observation operators and observation error covariances

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

• EnKF (96 members) is used to initialize global Ensemble Prediction System (20 members)
Contents

• Brief description of operational systems
• Configurations used for the intercomparison
• Idealized experiments:
  – effect of covariance localization
  – effect of covariance evolution
• Full analysis-forecast experiments (February 2007)
  – scores from analyses and 56 6-day deterministic forecasts (vs. radiosondes and analyses)
  – precipitation scores against GPCP analyses

• Conclusions
Operational Systems

• 4D-Var
  – operational since March 2005
  – incremental approach: ~35km/150km grid spacing, 58 levels, 10hPa top

• EnKF
  – operational since January 2005
  – 96 ensemble members: ~100km grid spacing, 28 levels, 10hPa top

• Dependence between systems
  – EnKF uses 4D-Var bias correction of satellite observations and quality control for all observations
Experimental Configurations
Modifications relative to operational systems

• Same observations assimilated in all experiments:
  – radiosondes, aircraft observations, AMVs, US wind profilers, QuikSCAT, AMSU-A/B, surface observations
  – eliminated AIRS, SSM/I, GOES radiances from 4D-Var
  – quality control decisions and bias corrections extracted from an independent 4D-Var experiment

• Increased number of levels in EnKF to match 4D-Var
• Increased horizontal resolution of 4D-Var inner loop to match EnKF (but 4D-Var uses Gaussian Grid, EnKF uniform lat-lon)
• Other minor modifications in both systems to obtain nearly identical innovations (each tested to ensure no degradation)
Experimental Configurations

• 3/4D-Var:
  – 3D-FGAT and 4D-Var with $B$ matrix nearly same as operational system (NMC method)
  – 3D-FGAT and 4D-Var with flow-dependent $B$ matrix from EnKF at middle or beginning of assimilation window (same localization parameters as in EnKF)
  – Ensemble-4D-Var (En-4D-Var): use 4D ensemble covariances to produce 4D analysis increment without TL/AD models (most similar to EnKF approach)

• EnKF:
  – Deterministic forecasts initialized with EnKF ensemble mean analysis (requires interpolation from ~100km to ~35km grid)
Experimental Configurations

Remaining differences between two systems

• Differences in spatial localization (most evident with radiance obs):
  – 4D-Var: \( K = (\rho \circ P)H^T \left( H(\rho \circ P)H^T + R \right)^{-1} \) (also En-4D-Var approach)
  – EnKF: \( K = \rho \circ (P H^T) \left( \rho \circ (PH^T) + R \right)^{-1} \)

• Differences in temporal propagation of error covariances:
  – 4D-Var: implicitly done with TL/AD model (with NLM from beginning to middle of assimilation window)
  – EnKF: explicitly done with NLM in subspace of background ensemble (also En-4D-Var approach)

• Differences in solution technique:
  – 4D-Var: limited convergence towards global solution (30+25 iterations)
  – EnKF: sequential-in-obs-batches explicit solution (not equivalent to global solution)

• Differences in time interpolation to obs in assimilation window:
  – 4D-Var: 45min timestep, nearest neighbour (NN) interpolation in time
  – EnKF: 90min timestep, linear interpolation in time
  – En-4D-Var: 45min, NN for innovation, 90min, linear interp. for increment
Single observation experiments
Difference in vertical localization between 3D-Var and EnKF

- AMSU-A ch9
- peak sensitivity near 70hPa
- with same $B$, increment **slightly** larger & less local with 3D-Var than EnKF
- without localization increments nearly identical
Single observation experiments
Difference in vertical localization between 3D-Var and EnKF

- all AMSU-A channels (4-10)
- with same B, largest differences near model top

- entire temp. profile of nearby raob
- all experiments give more similar increments
- same general shape as with AMSU-A in layer 150hPa-700hPa
4D error covariances
Temporal covariance evolution

3D-Var-Benkf:
96 NLM integrations

EnKF (and En-4D-Var):
96 NLM integrations

4D-Var-Benkf:
96 NLM
55 TL/AD integrations, 2 outer loop iterations
Single observation experiments
Difference in temporal covariance evolution

- radiosonde temperature observation at 500hPa
- observation at beginning of assimilation window (-3h)
- with same B, increments very similar from 4D-Var, EnKF
- contours are 500hPa GZ background state at 0h (ci=10m)
Single observation experiments
Difference in temporal covariance evolution

- radiosonde temperature observation at 500hPa
- observation at middle of assimilation window (+0h)
- with same B, increments very similar from 4D-Var, EnKF
- contours are 500hPa GZ background state at 0h (ci=10m)

Contour plots at 500 hPa
Single observation experiments
Difference in temporal covariance evolution

- radiosonde temperature observation at 500hPa
- observation at end of assimilation window (+3h)
- with same B, increments very similar from 4D-Var, EnKF
- contours are 500hPa GZ background state at 0h (ci=10m)
Analysis and Forecast Verification Results – 4D-Var, EnKF and 4D-Var with EnKF covariances

EnKF (ensemble mean) vs. 4D-Var-Bnmc and 4D-Var-Benkf vs. 4D-Var-Bnmc
Analysis Results (O-A) – global

EnKF mean analysis vs. 4D-Var-Bnmc

4D-Var-Benkf vs. 4D-Var-Bnmc

stddev & bias relative to radiosondes

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Forecast Results:
EnKF (ens mean) vs. 4D-Var-Bnmc

Difference in stddev relative to radiosondes:

Positive $\Rightarrow$ EnKF better

Negative $\Rightarrow$ 4D-Var-Bnmc better
Forecast Results: EnKF (ens mean) vs. 4D-Var-Bnmc

Significance level of difference in stddev relative to radiosondes:

Positive → EnKF better

Negative → 4D-Var-Bnmc better

Computed using bootstrap resampling of the individual scores for the 56 cases (28 days, twice per day).

Shading for 90% and 95% confidence levels

Environnement Canada

Environment Canada
Forecast Results: 4D-Var-Benkf vs. 4D-Var-Bnmc

**Difference in stddev relative to radiosondes:**

- **Positive →** 4D-Var-Benkf better
- **Negative →** 4D-Var-Bnmc better
Forecast Results:
4D-Var-Benkf vs. 4D-Var-Bnmc

Significance level of difference in stddev relative to radiosondes:

Positive →
4D-Var-Benkf better

Negative →
4D-Var-Bnmc better

Computed using bootstrap resampling of the individual scores for the 56 cases (28 days, twice per day).

Shading for 90% and 95% confidence levels.
Results – 500hPa GZ anomaly correlation
Verifying analyses from 4D-Var with Bnmc
Forecast Results – Precipitation
24-hour accumulation verified against GPCP analyses

Equitable Threat Score for Tropics

EnKF (ens mean)
4D-Var-Bnmc

4D-Var-Benkf
4D-Var-Bnmc

threshold (mm)
Analysis and Forecast Verification Results – Differences in covariance evolution

En-4D-Var vs. 3D-Var-Benkf
and
En-4D-Var vs. 4D-Var-Benkf
Temporal covariance evolution

3D-Var-Benkf:
- 96 NLM integrations

En-4D-Var:
- 96 NLM integrations

4D-Var-Benkf:
- 96 NLM
- 55 TL/AD integrations, 2 outer loop iterations
Forecast Results: En-4D-Var vs. 3D-Var-Benkf

Difference in stddev relative to radiosondes:

**Positive** ⇒ En-4D-Var better

**Negative** ⇒ 3D-Var-Benkf better
Forecast Results: En-4D-Var vs. 3D-Var-Benkf

Significance level of difference in stddev relative to radiosondes:

Positive → En-4D-Var better

Negative → 3D-Var-Benkf better

Shading for 90% and 95% confidence levels
Forecast Results:
En-4D-Var vs. 4D-Var-Benkf

Difference in stddev relative to radiosondes:
- **Positive**: En-4D-Var better
- **Negative**: 4D-Var-Benkf better

- **Zonal Wind**
  - North
  - Tropics
  - South

- **Temperature**
  - North
  - Tropics
  - South

- **Height**
  - North
  - Tropics
  - South
Forecast Results: En-4D-Var vs. 4D-Var-Benkf

**Significance level of difference** in stddev relative to radiosondes:

Positive → En-4D-Var better

Negative → 4D-Var-Benkf better

Shading for 90% and 95% confidence levels
Results – 500hPa GZ anomaly correlation
Verifying analyses from 4D-Var with Bnmc

Northern hemisphere

Southern hemisphere

3D-Var Benkf
En-4D-Var
4D-Var Benkf

3D-Var Benkf
En-4D-Var
4D-Var Benkf
Conclusions

Based on 1-month data assimilation experiments

• Deterministic forecasts initialized with 4D-Var with operational B and EnKF (ensemble mean) analyses have comparable quality (4D-Var better in north, EnKF better in tropics and south but with spin-up problem in tropics)

• Largest impact (~10h gain at day 5) in southern extra-tropics for 4D-Var with flow-dependent EnKF B vs. 4D-Var with operational B (also better in tropics)

• Use of 4D ensemble B (i.e. En-4D-Var) improves on 3D-Var, but inferior to 4D-Var (both with 3D ensemble B) and least sensitive to covariance evolution in tropics