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

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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)

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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

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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

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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)

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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)

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Experimental Configurations
Remaining differences between two systems

- Differences in spatial localization (most evident with radiance obs):
  - 4D-Var: $\mathbf{K} = (\rho \circ \mathbf{P})\mathbf{H}^T (\mathbf{H}(\rho \circ \mathbf{P})\mathbf{H}^T + \mathbf{R})^{-1}$ (also En-4D-Var approach)
  - EnKF: $\mathbf{K} = \rho \circ (\mathbf{P}\,\mathbf{H}^T) (\rho \circ (\mathbf{HPH}^T) + \mathbf{R})^{-1}$

- 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

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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
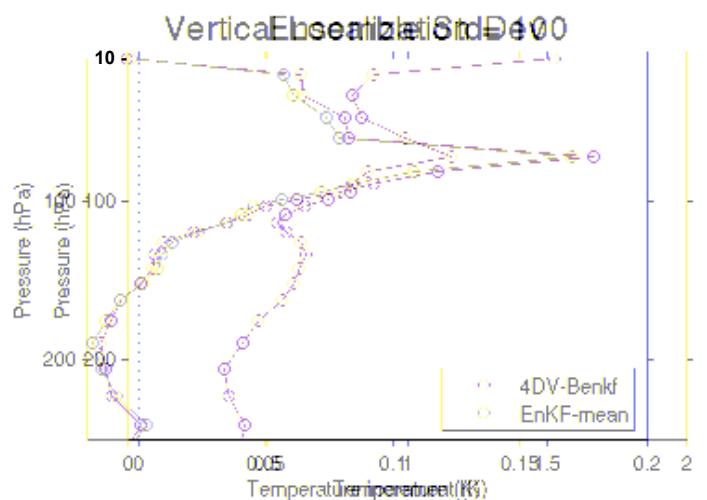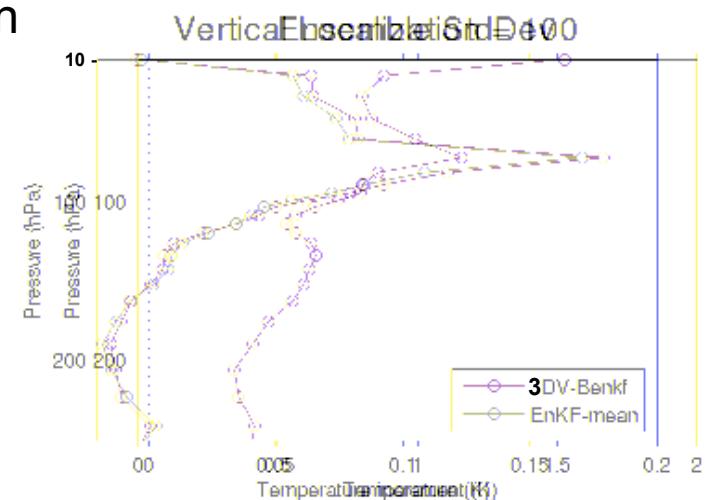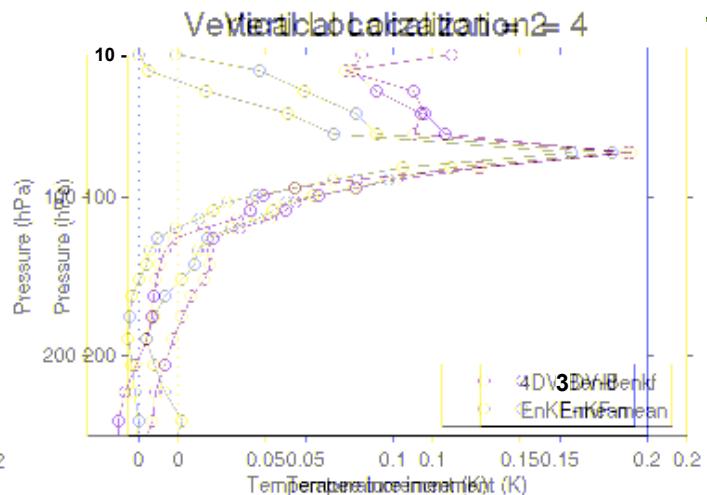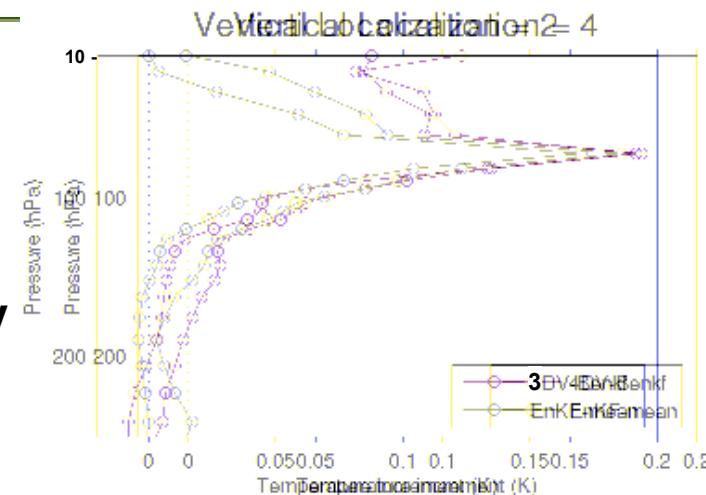
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Single observation experiments
Difference in vertical localization between 3D-Var and EnKF

- 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

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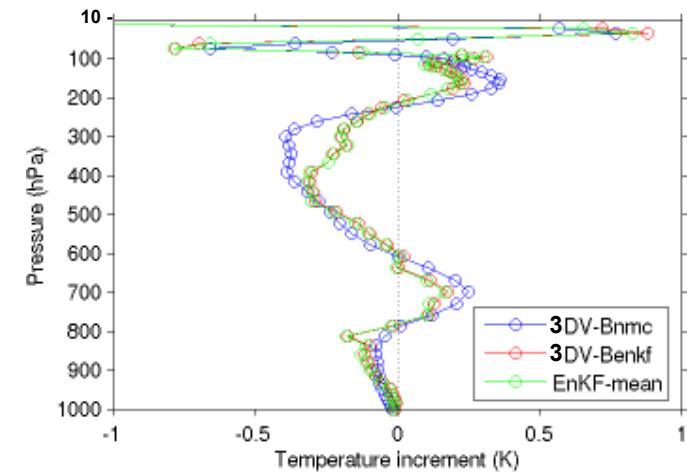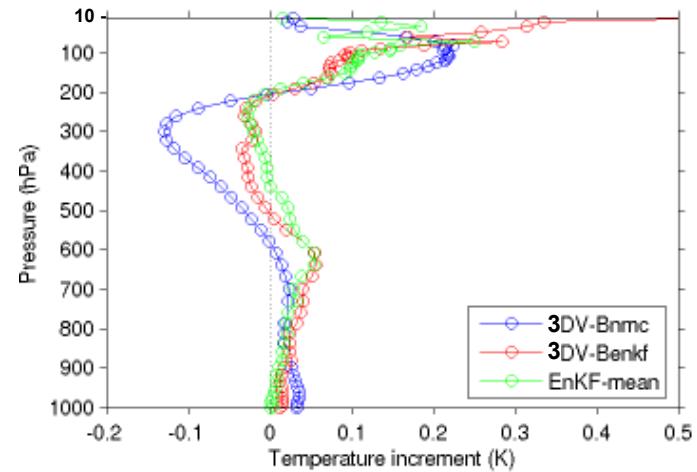
4D error covariances
Temporal covariance evolution
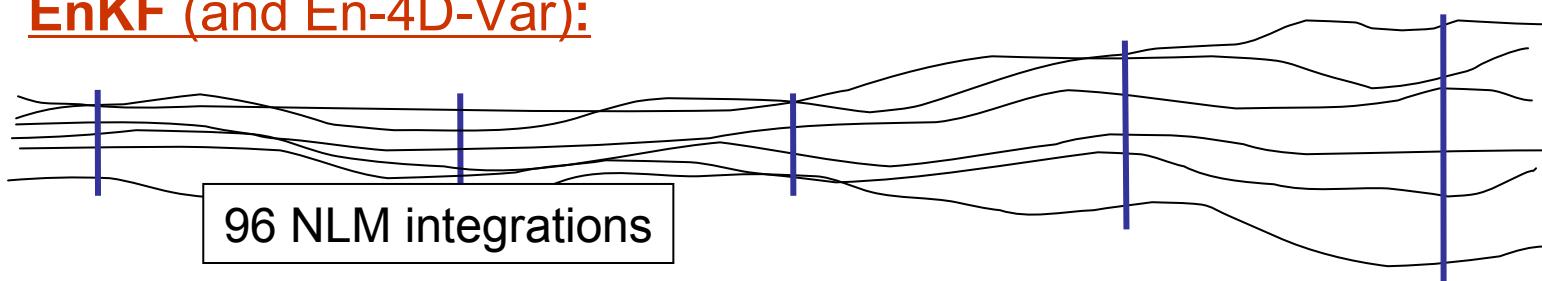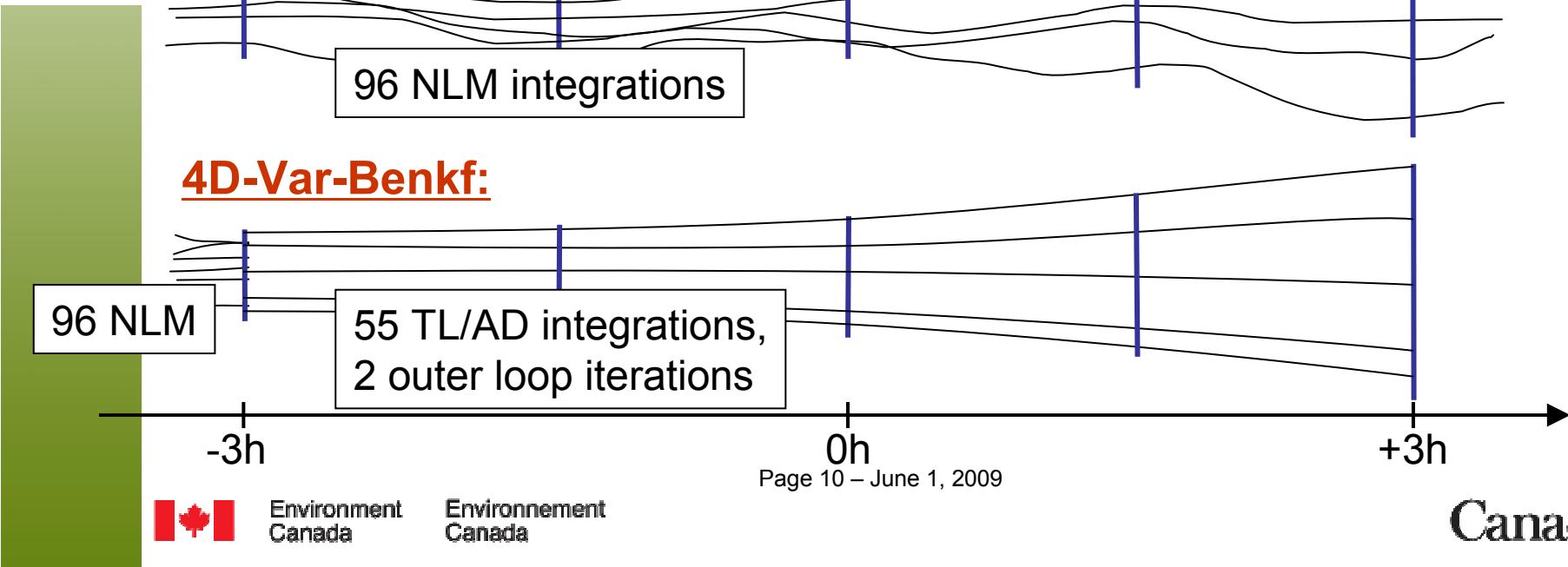
3D-Var-Benkf:

96 NLM integrations

EnKF (and En-4D-Var)**:**

96 NLM integrations

4D-Var-Benkf:

96 NLM

55 TL/AD integrations,
2 outer loop iterations

-3h

0h

+3h

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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)

4D-Var with Bnmc

En -4D-Var

contour plots at 500 hPa

4D-Var with Benkf

EnKF ensemble mean

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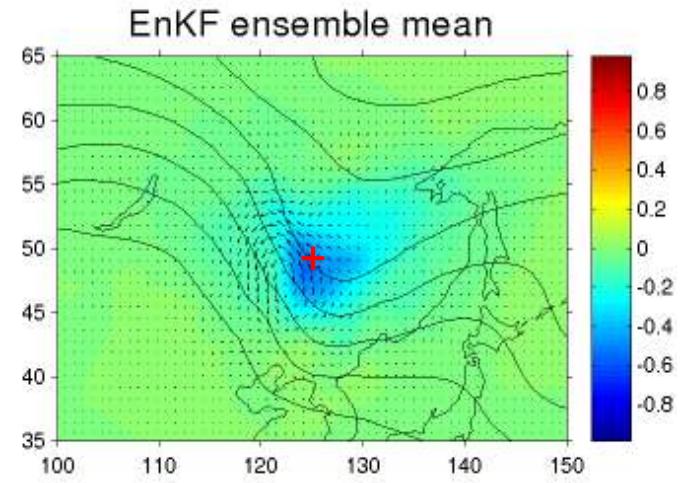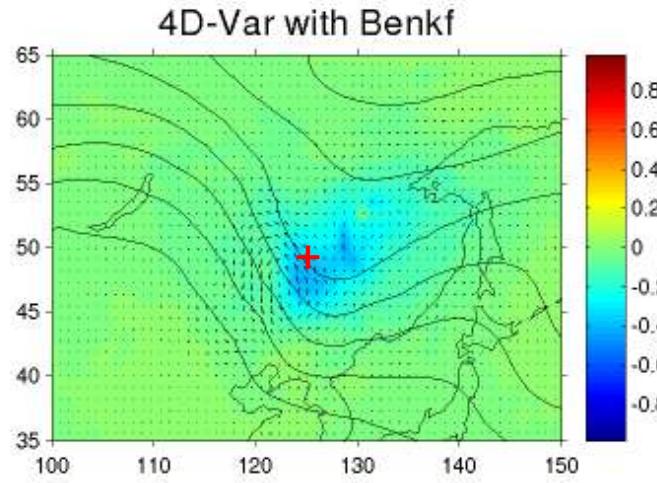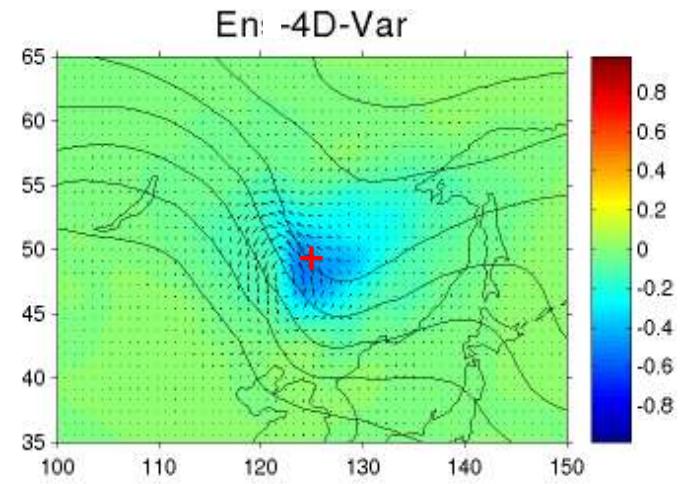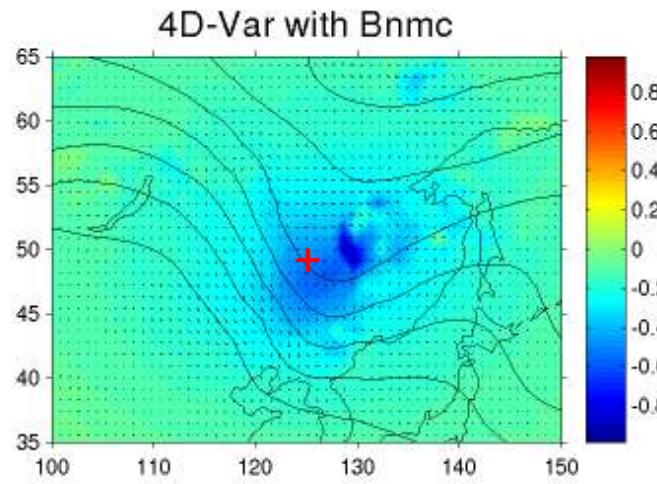
Single observation experiments
Difference in temporal covariance evolution

- 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)

4D-Var with Bnmc

En -4D-Var

contour plots at 500 hPa

4D-Var with Benkf

EnKF ensemble mean

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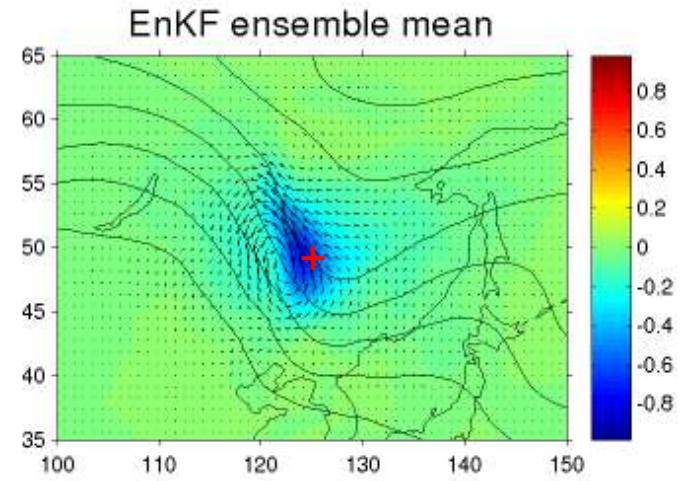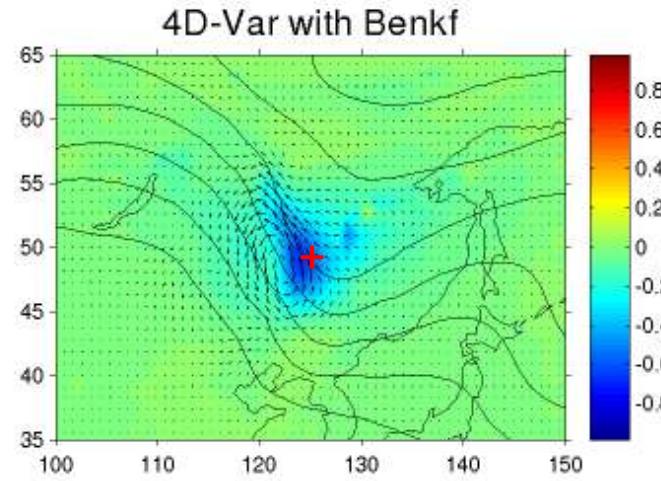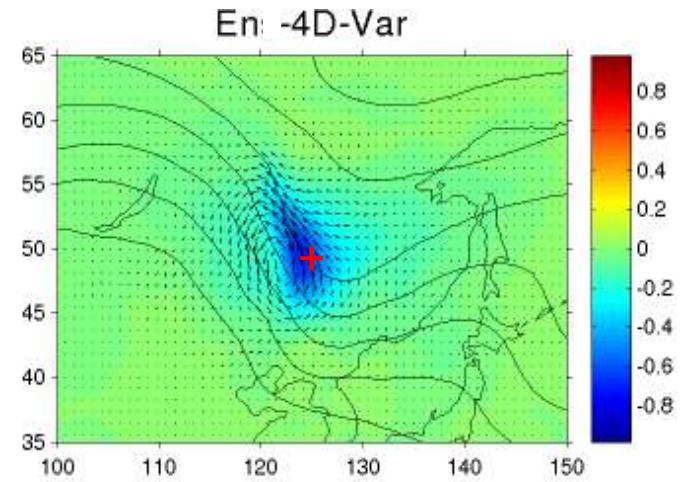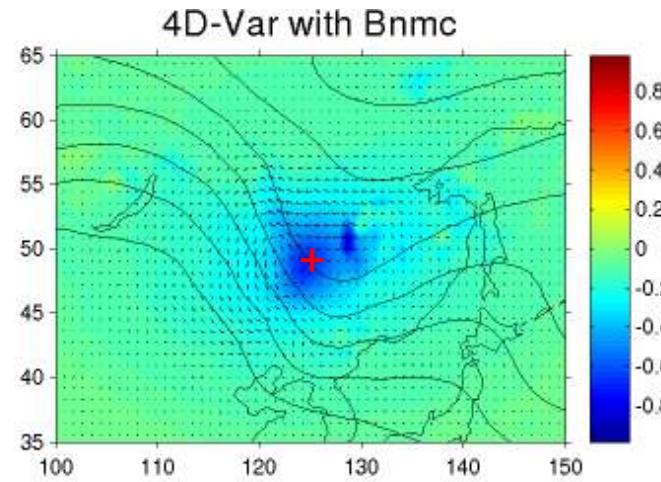
Single observation experiments
Difference in temporal covariance evolution

- 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)

4D-Var with Bnmc

Ens-4D-Var

contour plots at 500 hPa

4D-Var with Benkf

EnKF ensemble mean

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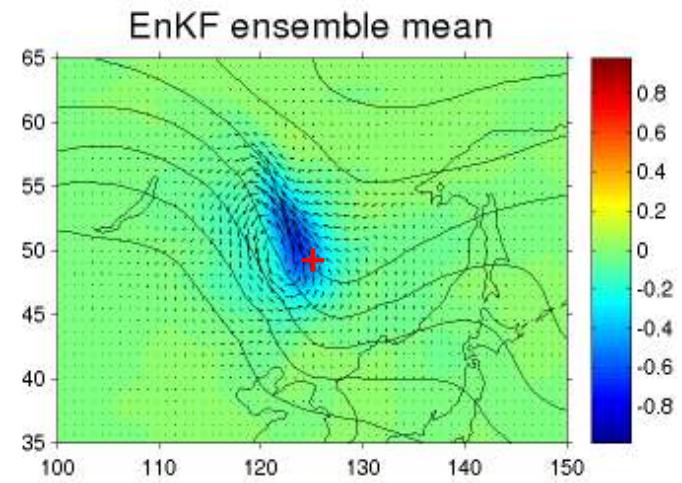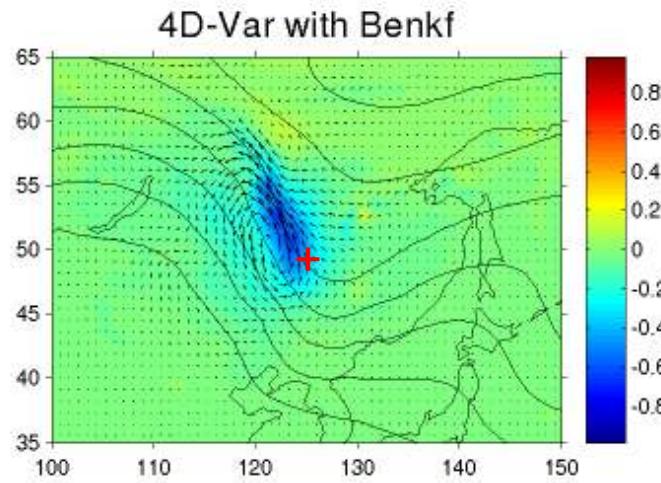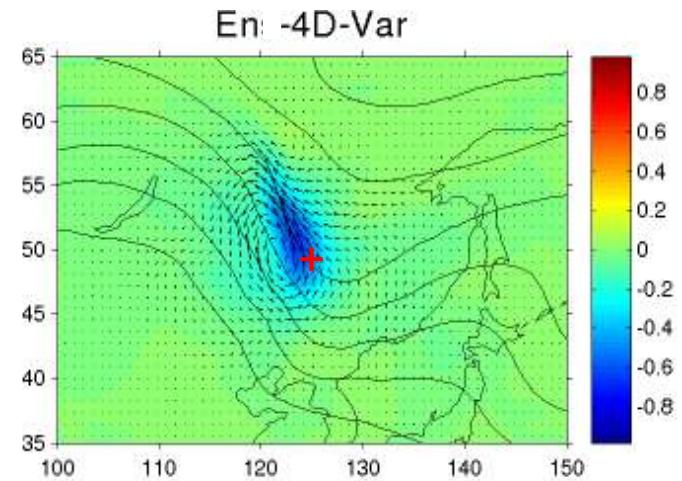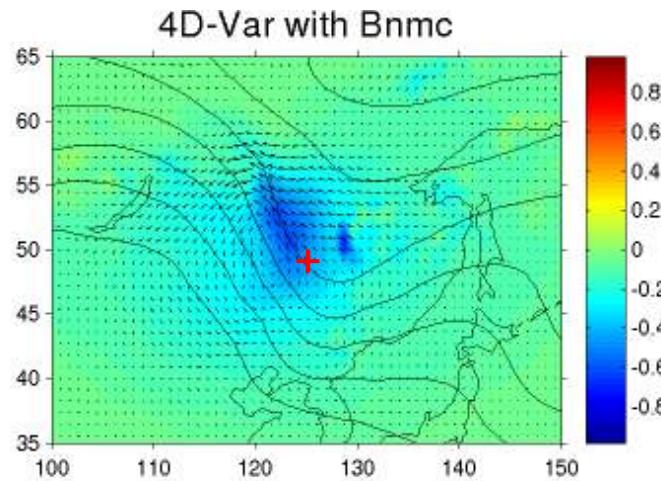
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Analysis and Forecast Verification Results – 4D-Var, EnKF and 4D-Var with EnKF covariances

EnKF (ensemble mean) vs. 4D-Var-Bnmc

and

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

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Analysis Results (O-A) – global

EnKF mean analysis vs. 4D-Var-Bnmc
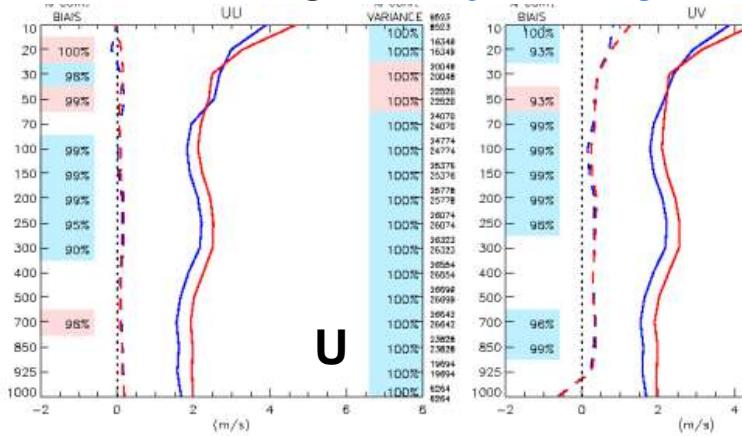
4D-Var-Benkf vs. 4D-Var-Bnmc
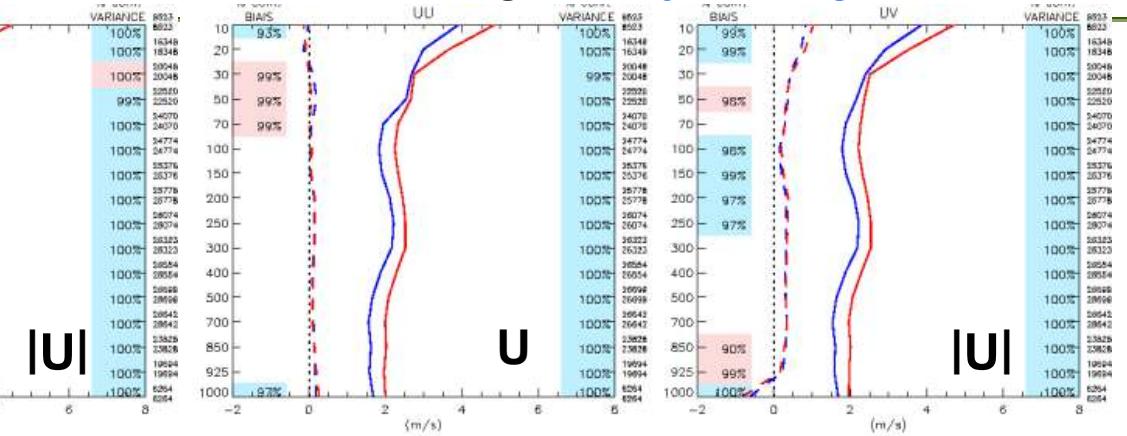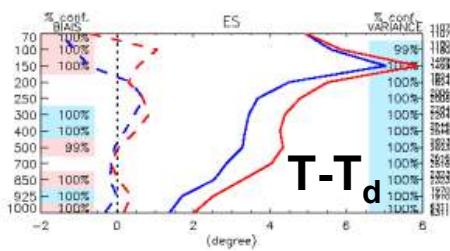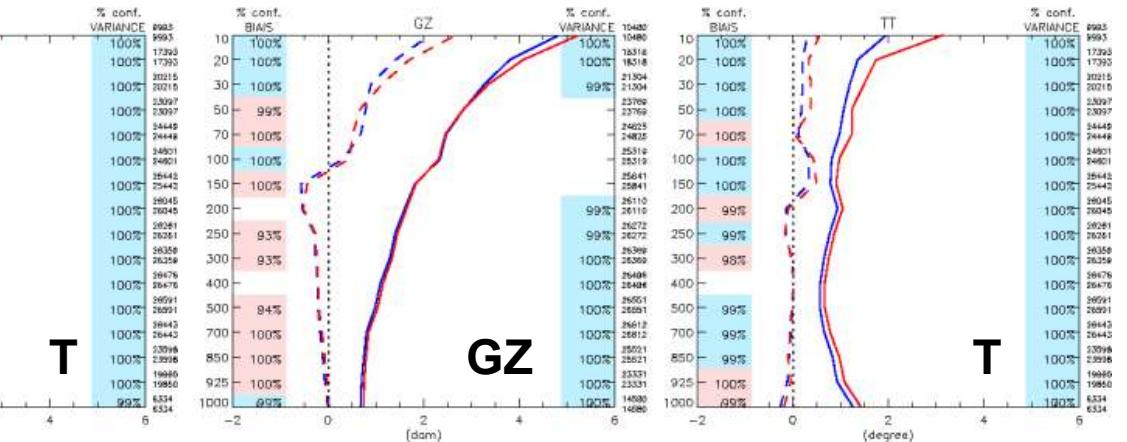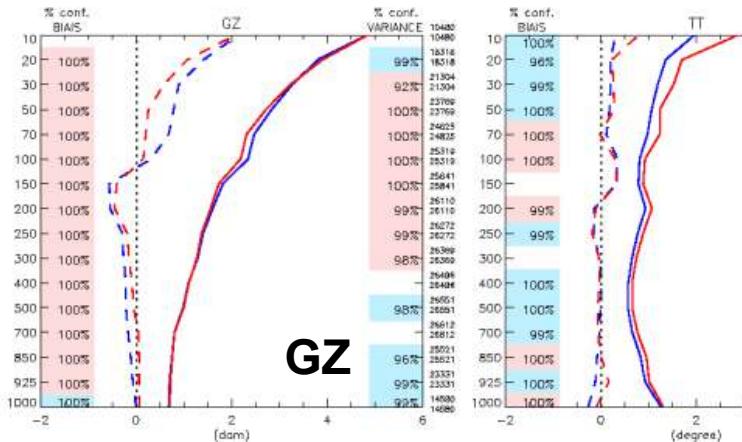
stddev & bias relative to radiosondes
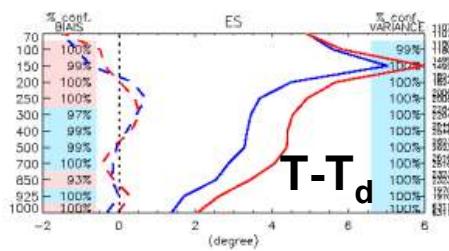
stddev & bias relative to radiosondes

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

Difference in stddev relative to radiosondes:

Positive →
EnKF better

Negative →
4D-Var-Bnmc better

zonal wind

temp.

height

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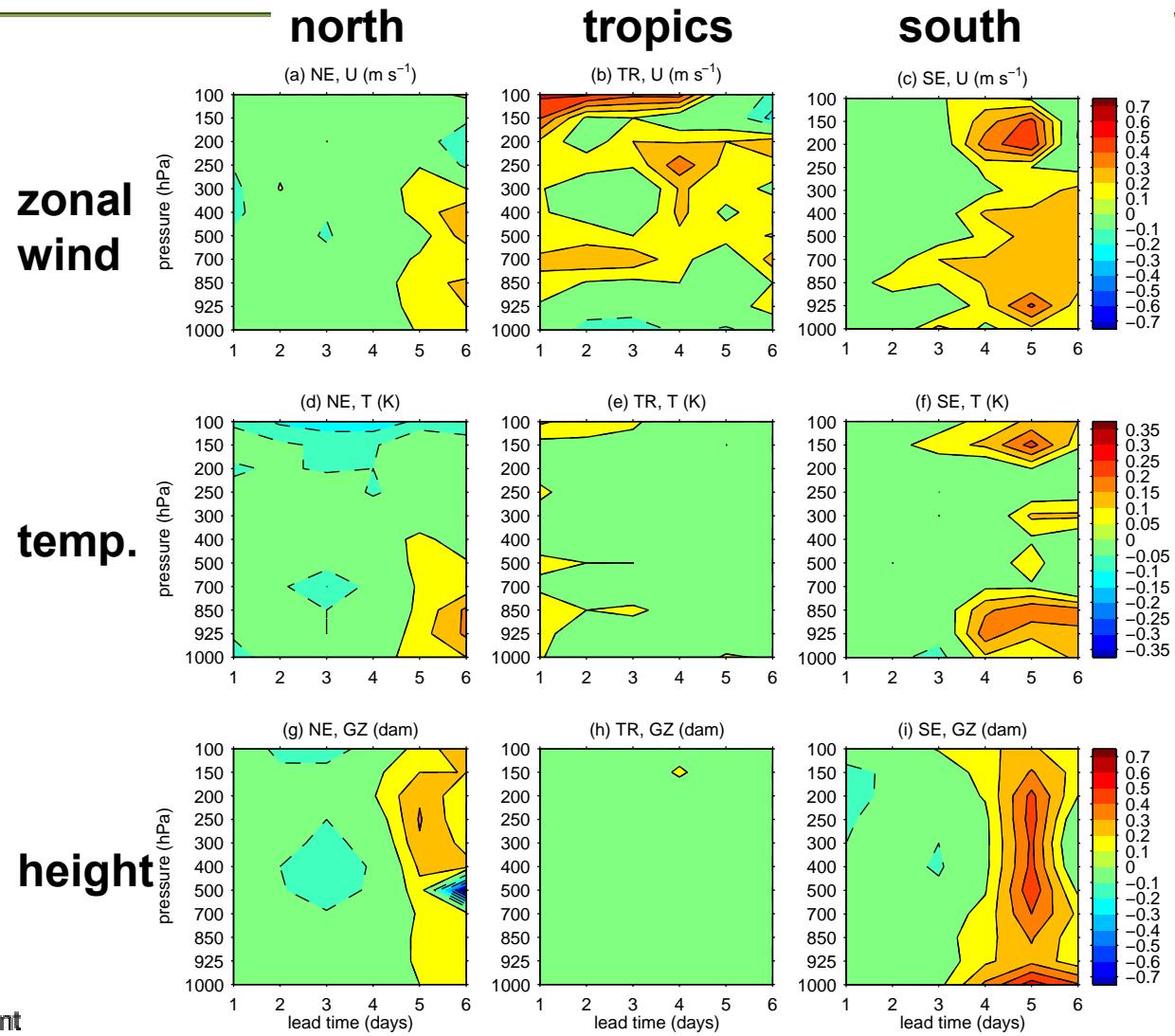
Forecast Results:
EnKF (ens mean) vs. 4D-Var-Bnmc

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

zonal wind

temp.

height

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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

zonal wind

temp.

height

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

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Results – 500hPa GZ anomaly correlation
## Verifying analyses from 4D-Var with Bnmc

Northern extra-tropics

Southern extra-tropics

4D-Var Bnmc
4D-Var Benkf
EnKF (ens mean)

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Forecast Results – Precipitation
24-hour accumulation verified against GPCP analyses

Equitable Threat Score
for Tropics

day 1   day 2   day 3

EnKF (ens mean)
4D-Var-Bnmc

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

threshold (mm)

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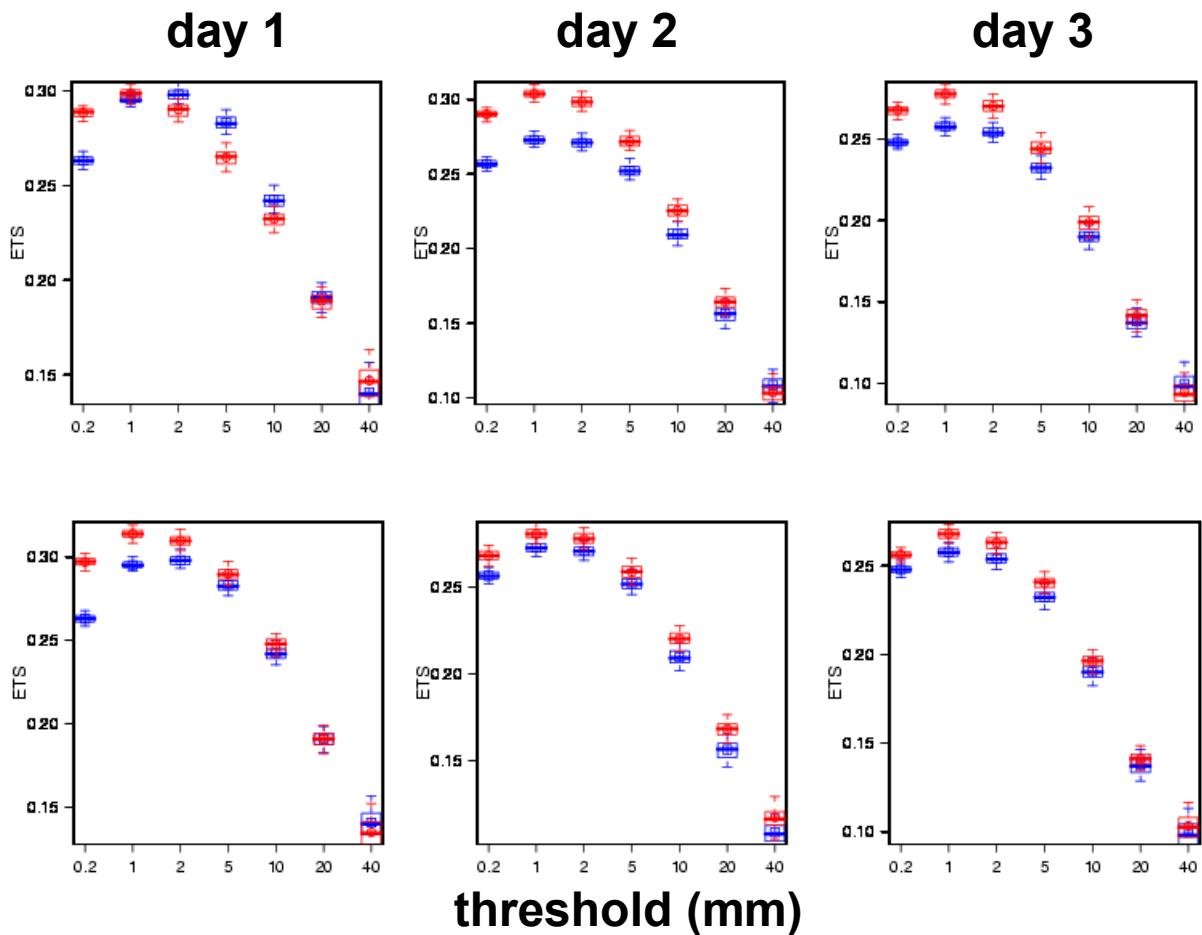
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Analysis and Forecast Verification Results – Differences in covariance evolution

En-4D-Var vs. 3D-Var-Benkf

and

En-4D-Var vs. 4D-Var-Benkf

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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

-3h

0h

+3h

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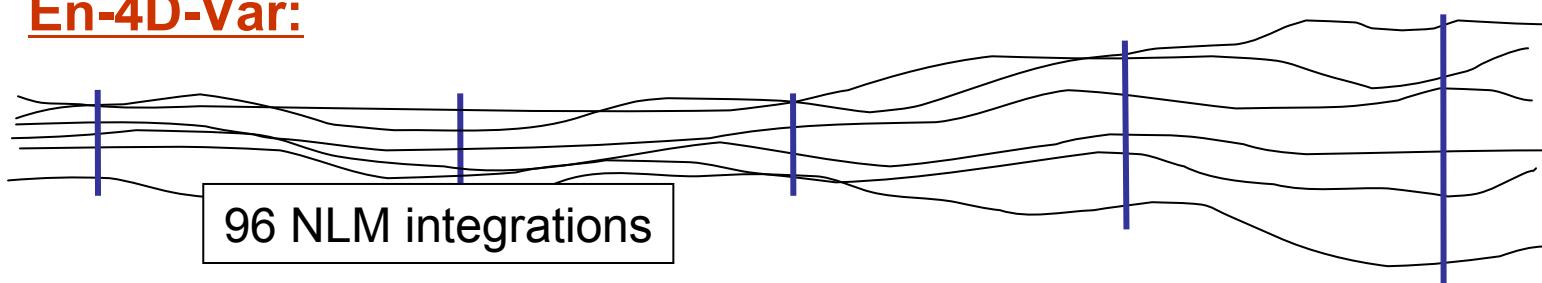
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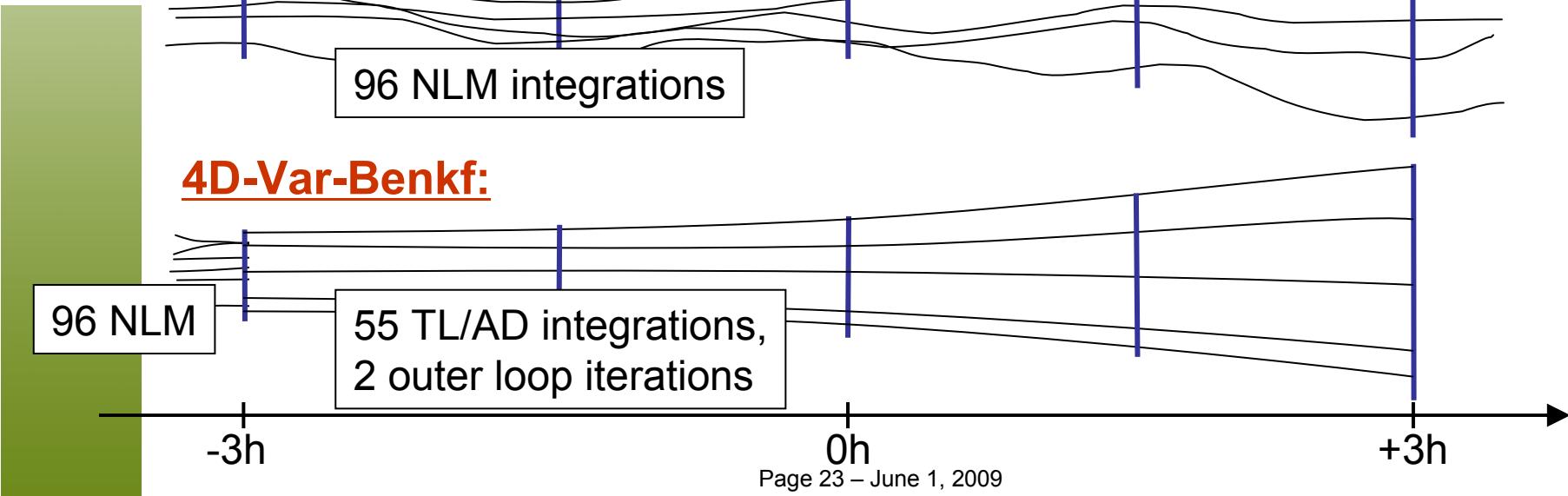
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Forecast Results:
En-4D-Var vs. 3D-Var-Benkf

Difference in stddev relative to radiosondes:

Positive →
En-4D-Var better

Negative →
3D-Var-Benkf better

zonal wind
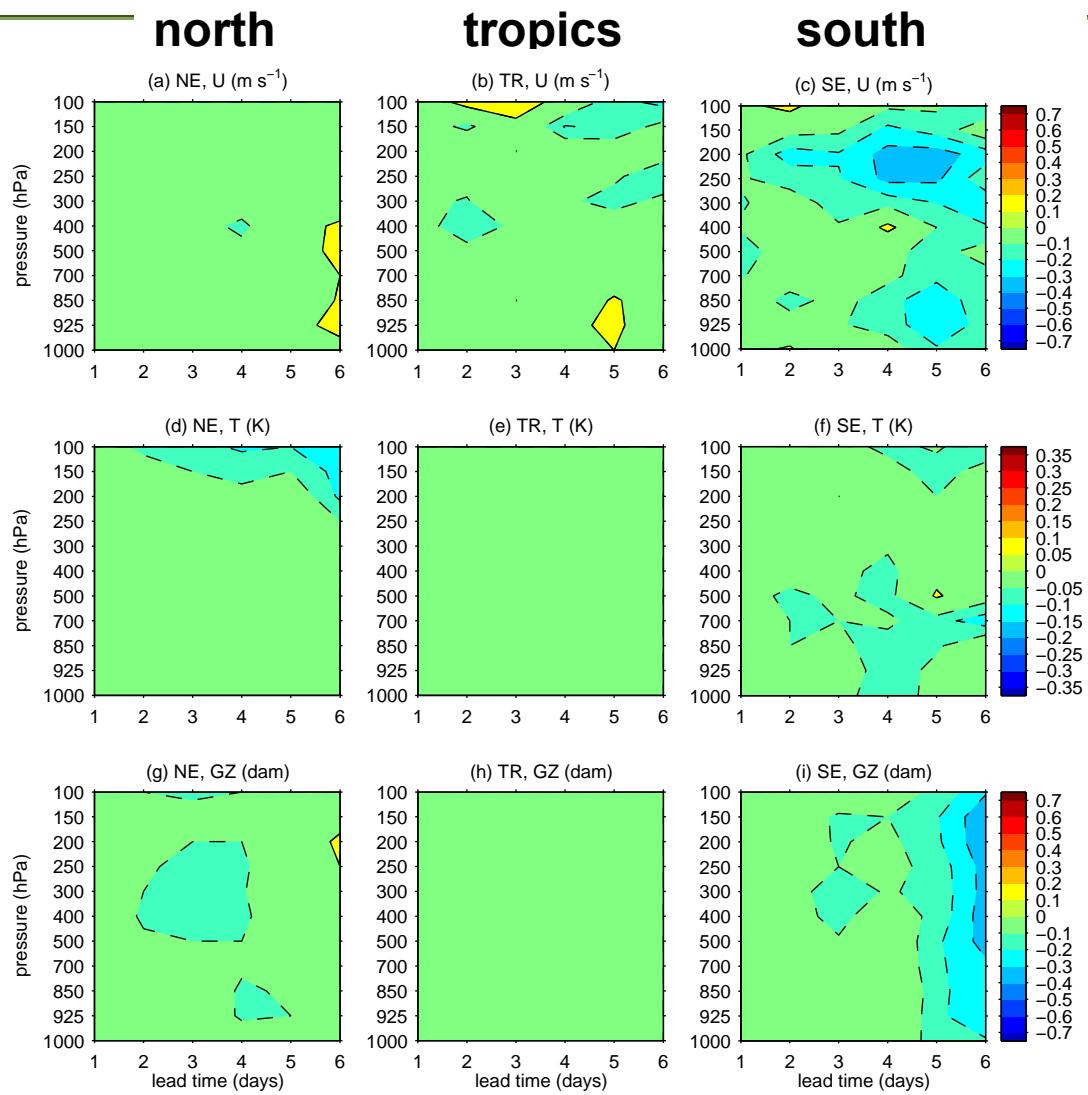
temp.

height

north   tropics   south

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

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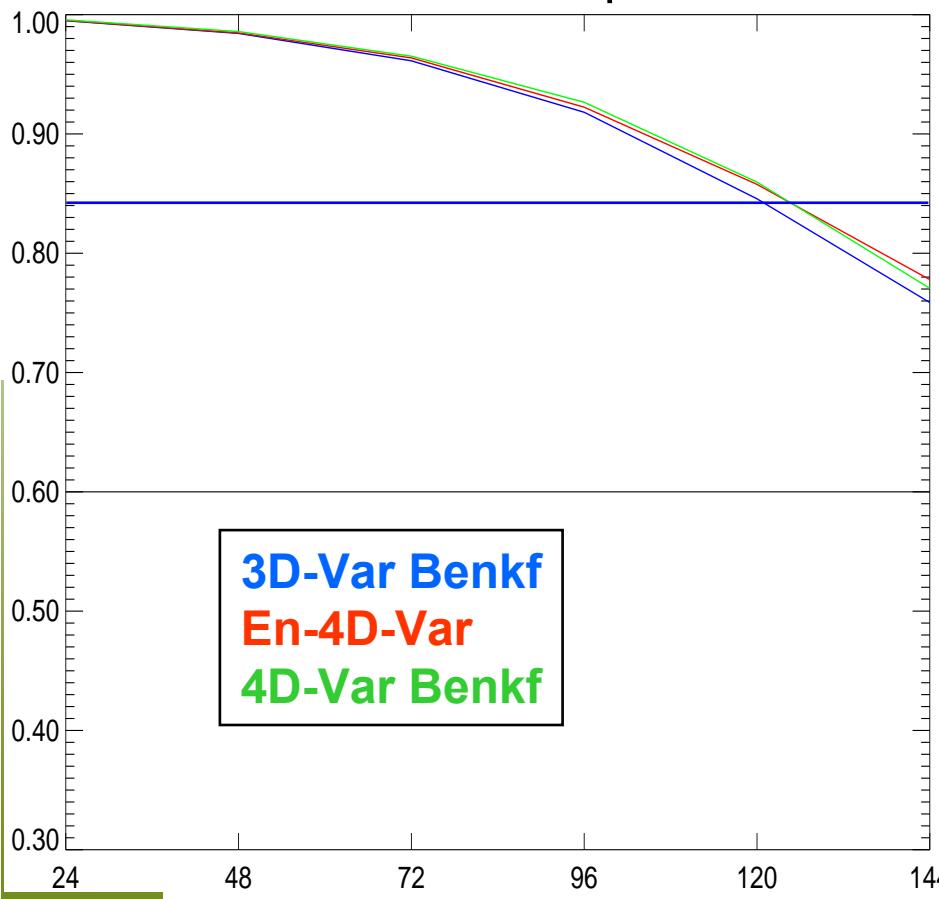
3D-Var Benkf
En-4D-Var
4D-Var Benkf

Southern hemisphere

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

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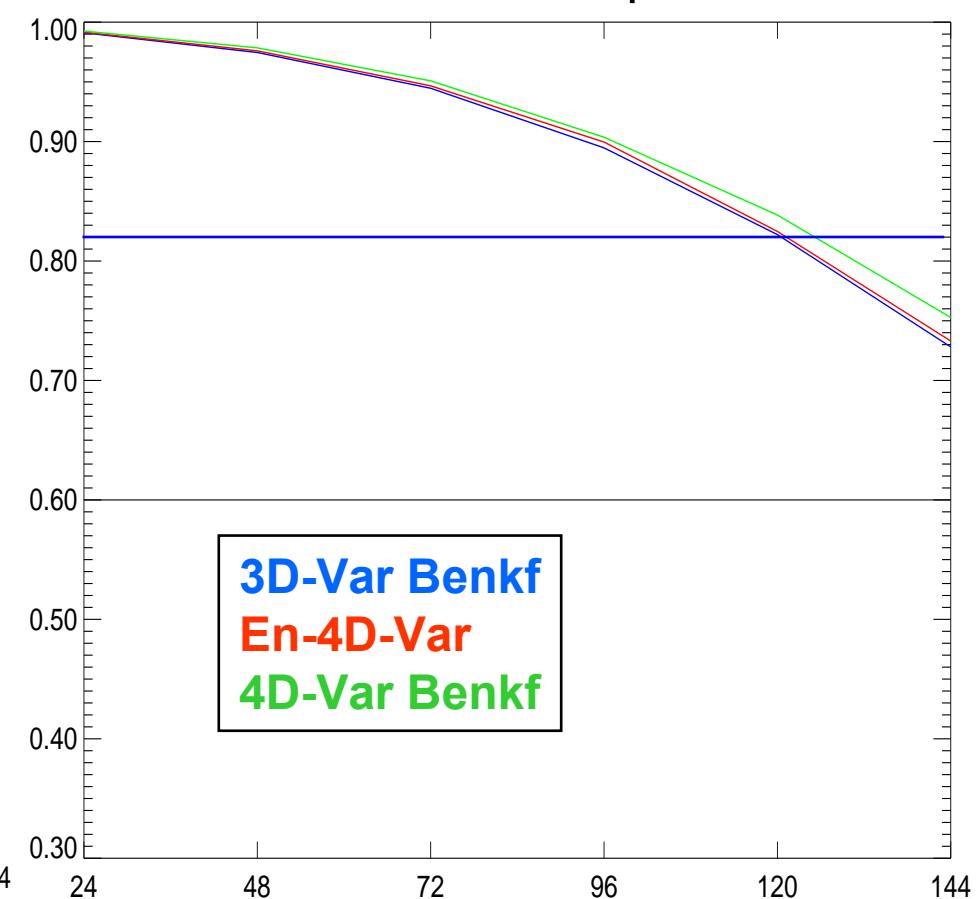
Conclusions
Based on 1-month data assimilation experiments

- 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

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