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A comparison of Ensemble-Variational (EnVar) data assimilation and 4D-Var for global deterministic weather prediction

Mark Buehner[1], Josée Morneau[2] and Cecilien Charette[1]

[1]Data Assimilation and Satellite Meteorology Research Section

[2]Data Assimilation and Quality Control Development Section

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Contents

- Background
- The ensemble-variational (EnVar) data assimilation approach
- Recent results from using EnVar compared with standard 3D-Var and 4D-Var (but NO comparisons with 4D-Var-Ben or EnKF)
- Conclusions and next steps

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 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
- Results presented at WMO workshop on intercomparison of 4D-Var and EnKF, Buenos Aires, November 2008 (Buehner et al 2010)

Ensemble-Variational assimilation: EnVar

- EnVar approach is currently being tested in the context of replacing 4D-Var in the operational Global Deterministic Prediction System
- 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 NMC-method covariances
- Like 4D-Var, EnVar uses an incremental approach with:
  - analysis increment at the horizontal/temporal resolution of EnKF ensembles
  - background state and analysis at the horizontal/temporal resolution of the higher-resolution deterministic forecast model

EnVar formulation

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

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

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

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

- Computations involving ensemble-based $\mathbf{B}_{4D}$ can be more expensive than with $\mathbf{B}_{nmc}$ depending on ensemble size and spatial/ temporal resolution, but significant parallelization is possible

EnVar formulation: Preconditioning

- Preconditioned cost function formulation at Environment Canada:

$$J(\xi) = \frac{1}{2}\xi^T\xi + \frac{1}{2}(H_{4D}(\mathbf{x}_b) + \mathbf{H}\Delta\mathbf{x}(\xi) - \mathbf{y})^T \mathbf{R}^{-1}(H_{4D}(\mathbf{x}_b) + \mathbf{H}\Delta\mathbf{x}(\xi) - \mathbf{y})$$

- In EnVar with hybrid covariances, the control vector (ξ) is composed of 2 vectors:

$$[\xi] = \begin{bmatrix} \xi_{\text{nmc}} \\ \xi_{\text{ens}} \end{bmatrix} \quad \rightarrow \quad [\xi_{\text{ens}}] = \begin{bmatrix} \xi_{\text{ens}}^1 \\ \vdots \\ \xi_{\text{ens}}^{N_{\text{ens}}} \end{bmatrix}$$

- The analysis increment is computed as ($\mathbf{e}_k$ is k'th ensemble perturbation divided by sqrt(N_{ens}-1)):

$$\Delta\mathbf{x}(\xi) = \beta_{\text{nmc}}^{1/2}\mathbf{B}_{\text{nmc}}^{1/2}\xi_{\text{nmc}} + \beta_{\text{ens}}^{1/2}\sum_{k=1}^{N_{\text{ens}}}\mathbf{e}_k \circ (\mathbf{L}^{1/2}\xi_{\text{ens}}^k) \quad \rightarrow \quad \mathbf{B} = \beta_{\text{nmc}}\mathbf{B}_{\text{nmc}} + \beta_{\text{ens}}\sum_{k=1}^{N_{\text{ens}}}(\mathbf{e}_k\mathbf{e}_k^T)\circ\mathbf{L}$$

- Better preconditioned than original "alpha control vector" formulation (with $\mathbf{L}^{-1}$ and $1/\beta$ in background term of J)
- Most, but maybe not all, applications of the approach use the better preconditioned formulation

Experimental results:
Configuration

EnVar tested in comparison with new version of forecast system currently being implemented in operations:

- model top at 0.1hPa, 80 levels
- ~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
- ~66km grid spacing → EnVar increments ~66km grid spacing

Experimental results:
Computational cost

Overall, EnVar analysis ~3X 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 uses Hybrid Covariance Matrix

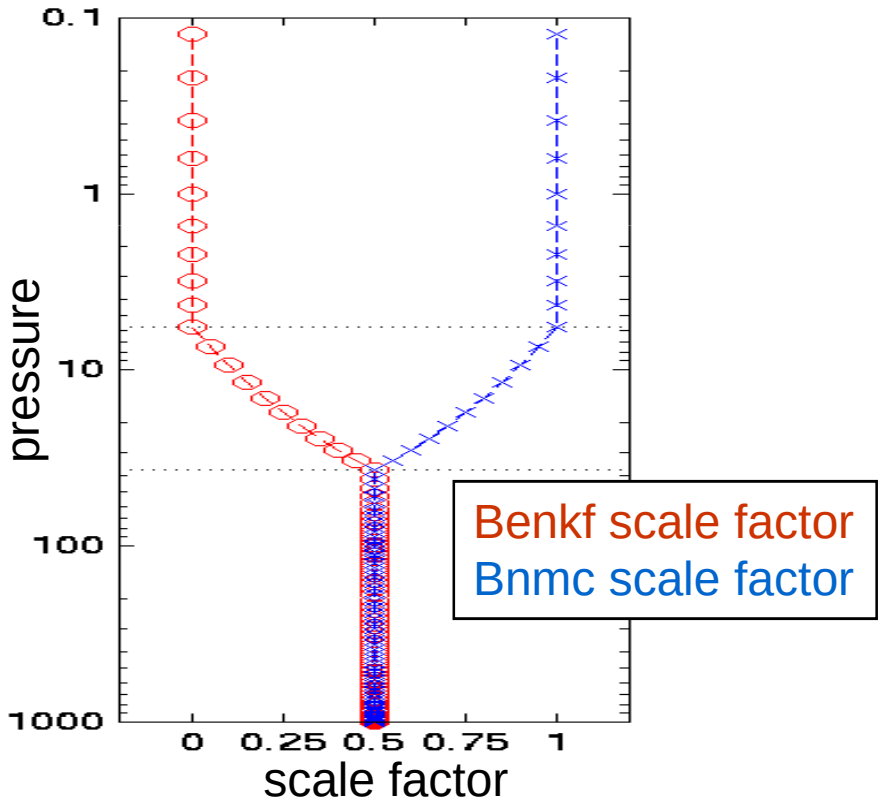
Model top of EnKF is lower than GDPS

Benkf and Bnmc are averaged in troposphere ½ & ½, 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

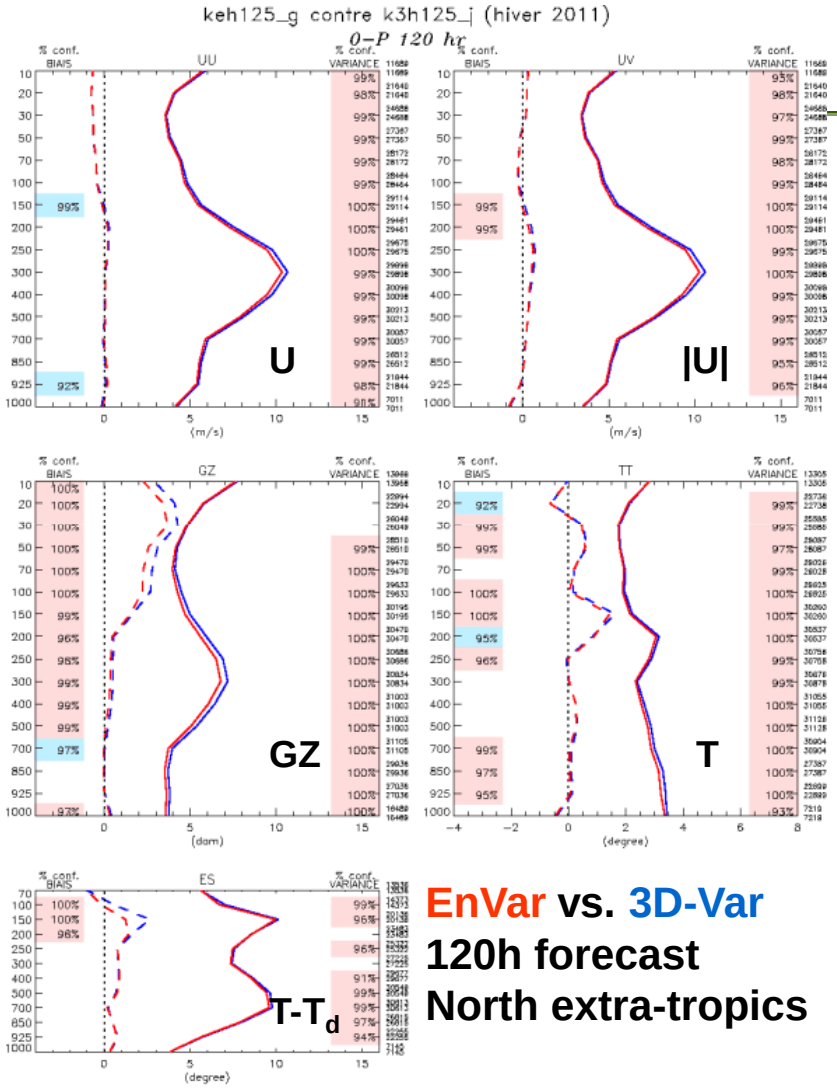
Also tested 75% Benkf and 25% Bnmc in troposphere, but results slightly worse

Also did preliminary tests with a full outer loop, but degraded the results



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

Radiosonde verification scores – 6 weeks, Feb/Mar 2011



EnVar vs. 3D-Var
120h forecast
North extra-tropics

Canada

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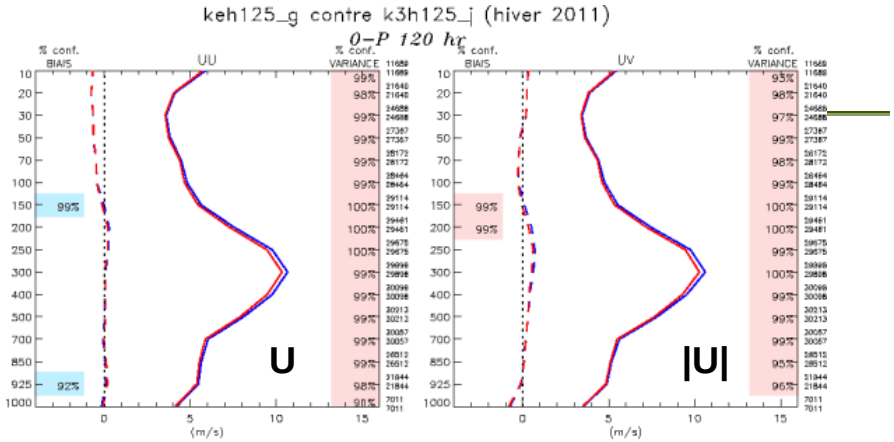

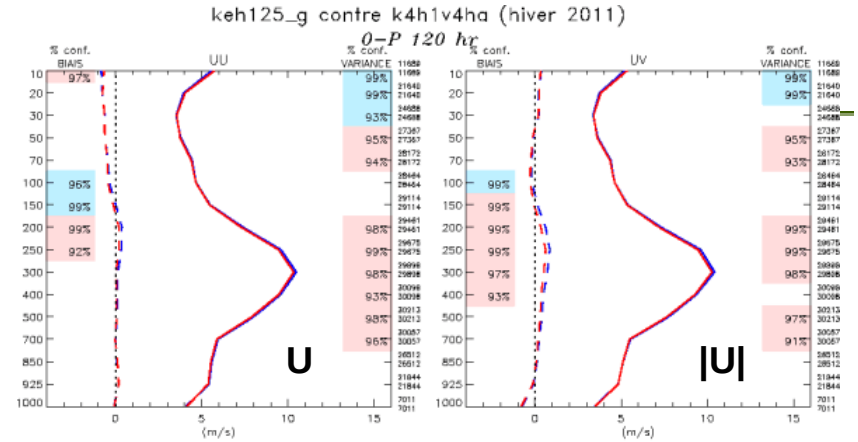

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EnVar vs. 4D-Var
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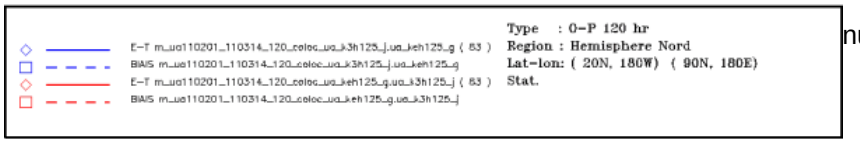

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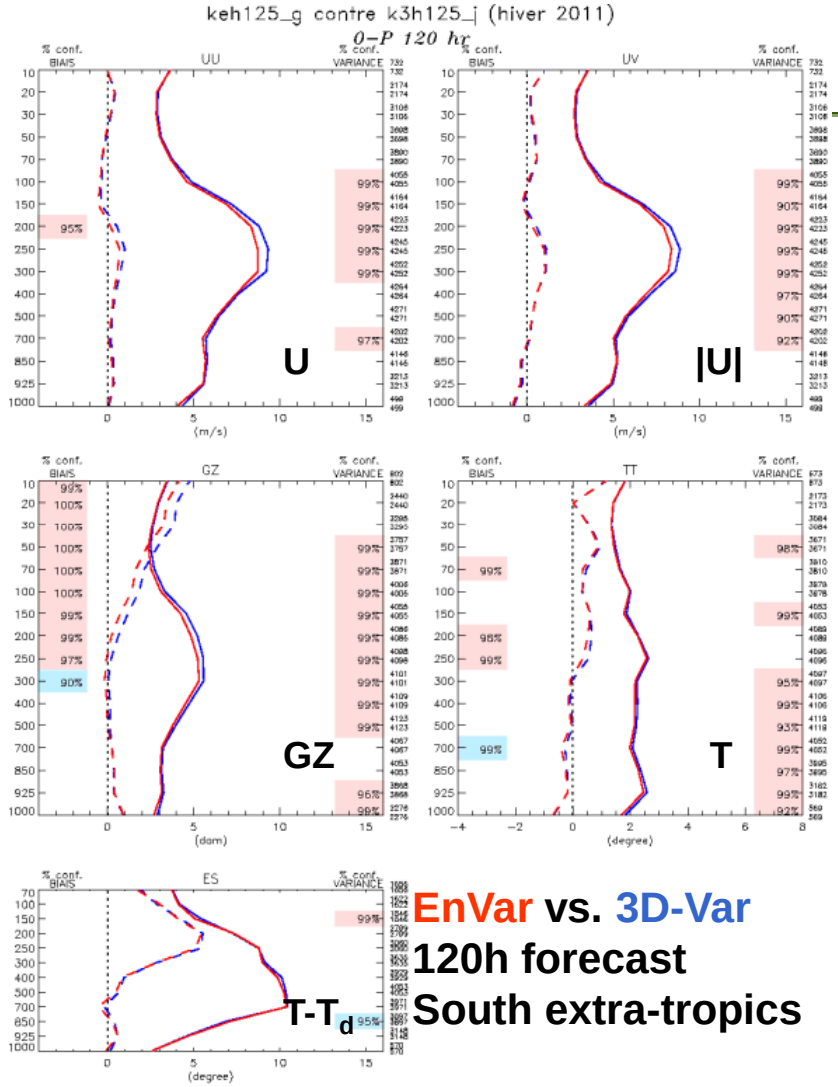

EnVar vs. 3D-Var
120h forecast
South extra-tropics

Canada

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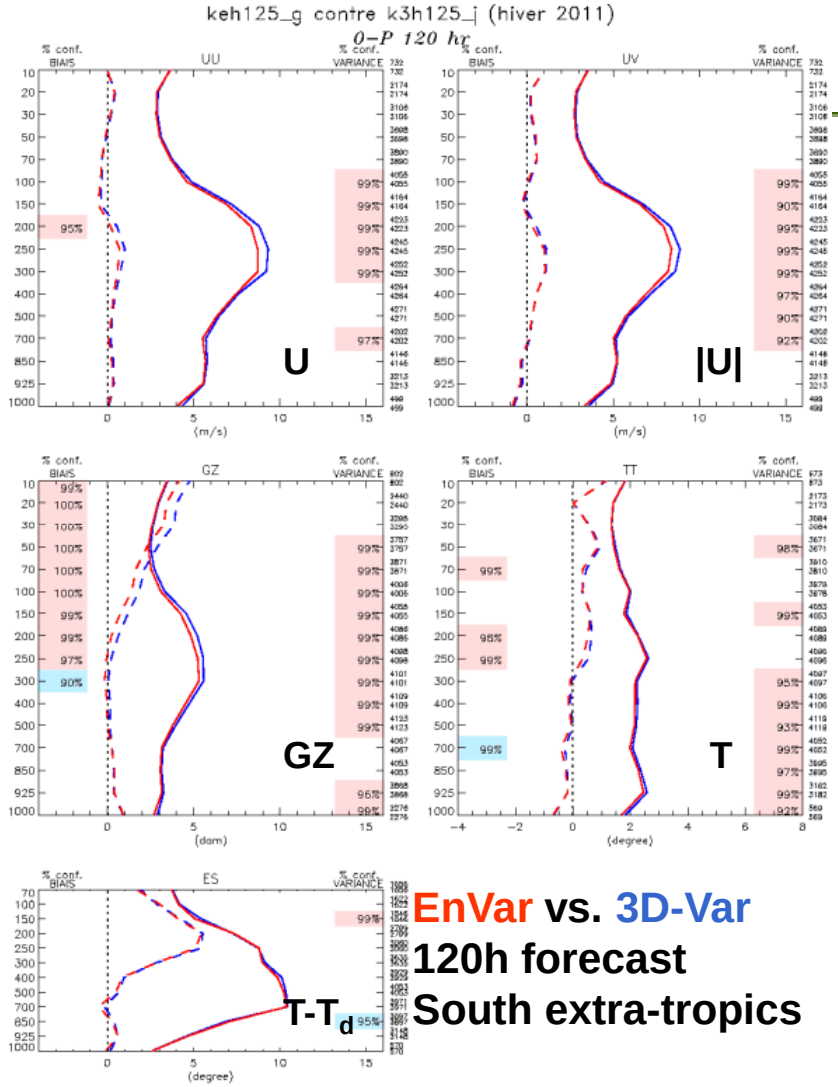
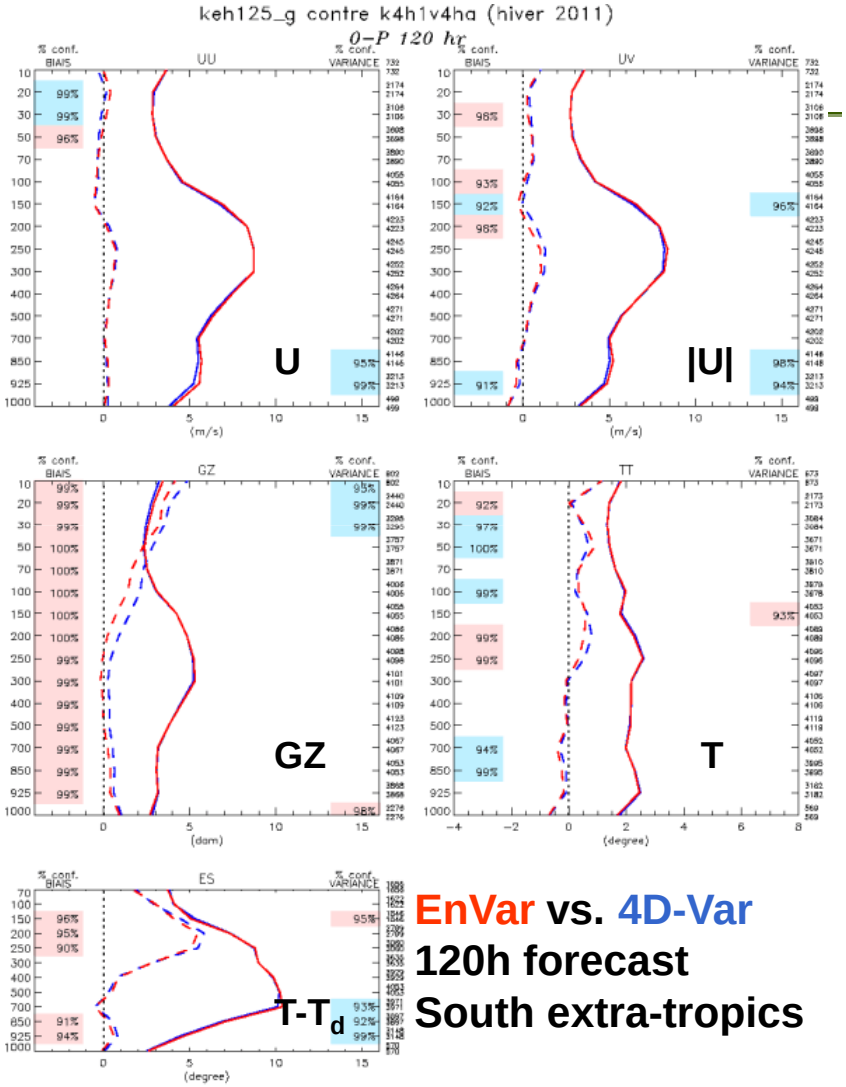
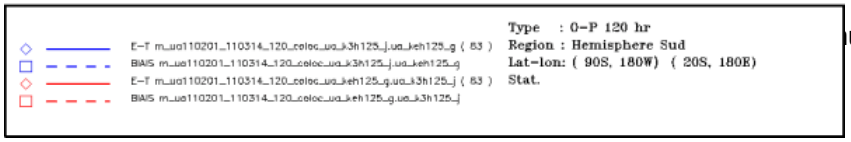
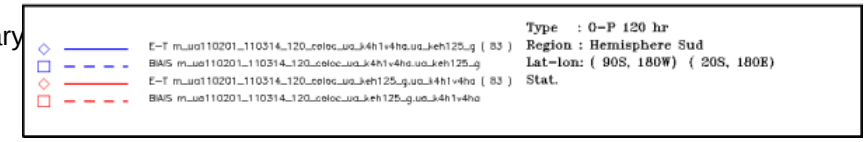


EnVar vs. 3D-Var
120h forecast
South extra-tropics



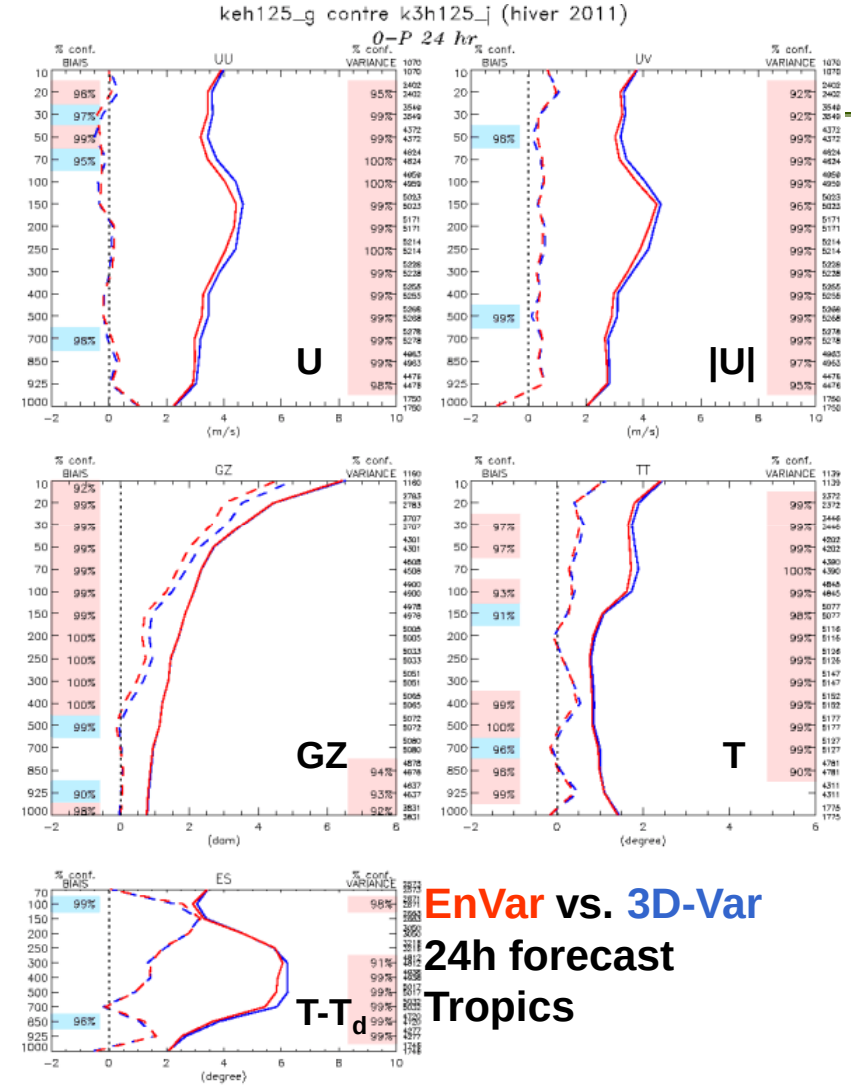
EnVar vs. 4D-Var
120h forecast
South extra-tropics





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

Radiosonde verification scores – 6 weeks, Feb/Mar 2011



EnVar vs. 3D-Var
24h forecast
Tropics

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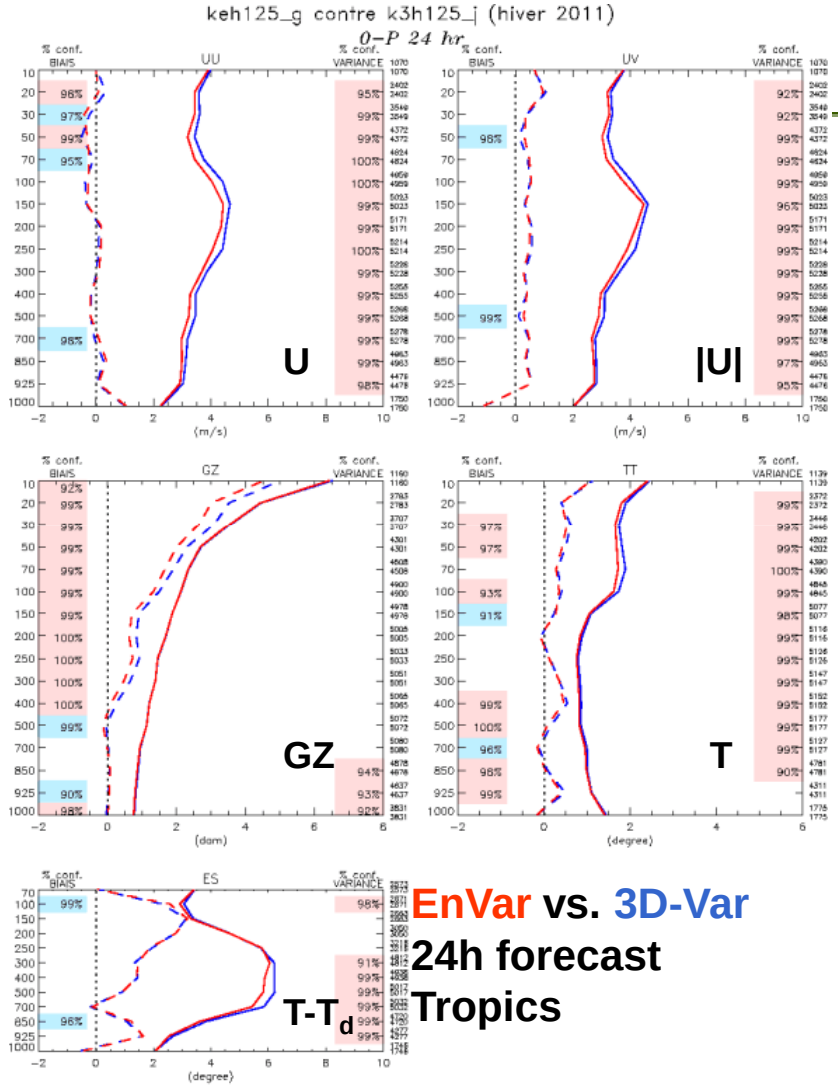
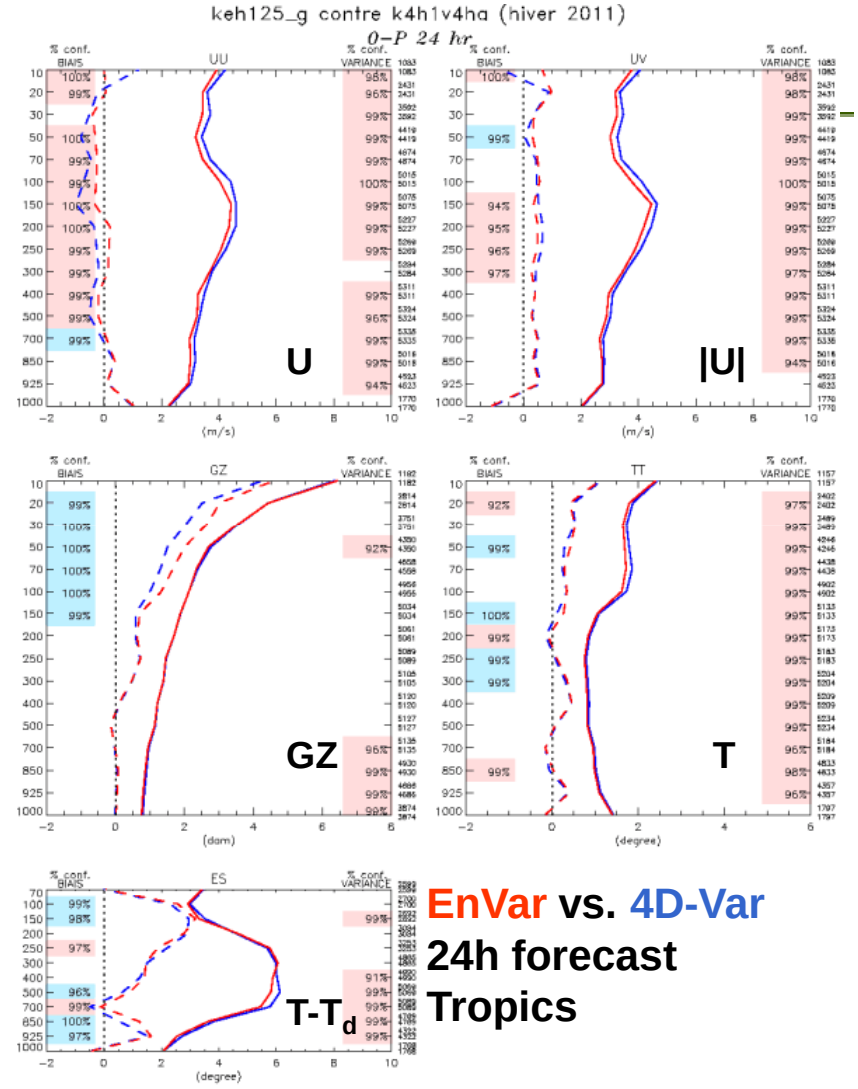
Forecast Results: EnVar vs. 3D-Var and 4D-Var

Radiosonde verification scores – 6 weeks, Feb/Mar 2011



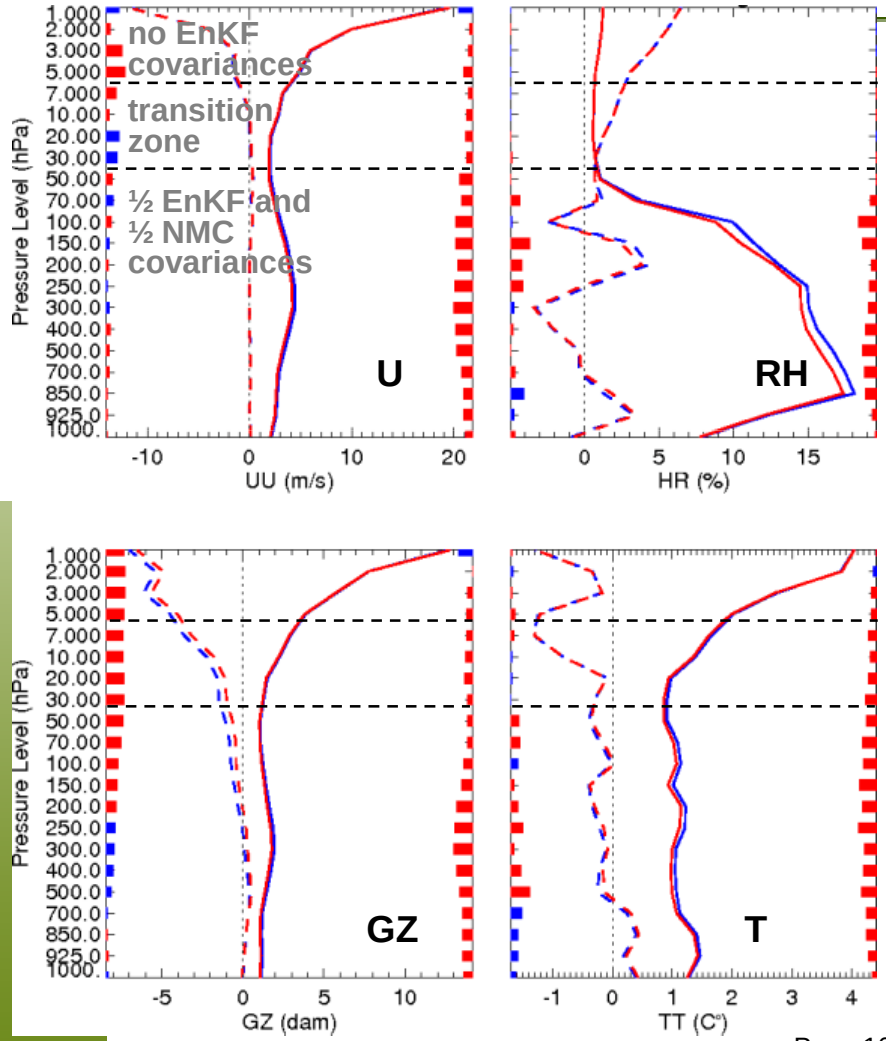


Forecast Results: EnVar vs. 3D-Var and 4D-Var

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

EnVar vs. 3D-Var

48h forecast, global domain



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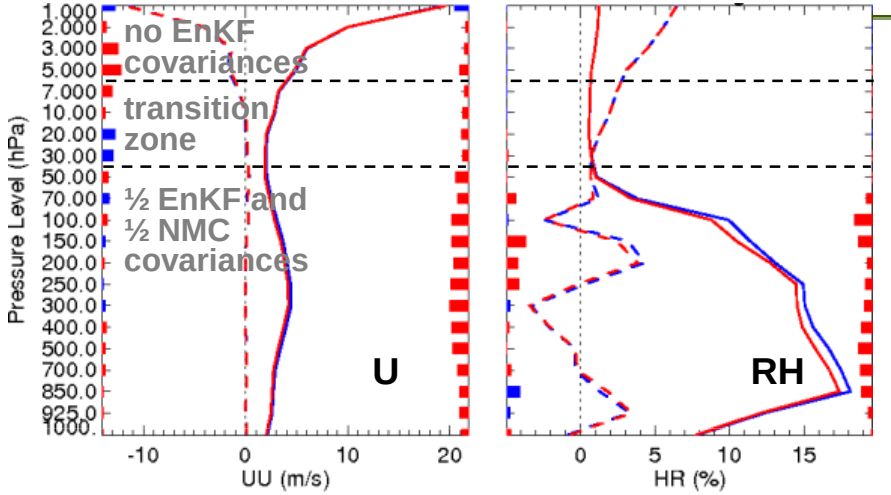
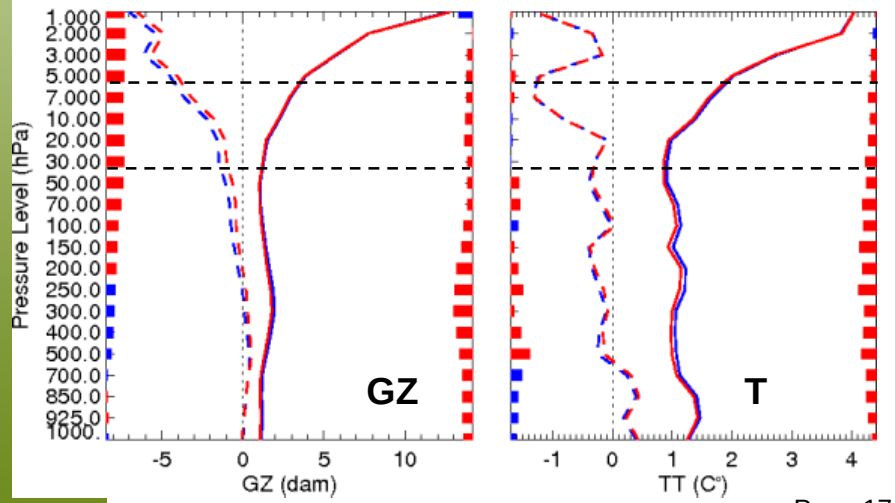
Forecast Results: EnVar vs. 3D-Var and 4D-Var

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

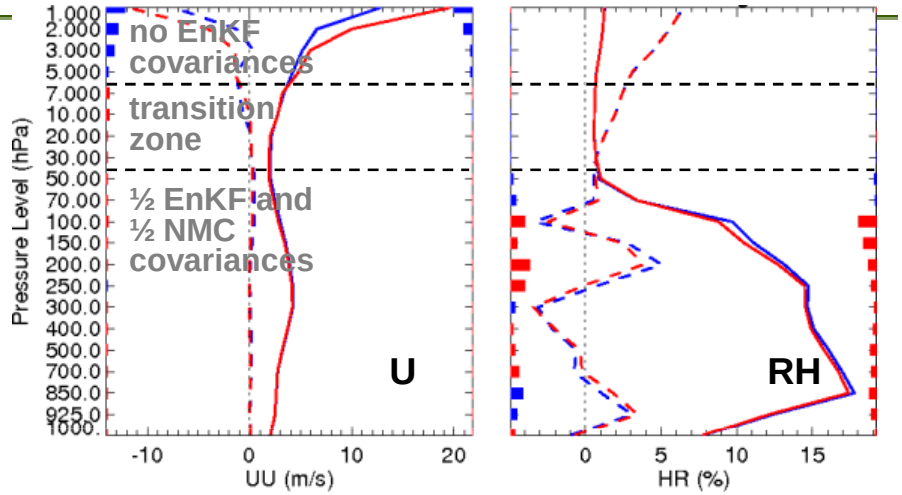
48h forecast, global domain

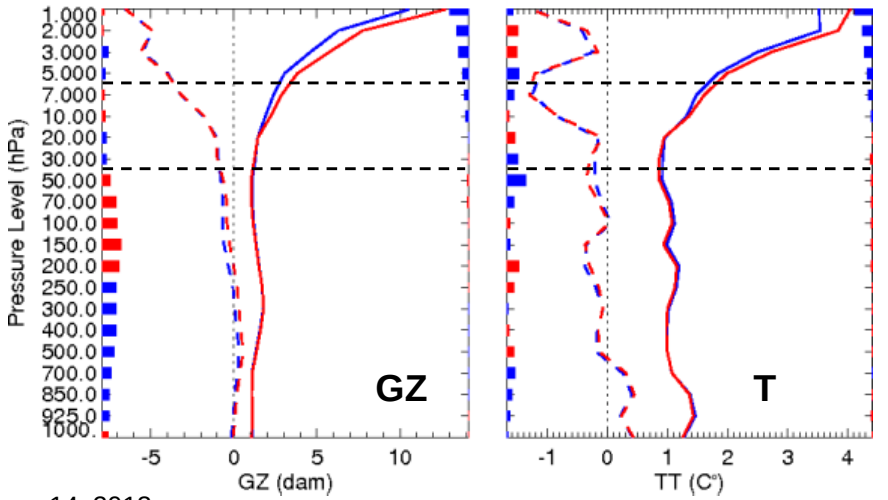
EnVar vs. 3D-Var





EnVar vs. 4D-Var

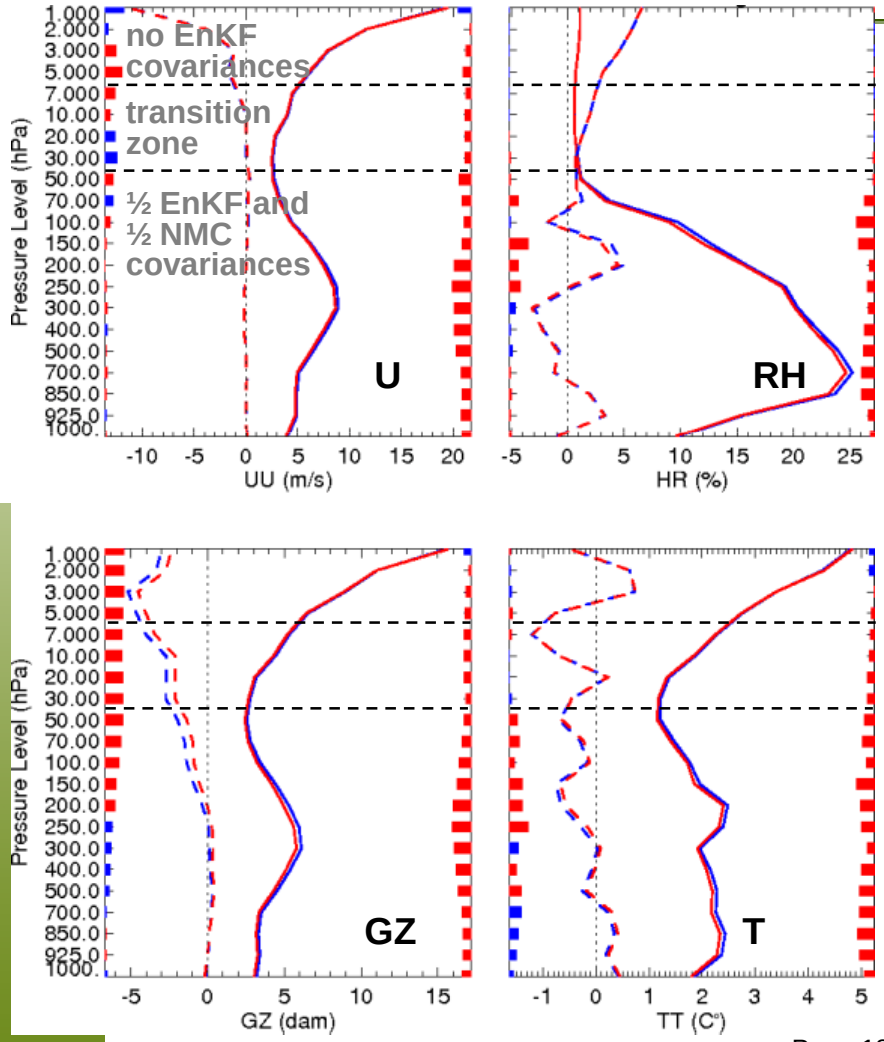




Forecast Results: EnVar vs. 3D-Var and 4D-Var

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

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



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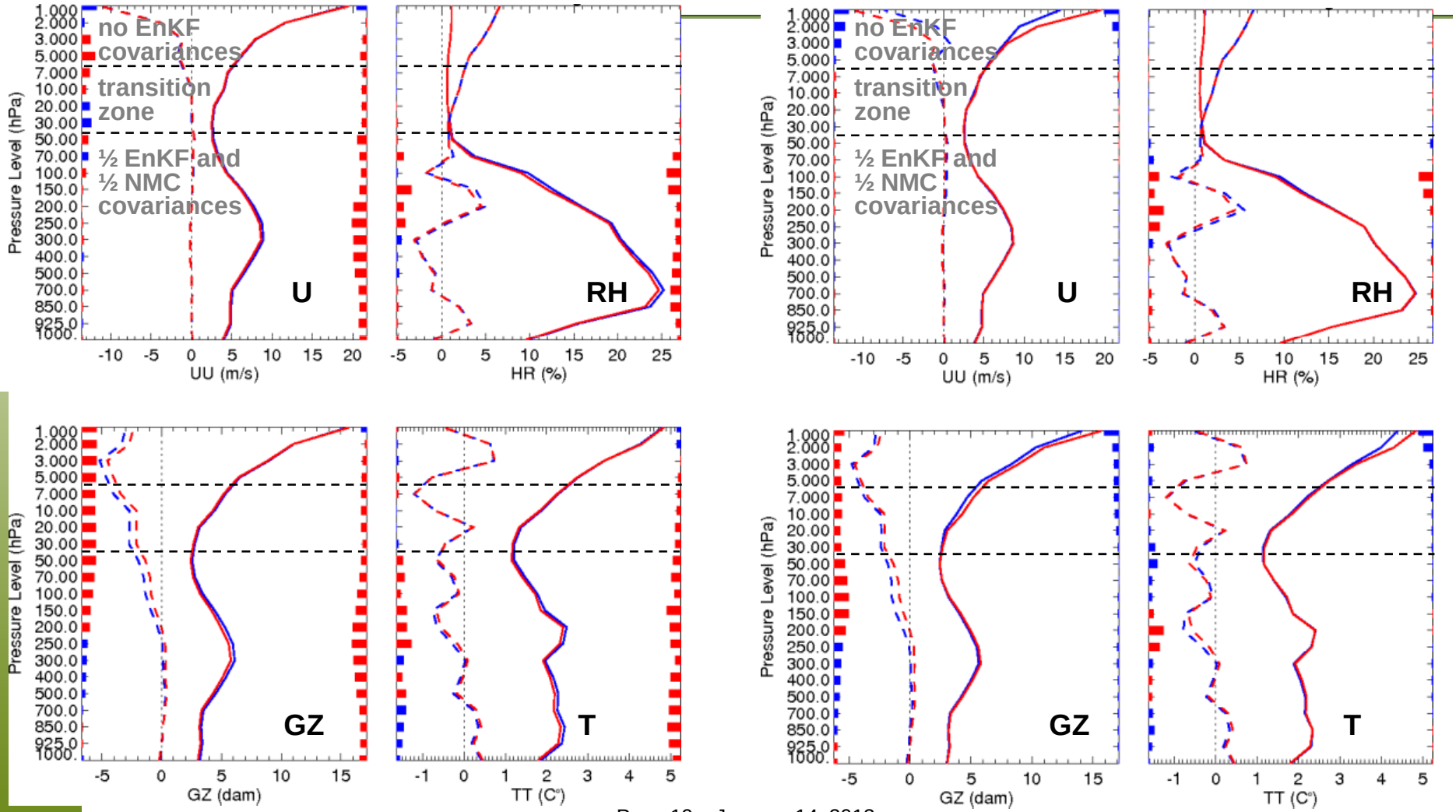
Forecast Results: EnVar vs. 3D-Var and 4D-Var

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

EnVar vs. 3D-Var | **120h forecast, global domain** | **EnVar vs. 4D-Var**



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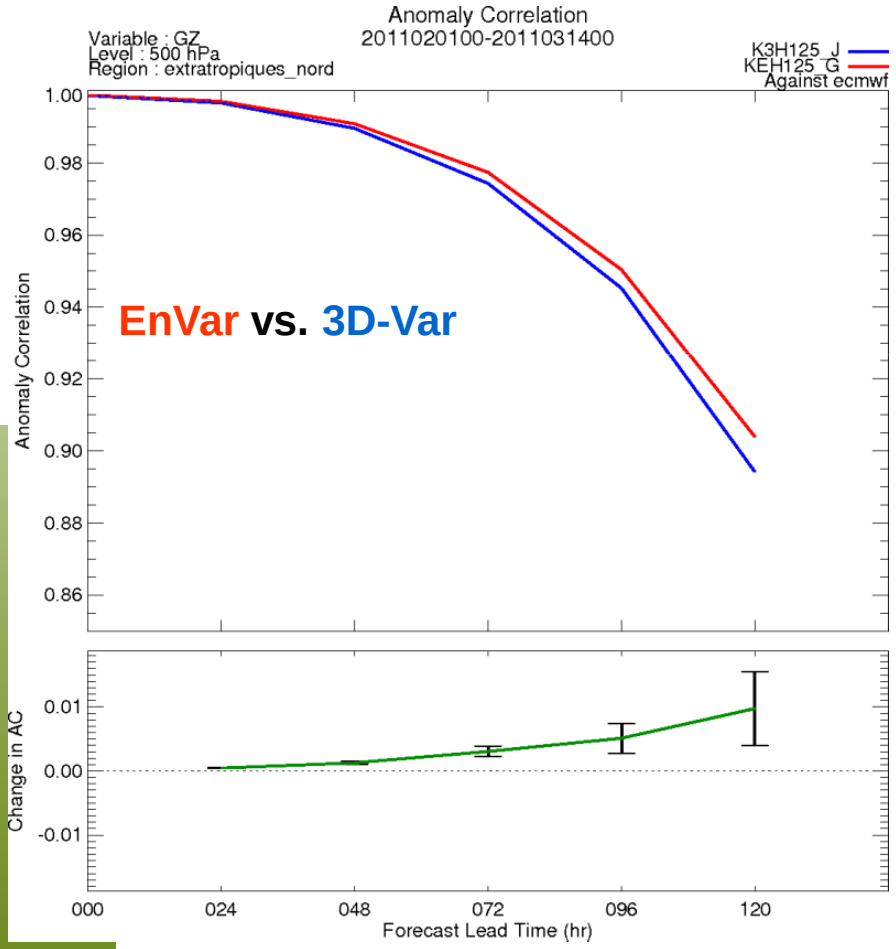
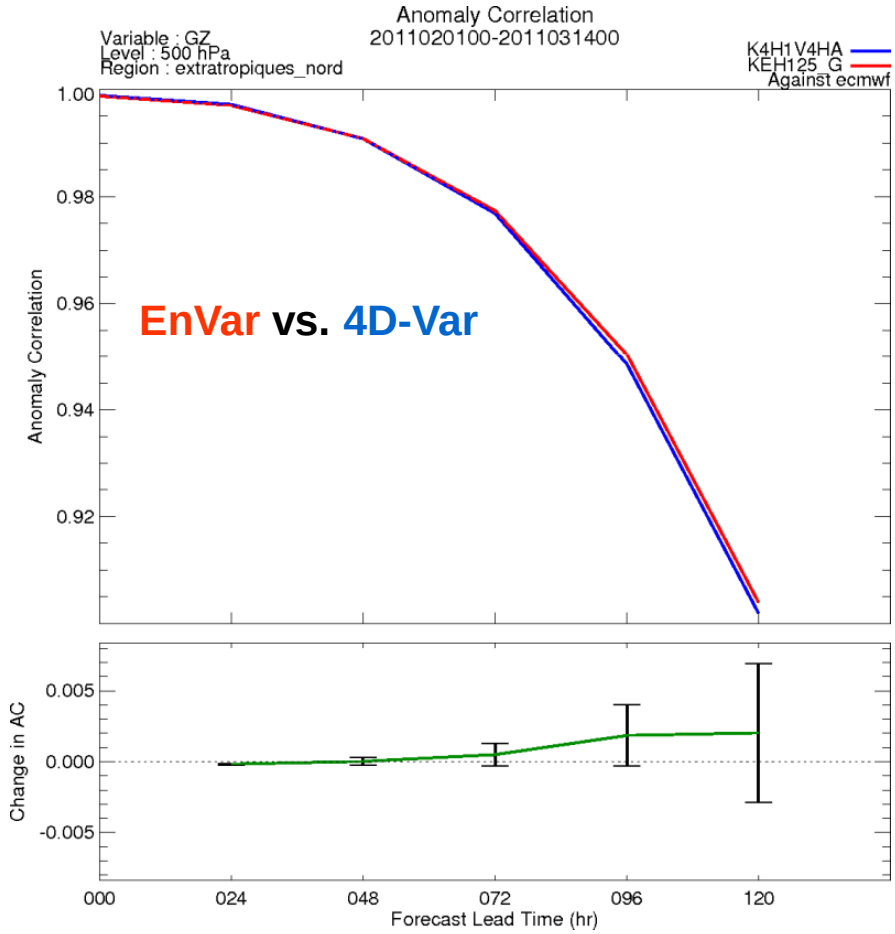
Forecast Results: EnVar vs. 3D-Var and 4D-Var

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

North extra-tropics
500hPa GZ correlation anomaly





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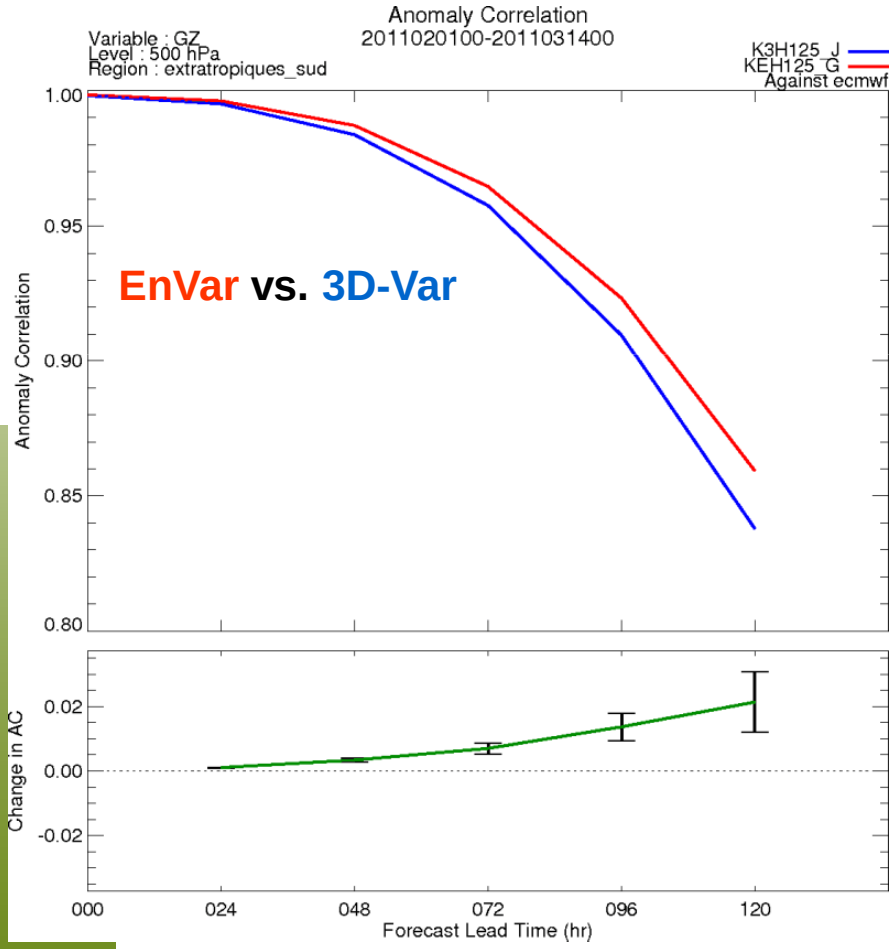
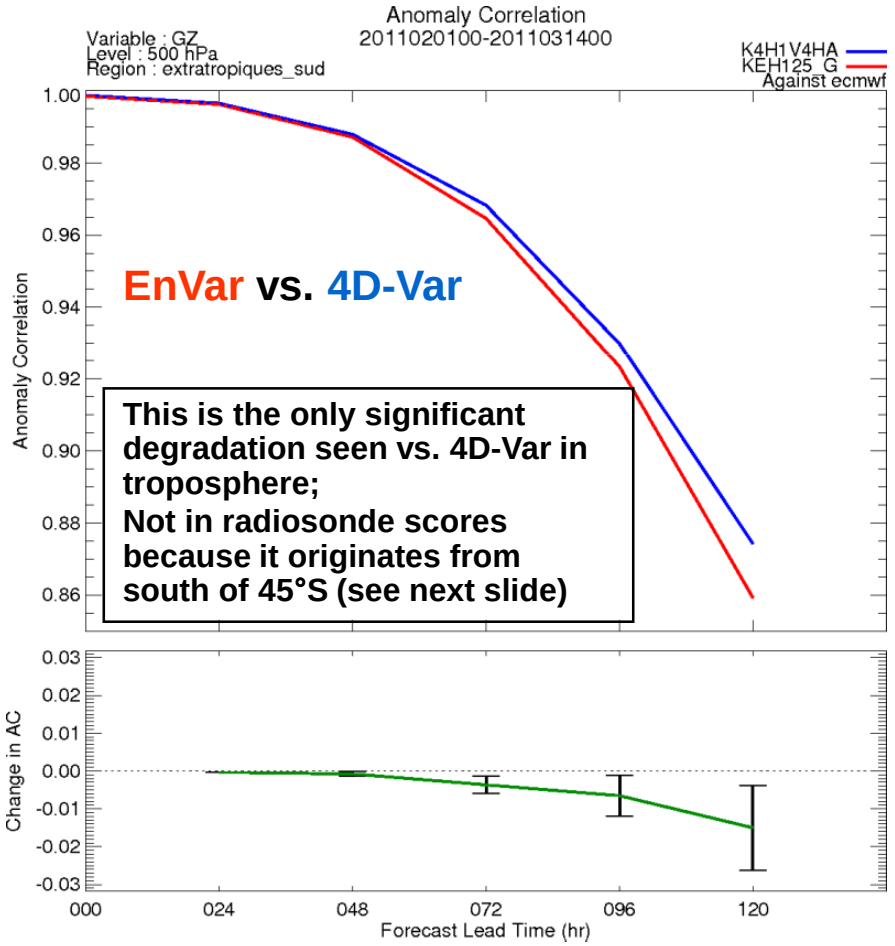
Forecast Results: EnVar vs. 3D-Var and 4D-Var

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

South extra-tropics
500hPa GZ correlation anomaly





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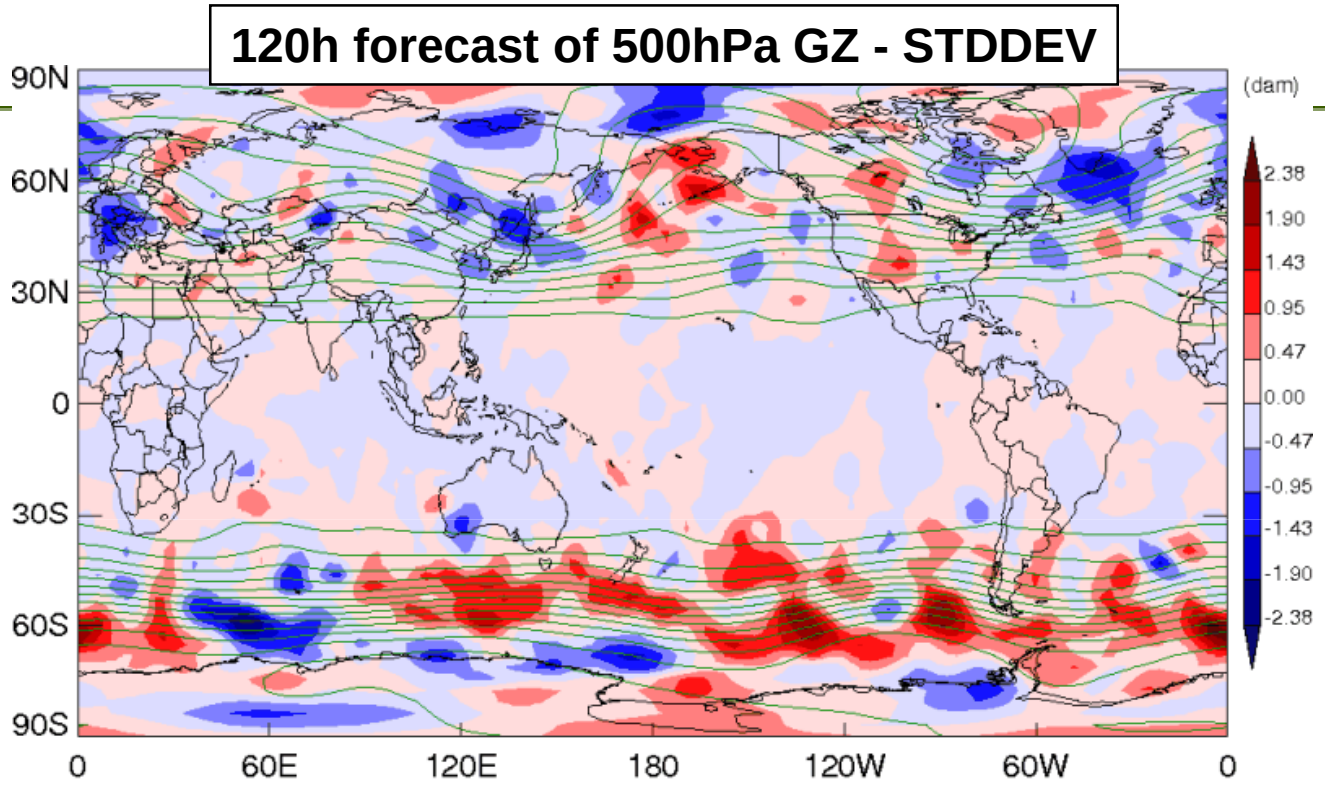
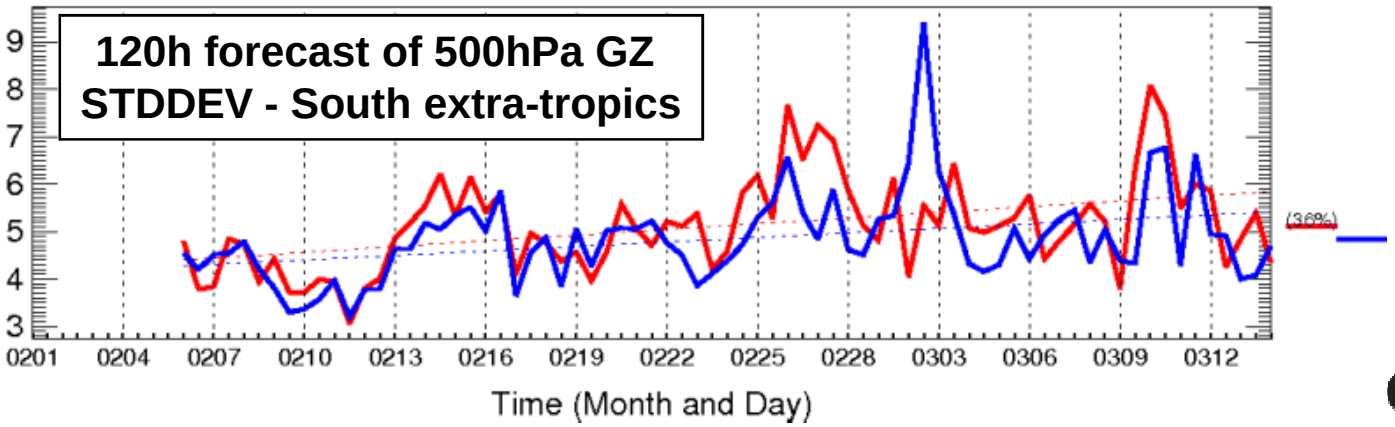
Verification against ERA-Interim analyses – 6 weeks, Feb/Mar 2011





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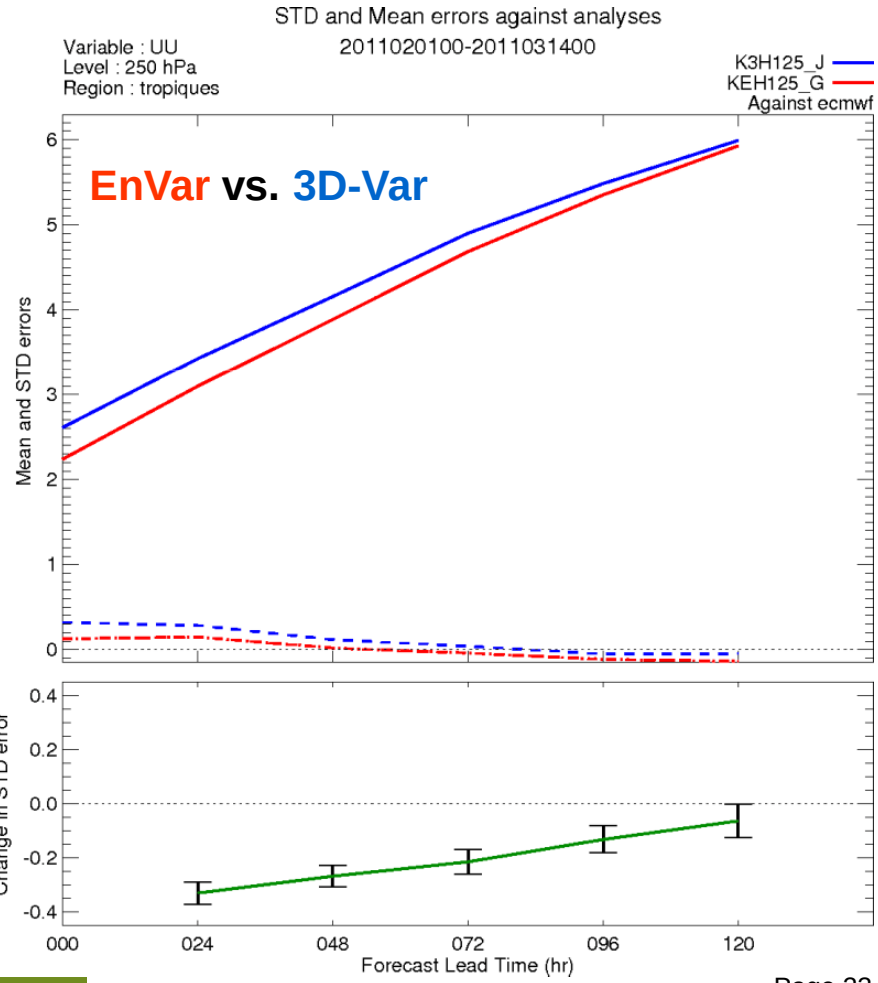
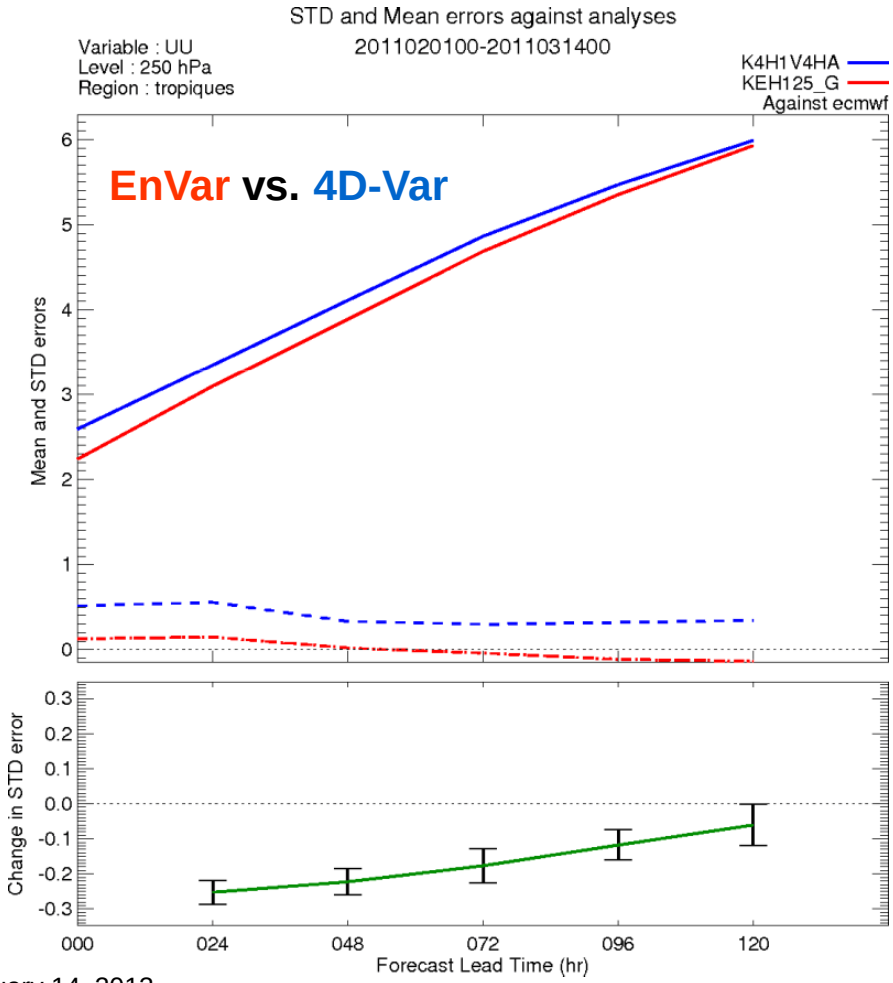
Forecast Results: EnVar vs. 3D-Var and 4D-Var

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

Tropics
250hPa U-wind STDDEV





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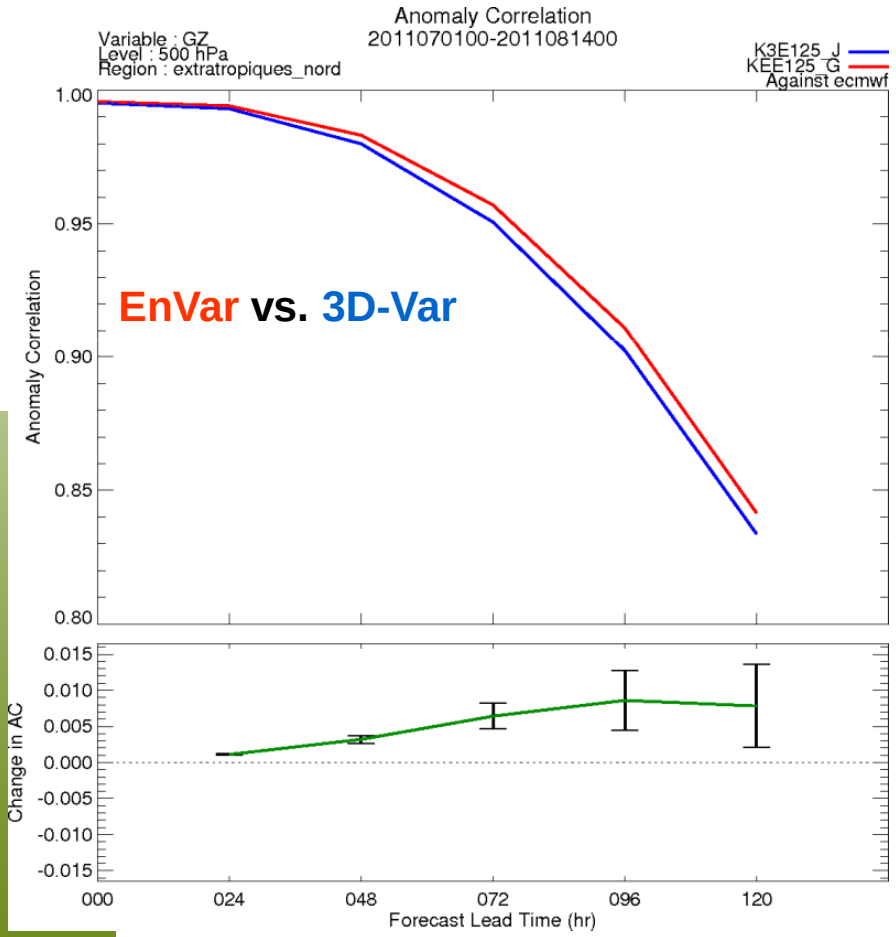
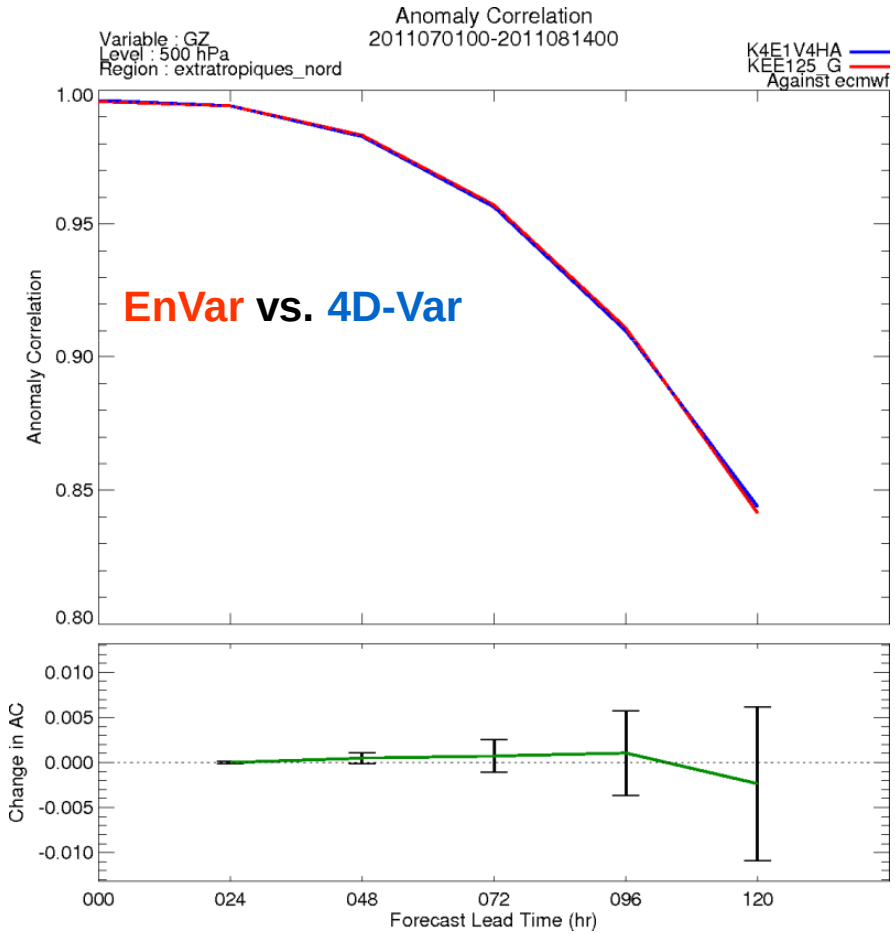
Forecast Results: EnVar vs. 3D-Var and 4D-Var

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

North extra-tropics
500hPa GZ correlation anomaly

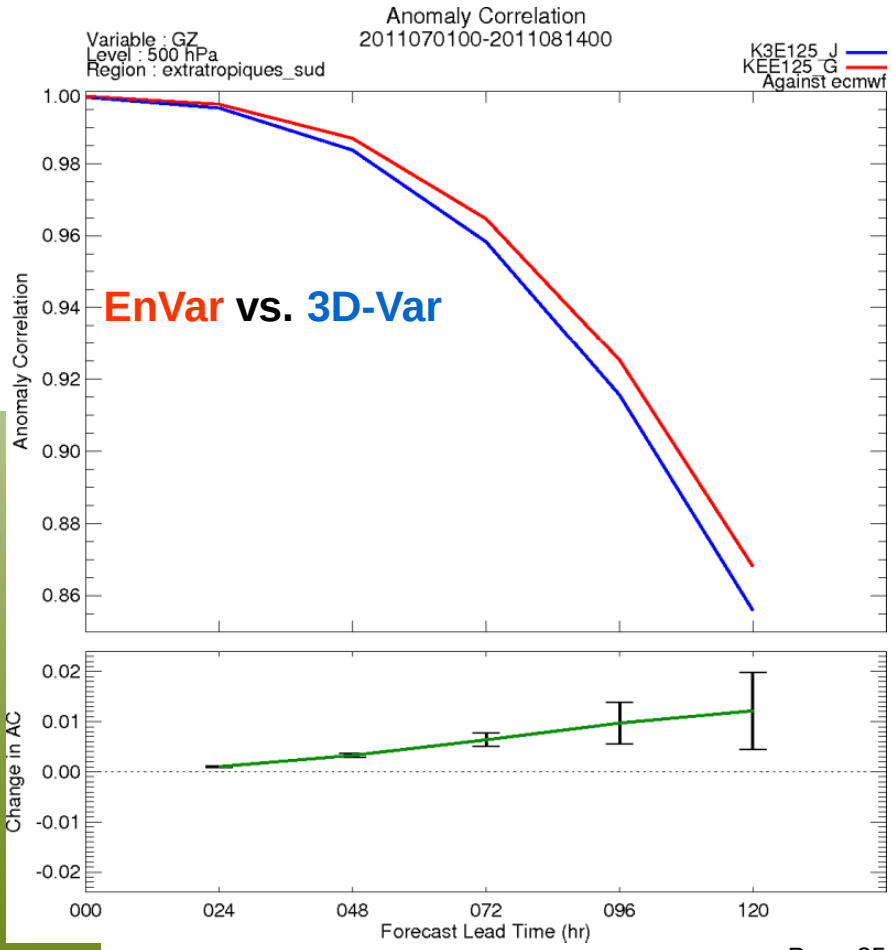


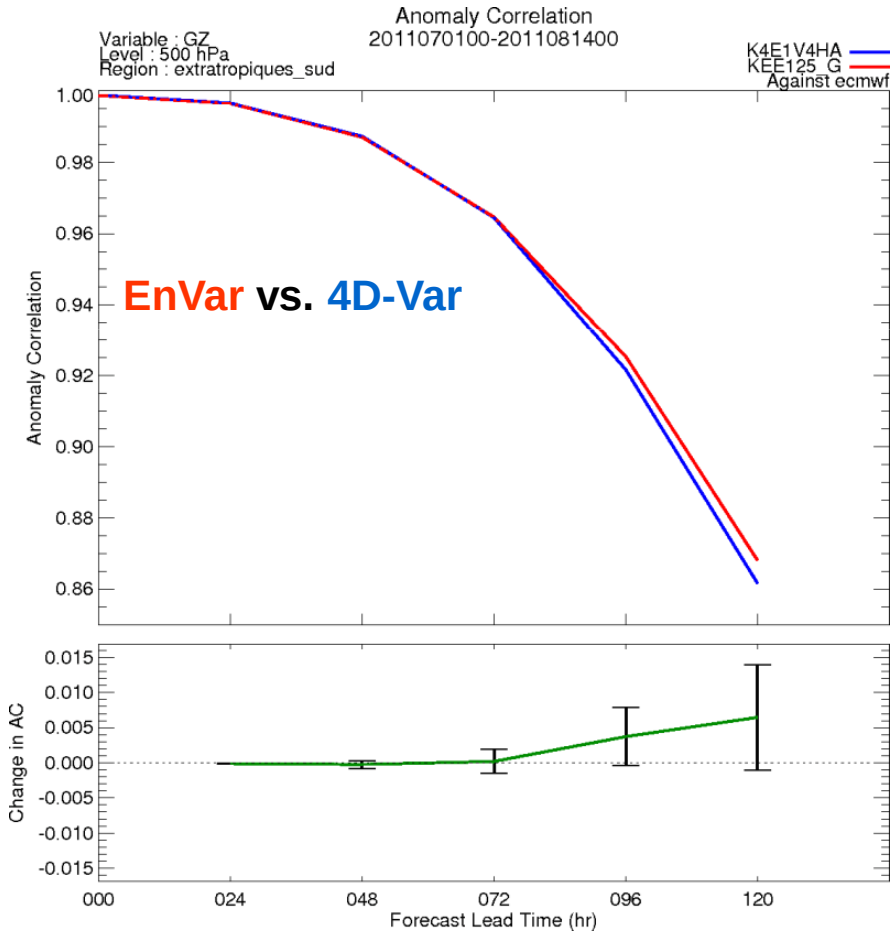


Forecast Results: EnVar vs. 3D-Var and 4D-Var

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

South extra-tropics
500hPa GZ correlation anomaly

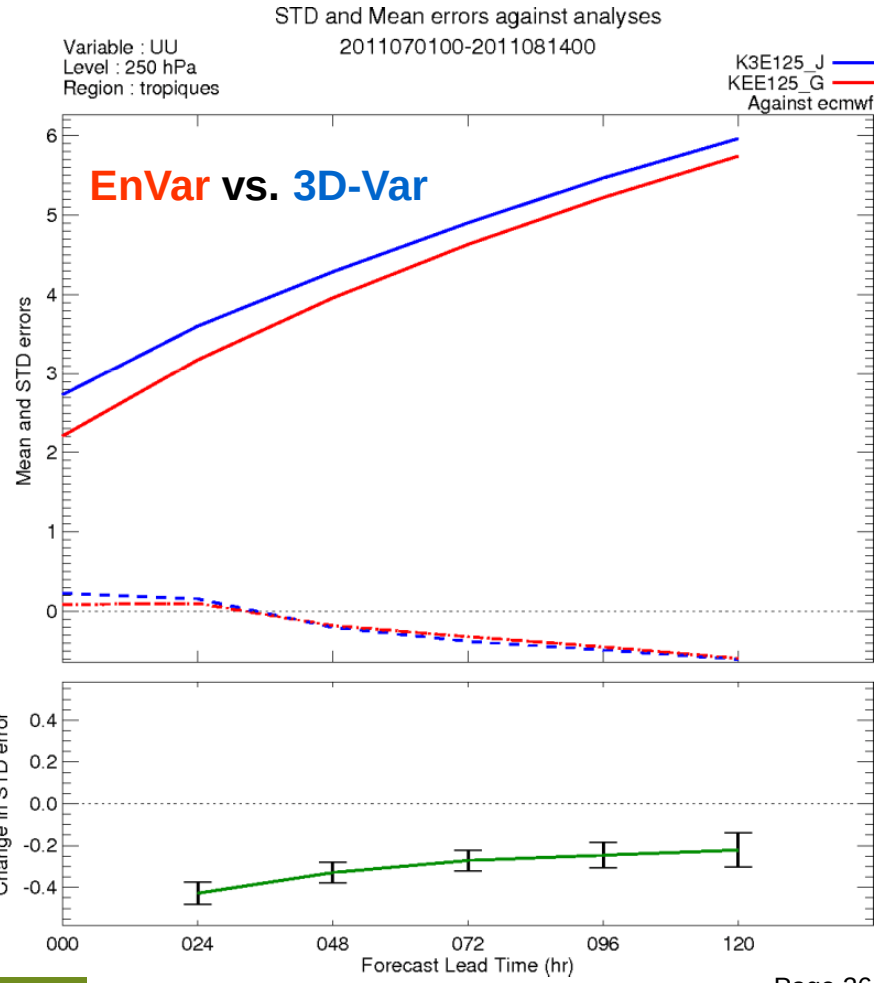


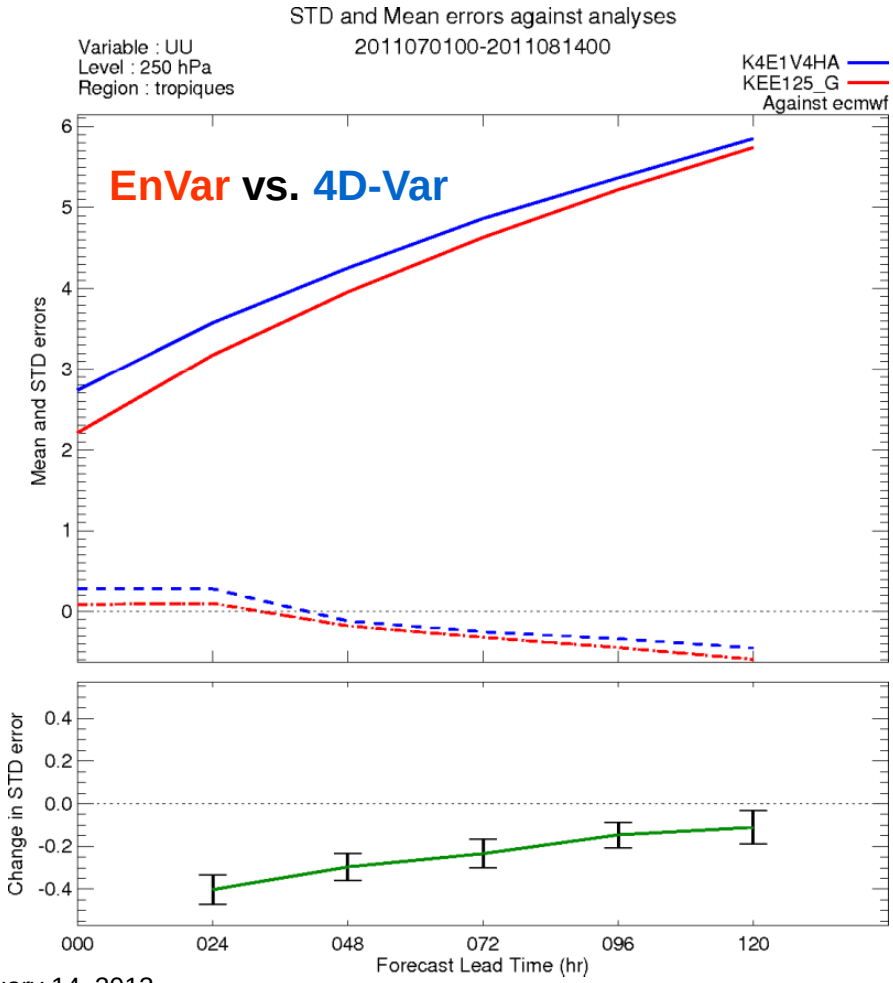


Forecast Results: EnVar vs. 3D-Var and 4D-Var

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

Tropics
250hPa U-wind STDDEV





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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

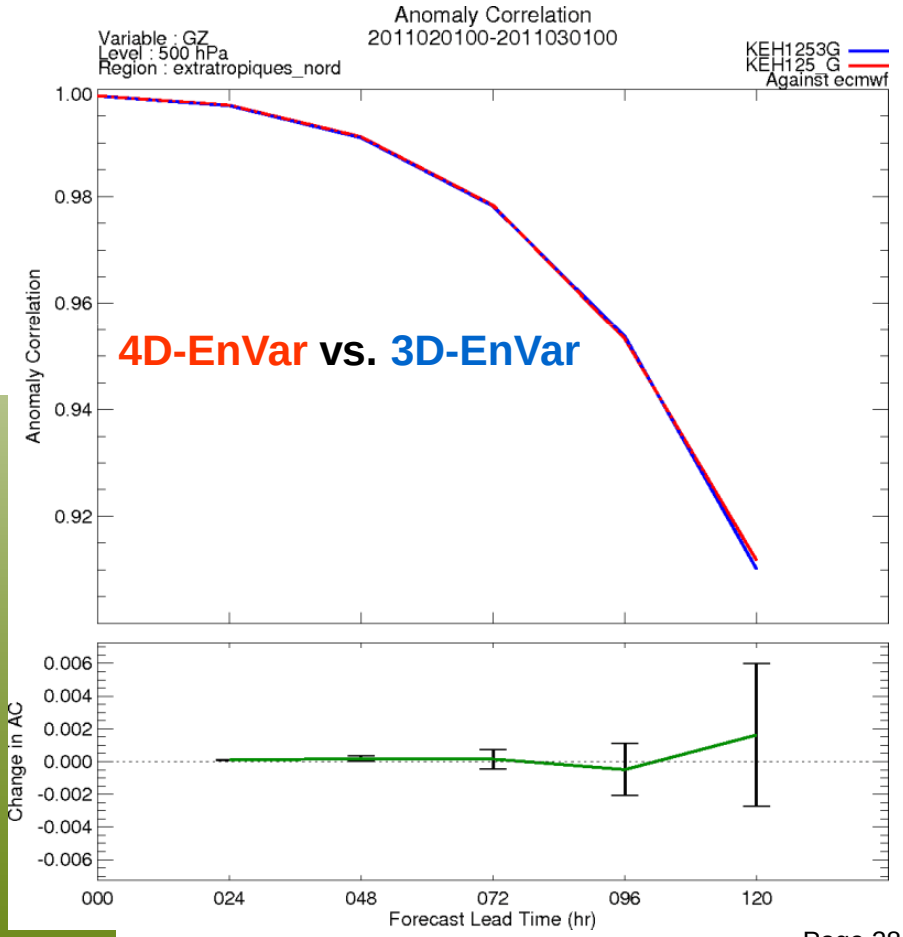
3D-EnVar compared with:

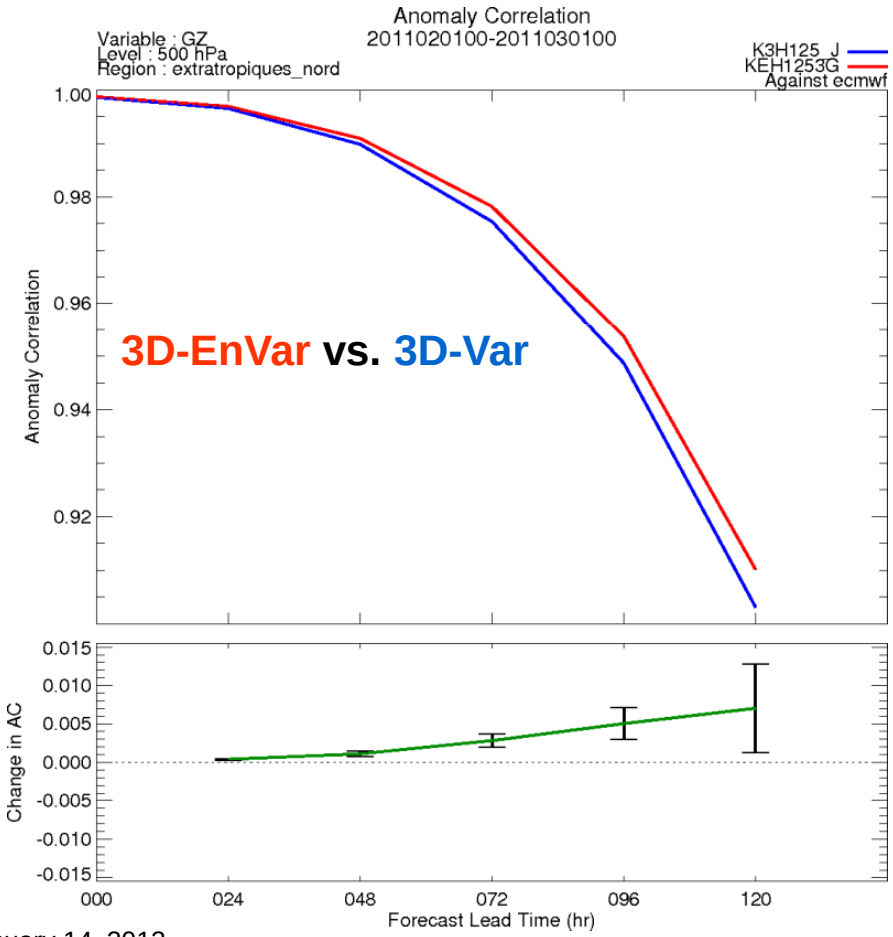
- 4D-EnVar: impact of 4D covariances, and
- 3D-Var: impact of flow dependent vs stationary (NMC) covariances (both 3D)

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

Verification against ERA-Interim analyses – 4 weeks, Feb 2011

North extra-tropics
500hPa GZ correlation anomaly

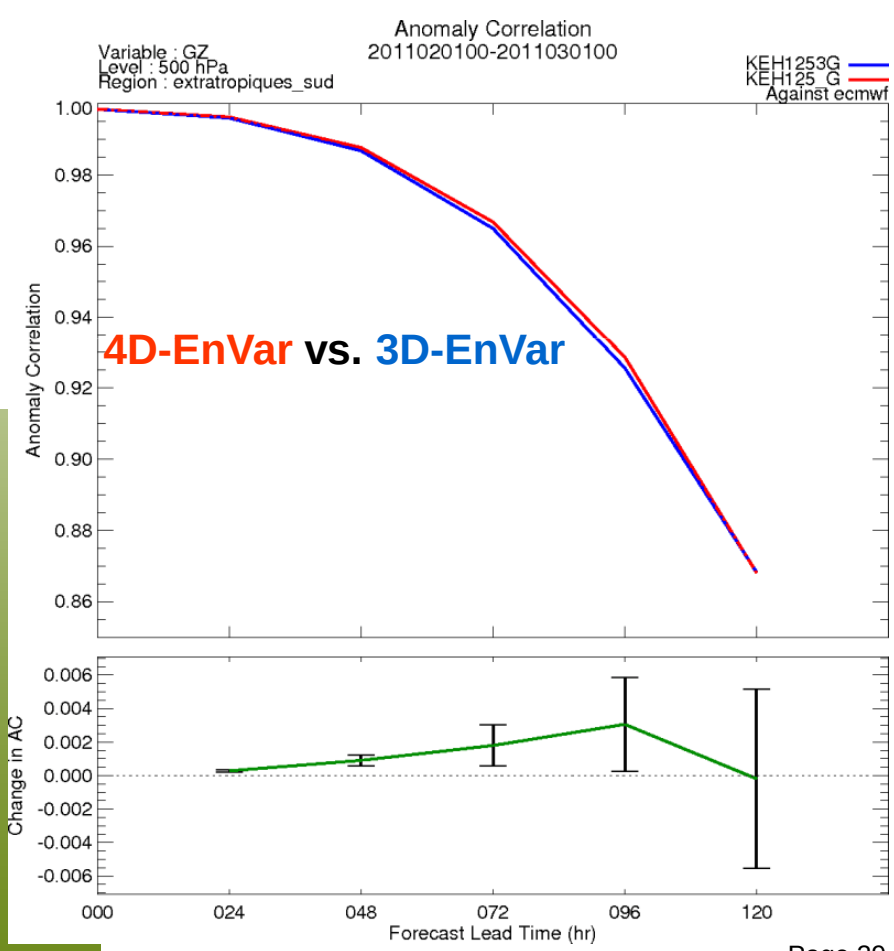


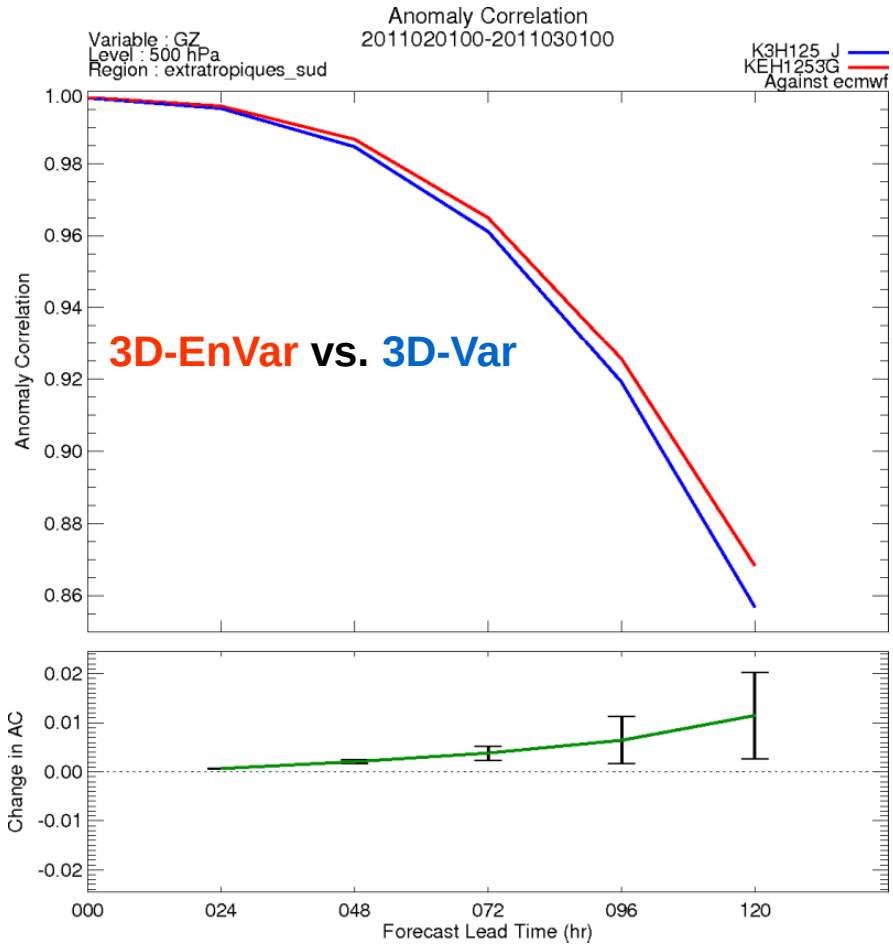


Forecast Results: 4D-EnVar vs. 3D-EnVar

Verification against ERA-Interim analyses – 4 weeks, Feb 2011

South extra-tropics
500hPa GZ correlation anomaly





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

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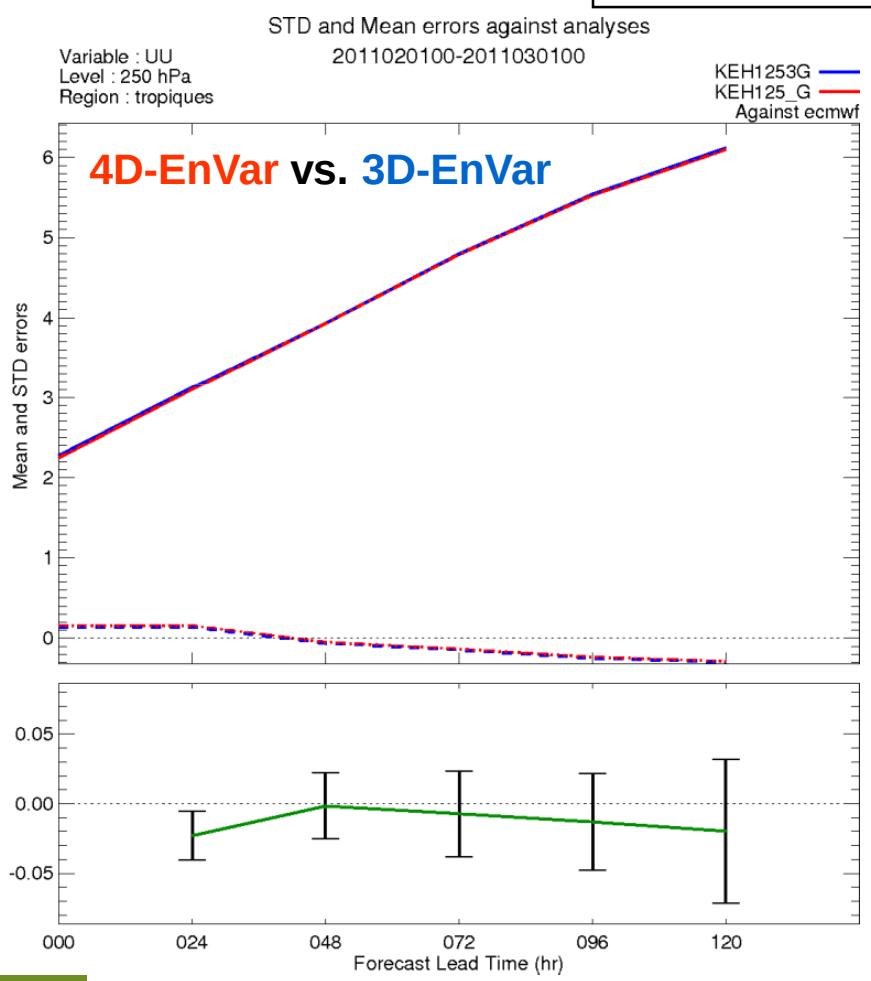
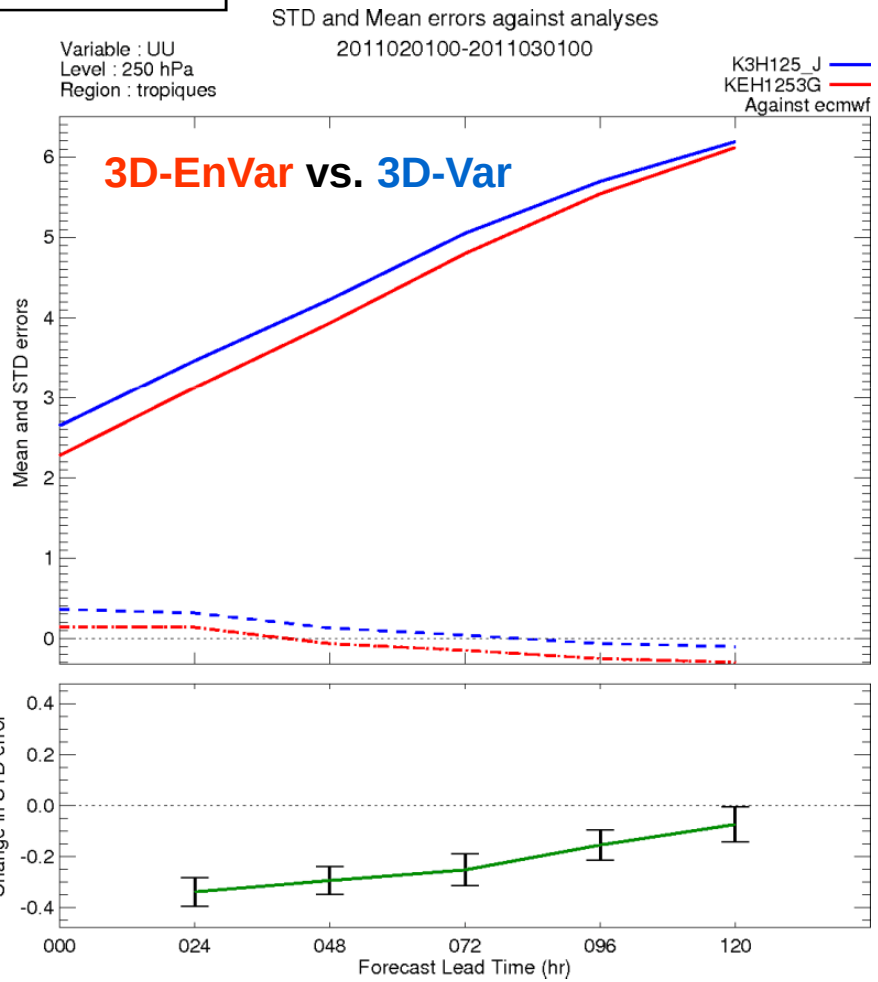
250hPa U-wind STDDEV





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Conclusions

- Comparison of EnVar with 3D-Var and 4D-Var:
  - EnVar produces similar quality forecasts as 4D-Var below ~20hPa in extra-tropics, 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 is an attractive 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 ensembles
  - 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; more computational resources for EnKF and forecasts

Next Steps

- Finalize testing EnVar with goal of replacing 4D-Var in operational prediction system during 2013 in combination with other changes:
  - GEM global model on 15km Yin-Yang grid
  - CALDAS: new surface analysis system based on EnKF
  - modified satellite radiance bias correction scheme that gives conventional observations more influence on correction
  - improved use of radiosonde and aircraft data
  - additional AIRS/IASI channels and modified observation error variances for all radiances
  - possibly increased resolution of EnKF 66km → 50km
- Testing of EnVar in regional prediction system as possible replacement of 4D-Var already started