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Intercomparison of Variational and EnKF Data Assimilation Approaches for Deterministic NWP

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January 30, 2009

Introduction

- **Goal**: compare 4D-Var and EnKF approaches in the context of producing **global high-resolution 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 used to initialize medium range global deterministic forecasts
- EnKF (96 members) used to initialize global Ensemble Prediction System (20 members)

Contents

- Brief description of operational systems
- Configurations used for the inter-comparison
- Single observation experiments:
  - effect of localization
  - effect of covariance evolution
- Full analysis-forecast experiments (February 2007)
  - scores from analyses (vs. radiosondes)
  - scores from 56 6-day deterministic forecasts (vs. radiosondes and analyses)
- Conclusions and future work

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 independent 4D-Var experiment
  - observation error variance smaller for AMSU-A ch9+10 in EnKF
- Increased number of levels in EnKF to match 4D-Var
- Decreased grid spacing 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-Var and 4D-Var with **B** matrix nearly same as operational system (NMC method)
  - 3D-Var and 4D-Var with flow-dependent **B** matrix from EnKF at one time in assimilation window (same localization parameters and σ_{obs} for AMSU-A ch9+10 as in EnKF)
  - Ensemble-4D-Var – use 4D ensemble covariances to produce 4D analysis without TL and adjoint models (most similar to EnKF approach)

- EnKF – high resolution deterministic forecasts initialized with:
  - low resolution ensemble mean analysis
  - additional high resolution deterministic member (in progress):
    - using incremental approach similar to 4D-Var:
    - innovation computed directly from high resolution background state
    - low resolution increment added to high resolution background state
    - no obs error or model error perturbations
    - use all 96 members to compute covariances

Experimental Configurations

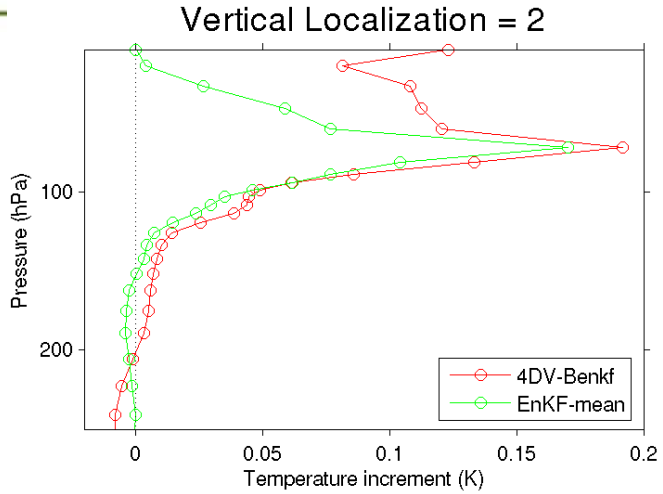
Remaining differences between two systems

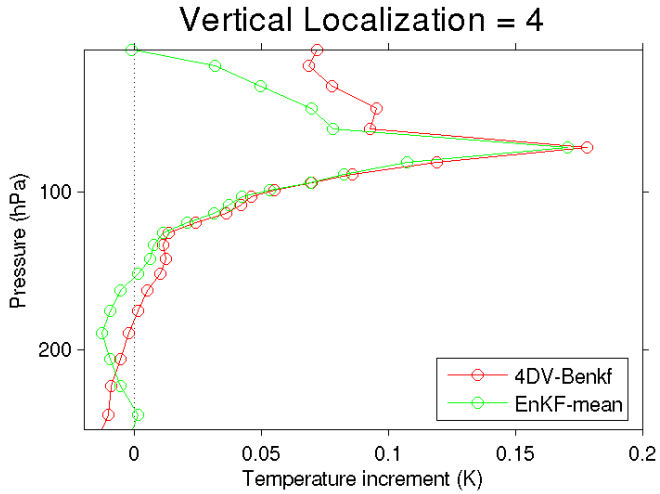
- Differences in spatial localization (most evident with radiance obs):
  - 4D-Var: $\mathbf{K} = (\rho \circ \mathbf{P})\mathbf{H}^T (\mathbf{H}(\rho \circ \mathbf{P})\mathbf{H}^T + \mathbf{R})^{-1}$ (also Ens-4D-Var approach)
  - EnKF: $\mathbf{K} = \rho \circ (\mathbf{P}\,\mathbf{H}^T) (\rho \circ (\mathbf{HPH}^T) + \mathbf{R})^{-1}$
- 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 when using spatial localization)
- 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 Ens-4D-Var approach)
- Differences in time interpolation to obs in assimilation window:
  - 4D-Var: 45min timestep, nearest neighbour interpolation in time
  - EnKF: 90min timestep, linear interpolation in time
  - Ens-4D-Var: 45min, NN for innovation, 90min, linear interp. for increment

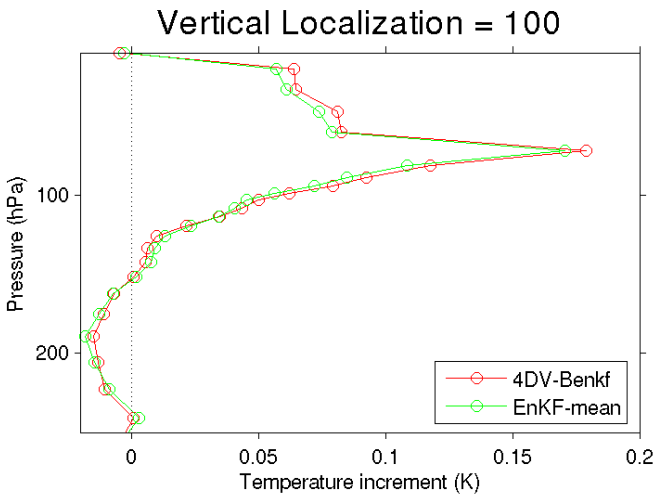
Single observation experiments

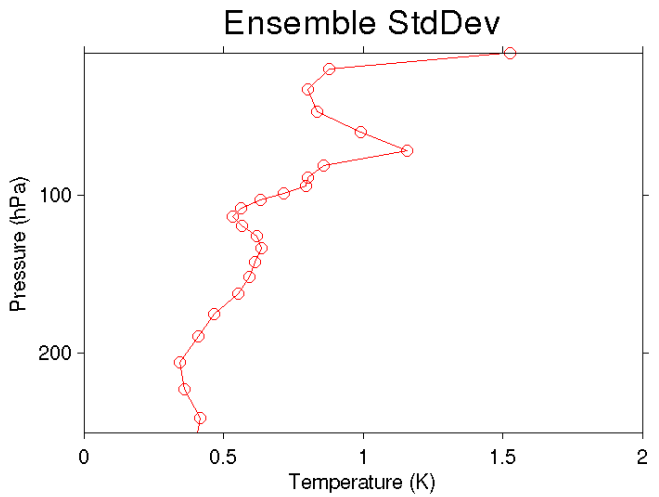
Difference in vertical localization between 3D-Var and EnKF

- 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





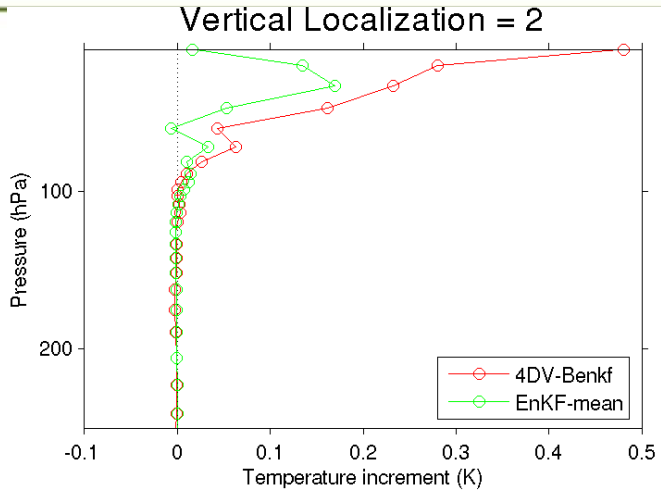


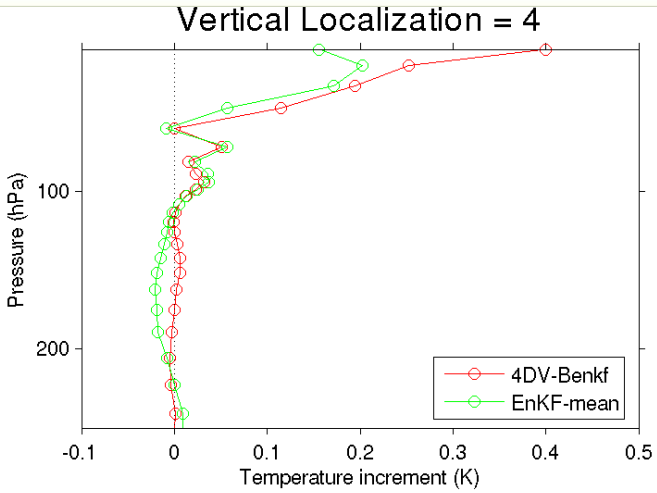


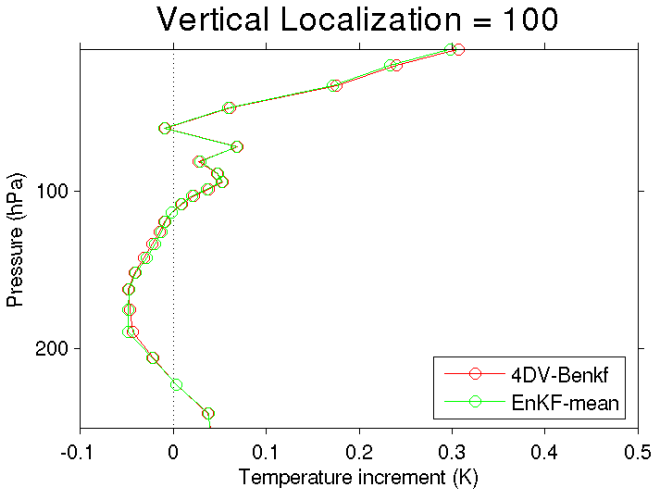
Single observation experiments

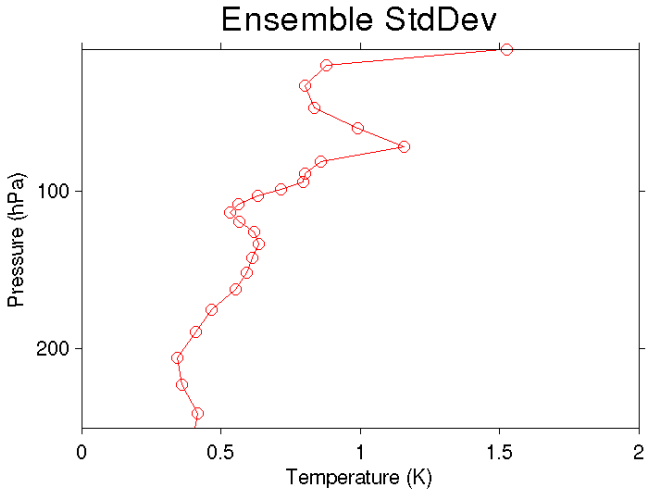
Difference in vertical localization between 3D-Var and EnKF

- AMSU-A ch10
- peak sensitivity near 30hPa
- with same **B**, increment larger & broader (peak at 10hPa, not 30hPa) with **3D-Var** vs. **EnKF**
- without localization increments nearly identical





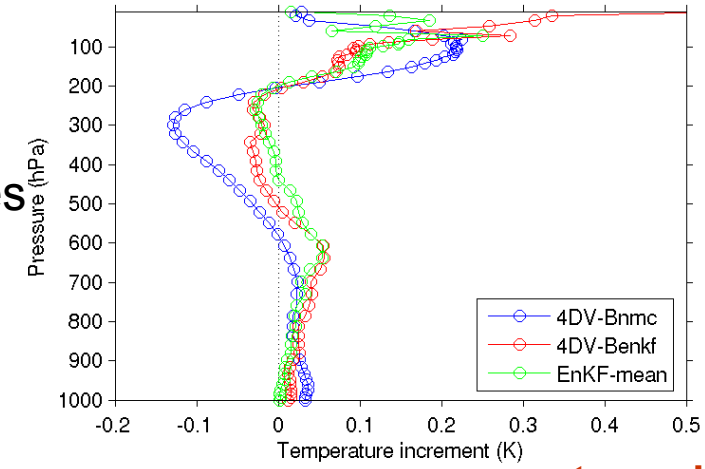


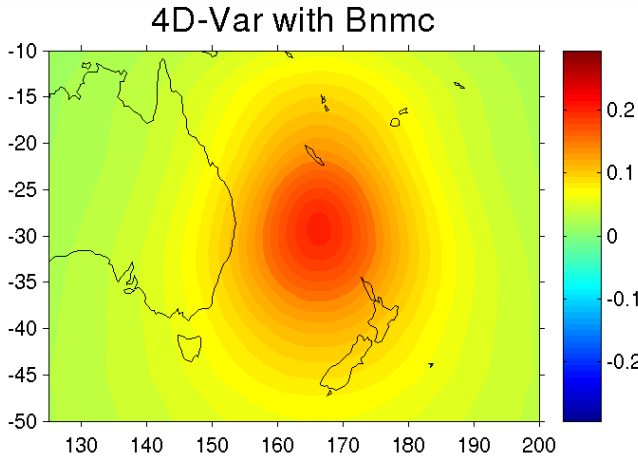


Single observation experiments

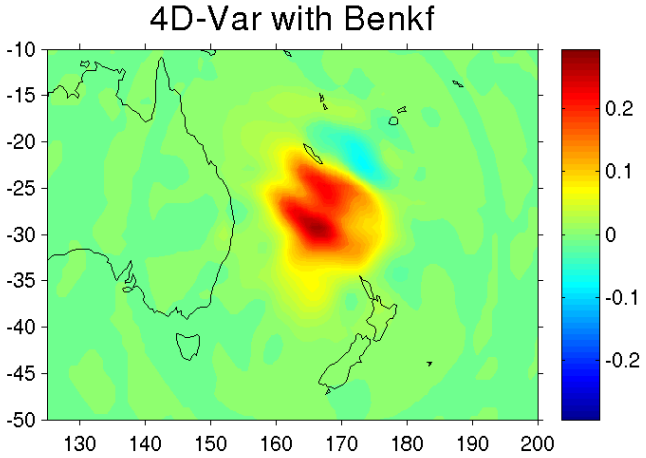
Difference in vertical localization between 3D-Var and EnKF

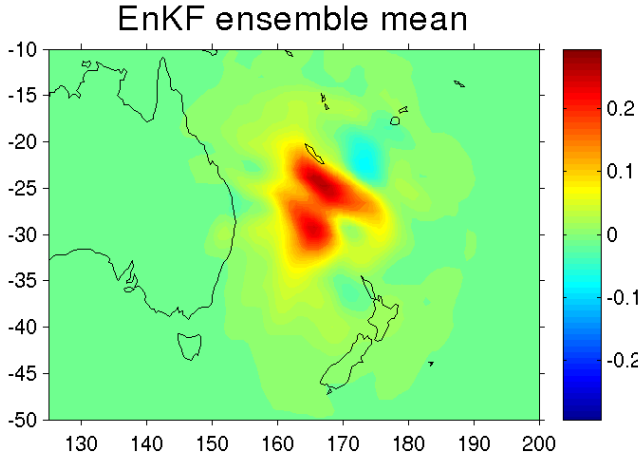
- all AMSU-A channels (4-10)
- with same **B**, largest differences near model top





contour plots at 70 hPa

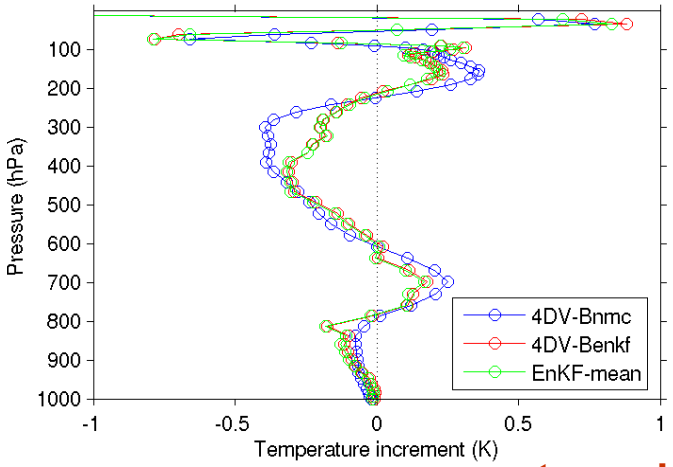


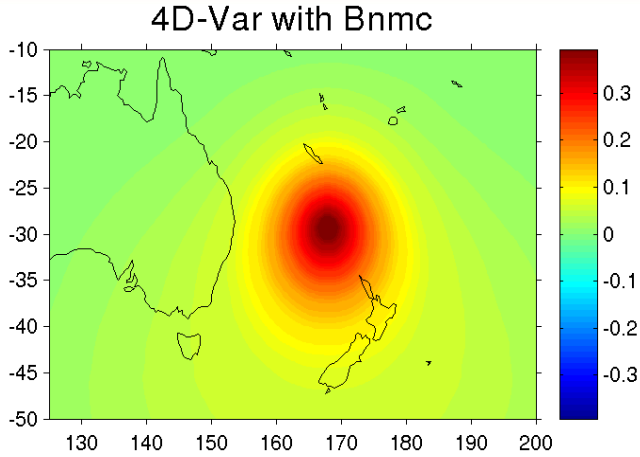


Single observation experiments

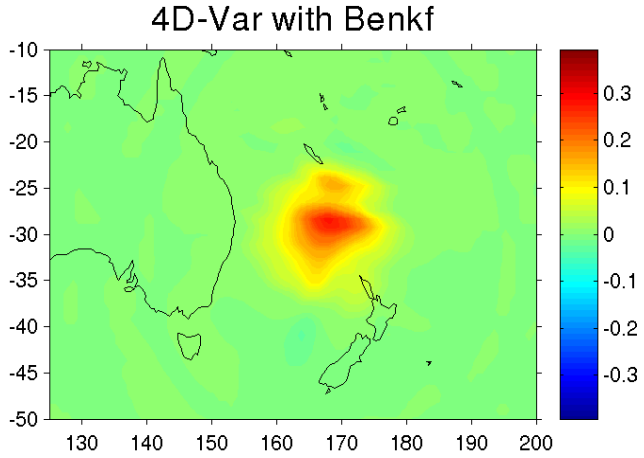
Difference in vertical localization between 3D-Var and EnKF

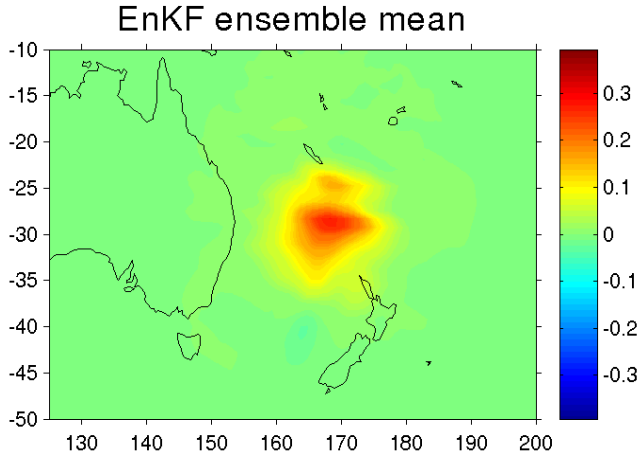
- entire temp. profile of nearby raobs
- all experiments give very similar increments (vertical profile)
- same general shape as with AMSU-A in layer 150hPa-700hPa





contour plots at 150 hPa





4D error covariances

Temporal covariance evolution

- EnKF and 4D-Var both use 4-dimensional error covariances to compute **analysis increment at the middle of assimilation window** (0h) from **observations throughout assimilation window**:

3D-Var (3D covariances):

$\rho \circ B_{ens}(0h,0h)$ $\rho \circ B_{ens}(0h,0h)$ $\rho \circ B_{ens}(0h,0h)$

EnKF (and Ens-4D-Var):

$\rho \circ B_{ens}(0h,-3h)$ $\rho \circ B_{ens}(0h,0h)$ $\rho \circ B_{ens}(0h,+3h)$

4D-Var:

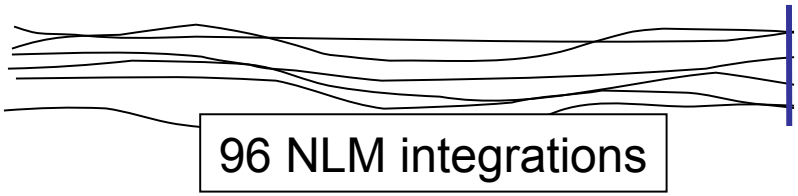
$M\ (\rho \circ B_{ens}(-3h,-3h))$ $M\ ((\rho \circ B_{ens}(-3h,-3h))\ M^T)$ $M\ ((\rho \circ B_{ens}(-3h,-3h))\ M^T M^T)$

-3h 0h +3h

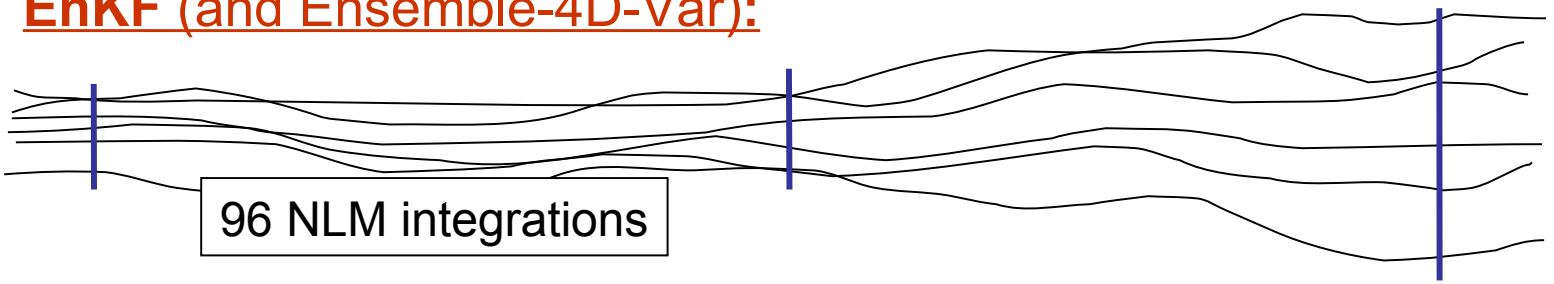
4D error covariances

Temporal covariance evolution

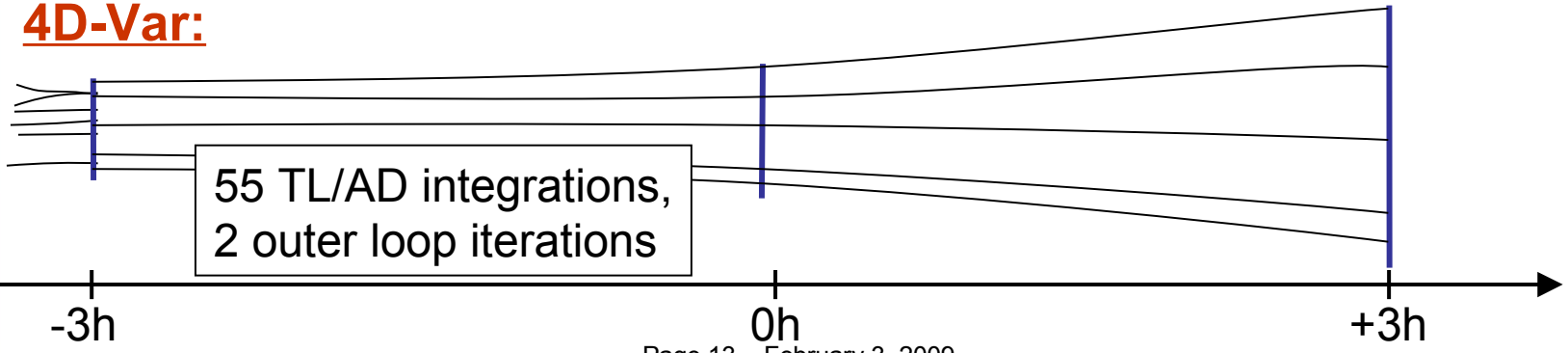
3D-Var:



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



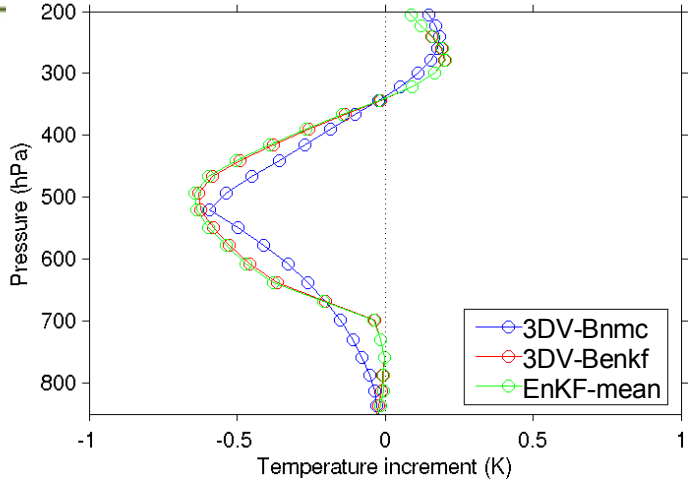
4D-Var:

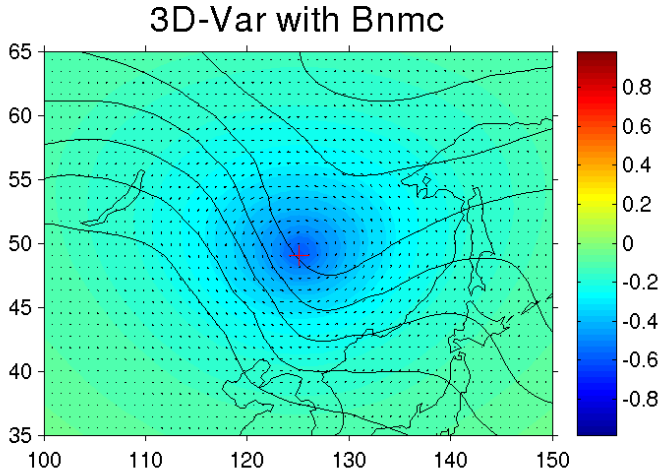


Single observation experiments – 3D-Var

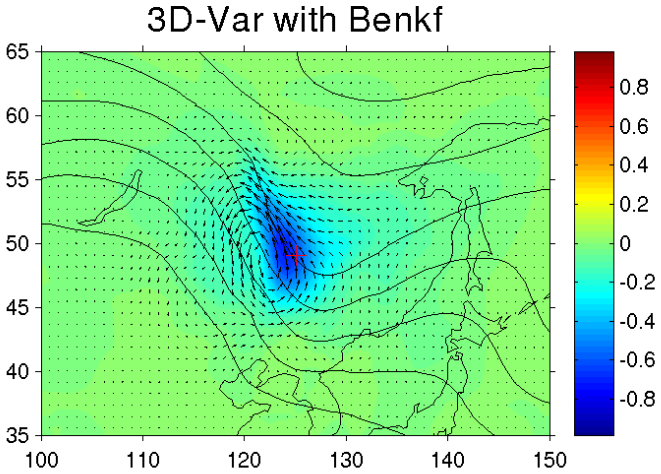
Difference in temporal covariance evolution

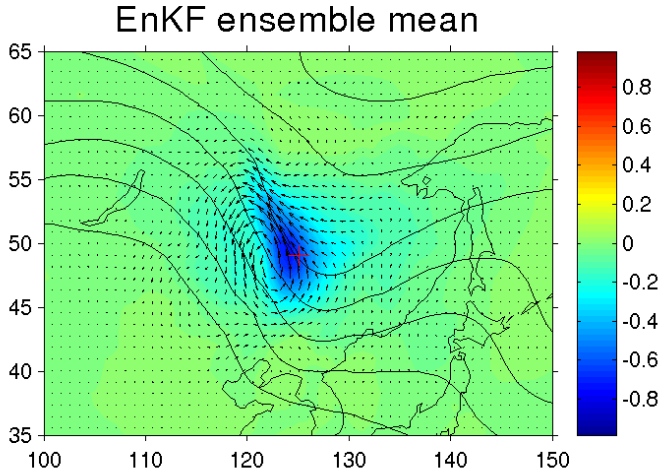
- radiosonde temperature observation at 500hPa
- observation at **middle of assimilation window (+0h)**
- with same **B**, increments nearly identical from **3D-Var**, **EnKF**
- contours are 500hPa GZ background state at 0h (ci=10m)





contour plots at 500 hPa

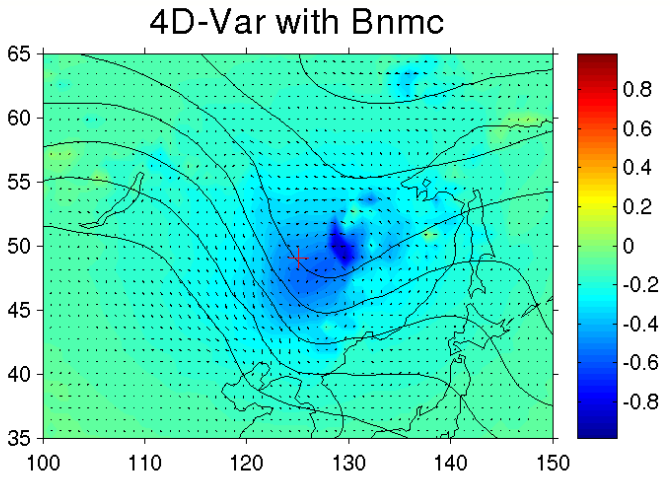


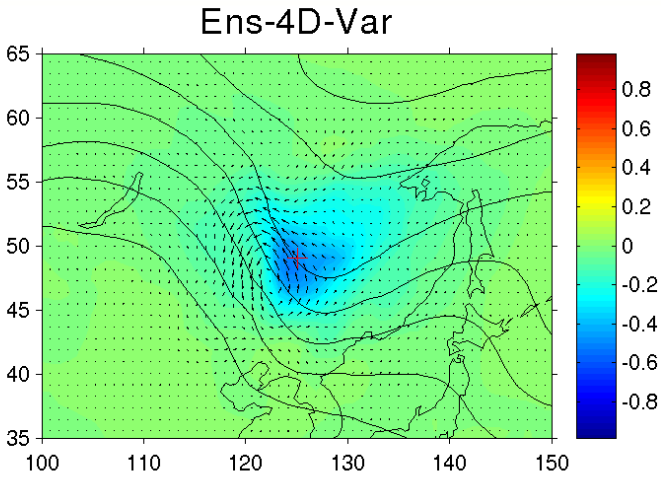


Single observation experiments

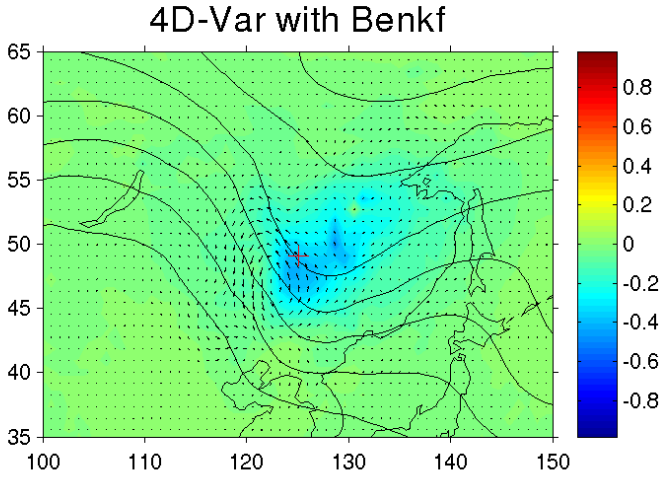
Difference in temporal covariance evolution

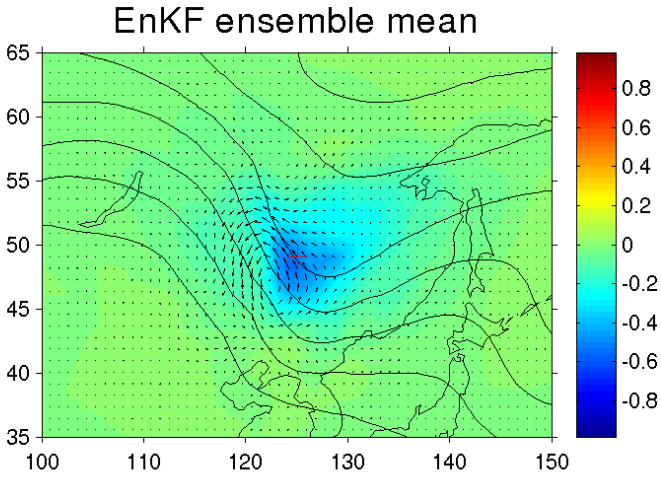
- radiosonde temperature observation at 500hPa
- observation at **beginning of assimilation window (-3h)**
- with same **B**, increments very similar from **4D-Var**, **EnKF**
- contours are 500hPa GZ background state at 0h (ci=10m)





contour plots at 500 hPa



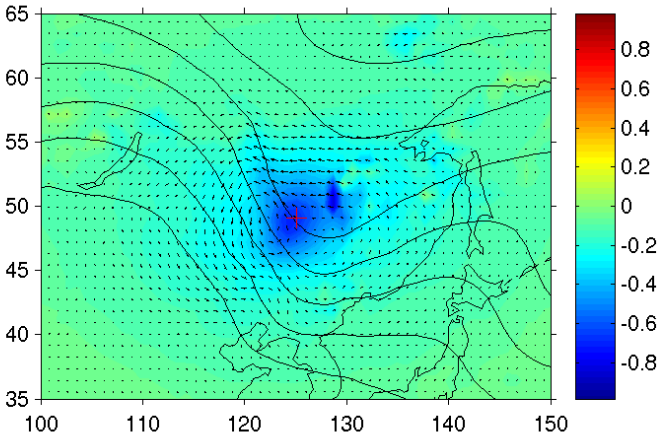


Single observation experiments

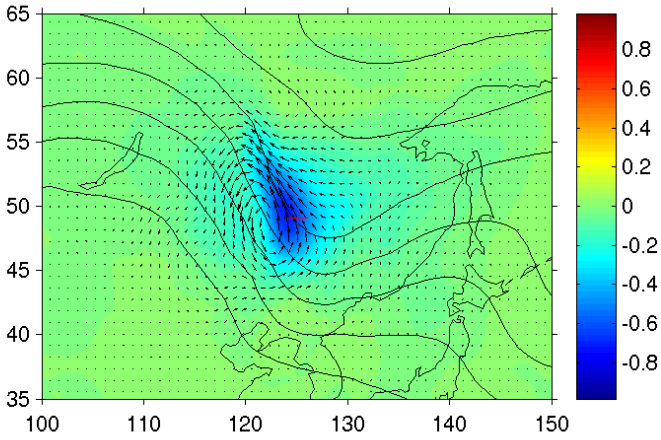
Difference in temporal covariance evolution

- 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

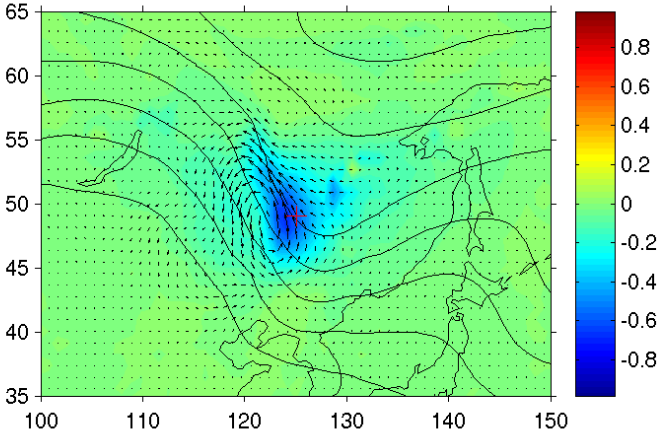


Ens-4D-Var

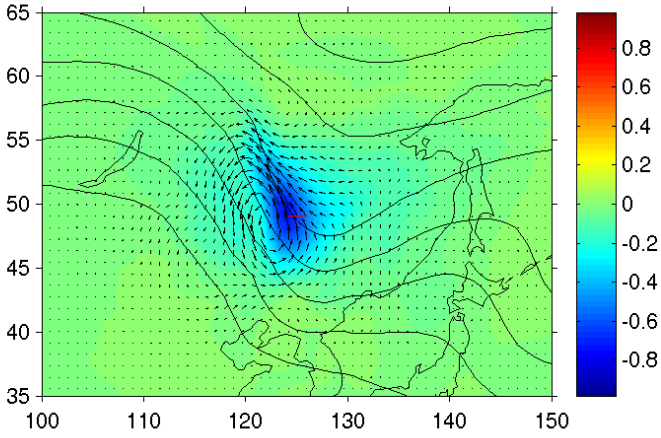


contour plots at 500 hPa

4D-Var with Benkf



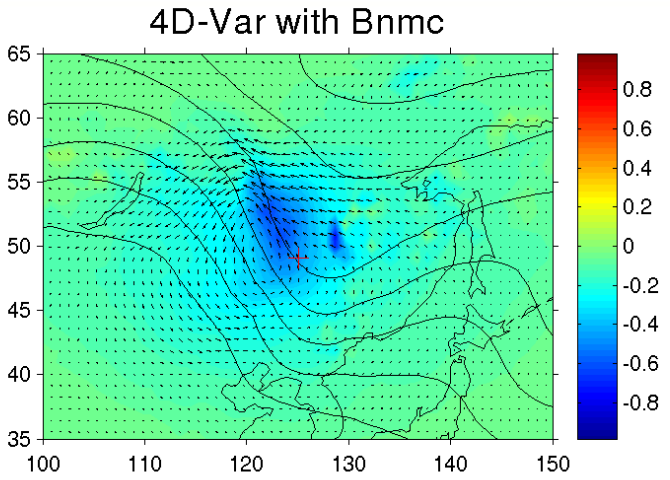
EnKF ensemble mean

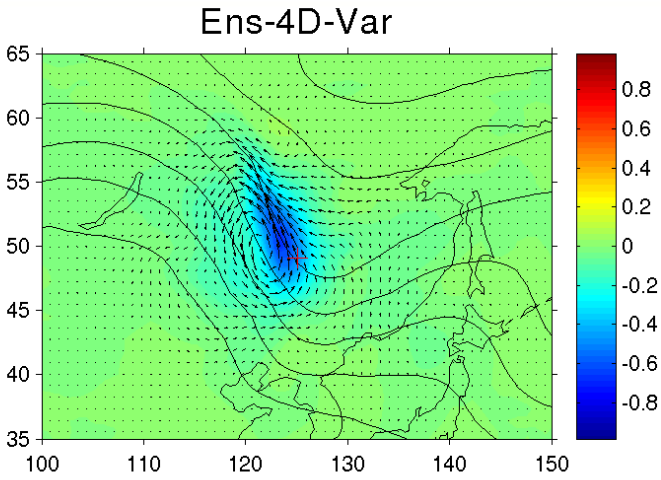


Single observation experiments

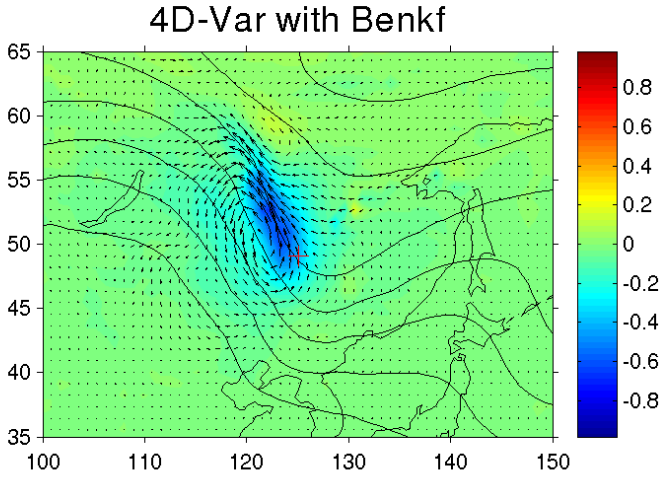
Difference in temporal covariance evolution

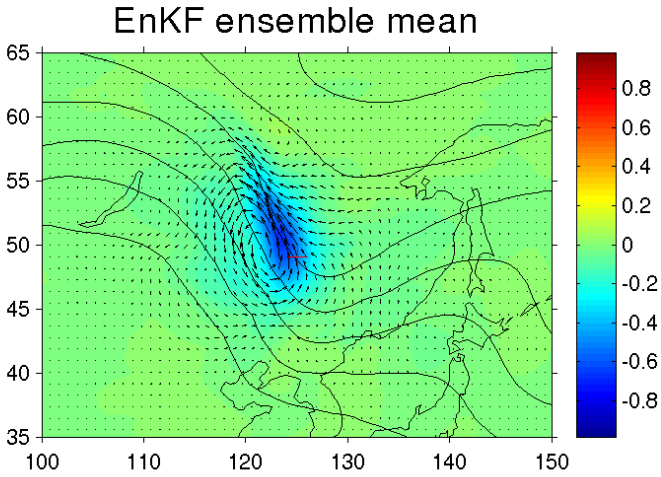
- radiosonde temperature observation at 500hPa
- observation at **end of assimilation window (+3h)**
- with same **B**, increments very similar from **4D-Var**, **EnKF**
- contours are 500hPa GZ background state at 0h (ci=10m)





contour plots at 500 hPa





Analysis and Forecast Verification Results – Forecasts with GEM-Meso (800x600x58L)

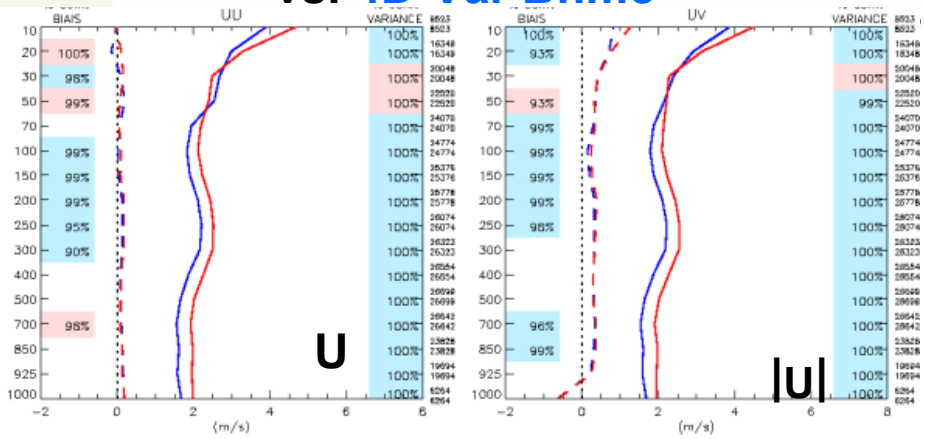
EnKF (ensemble mean) vs. 4D-Var Bnmc

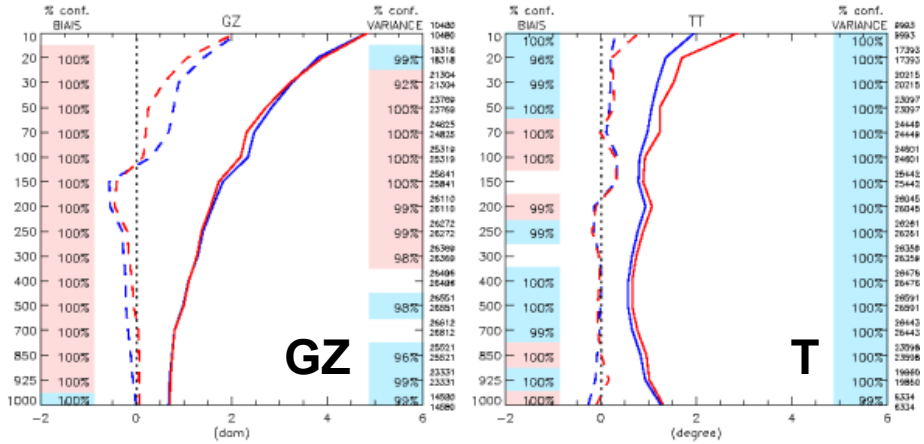
and

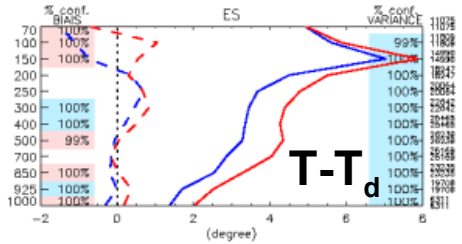
4D-Var Benkf vs. 4D-Var Bnmc

Analysis Results – global

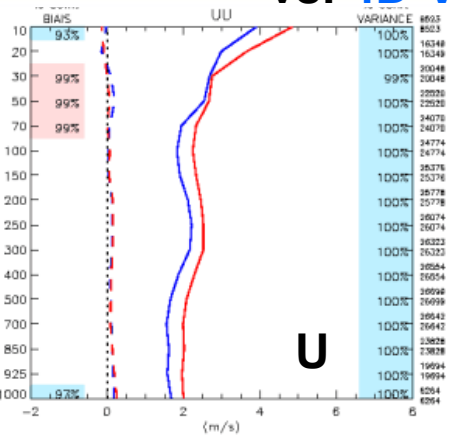
EnKF mean analysis
vs. 4D-Var Bnmc

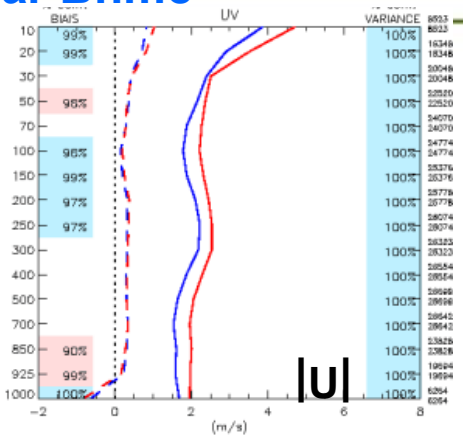


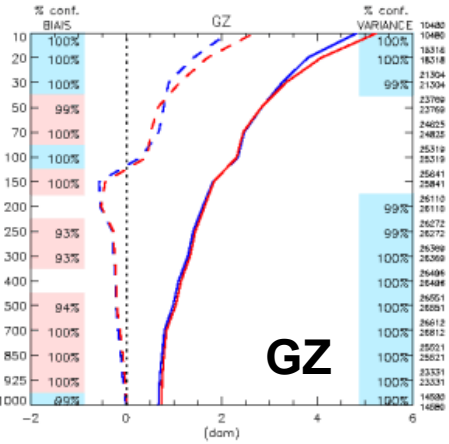


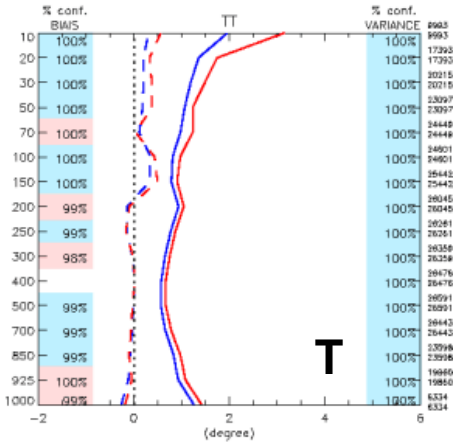


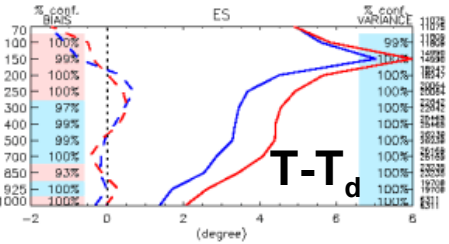
4D-Var Benkf
vs. 4D-Var Bnmc







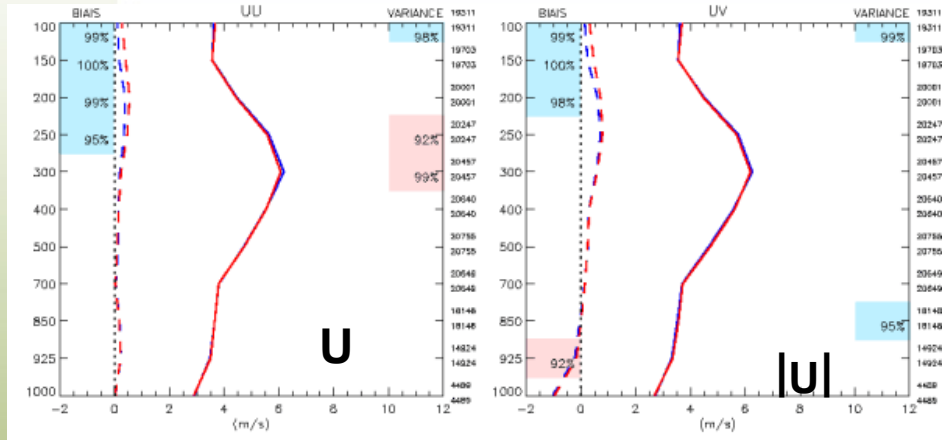


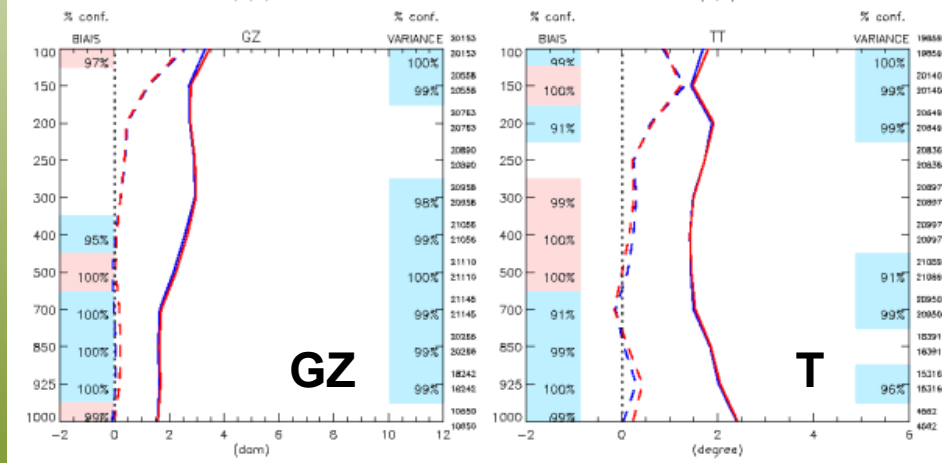


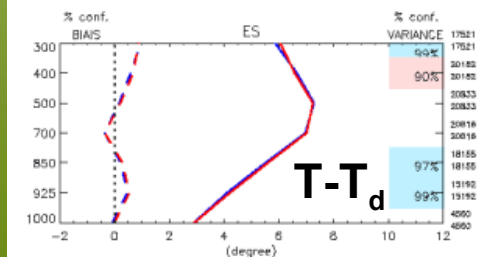
stddev & bias relative to radiosondes

Forecast Results – 48h northern hemisphere

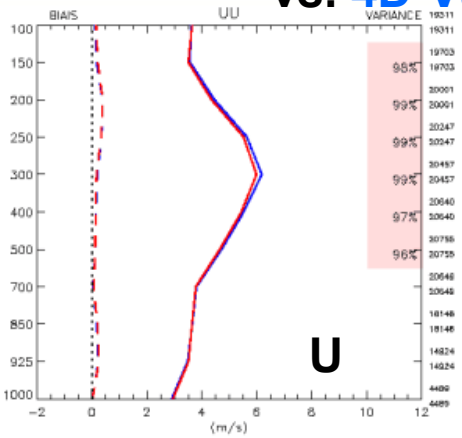
EnKF mean analysis
vs. 4D-Var Bnmc

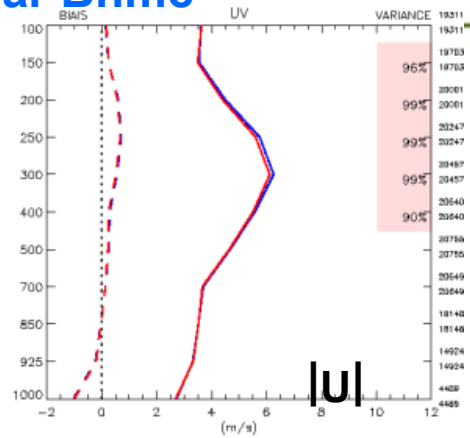


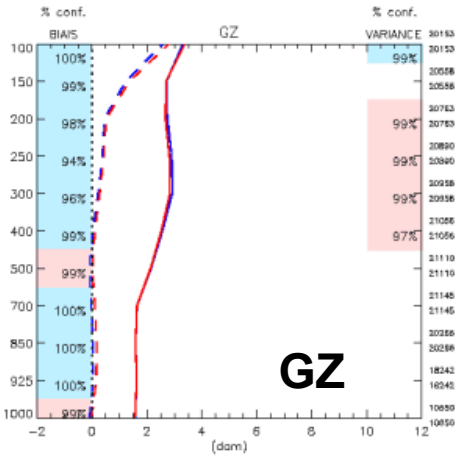


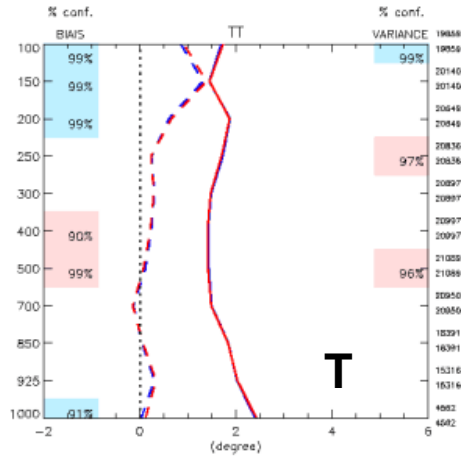


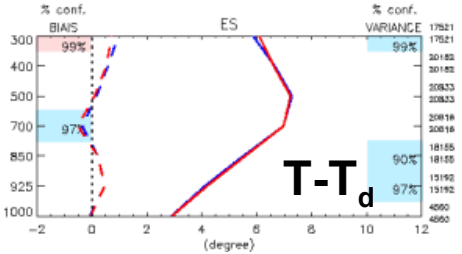
4D-Var Benkf
vs. 4D-Var Bnmc







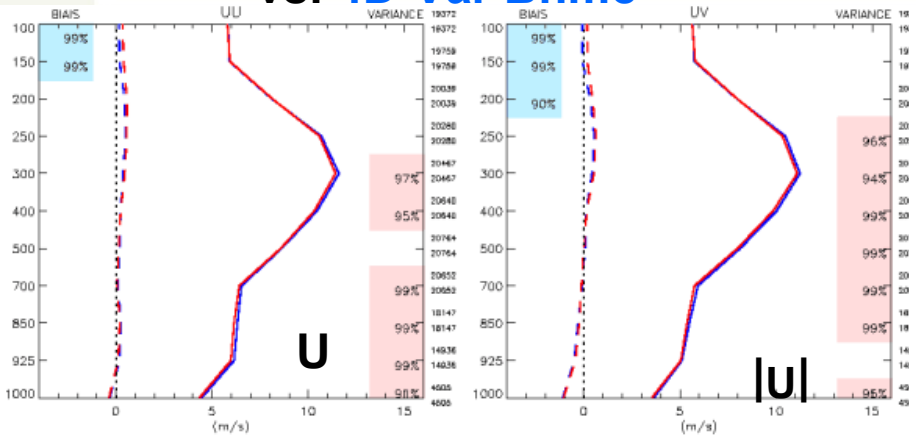


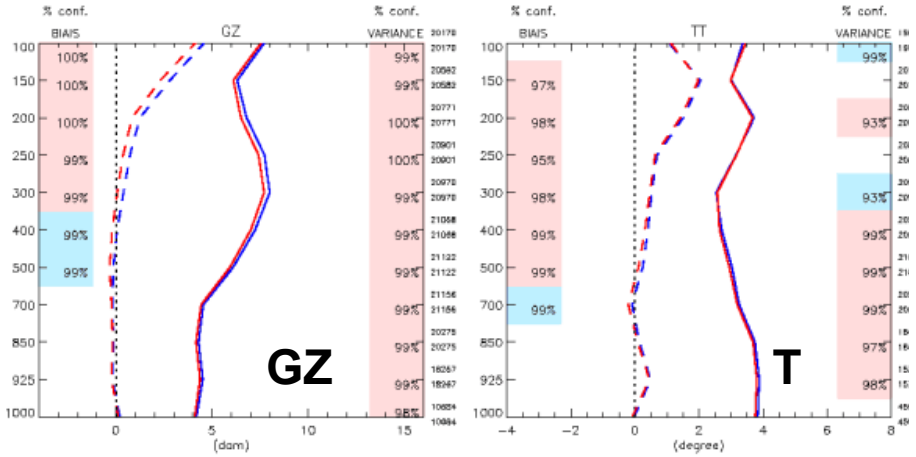


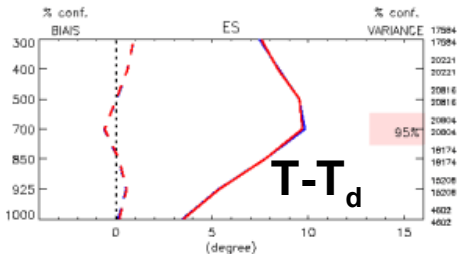
stddev & bias relative to radiosondes

Forecast Results – 120h northern hemisphere

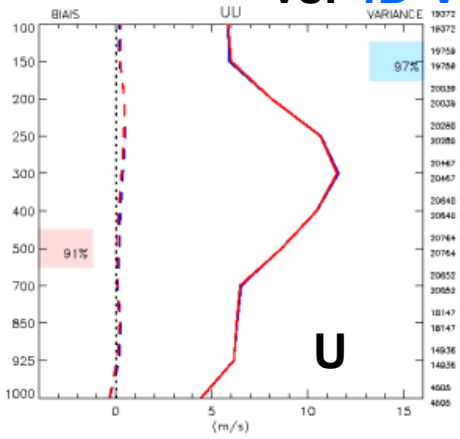
EnKF mean analysis
vs. 4D-Var Bnmc

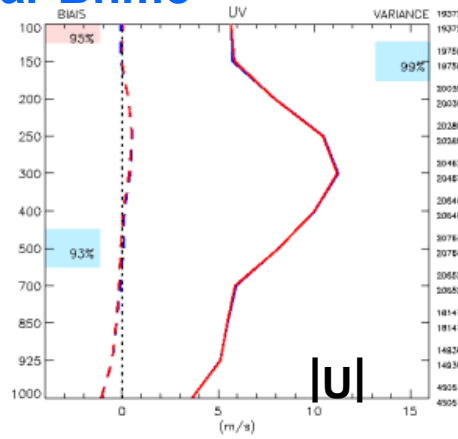


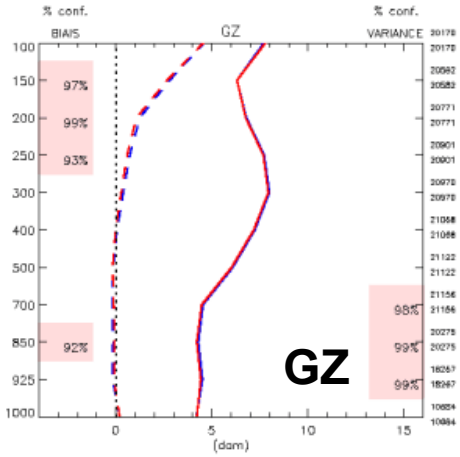


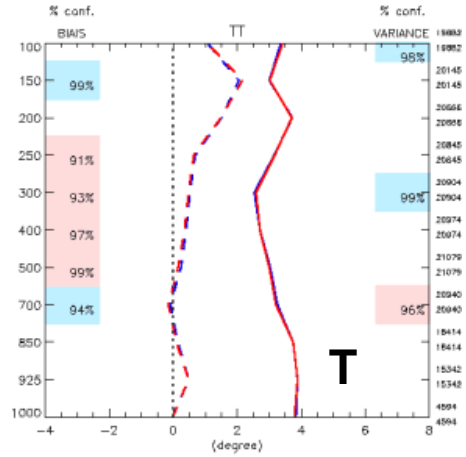


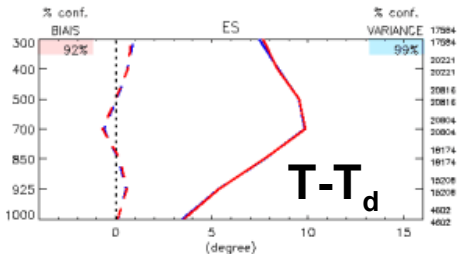
4D-Var Benkf
vs. 4D-Var Bnmc







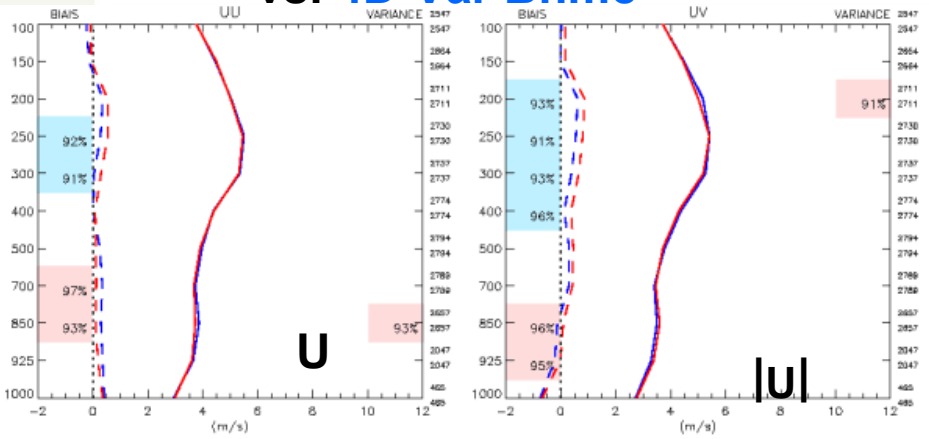


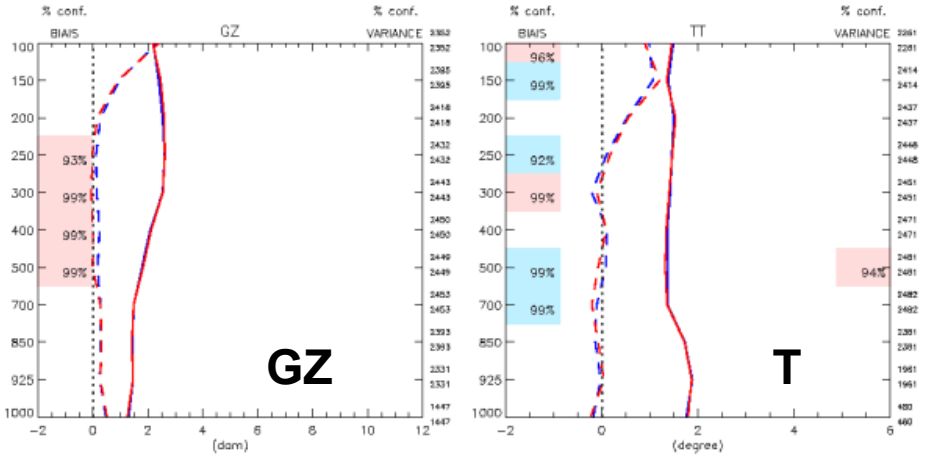


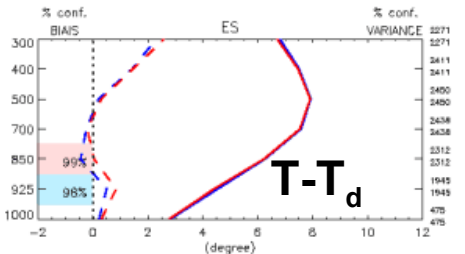
stddev & bias relative to radiosondes

Forecast Results – 48h southern hemisphere

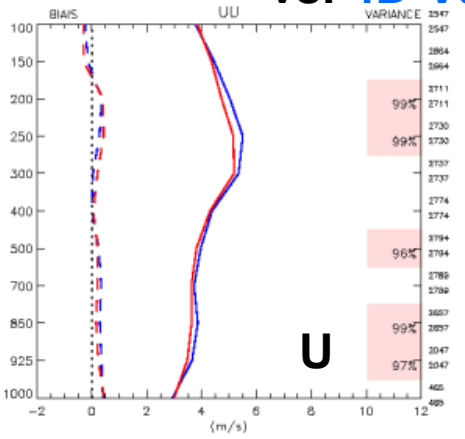
EnKF mean analysis
vs. 4D-Var Bnmc

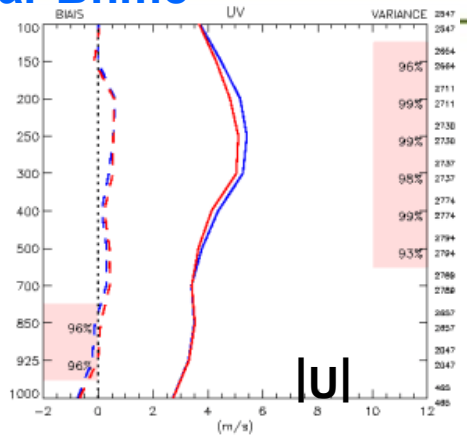


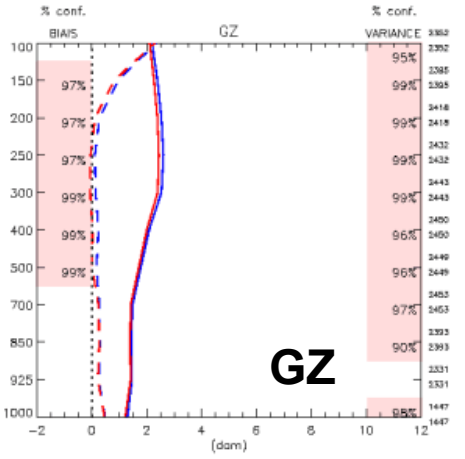


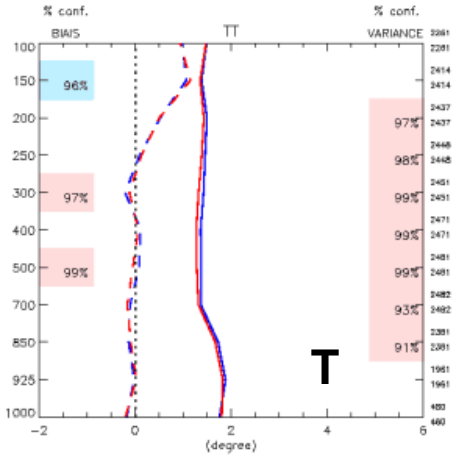


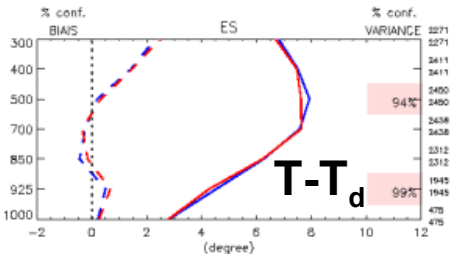
4D-Var Benkf
vs. 4D-Var Bnmc







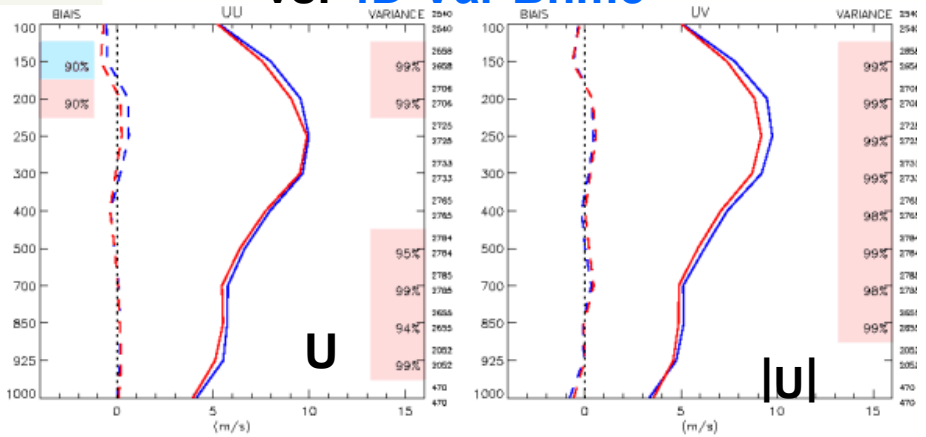


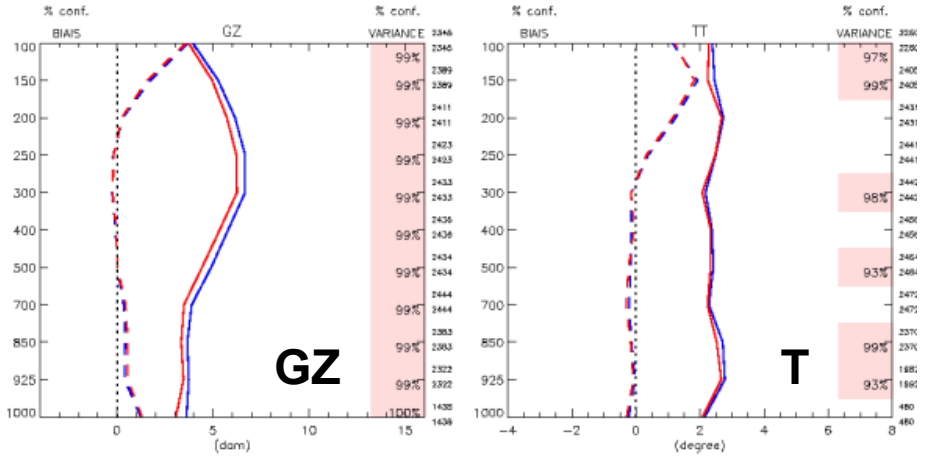


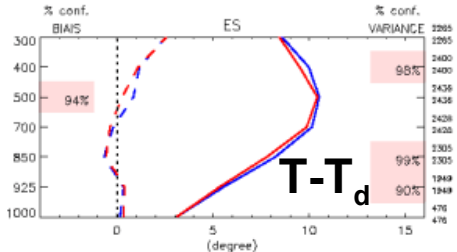
stddev & bias relative to radiosondes

Forecast Results – 120h southern hemisphere

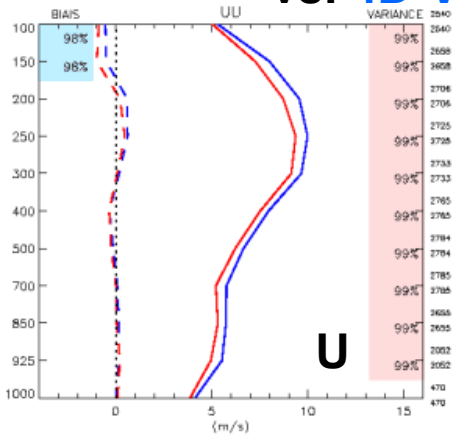
EnKF mean analysis vs. 4D-Var Bnmc

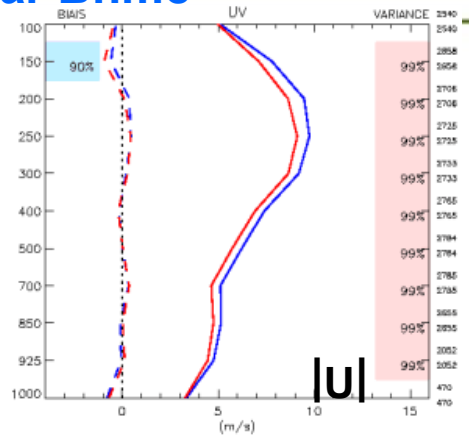


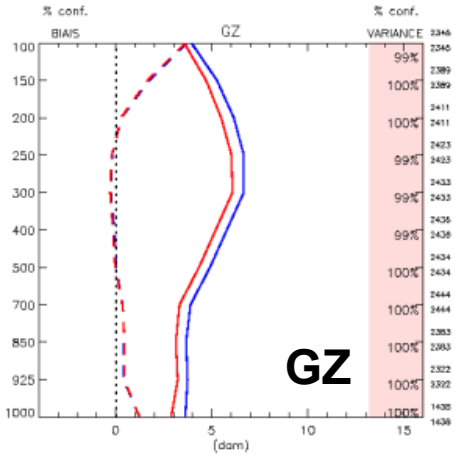


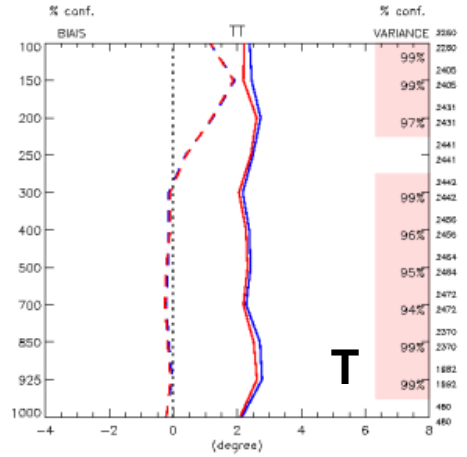


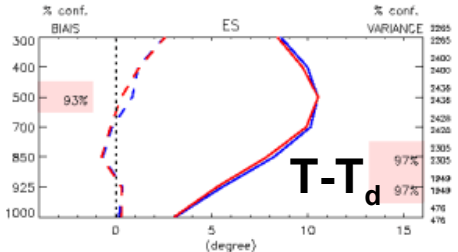
4D-Var Benkf vs. 4D-Var Bnmc







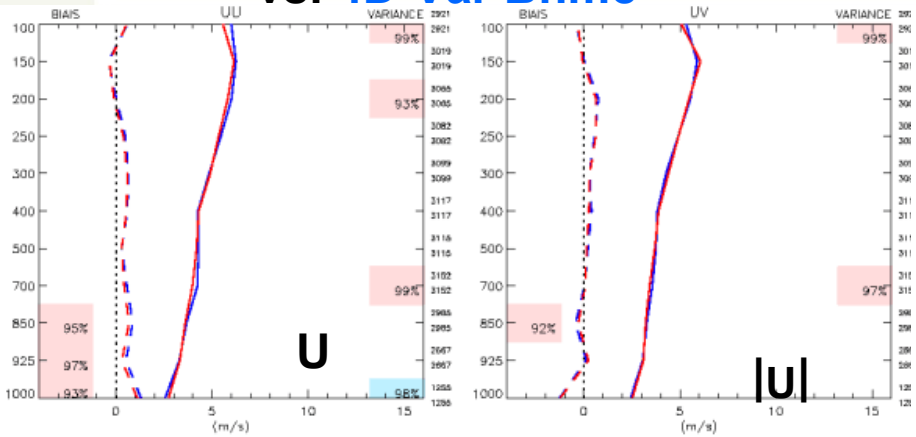


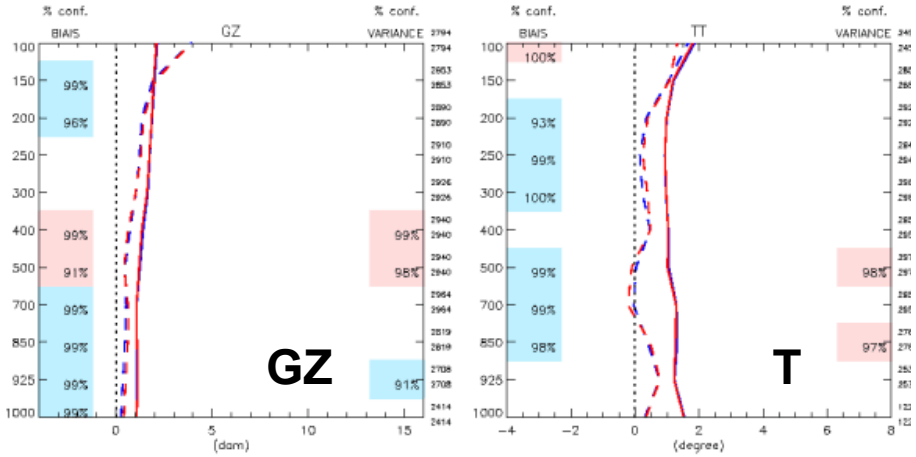


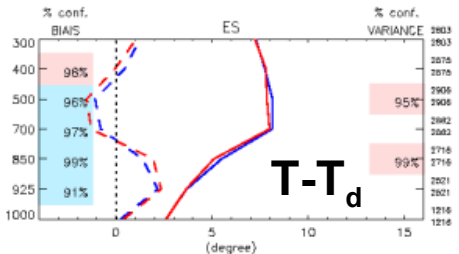
stddev & bias relative to radiosondes

Forecast Results – 72h tropics

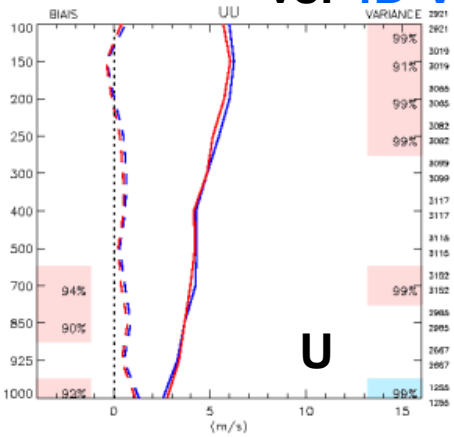
EnKF mean analysis vs. 4D-Var Bnmc

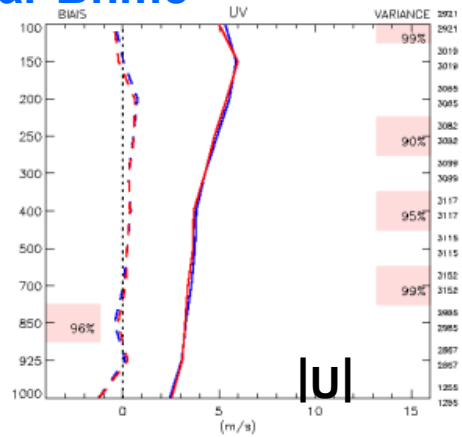


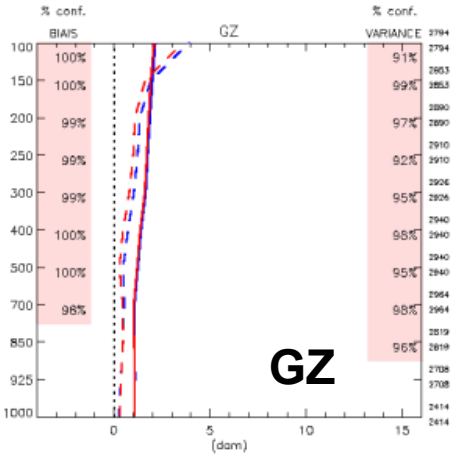


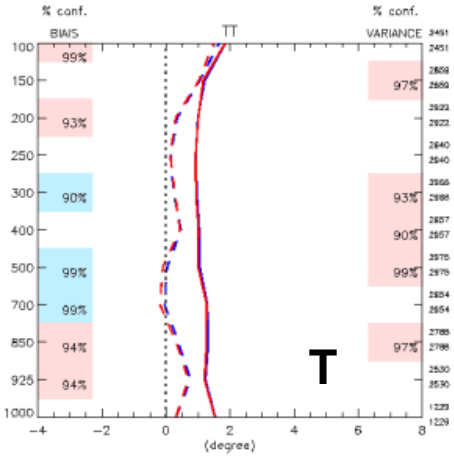


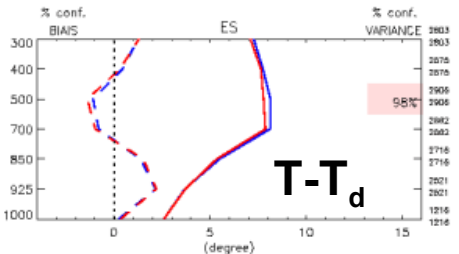
4D-Var Benkf vs. 4D-Var Bnmc









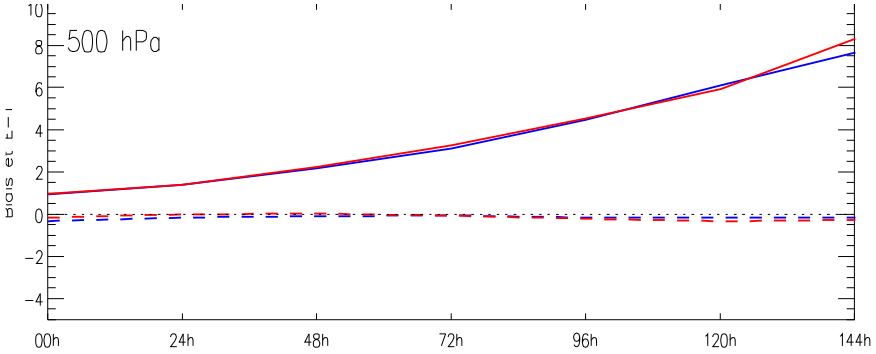


stddev & bias relative to radiosondes

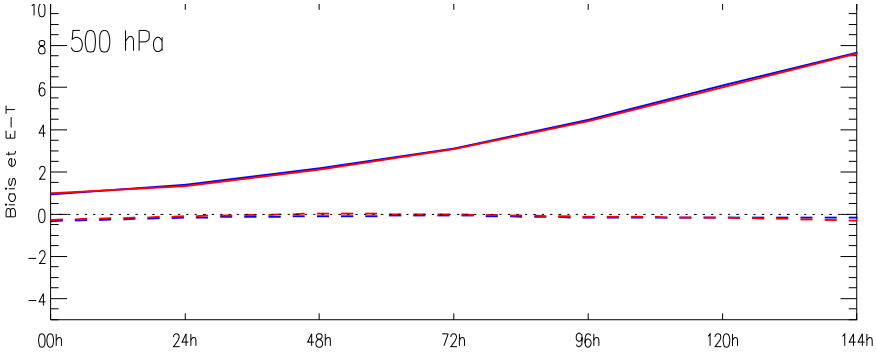
Forecast Results – 500 hPa GZ

Northern Hemisphere

EnKF Mean Analyses vs. 4D-Var Bnmc

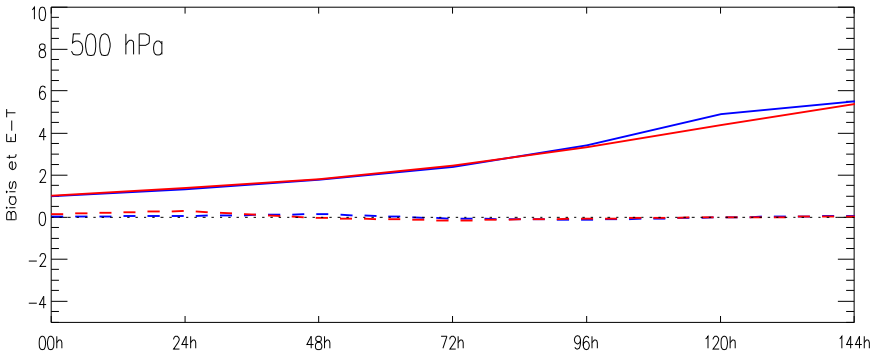


4D-Var with Benkf vs. 4D-Var Bnmc

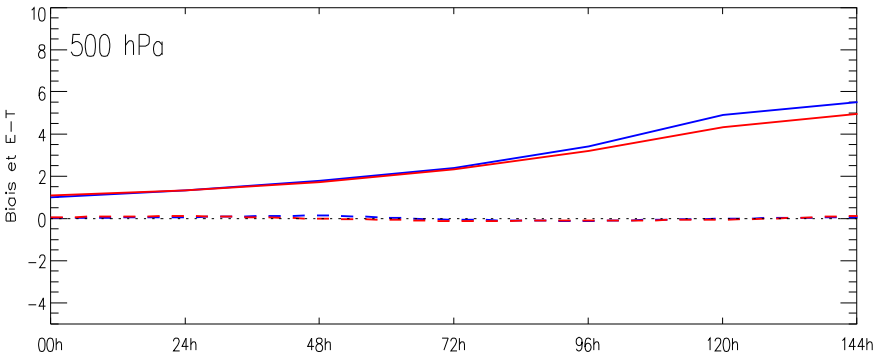


Southern Hemisphere

EnKF Mean Analyses vs. 4D-Var Bnmc



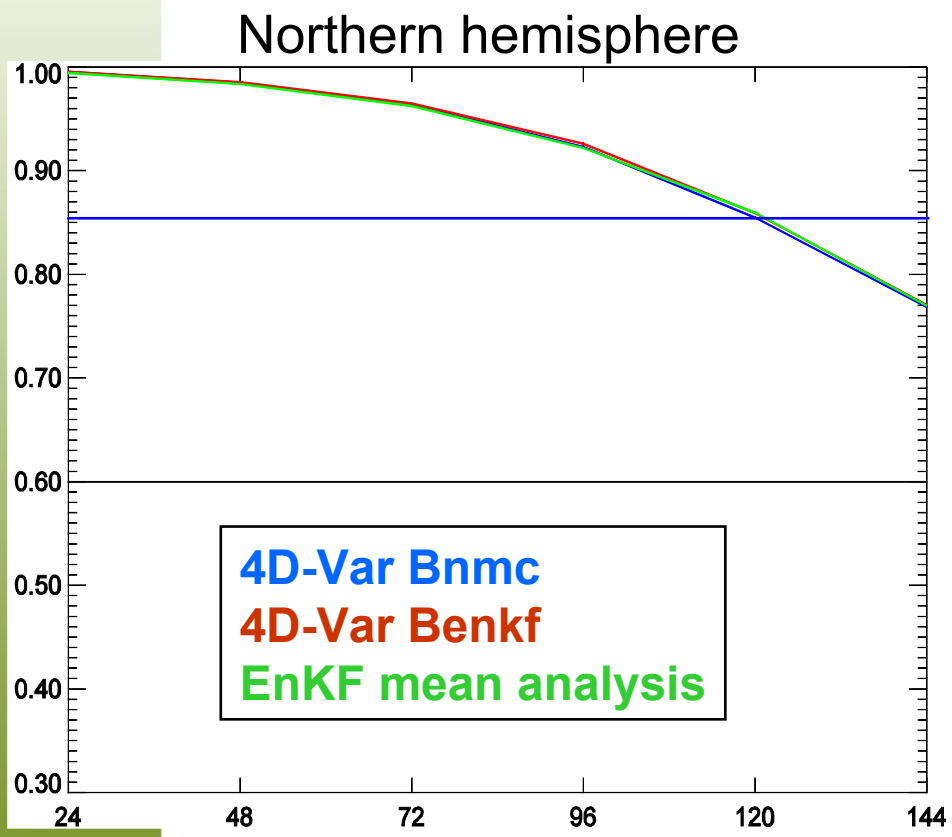
4D-Var with Benkf vs. 4D-Var Bnmc

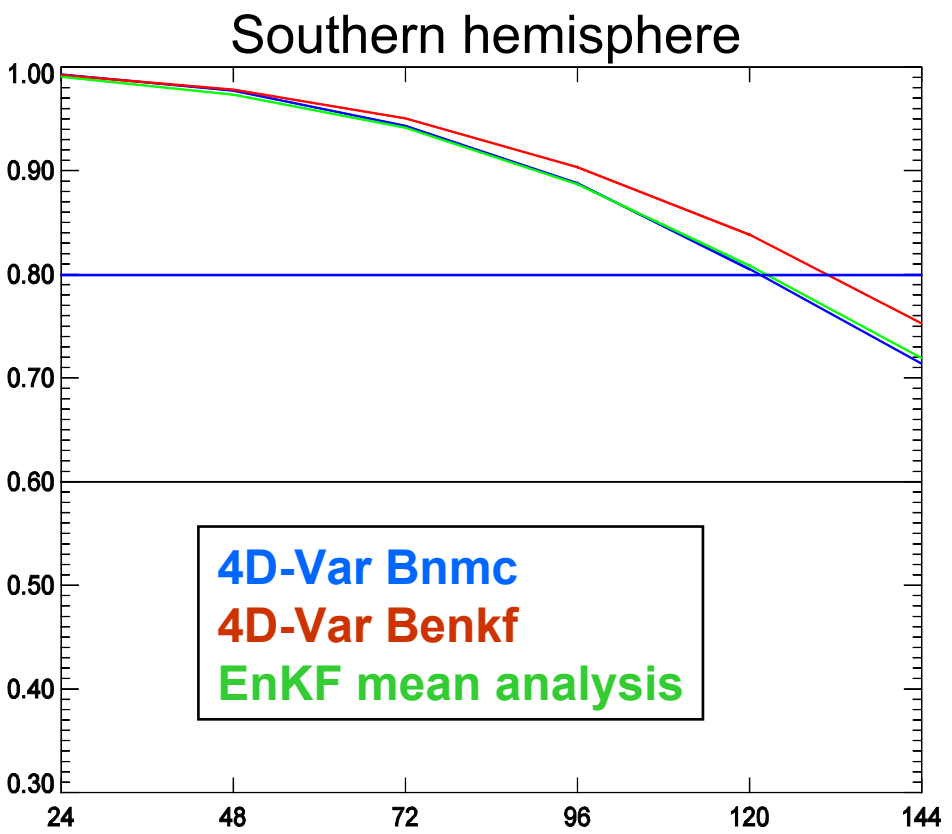


stddev & bias relative to radiosondes

Results – 500hPa GZ anomaly correlation

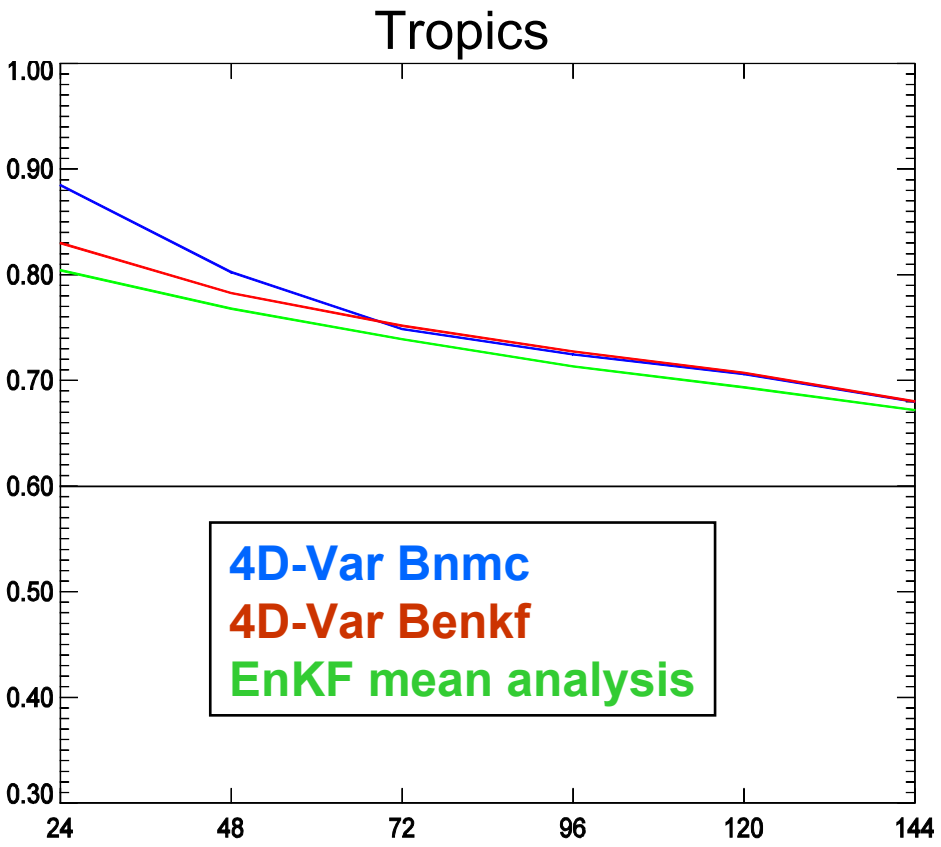
Verifying analyses from 4D-Var with Bnmc





Results – 850hPa T anomaly correlation

Verifying analyses from 4D-Var with Bnmc



Analysis and Forecast Verification Results – Differences in covariance evolution

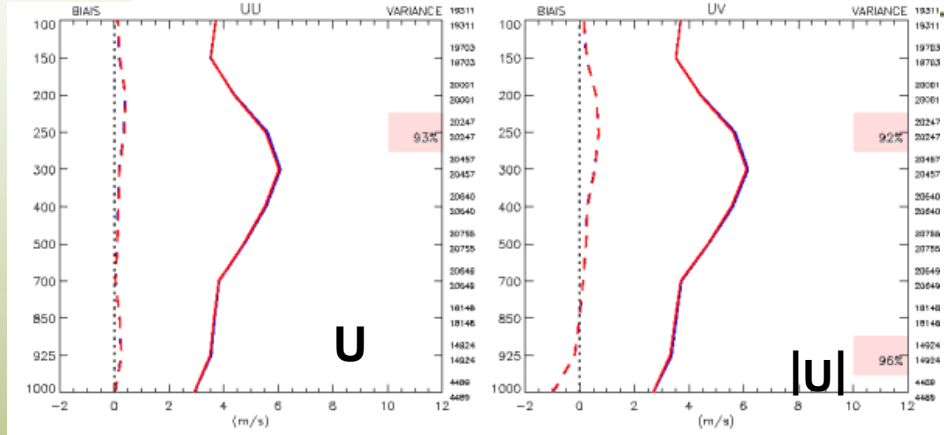
Ensemble-4D-Var vs. 3D-Var Benkf

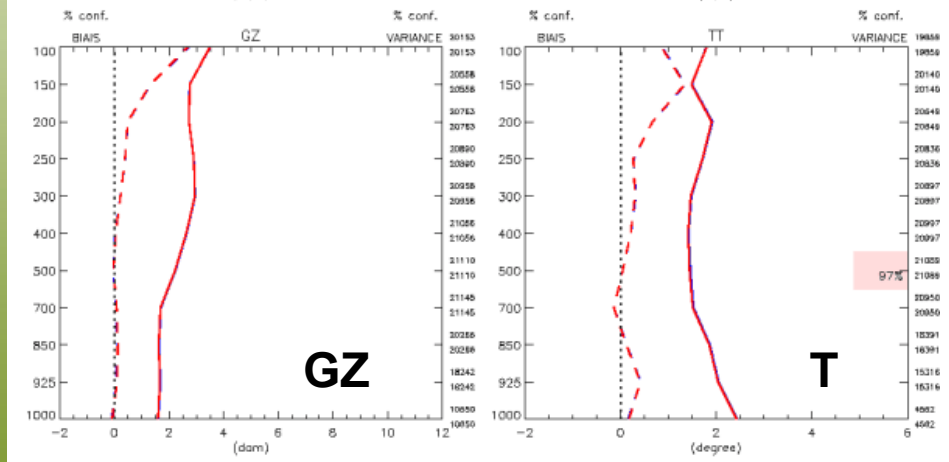
and

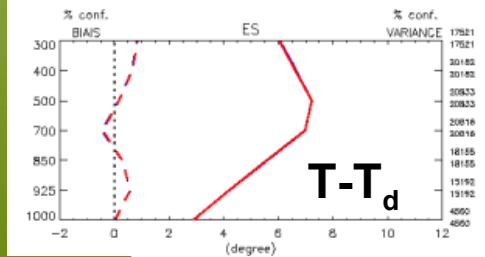
4D-Var Benkf vs. 3D-Var Benkf

Forecast Results – 48h northern hemisphere

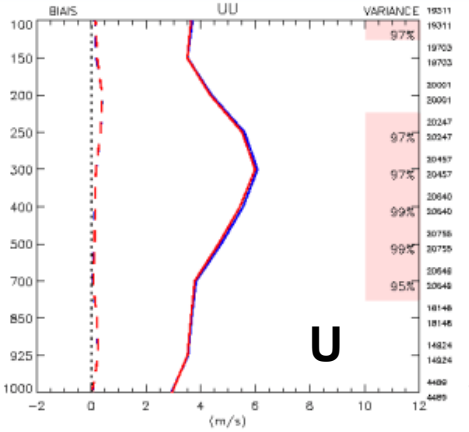
Ensemble-4D-Var vs. 3D-Var Benkf

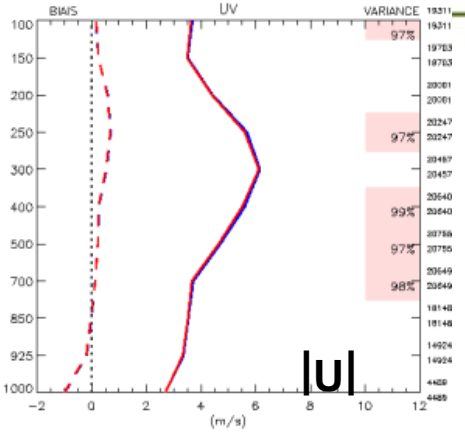


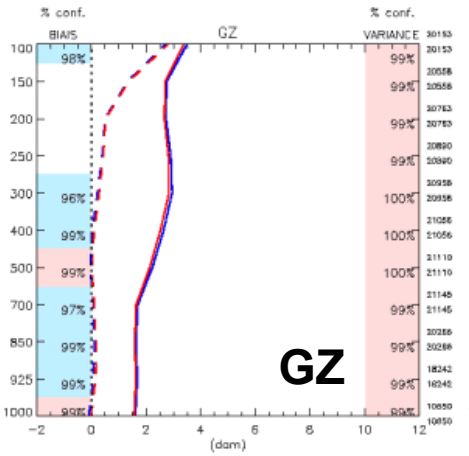


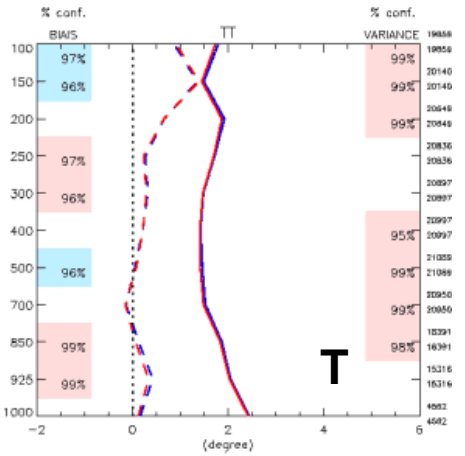


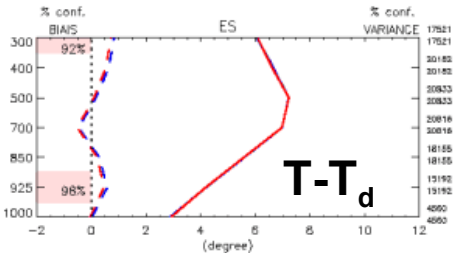
4D-Var Benkf vs. 3D-Var Benkf







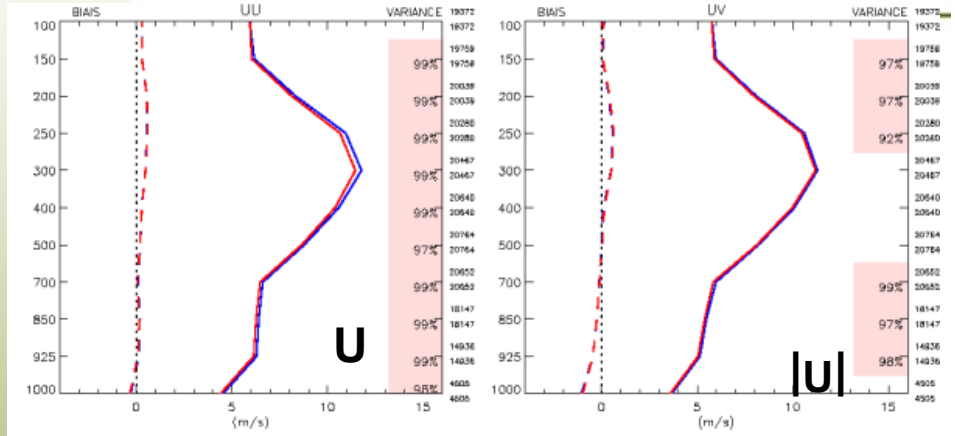


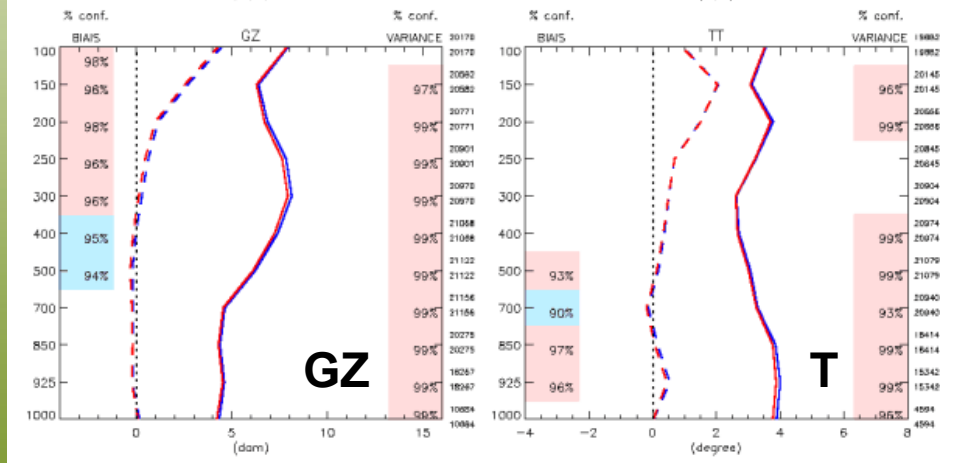


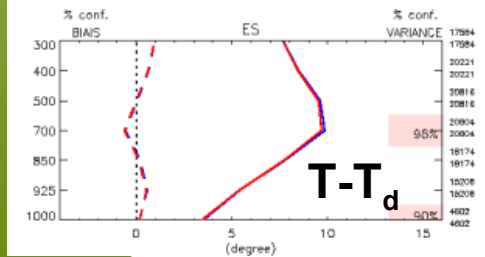
stddev & bias relative to radiosondes

Forecast Results – 120h northern hemisphere

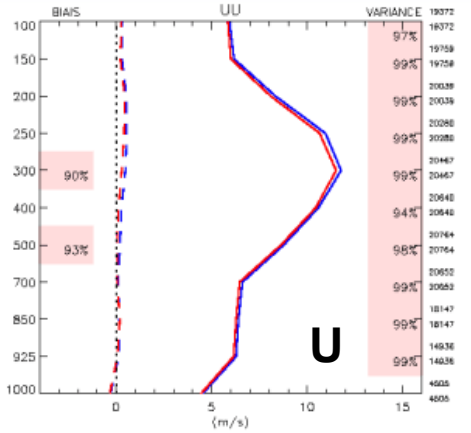
Ensemble-4D-Var
vs. 3D-Var Benkf

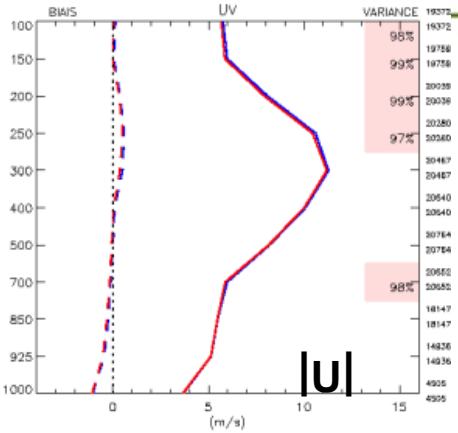


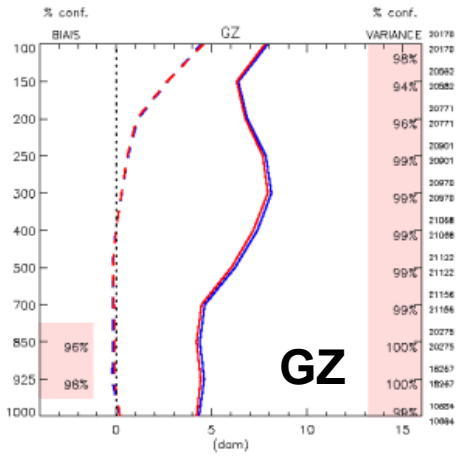


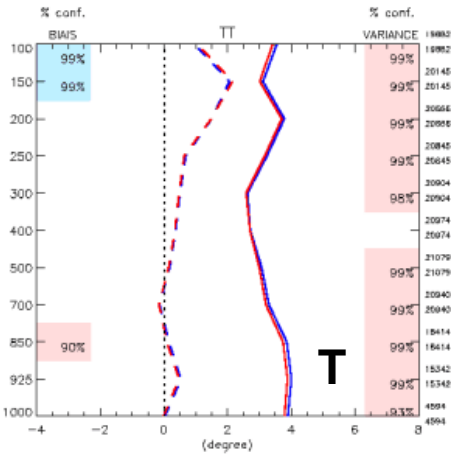


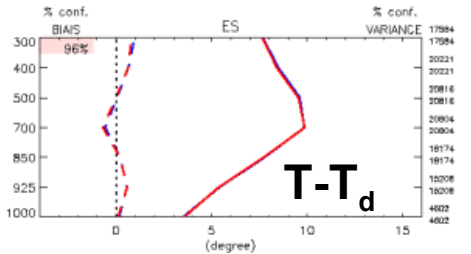
4D-Var Benkf
vs. 3D-Var Benkf







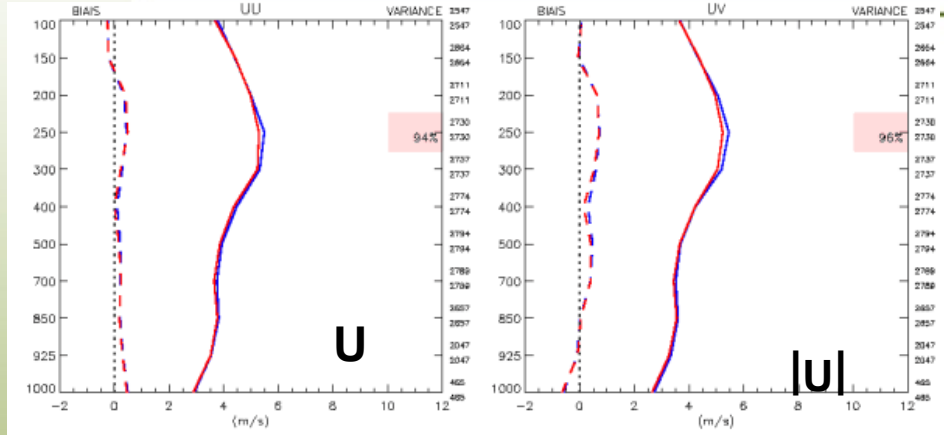


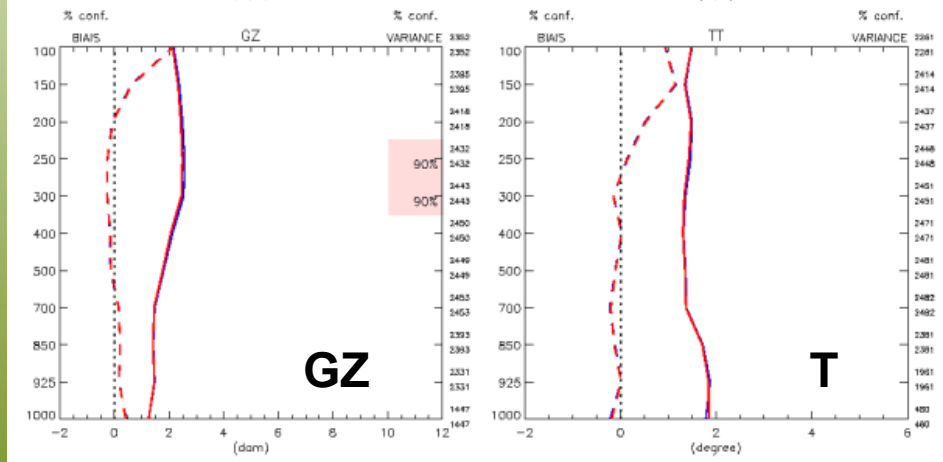


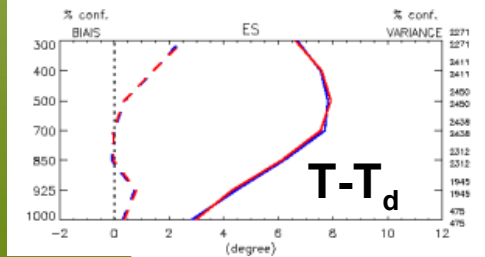
stddev & bias relative to radiosondes

Forecast Results – 48h southern hemisphere

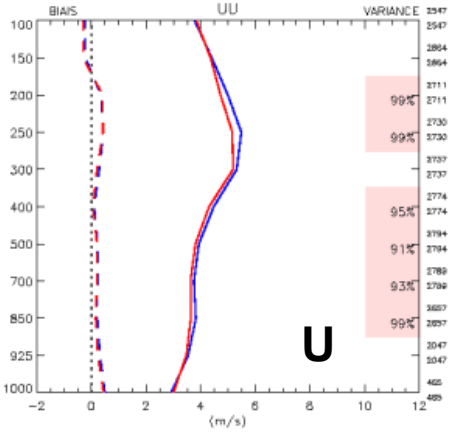
Ensemble-4D-Var vs. 3D-Var Benkf

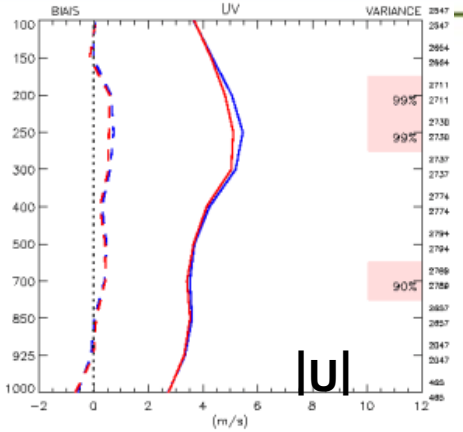


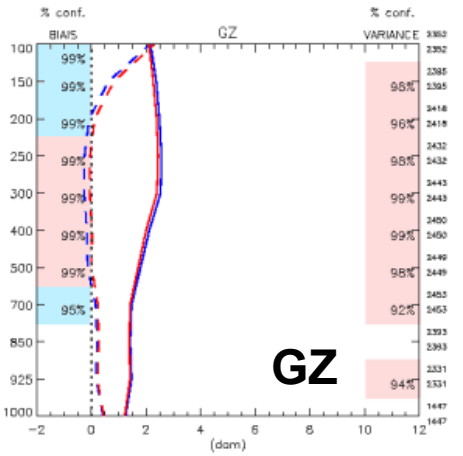


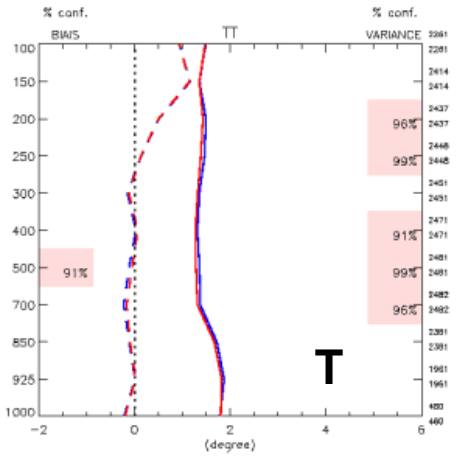


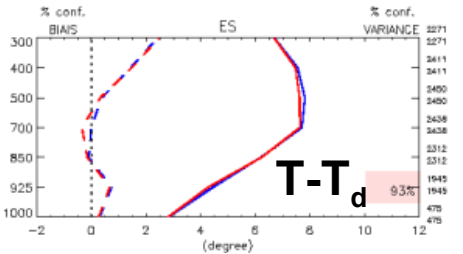
4D-Var Benkf vs. 3D-Var Benkf







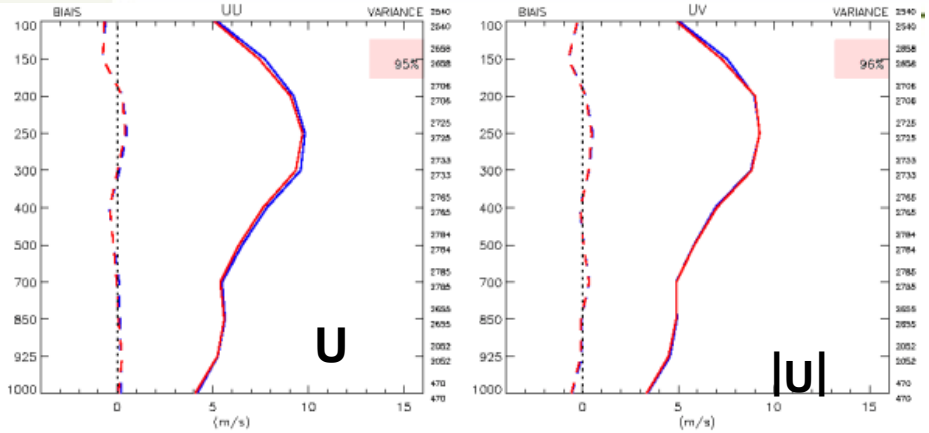


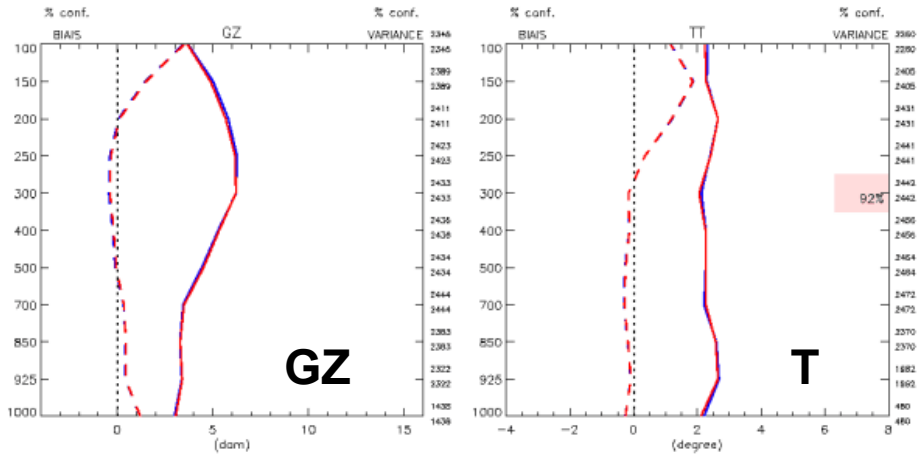


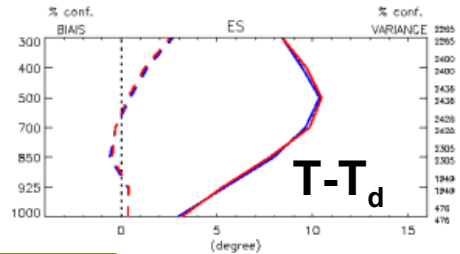
stddev & bias relative to radiosondes

Forecast Results – 120h southern hemisphere

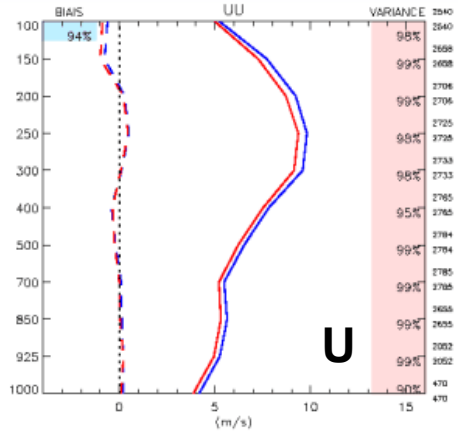
Ensemble-4D-Var vs. 3D-Var Benkf

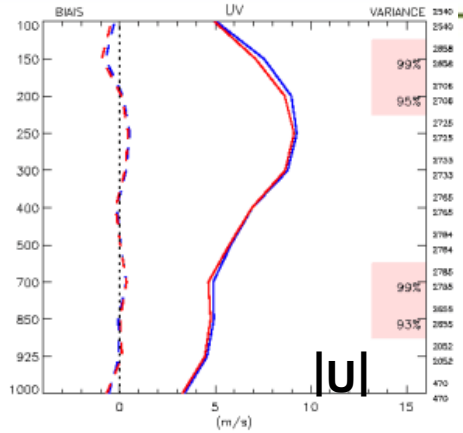


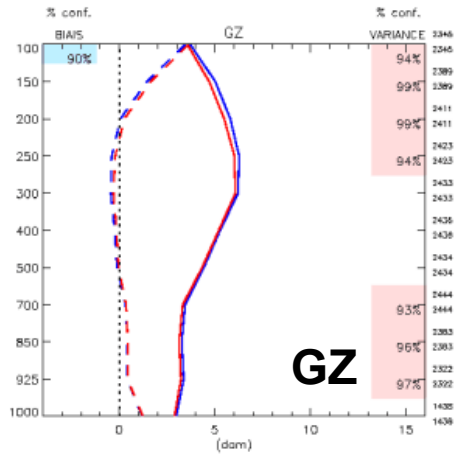


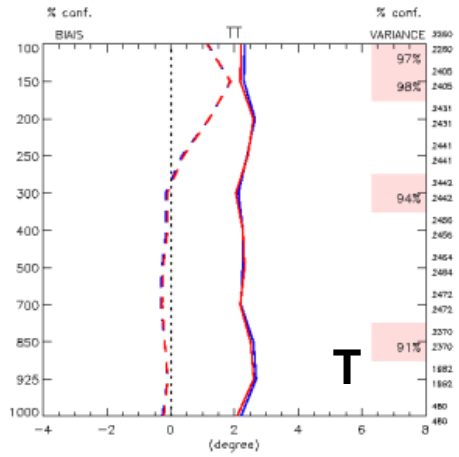


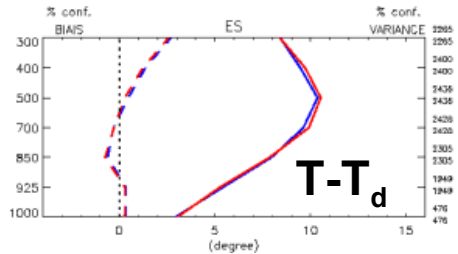
4D-Var Benkf vs. 3D-Var Benkf







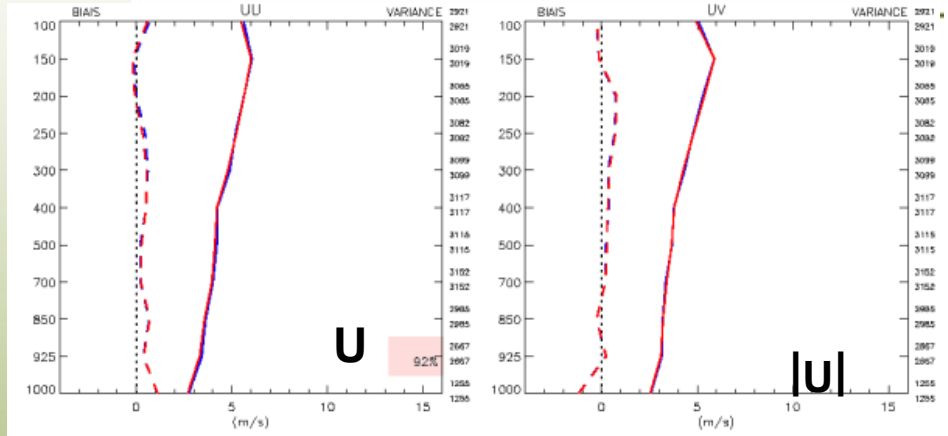


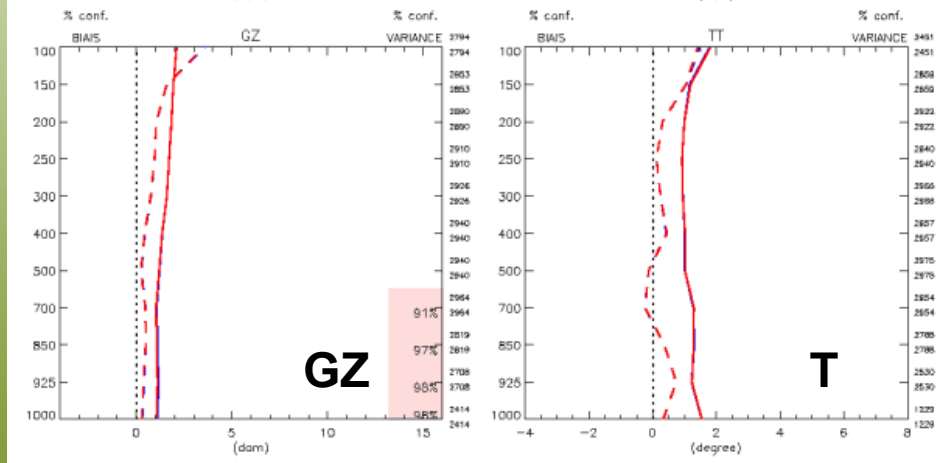


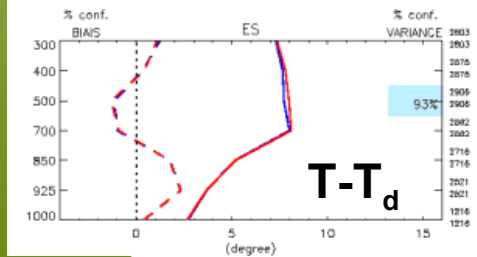
stddev & bias relative to radiosondes

Forecast Results – 72h tropics

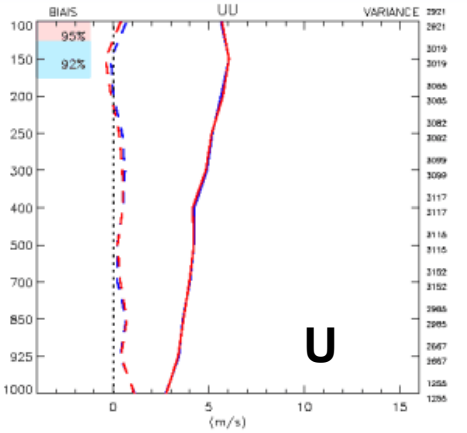
Ensemble-4D-Var vs. 3D-Var Benkf

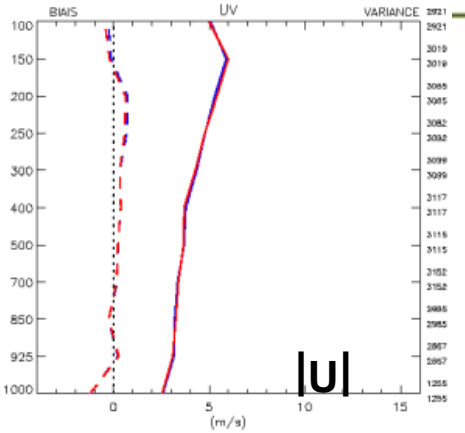


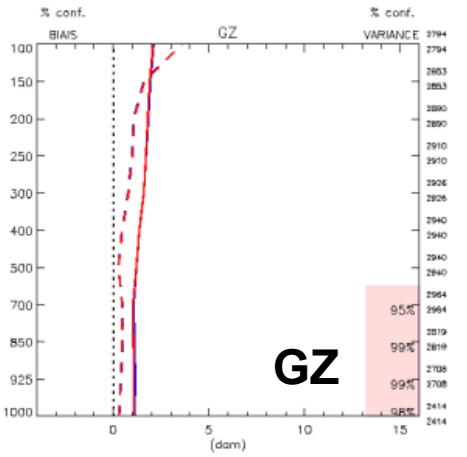


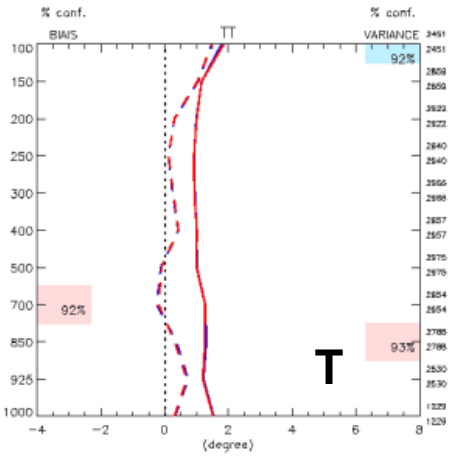


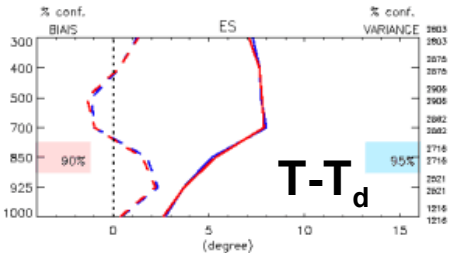
4D-Var Benkf vs. 3D-Var Benkf









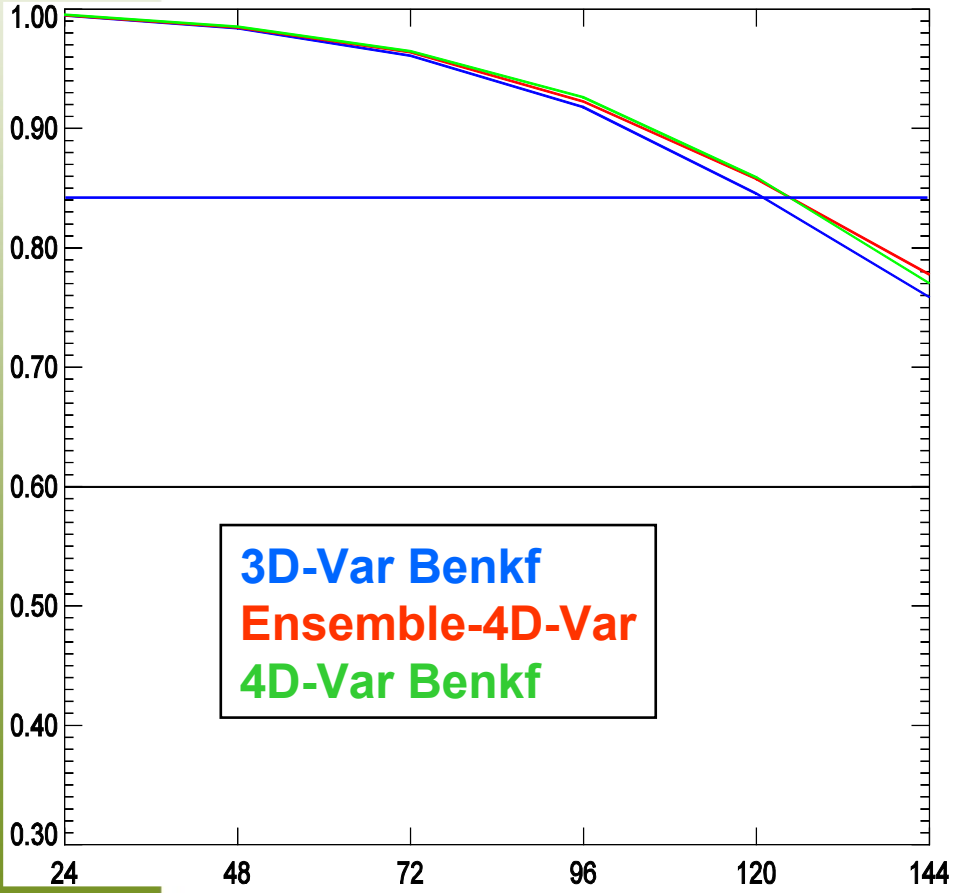


stddev & bias relative to radiosondes

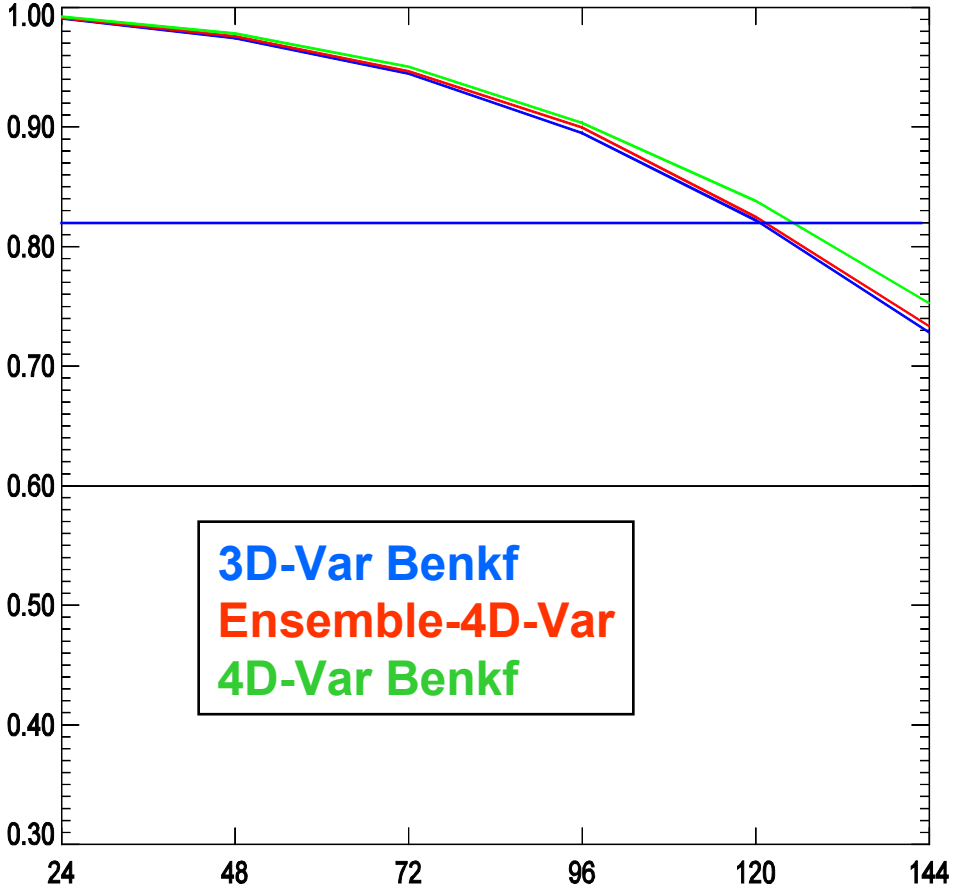
Results – 500hPa GZ anomaly correlation

Verifying analyses from 4D-Var with Bnmc

Northern hemisphere

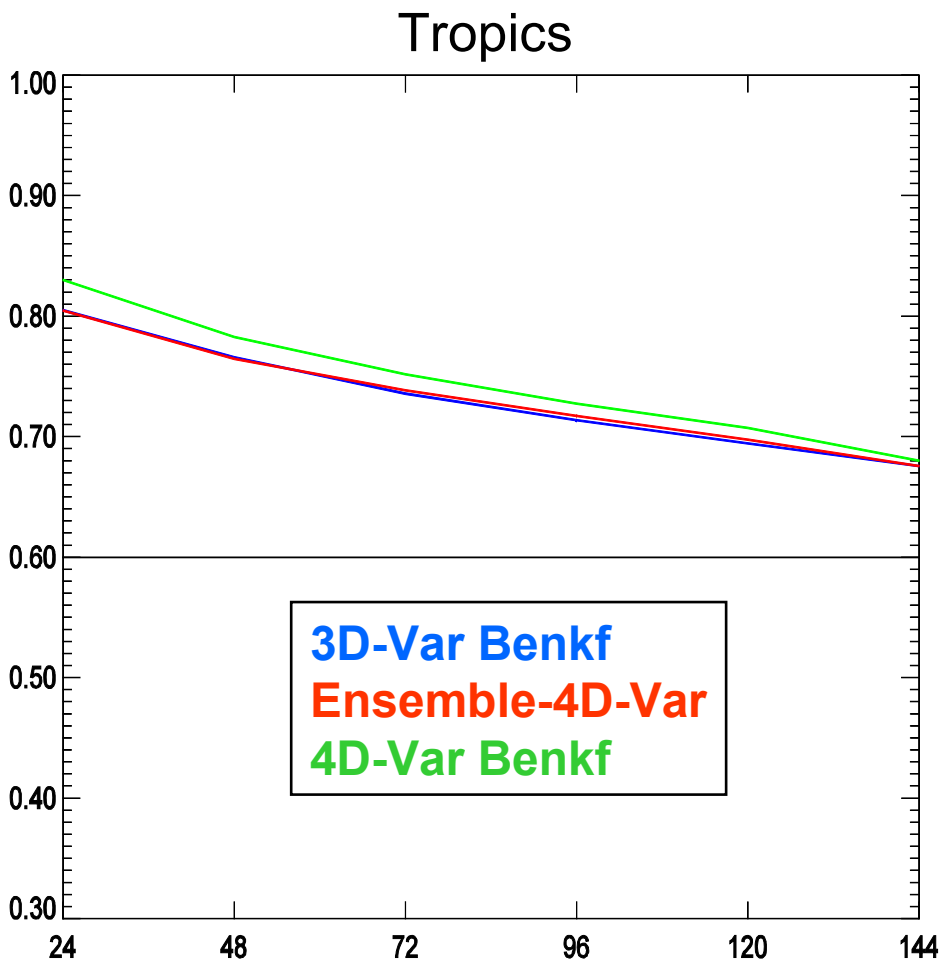


Southern hemisphere



Results – 850hPa T anomaly correlation

Verifying analyses from 4D-Var with Bnmc



Conclusions

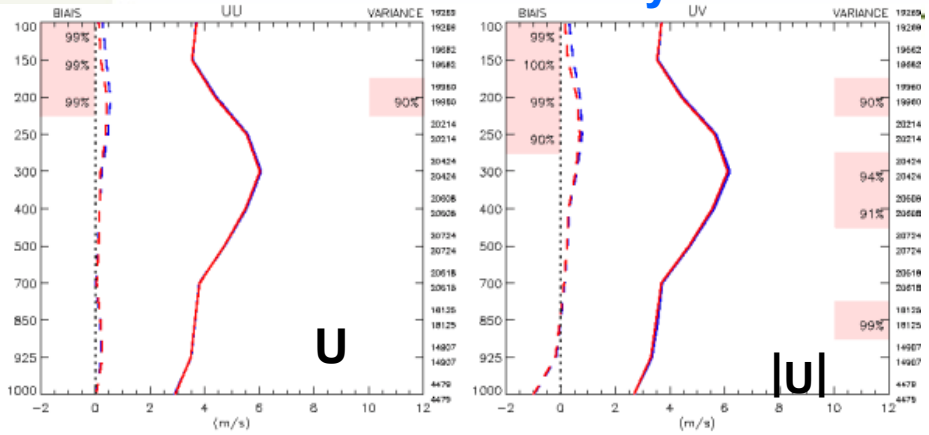
Based on 1-month data assimilation experiments

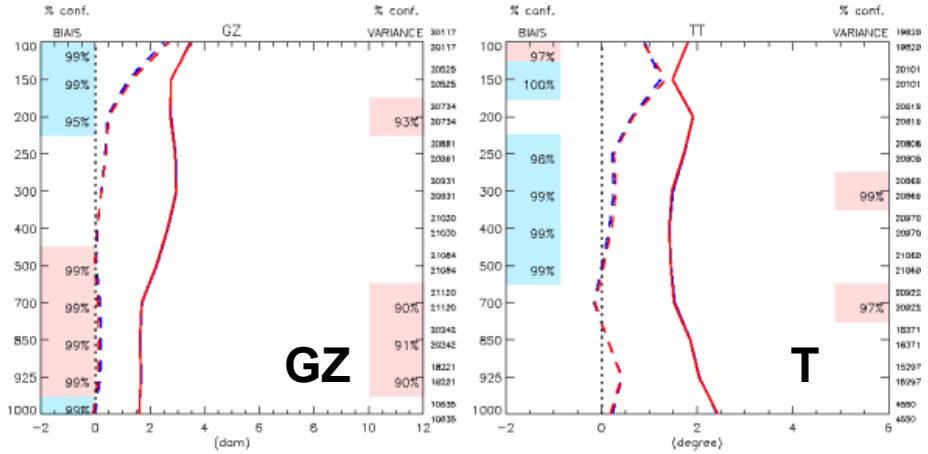
- Medium-range global deterministic forecasts initialized with 4D-Var and EnKF (ensemble mean) analyses have comparable quality
- Gain of ~10hours at day 5 in southern extra-tropics using 4D-Var with flow-dependent EnKF covariances
- New approach of Ensemble-4D-Var improves on 3D-Var, forecast quality similar to 4D-Var in northern extra-tropics
- Working to complete EnKF experiment using incremental approach to produce high-resolution deterministic analysis and understand differences with Ens-4D-Var

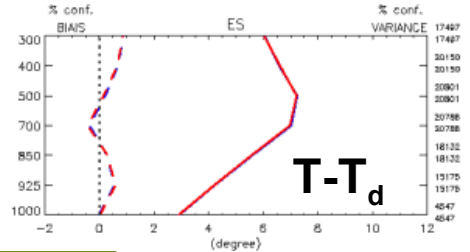
Extra Slides

Forecast Results – 48h, 120h northern hemisphere

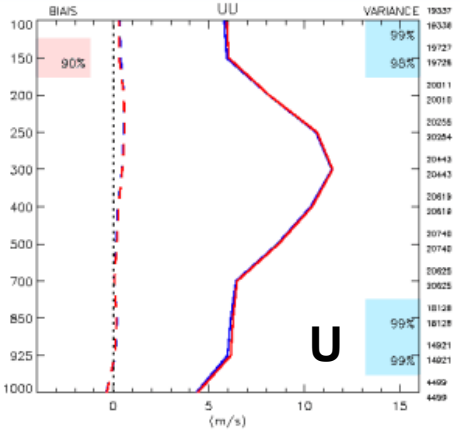
Ensemble-4D-Var
vs. EnKF mean analysis

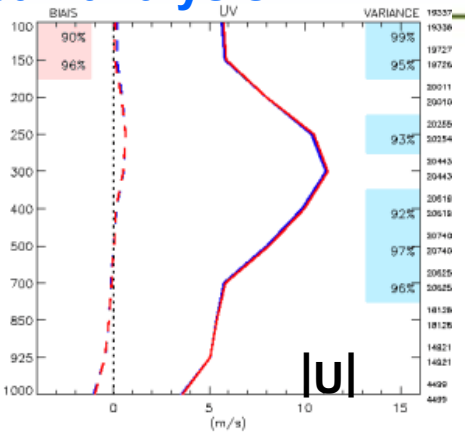


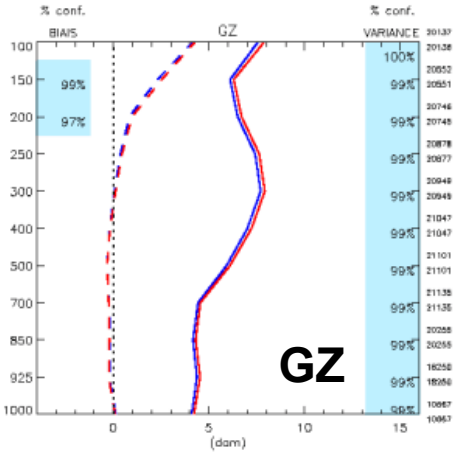


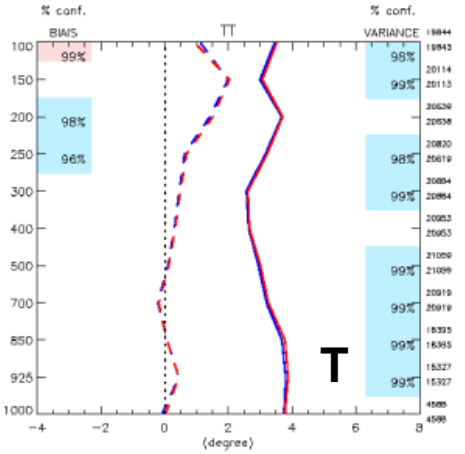


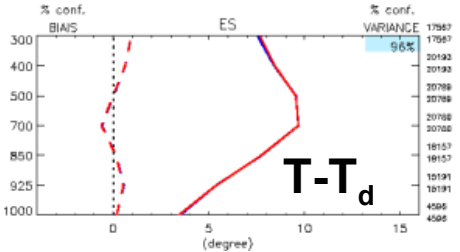
Ensemble-4D-Var
vs. EnKF mean analysis







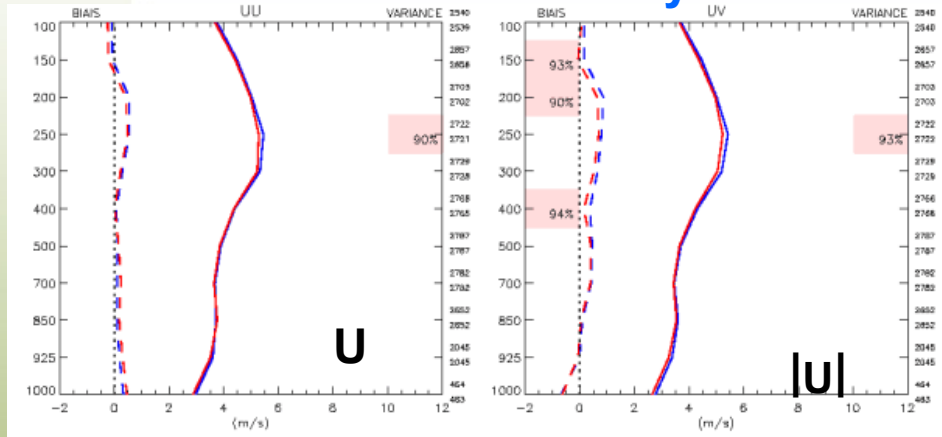


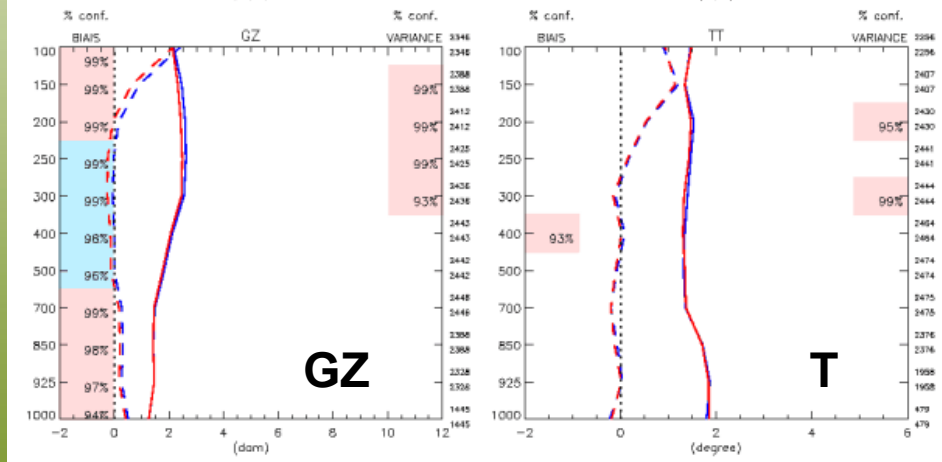


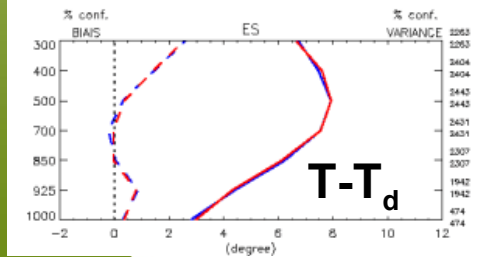
stddev & bias relative to radiosondes

Forecast Results – 48h, 120h southern hemisphere

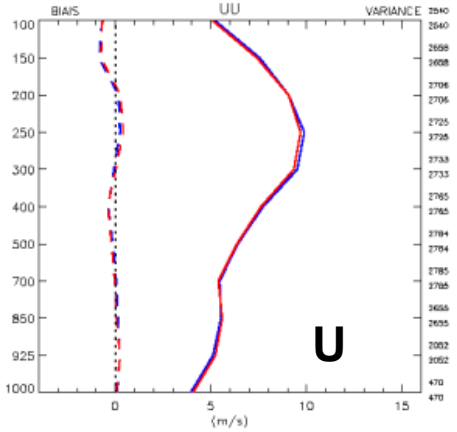
Ensemble-4D-Var
vs. EnKF mean analysis

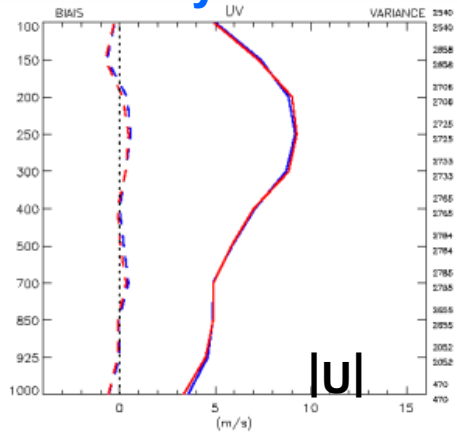


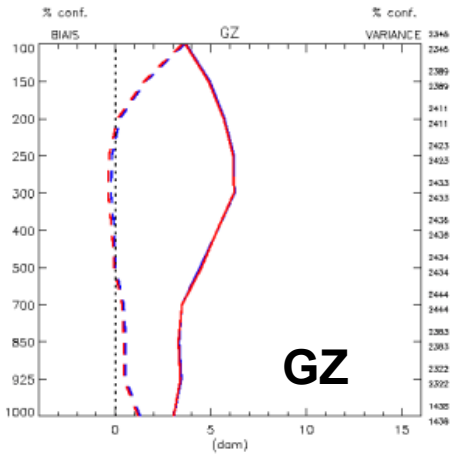


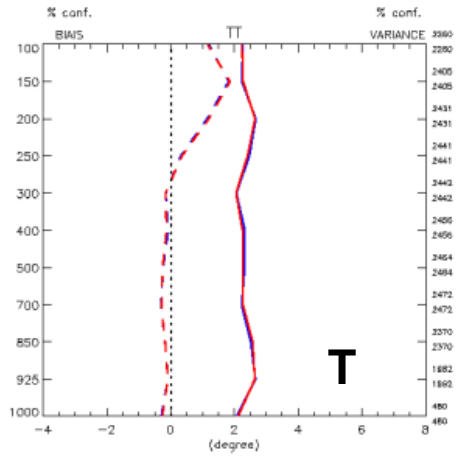


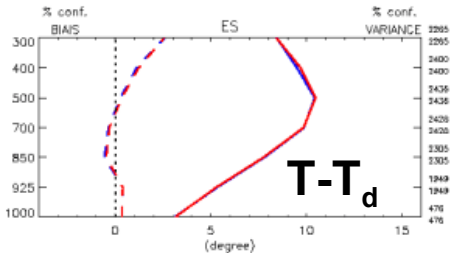
Ensemble-4D-Var
vs. EnKF mean analysis







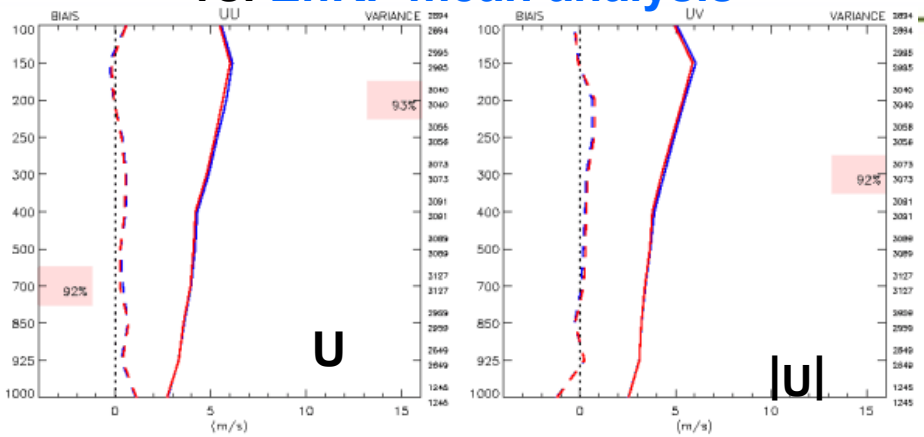


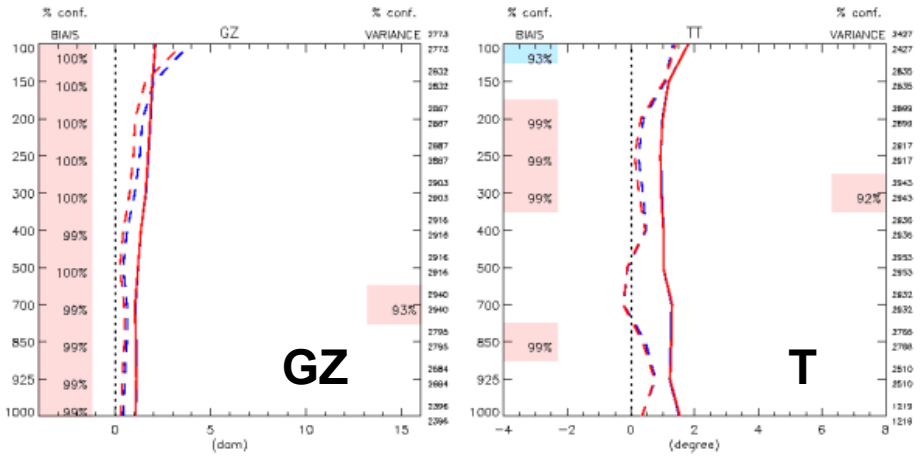


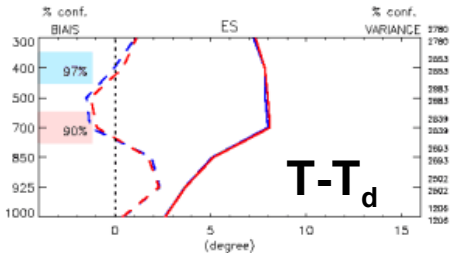
stddev & bias relative to radiosondes

Forecast Results – 72h tropics

Ensemble-4D-Var
vs. EnKF mean analysis





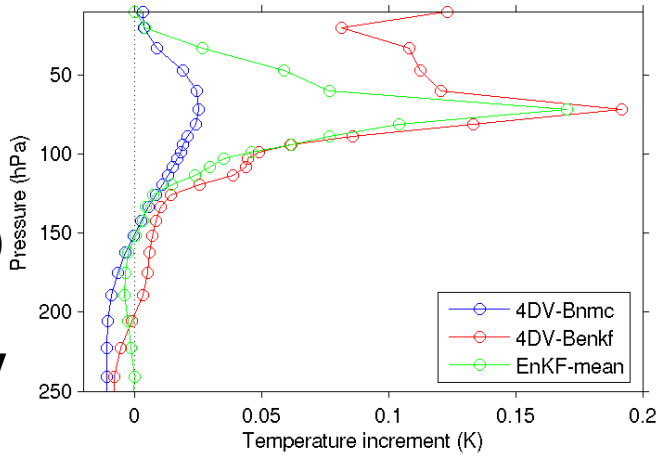


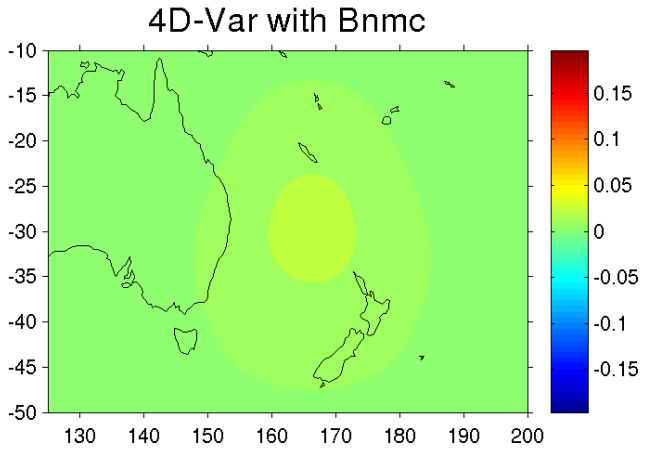
stddev & bias relative to radiosondes

Single observation experiments

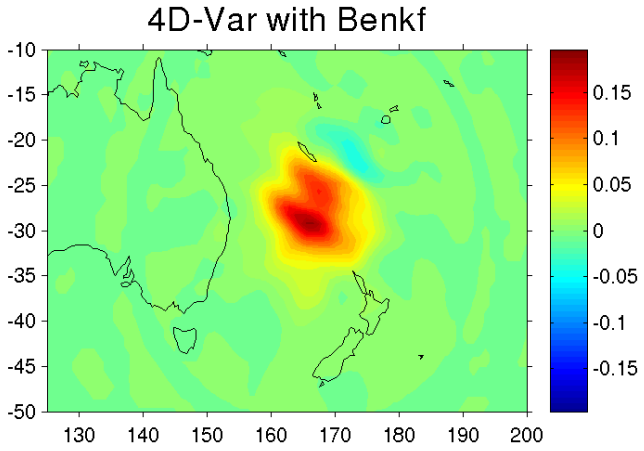
Difference in vertical localization between 4D-Var and EnKF

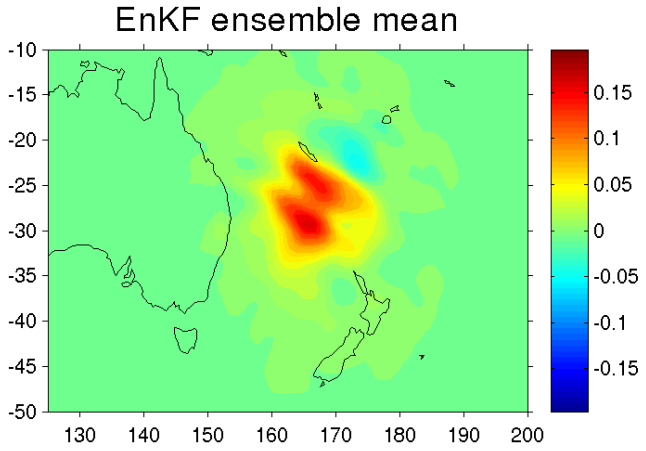
- AMSU-A ch9
- peak sensitivity near 70hPa
- no covariance evolution (3D-Var)
- with same B, increment **slightly** larger & broader with **4D-Var** than **EnKF**





contour plots at 70 hPa

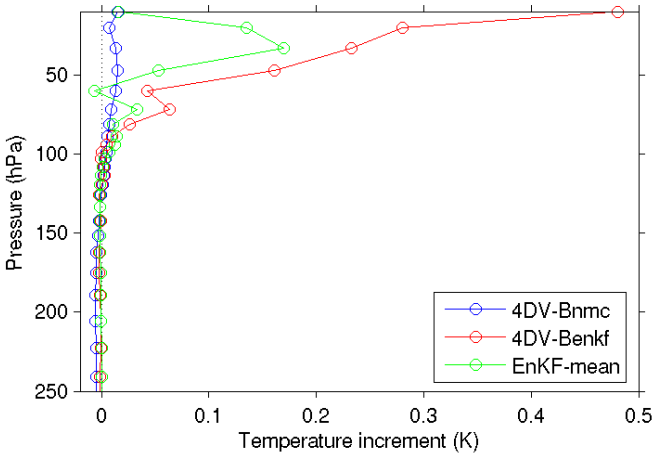


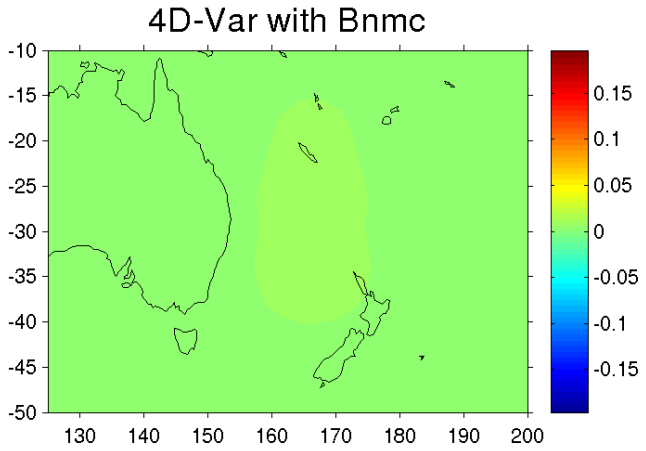


Single observation experiments

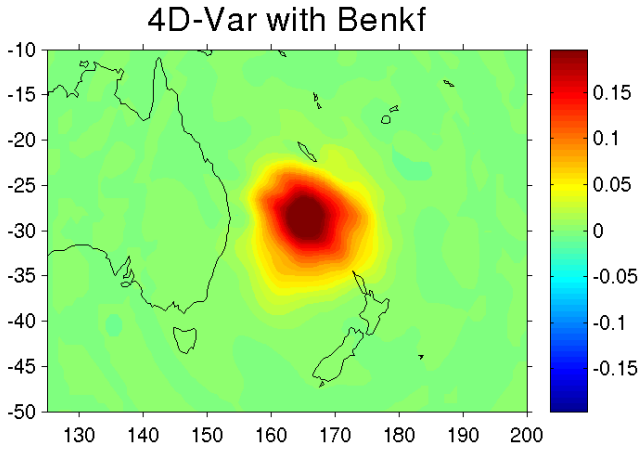
Difference in vertical localization between 4D-Var and EnKF

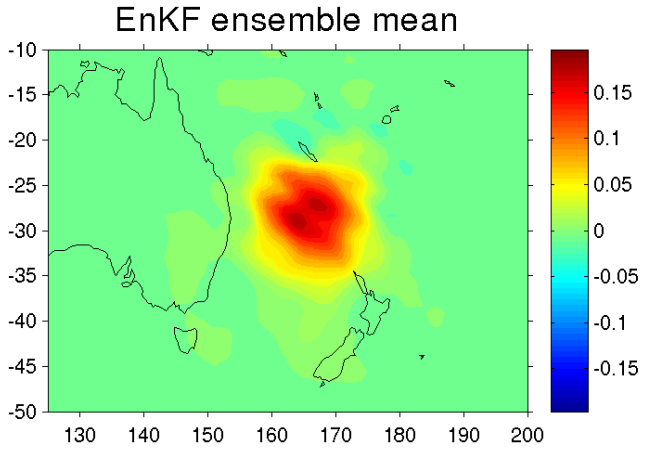
- AMSU-A ch10
- peak sensitivity near 40hPa
- no covariance evolution (3D-Var)
- with same B, increment **much** larger (esp. at 10hPa) & broader with **4D-Var** than **EnKF**





contour plots at 30 hPa

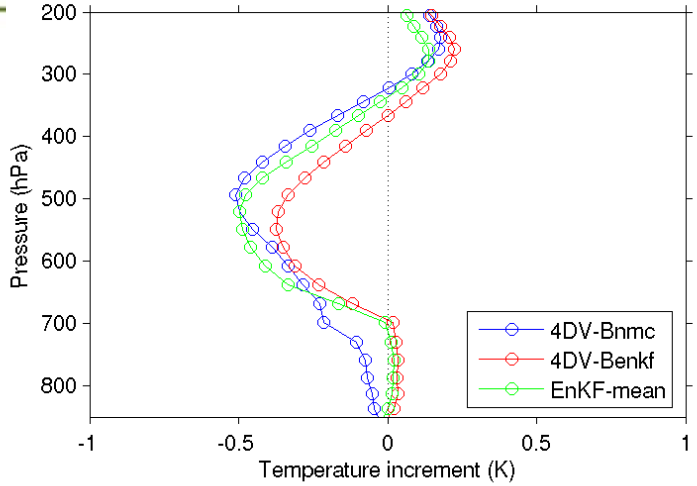


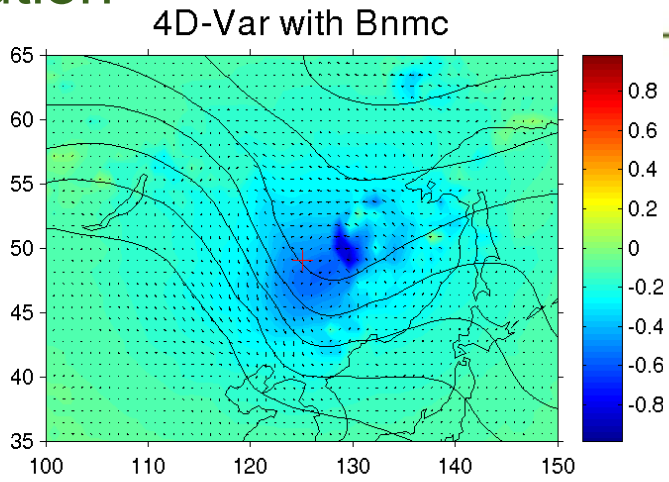


Single observation experiments

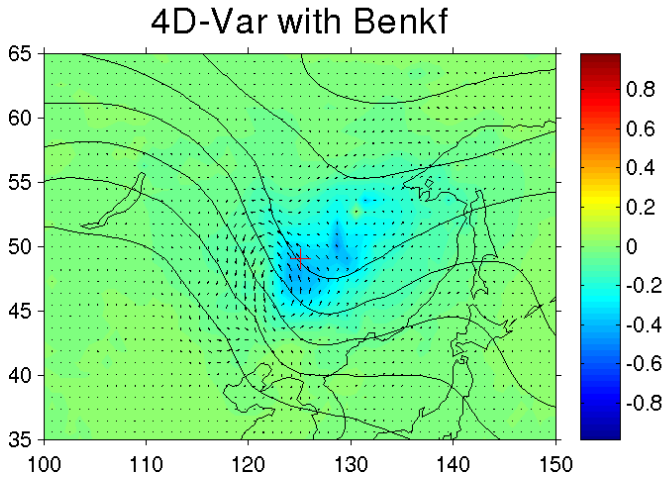
Difference in temporal covariance evolution

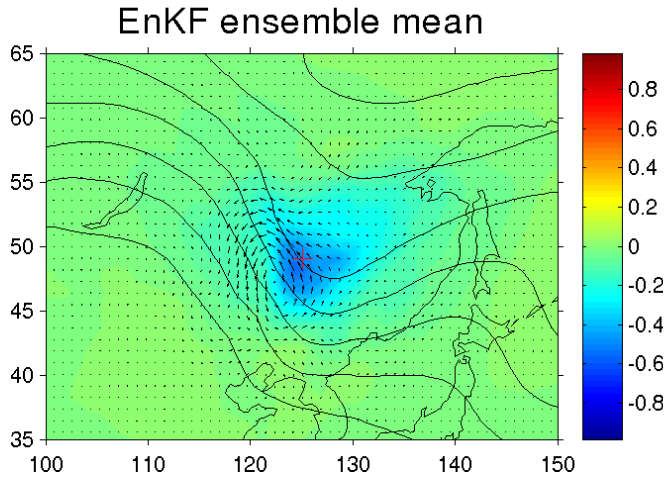
- radiosonde temperature observation at 500hPa
- observation at **beginning of assimilation window (-3h)**
- with same B, increments very similar from **4D-Var**, **EnKF**
- contours are 500hPa GZ background state at 0h (ci=10m)





contour plots at 500 hPa

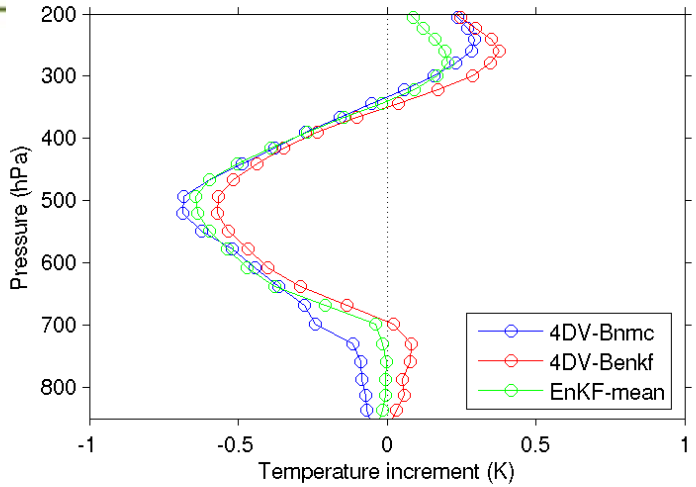


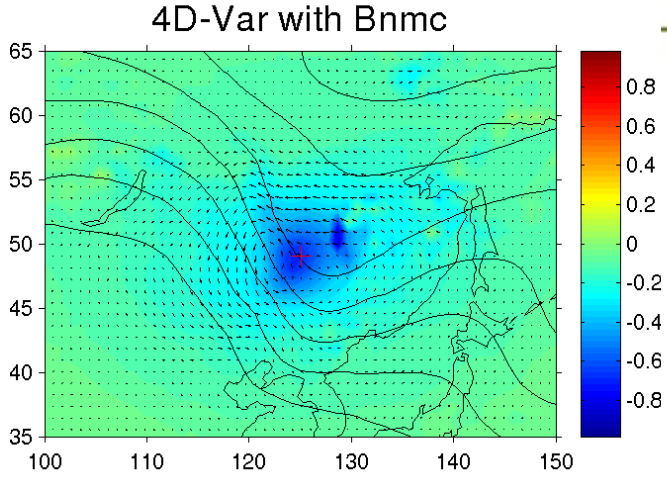


Single observation experiments

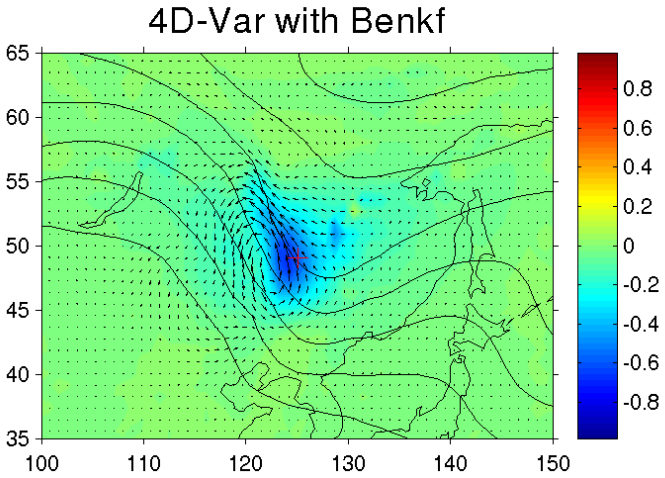
Difference in temporal covariance evolution

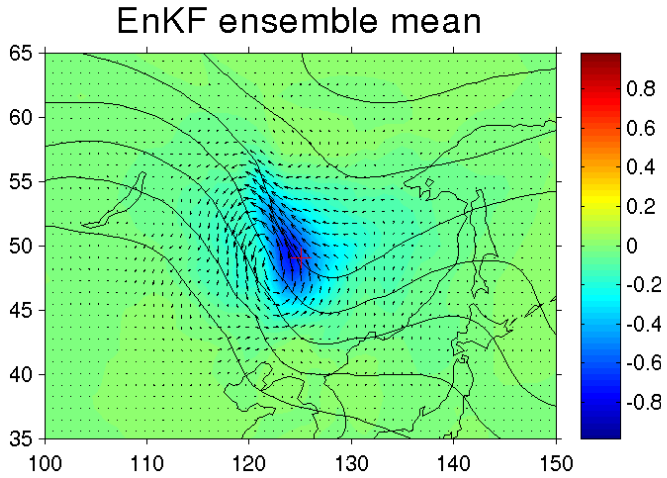
- radiosonde temperature observation at 500hPa
- observation at **middle of assimilation window (+0h)**
- with same B, increments very similar from **4D-Var**, **EnKF**
- contours are 500hPa GZ background state at 0h (ci=10m)





contour plots at 500 hPa

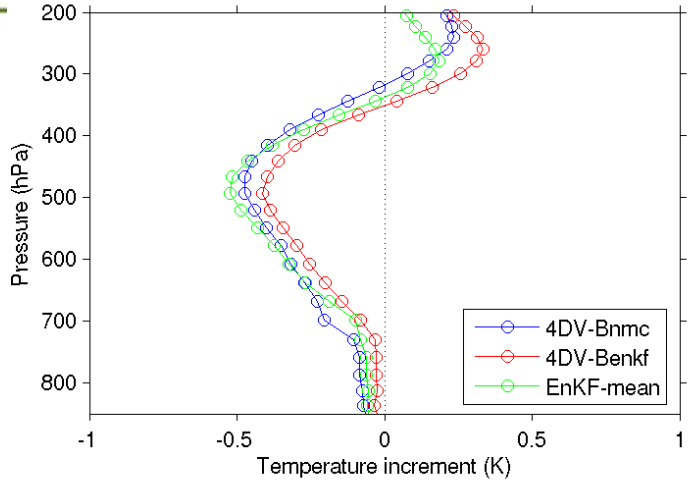


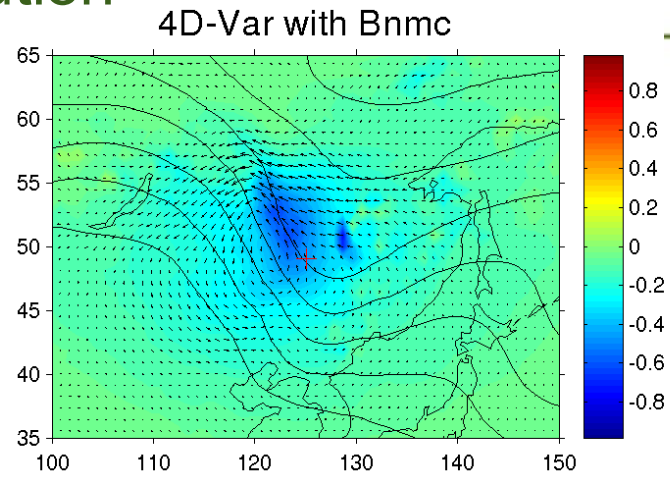


Single observation experiments

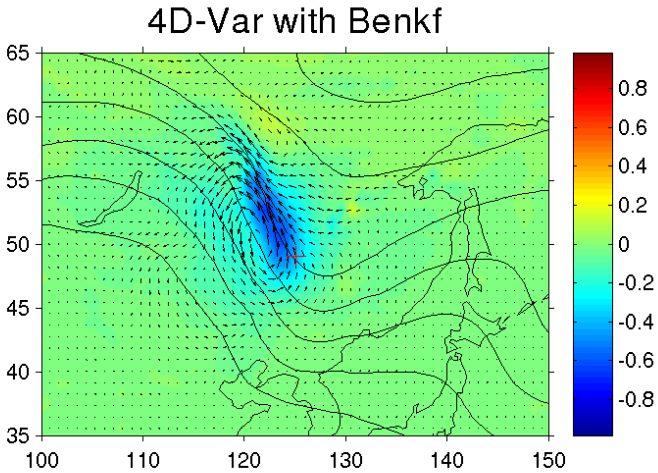
Difference in temporal covariance evolution

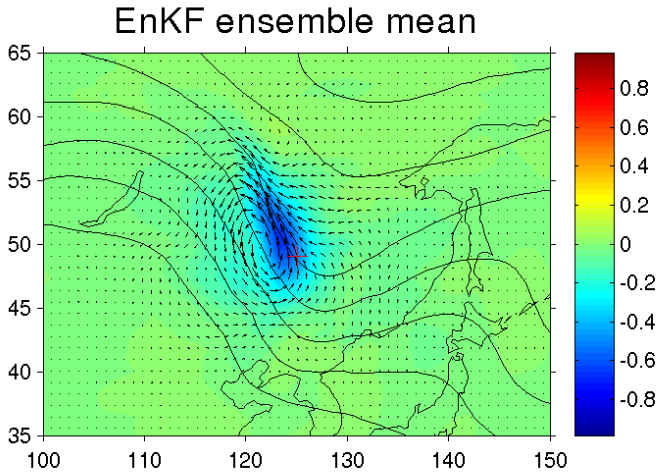
- radiosonde temperature observation at 500hPa
- observation at **end of assimilation window (+3h)**
- with same B, increments very similar from **4D-Var**, **EnKF**
- contours are 500hPa GZ background state at 0h (ci=10m)





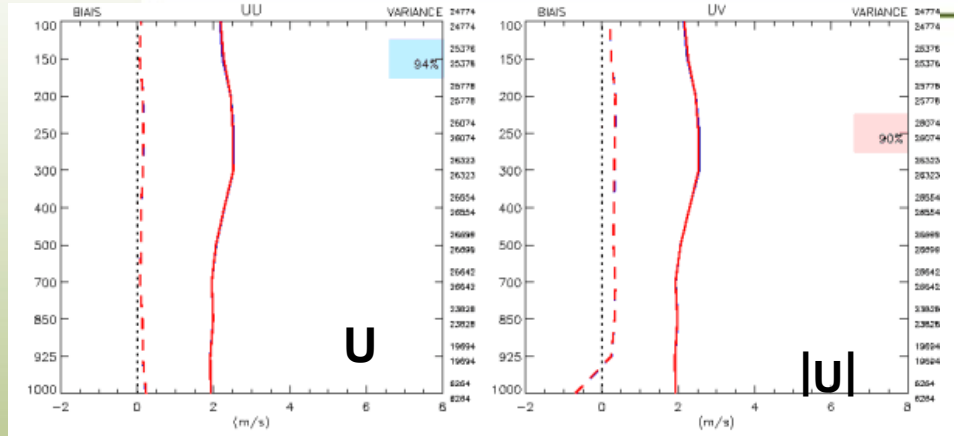
contour plots at 500 hPa

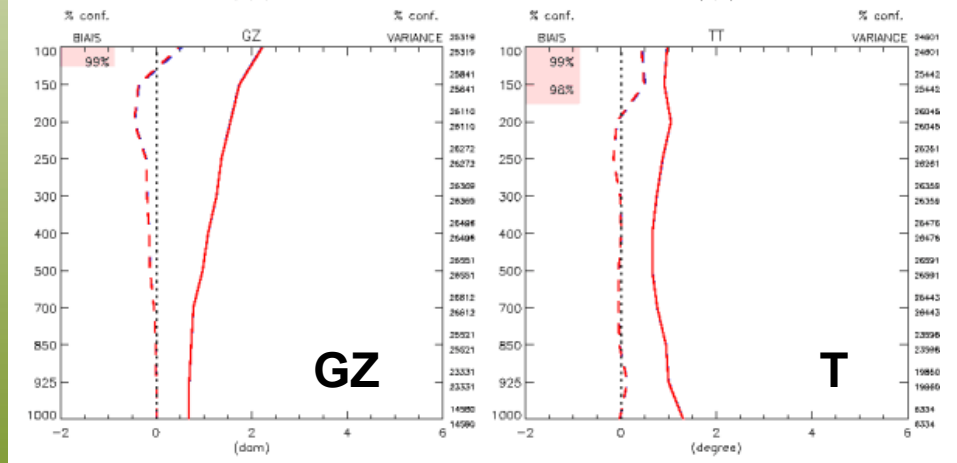


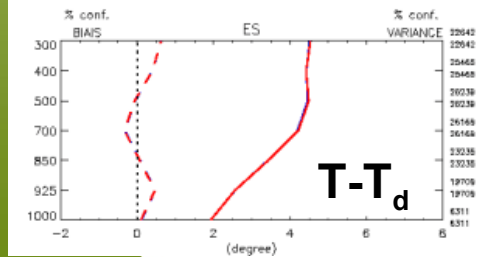


Analysis Results – global

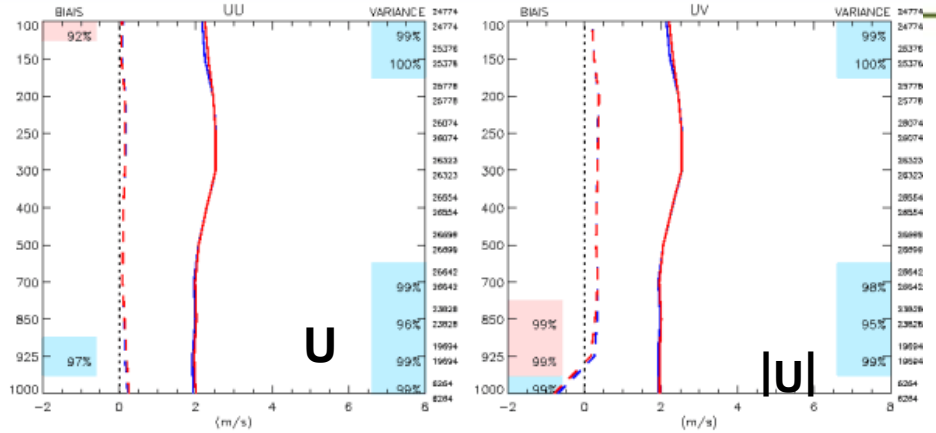
Ensemble-4D-Var vs. **3D-Var Benkf**

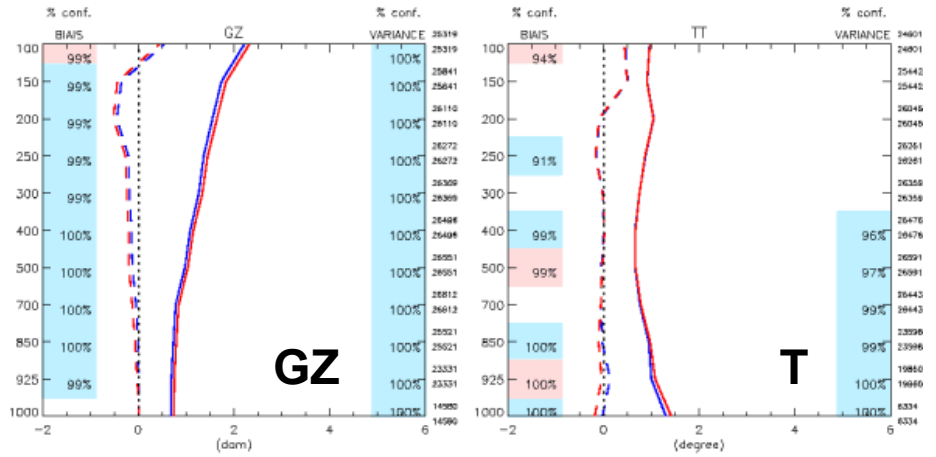


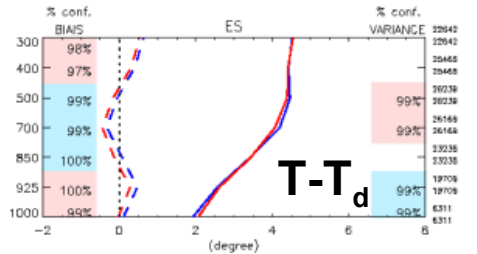




4D-Var Benkf vs. **3D-Var Benkf**



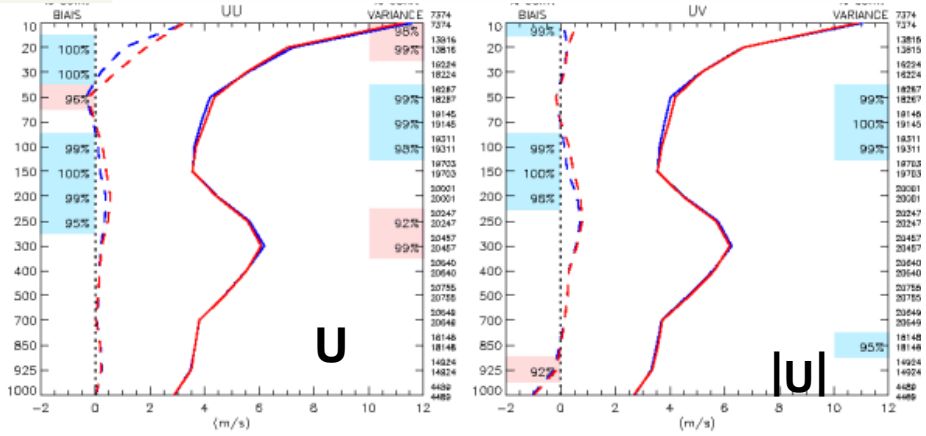


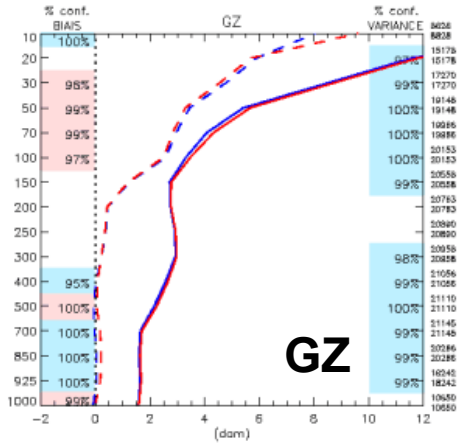


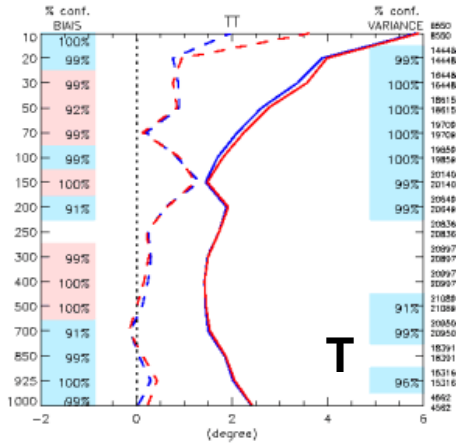
stddev & bias relative to radiosondes

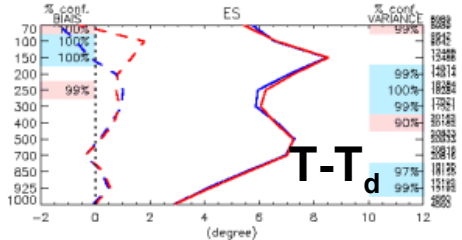
Forecast Results – 48h northern hemisphere

EnKF mean analysis vs. 4D-Var Bnmc

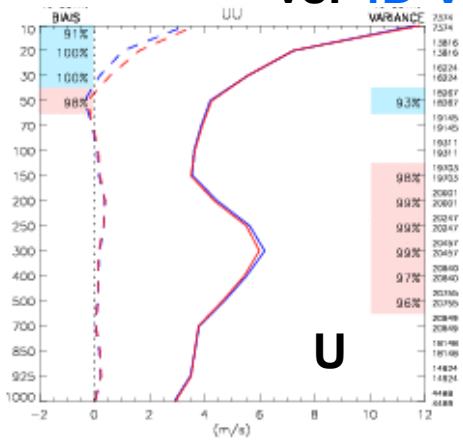


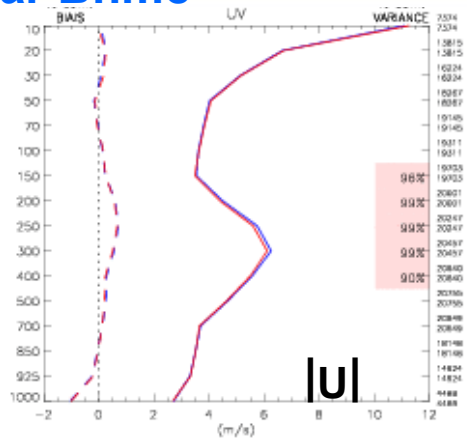


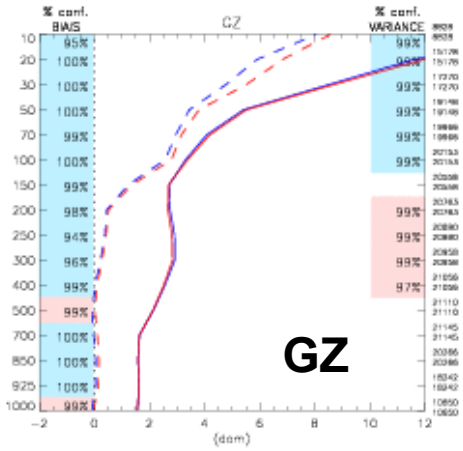


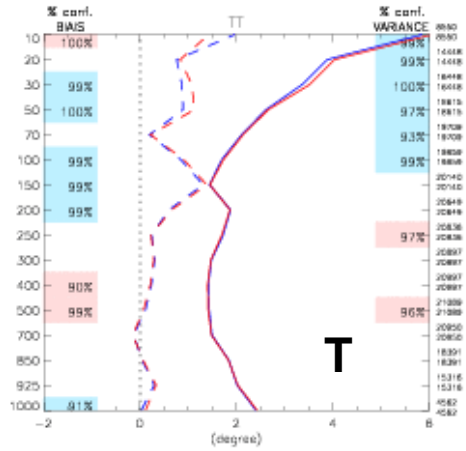


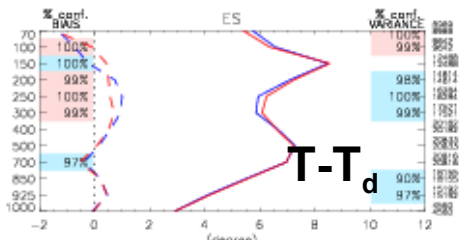
4D-Var Benkf vs. 4D-Var Bnmc







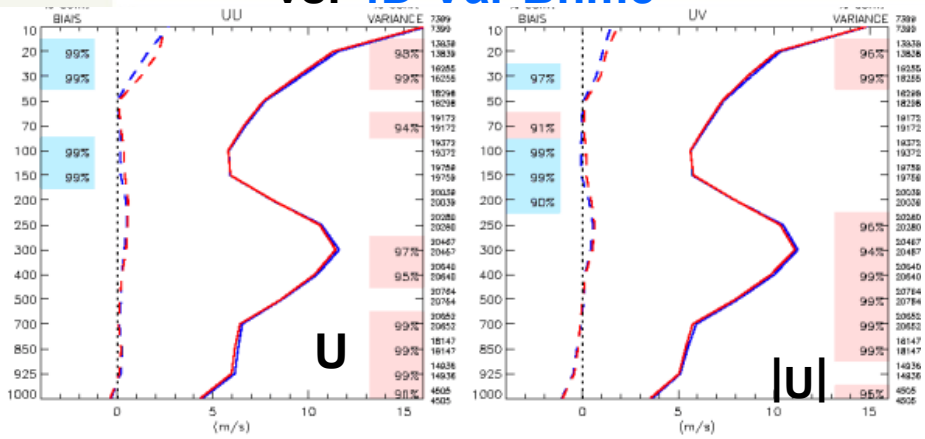


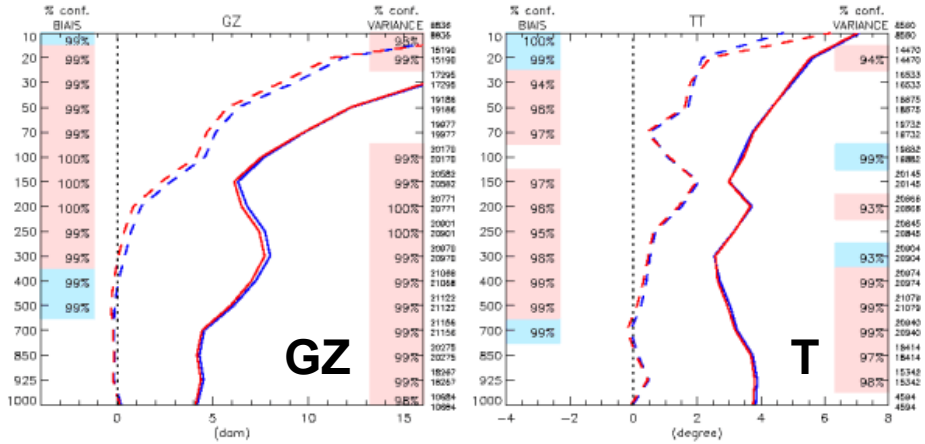


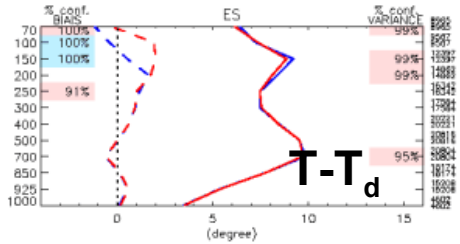
stddev & bias relative to radiosondes

Forecast Results – 120h northern hemisphere

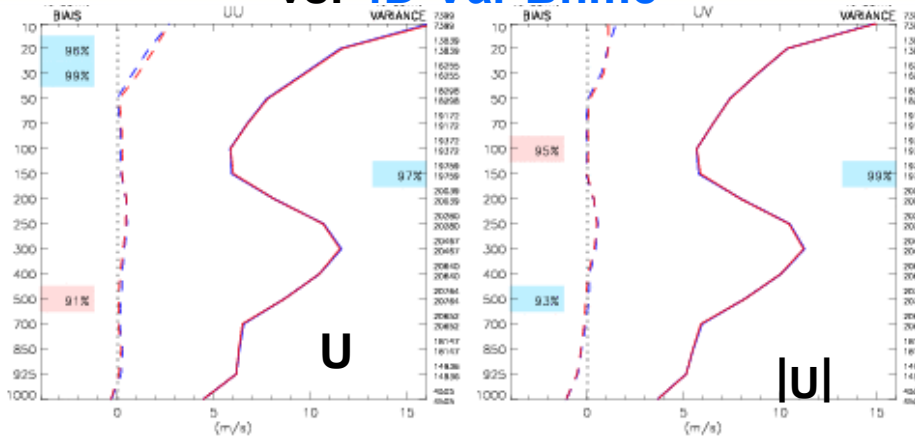
EnKF mean analysis
vs. 4D-Var Bnmc

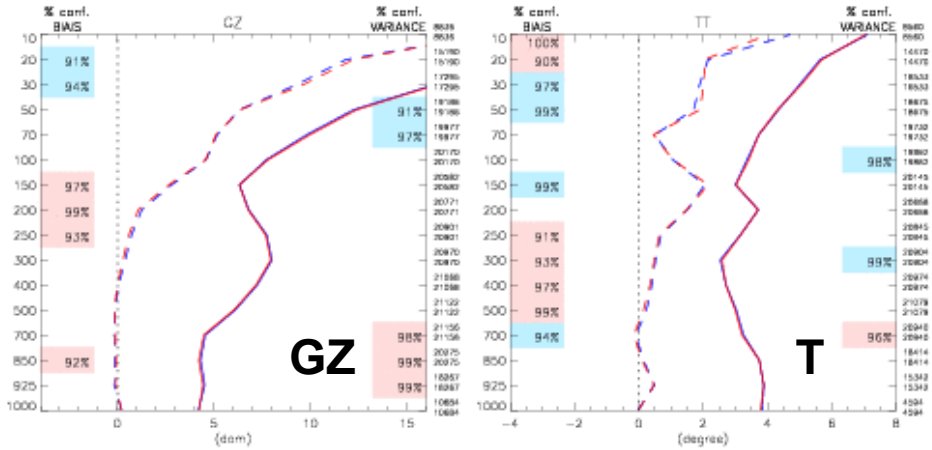


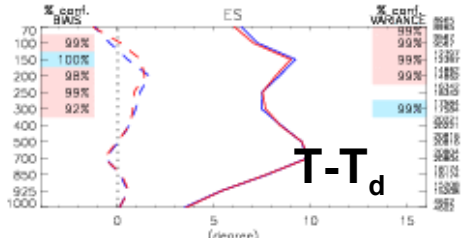




4D-Var Benkf
vs. 4D-Var Bnmc



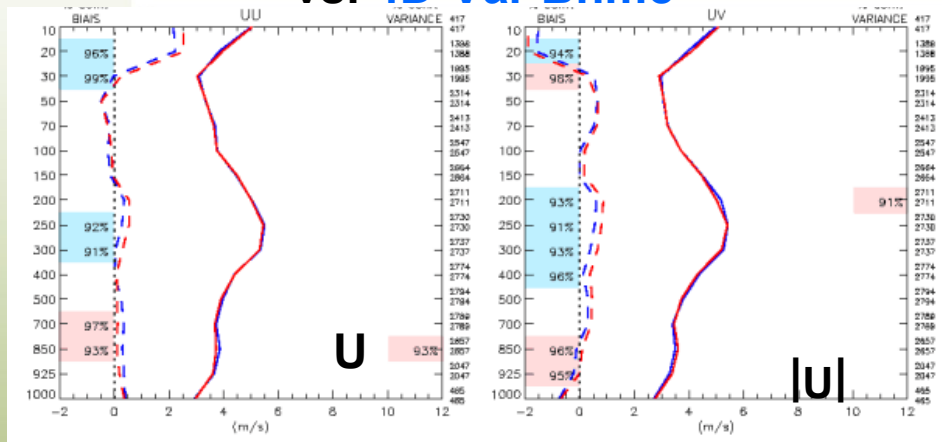


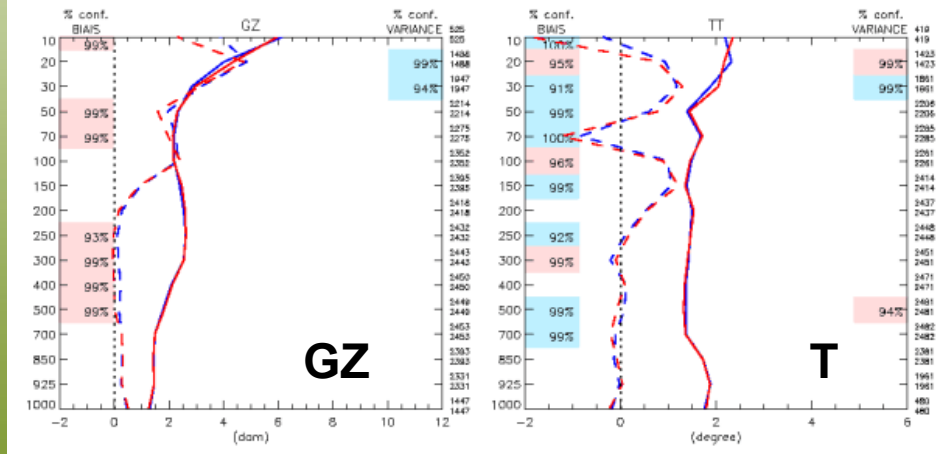


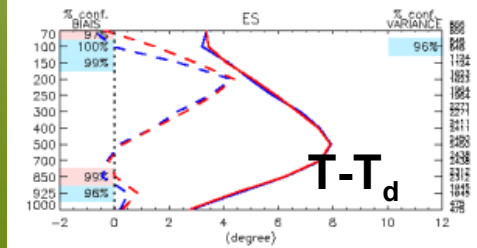
stddev & bias relative to radiosondes

Forecast Results – 48h southern hemisphere

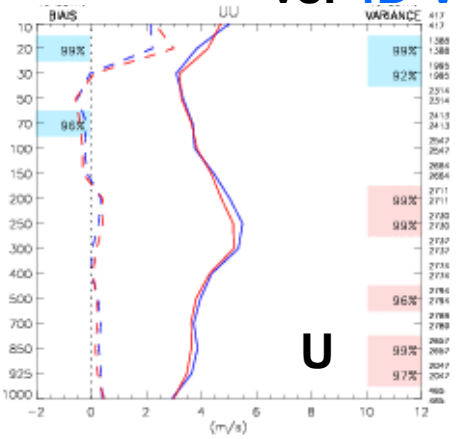
EnKF mean analysis vs. 4D-Var Bnmc

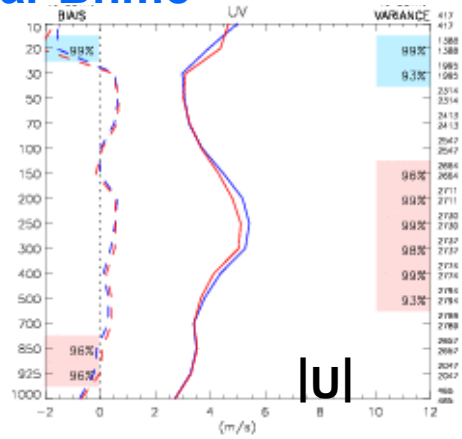


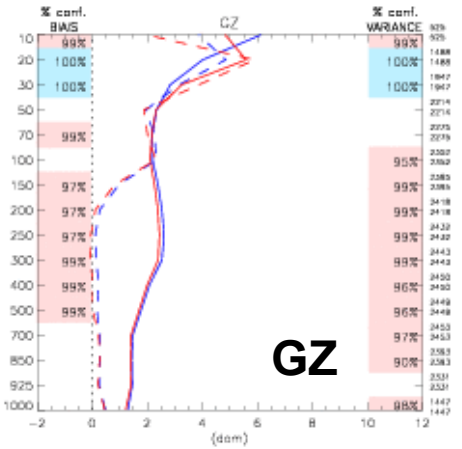


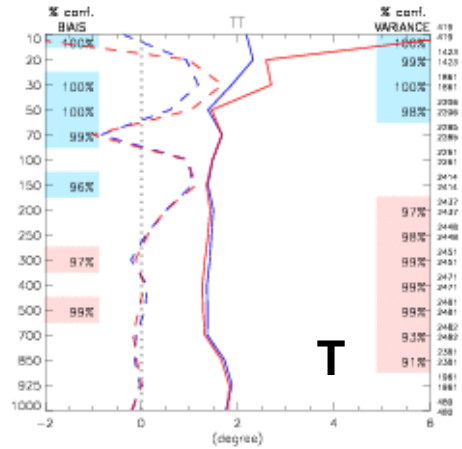


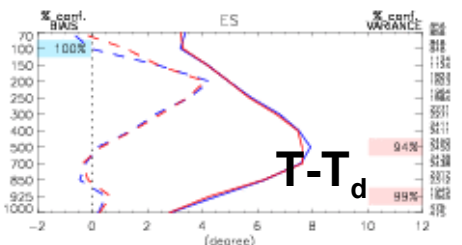
4D-Var Benkf vs. 4D-Var Bnmc







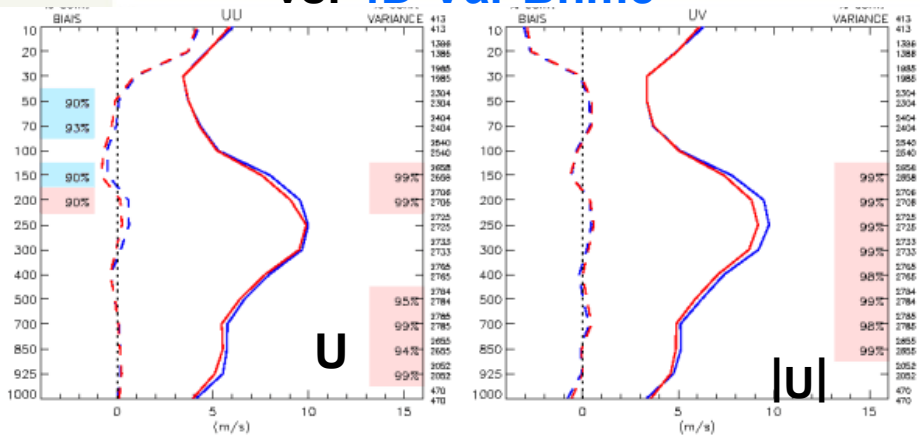


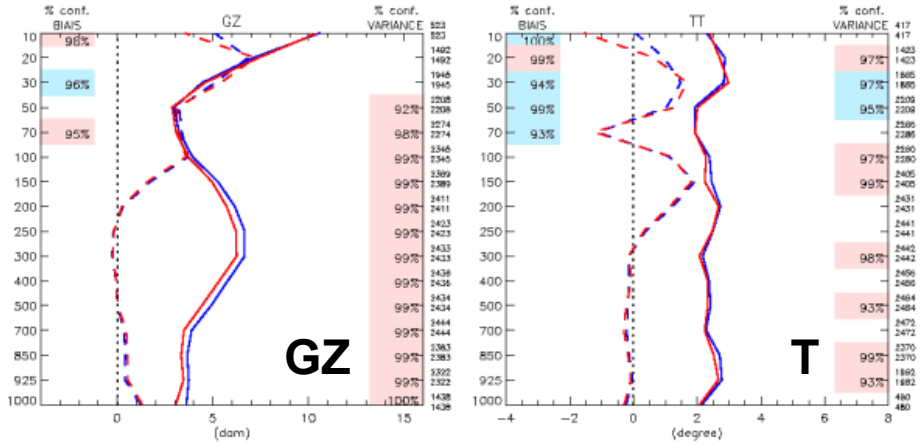


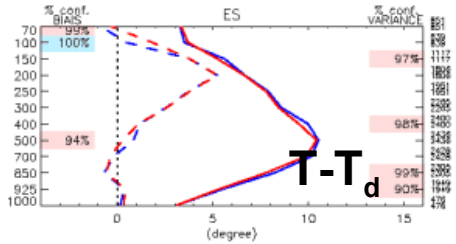
stddev & bias relative to radiosondes

Forecast Results – 120h southern hemisphere

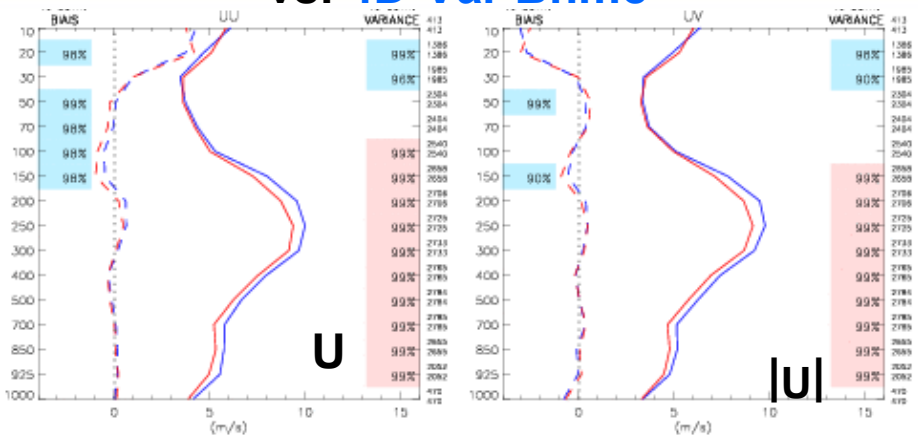
EnKF mean analysis vs. 4D-Var Bnmc

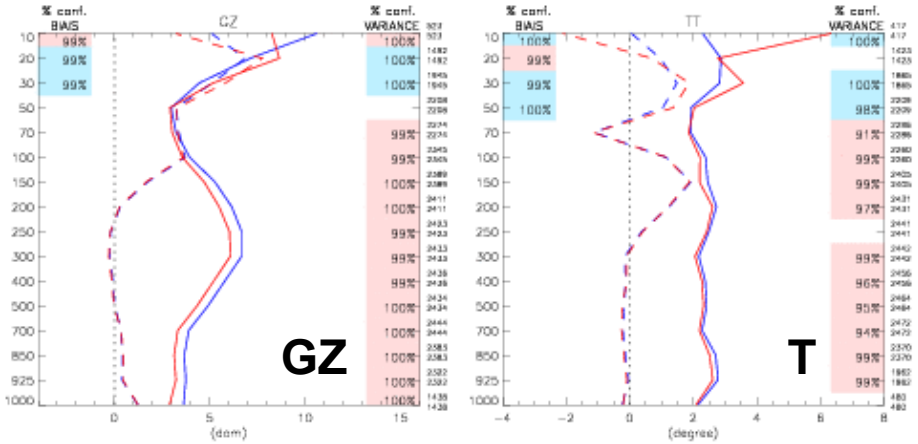


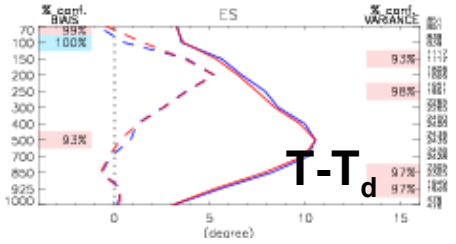




4D-Var Benkf vs. 4D-Var Bnmc



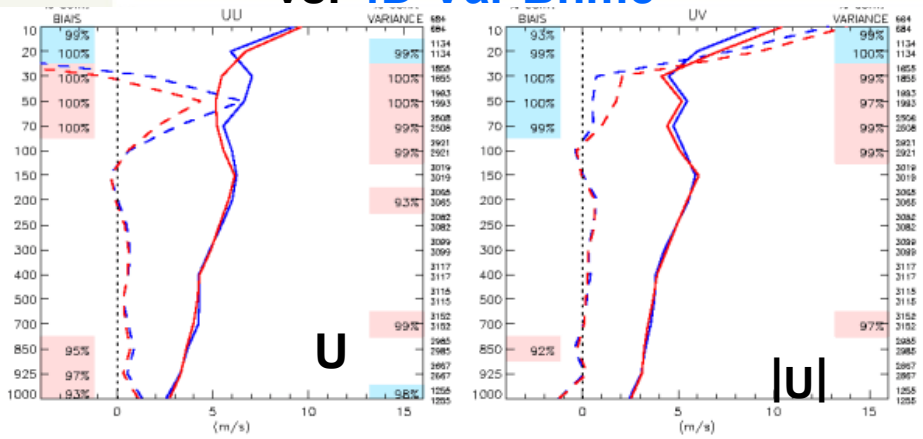


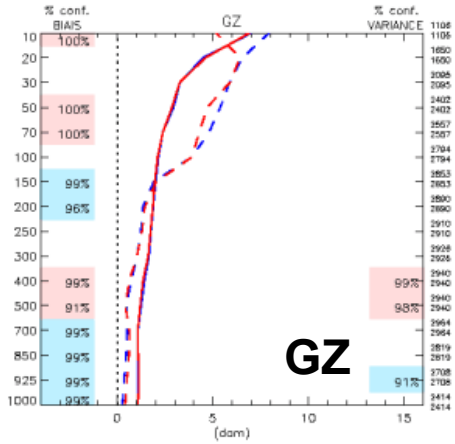


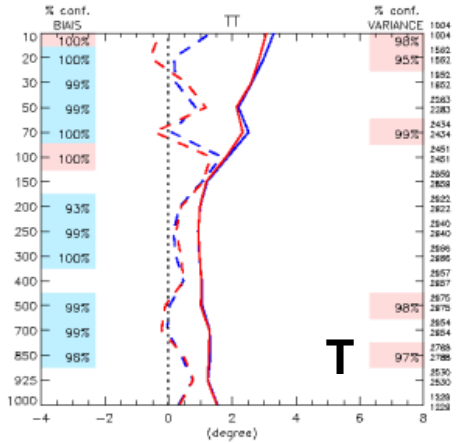
stddev & bias relative to radiosondes

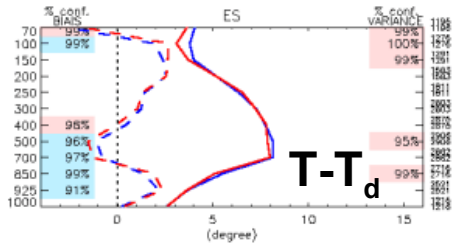
Forecast Results – 72h tropics

EnKF mean analysis vs. 4D-Var Bnmc

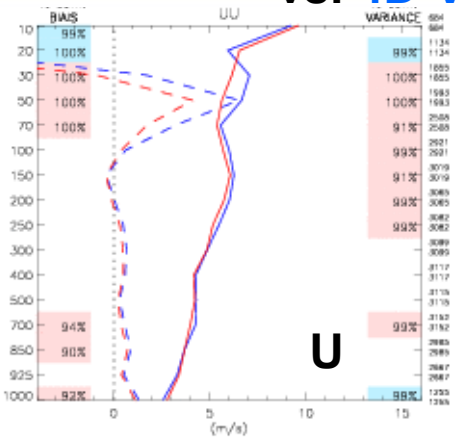


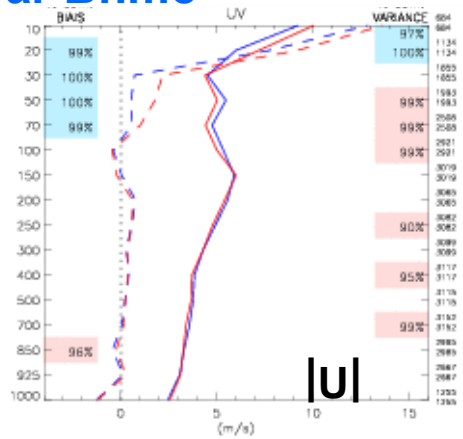


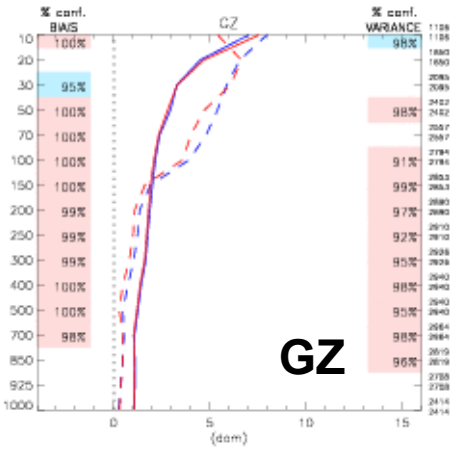


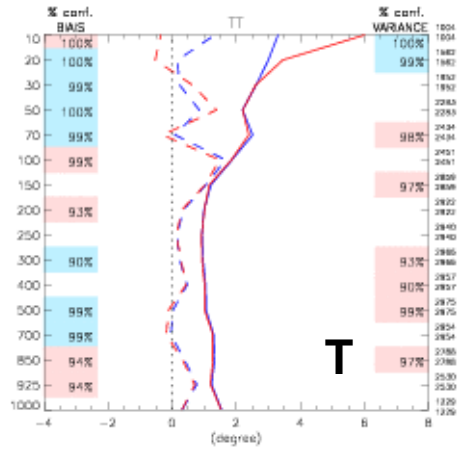


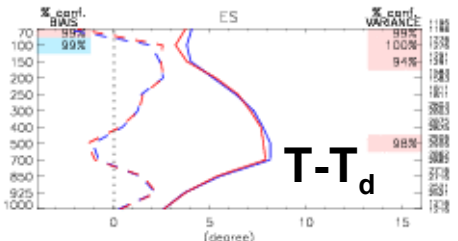
4D-Var Benkf vs. 4D-Var Bnmc











stddev & bias relative to radiosondes

4D error covariances

- EnKF and 4D-Var both use 4-dimensional error covariances to **update background state at the middle of assimilation window** (0h) from **observations throughout assimilation window**:

EnKF (and Ensemble-4D-Var):

$\rho \circ B_{ens}(0h,-3h) = \rho \circ (M(ens(-3h))\ ens(-3h)^T)$

$\rho \circ B_{ens}(0h,0h) = \rho \circ (M(ens(-3h))\ M(ens(-3h))^T)$

$\rho \circ B_{ens}(0h,+3h) = \rho \circ (\ M(ens(-3h))\ M(M(ens(-3h)))^T\ )$

4D-Var:

$M\ (\rho \circ B_{ens}(-3h,-3h))$

$M\ ((\rho \circ B_{ens}(-3h,-3h))\ M^T)$

$M\ ((\rho \circ B_{ens}(-3h,-3h))\ M^T M^T)$