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Inter-comparison of 4D-Var and EnKF systems for operational deterministic NWP

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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 Canadian GEM forecast model
  - both assimilate similar set of observations using mostly the same observation operators and observation error covariances
- 4D-Var used to initialize short to medium range global deterministic forecasts
- EnKF (96 members) used to initialize medium range global Ensemble Prediction System (20 members)

Contents

- Description of operational systems
- Configurations used for the inter-comparison
- Single observation experiments:
  - differences in localization
  - differences in covariance evolution
- Full analysis-forecast experiments (February 2007)
  - global model at ~35km grid spacing, 58 levels, 10 hPa top
  - scores from analyses (vs. radiosondes)
  - scores from 56 6-day deterministic forecasts (vs. radiosondes and analyses)
- Conclusions and future work

Operational Configurations

- 4D-Var
  - operational since March, 2005
  - incremental approach: ~35km/150km grid spacing, 58 levels, 10hPa top, 6h assimilation window
- EnKF
  - operational since January 2005
  - 96 ensemble members: ~100km grid spacing, 28 levels, 10hPa top, 6h assimilation window
- Dependence between systems
  - EnKF uses 4D-Var bias correction of satellite observations and quality control for all observations
  - model-error covariances in EnKF are similar to a scaled down version of 4D-Var background-error covariances

Experimental Configurations
Modifications relative to operational systems

- Same observations assimilated in all experiments:
  - radiosondes, aircraft observations, AMVs, US wind profilers, QuikSCAT, AMSU-A/B, *in situ* 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
- Increased horizontal resolution of 4D-Var inner loop to match EnKF
- Other minor modifications in both systems to obtain essentially identical innovations (each tested to ensure no degradation)

Experimental Configurations

Four main experiments (2 standard, 2 "new" approaches)

- 4D-Var:
  - with B matrix same as operational system (NMC method, Bnmc)
  - with flow-dependent B matrix from EnKF (Benkf) at beginning of assim. window (same localization parameters and σ_{obs} for AMSU-A ch9+10 as in EnKF)

- EnKF – high resolution 6-day forecasts initialized with:
  - low resolution ensemble mean analysis
  - high resolution deterministic member (in progress, no results yet):
    - incremental approach similar to 4D-Var:
      - innovation computed from high resolution background state
      - low resolution increment added to high res. background state
    - no obs error or model error perturbations
    - use all 96 members to compute K (deterministic member not used in covariance estimation)

Experimental Configurations

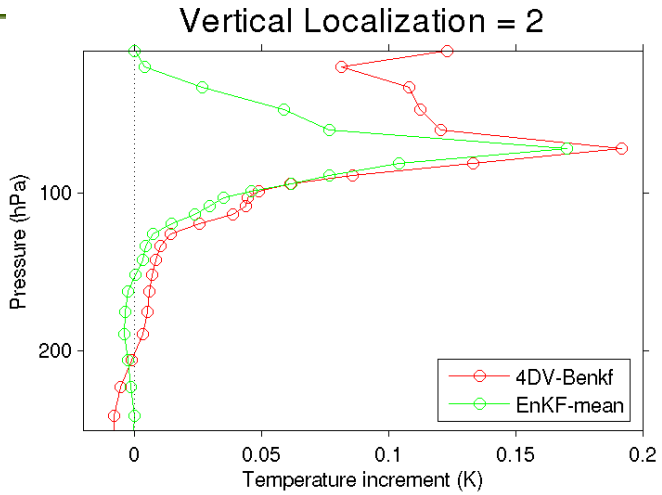
Remaining differences between two "new" approaches

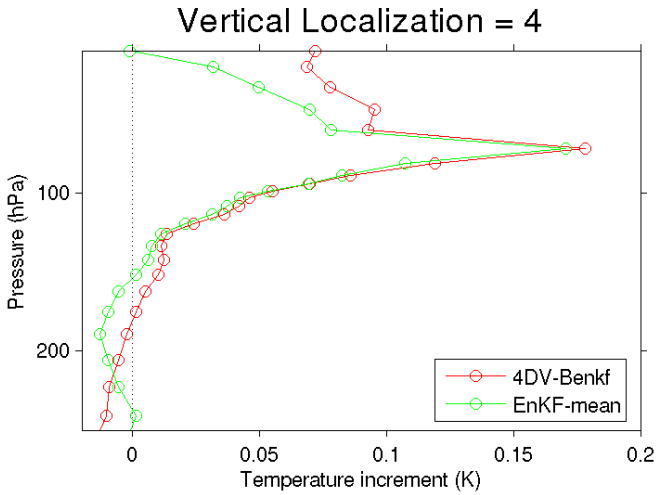
- Differences in spatial localization (most evident with radiance obs):
  - 4D-Var: $K = (\rho \circ P)\, H^T (H(\rho \circ P)H^T + R)^{-1}$ (P is 3D, H contains M)
  - EnKF: $K = \rho \circ (P\, H^T) (\rho \circ (HPH^T) + R)^{-1}$ (P is 4D)
- Differences in temporal propagation of error covariances:
  - 4D-Var: implicitly done with TL/AD model (also use NLM to propagate increment from beginning to middle of assimilation window)
  - EnKF: explicitly done with NLM in subspace of background ensemble
- Differences in solution technique:
  - 4D-Var: limited convergence towards global solution with 2 iterations of outer loop (30+25 iterations)
  - EnKF: sequential-in-obs-batches explicit solution (not equivalent to global solution when using spatial localization)
- Differences in time interpolation of obs in assimilation window:
  - 4D-Var: 0.75h timestep, nearest neighbour interpolation in time
  - EnKF: 1.5h timestep, linear interpolation in time

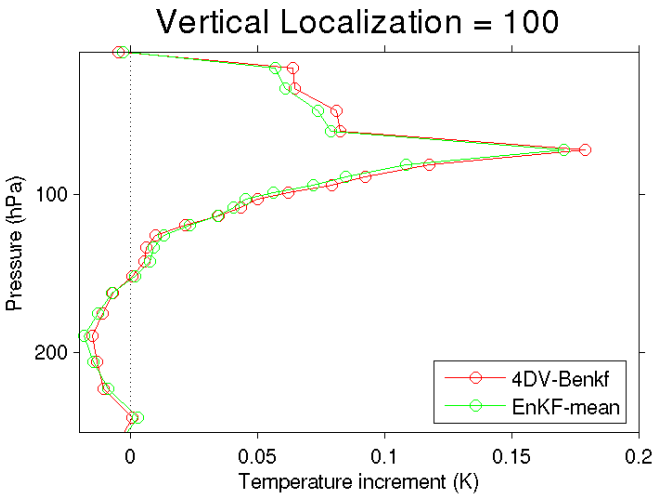
Single observation experiments

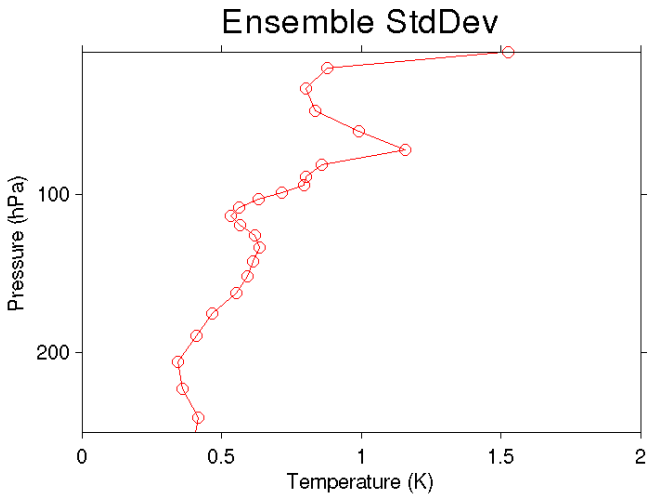
Difference in vertical localization between 4D-Var and EnKF

- AMSU-A ch9
- peak sensitivity near 70hPa
- no covariance evolution (3D-Var)
- with same B, increment **slightly** larger & less local with **4D-Var** than **EnKF**
- with very little localization increments nearly identical





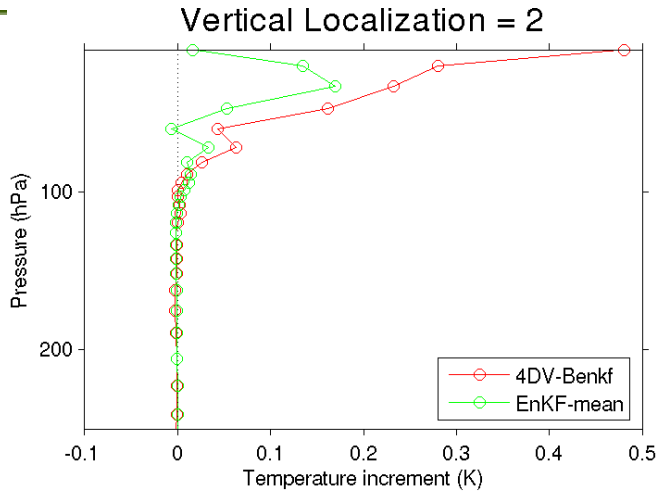


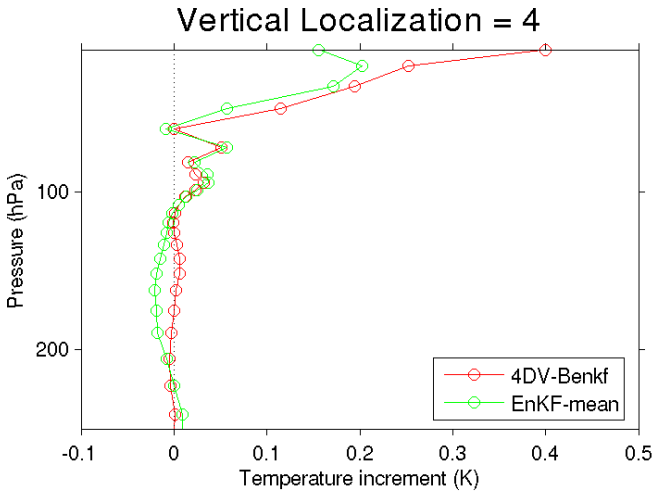


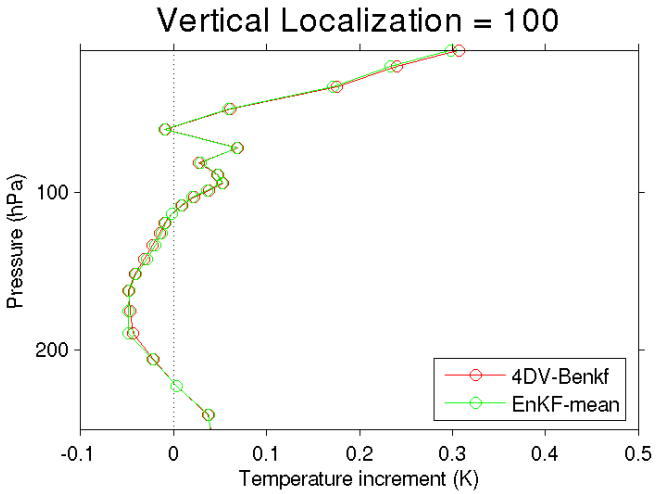
Single observation experiments

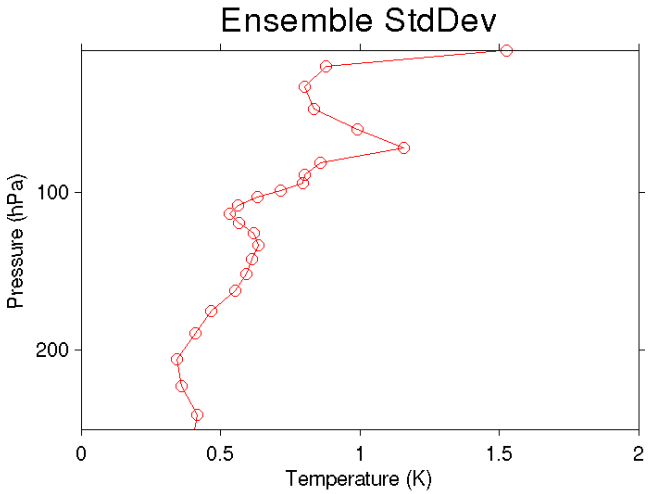
Difference in vertical localization between 4D-Var and EnKF

- AMSU-A ch10
- peak sensitivity near 30hPa
- no covariance evolution (3D-Var)
- with same B, increment larger & broader (peak at 10hPa, not 30hPa) with **4D-Var** vs. **EnKF**
- with **4D-Var**, local influence at 10hPa (amplified by large variance) not damped as with **EnKF**





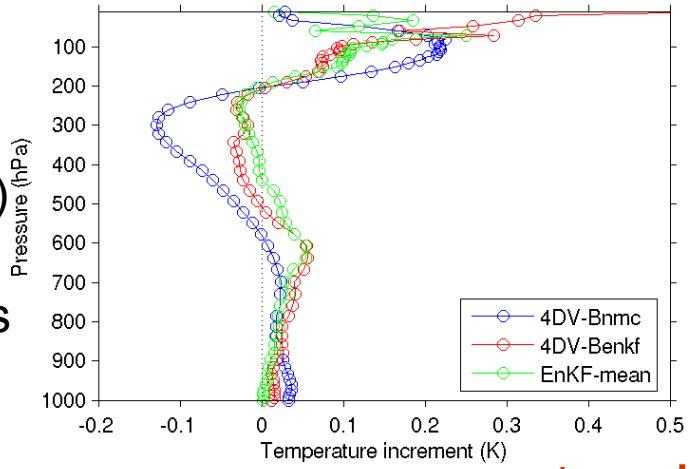


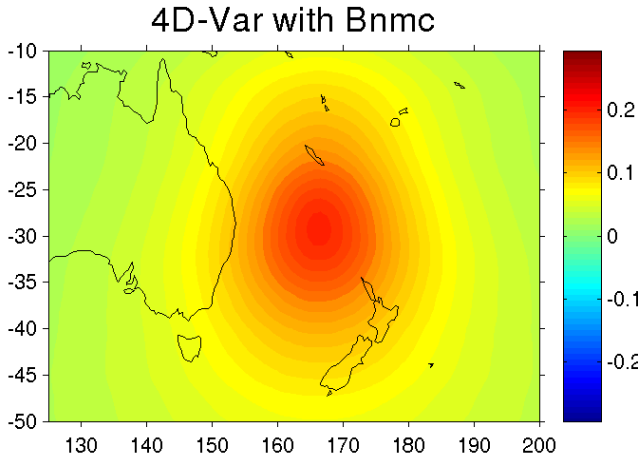


Single observation experiments

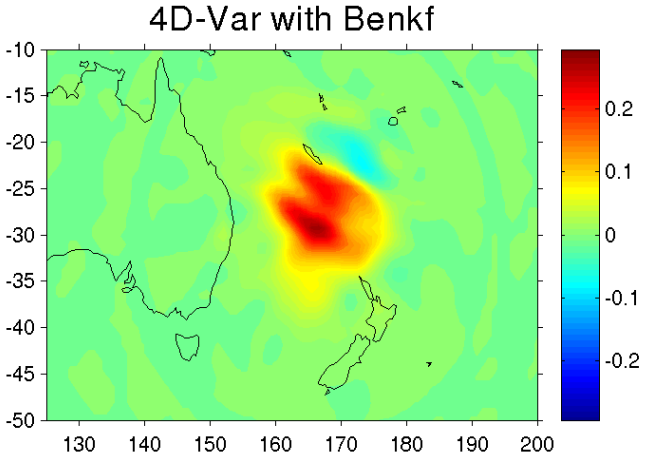
Difference in vertical localization between 4D-Var and EnKF

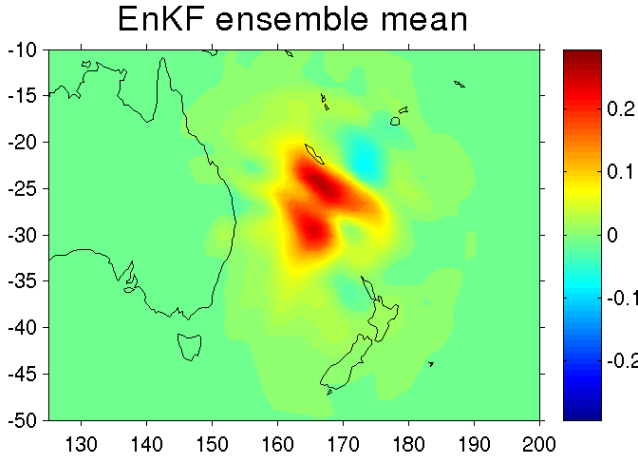
- all AMSU-A channels (4-10)
- no covariance evolution (3D-Var)
- with same B, largest differences near model top (much larger with 4D-Var-Benkf)
- likely explains larger forecast errors near model top with 4D-Var-Benkf in tropics, southern extra-tropics





contour plots at 70 hPa

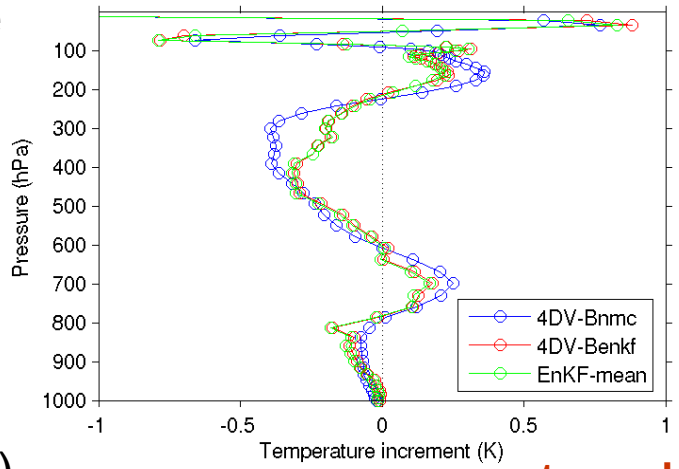


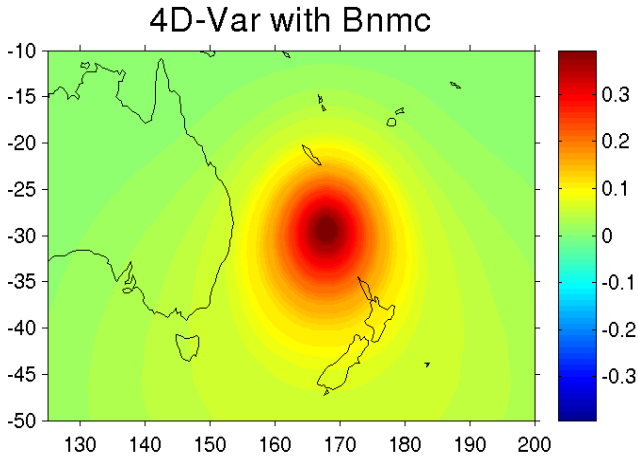


Single observation experiments

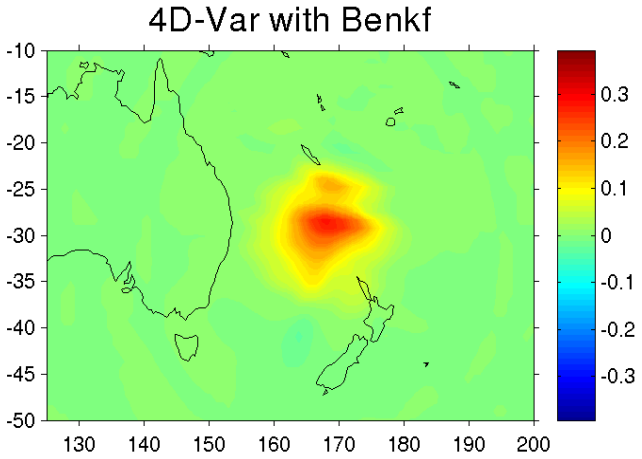
Difference in vertical localization between 4D-Var and EnKF

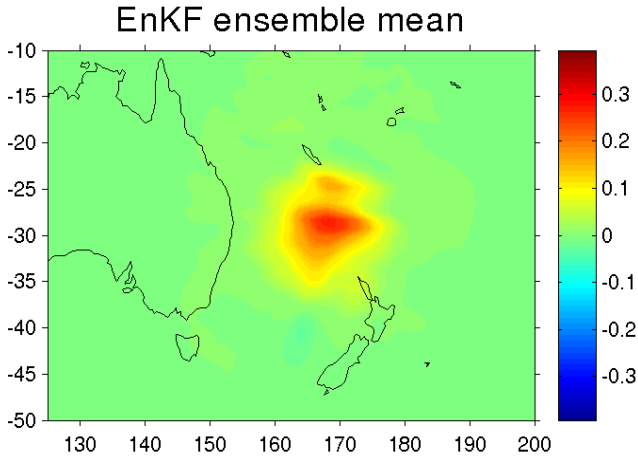
- entire temp. profile of nearby radiosonde
- no covariance evolution (3D-Var)
- all experiments give very similar increments (more than with AMSU-A)
- same general shape as with AMSU-A in layer 150hPa-700hPa





contour plots at 150 hPa

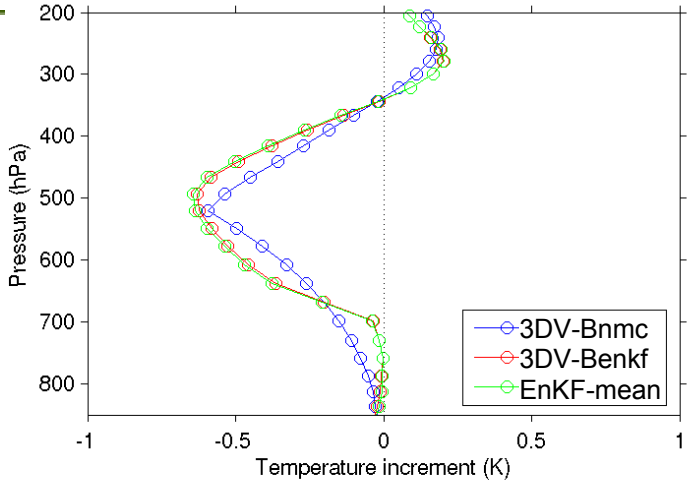


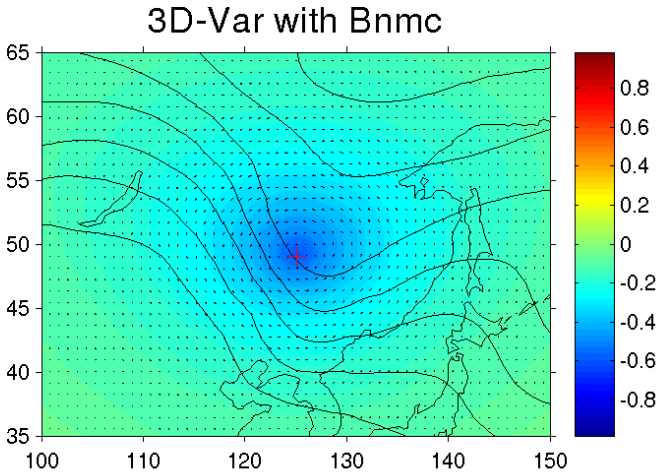


Single observation experiments – 3D-Var

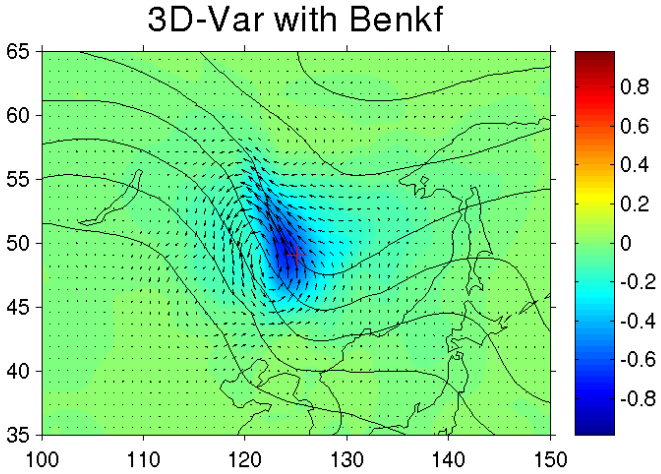
Difference in temporal covariance evolution

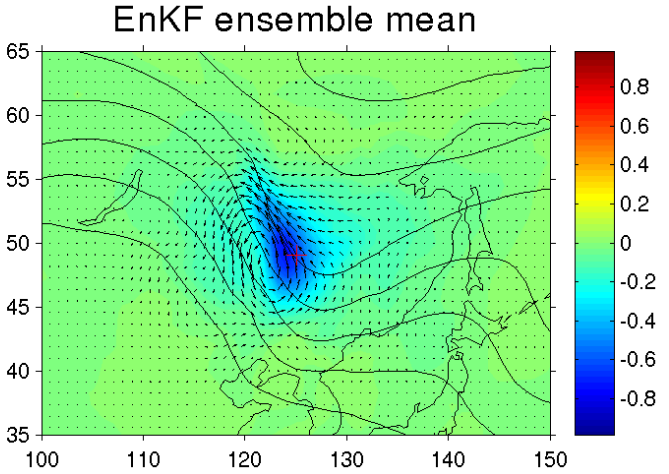
- radiosonde temperature observation at 500hPa
- observation at **middle of assimilation window (+0h)**
- with same B, increments nearly identical from **3D-Var**, **EnKF**
- contours are 500hPa GZ background state at 0h (ci=10m)





contour plots at 500 hPa





4D error covariances

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

EnKF:

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

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

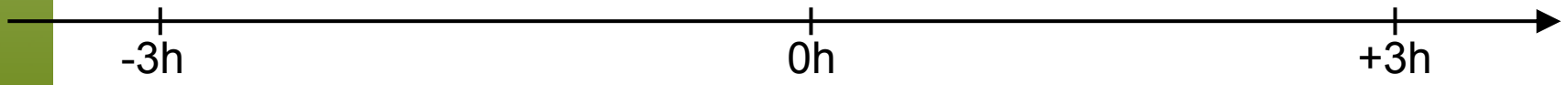
$B_{ens}(0h,+3h) = (\ \mathcal{M}(ens(-3h))\ \mathcal{M}(\mathcal{M}(ens(-3h)))^T\ )$

4D-Var:

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

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

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

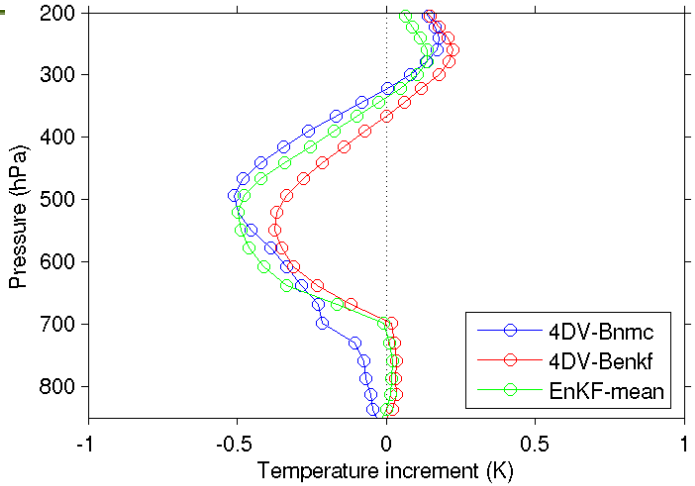


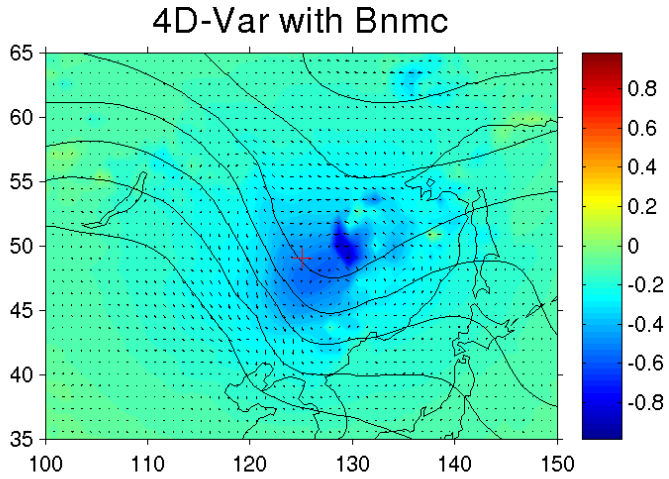
note: localization is ignored here for clarity

Single observation experiments

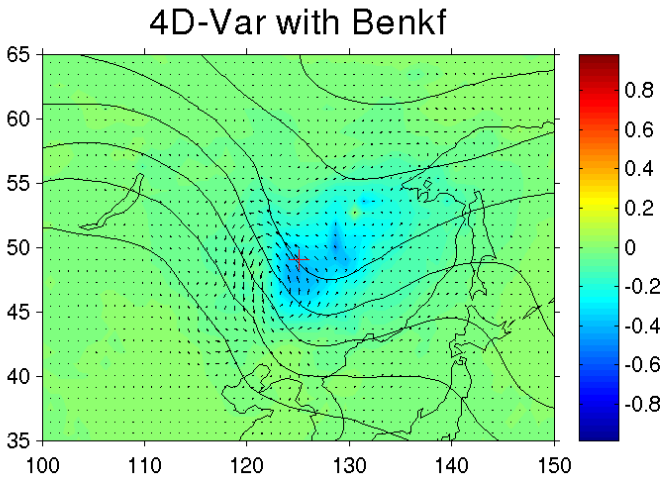
Difference in temporal covariance evolution

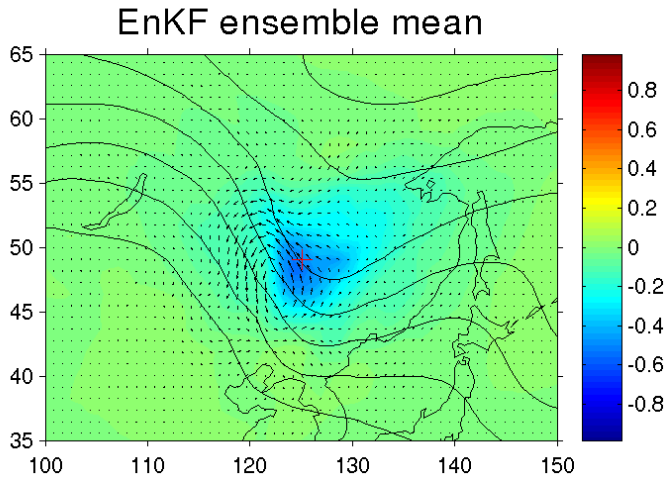
- radiosonde temperature observation at 500hPa
- observation at **beginning of assimilation window (-3h)**
- with same B, increments very similar from **4D-Var**, **EnKF**
- contours are 500hPa GZ background state at 0h (ci=10m)





contour plots at 500 hPa

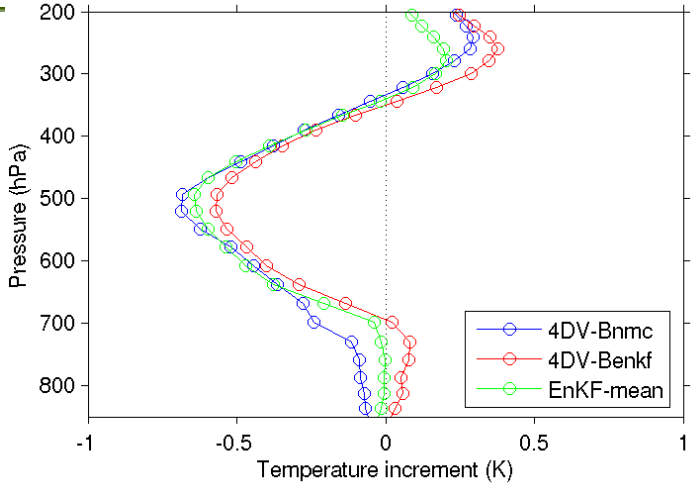


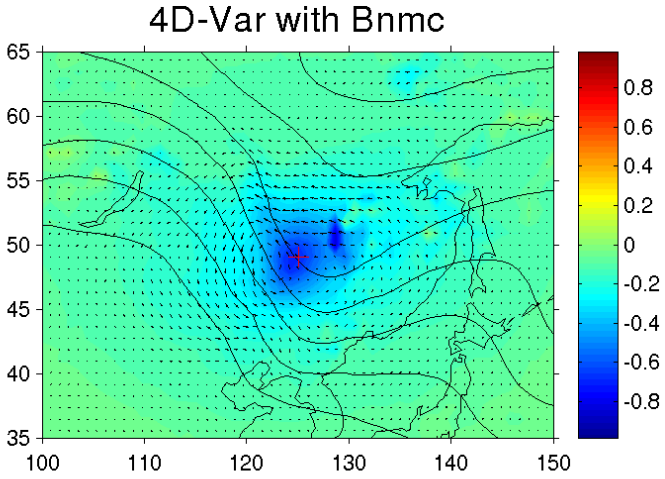


Single observation experiments

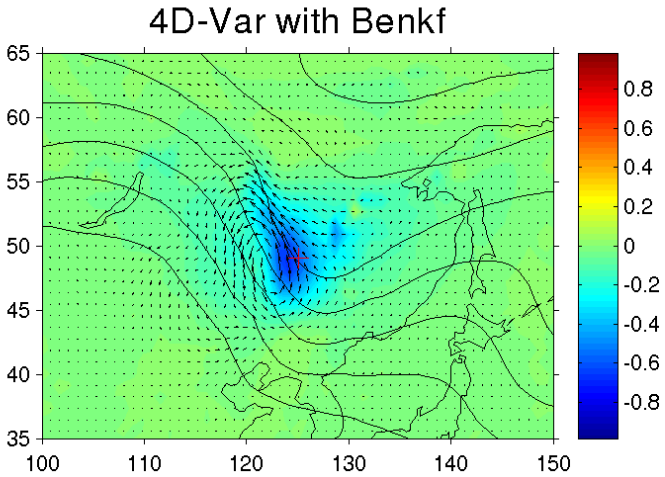
Difference in temporal covariance evolution

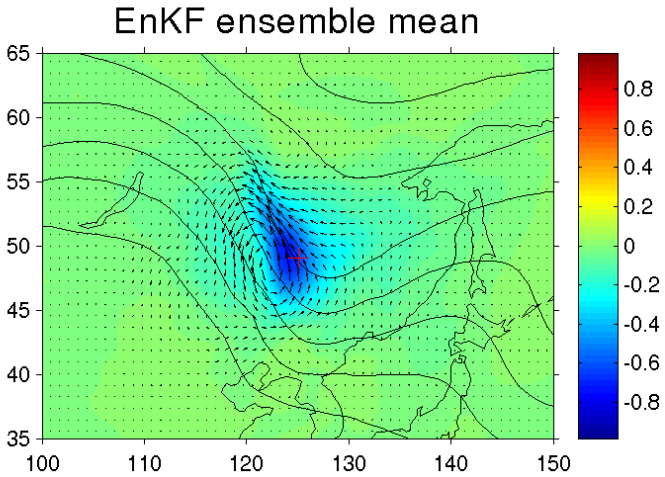
- radiosonde temperature observation at 500hPa
- observation at **middle of assimilation window (+0h)**
- with same B, increments very similar from **4D-Var**, **EnKF**
- contours are 500hPa GZ background state at 0h (ci=10m)





contour plots at 500 hPa

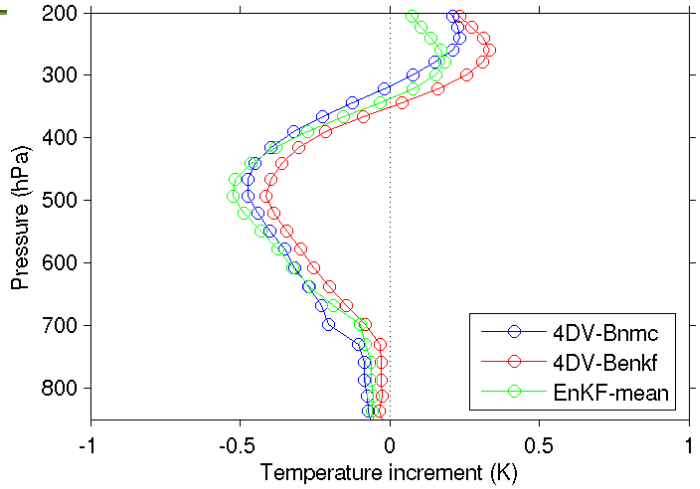


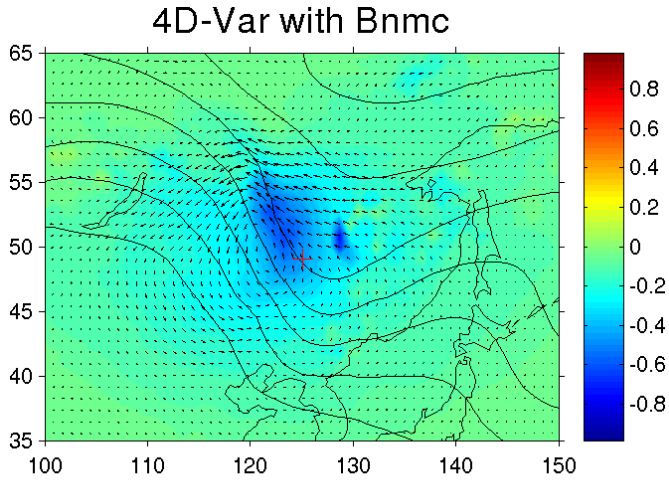


Single observation experiments

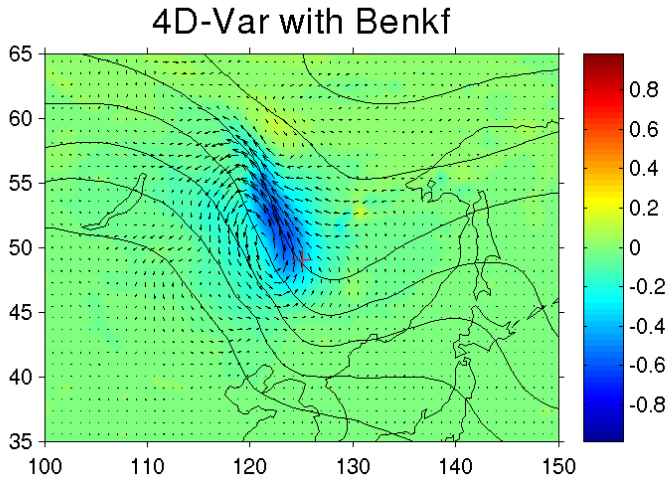
Difference in temporal covariance evolution

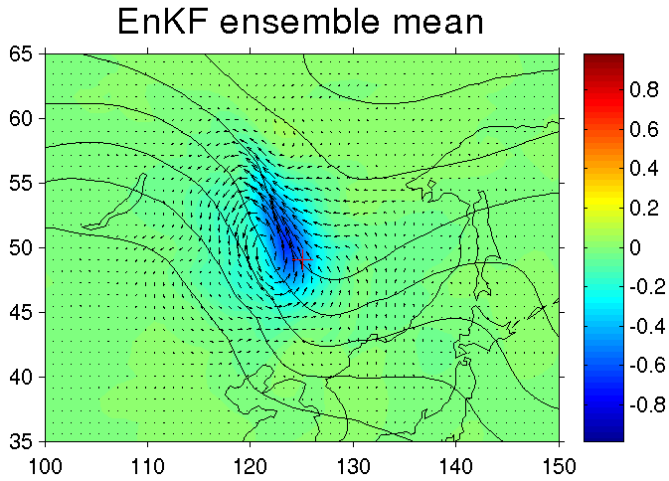
- radiosonde temperature observation at 500hPa
- observation at **end of assimilation window (+3h)**
- with same B, increments very similar from **4D-Var**, **EnKF**
- contours are 500hPa GZ background state at 0h (ci=10m)





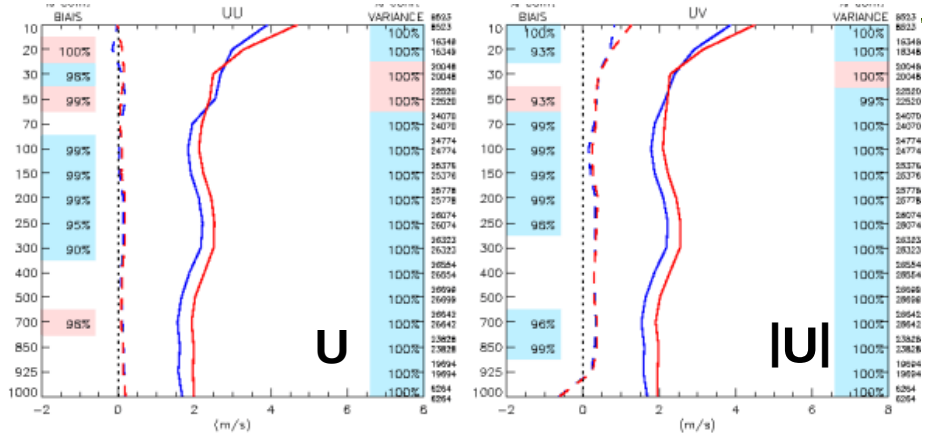
contour plots at 500 hPa

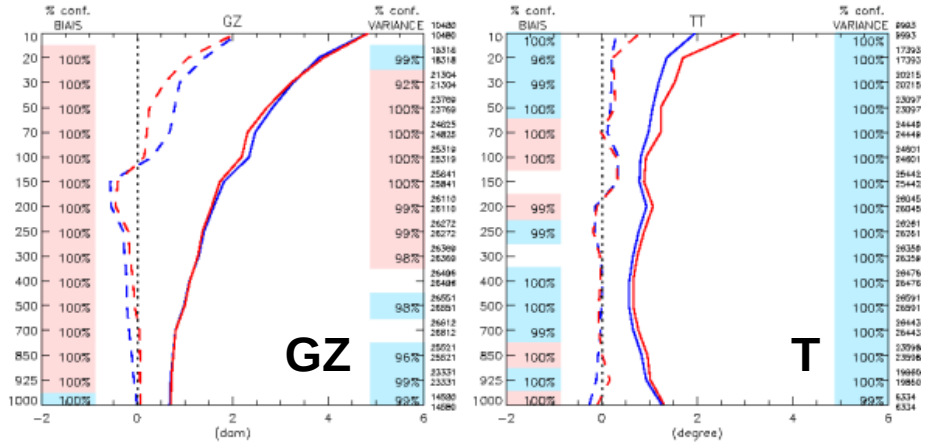


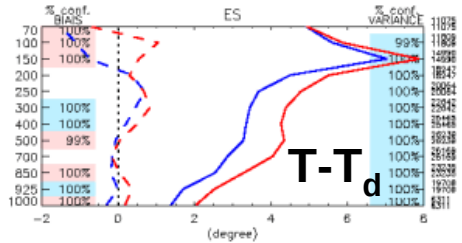


Fit of Analyses to Observations – global

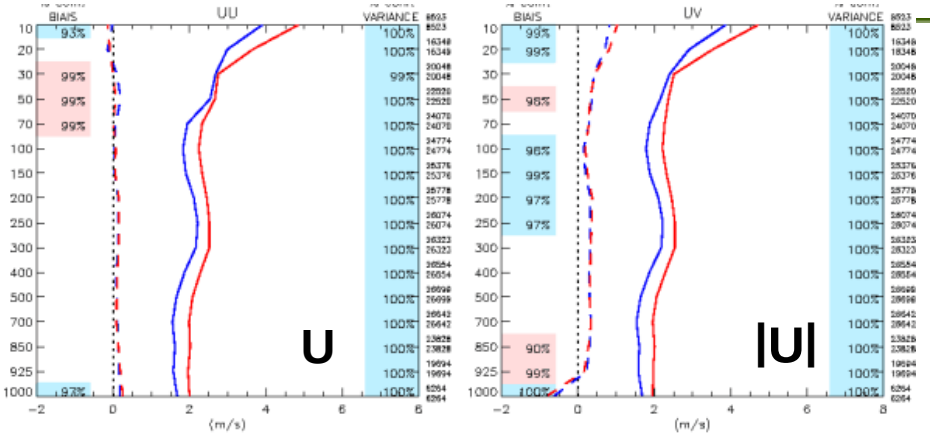
EnKF mean analysis
vs. 4D-Var Bnmc

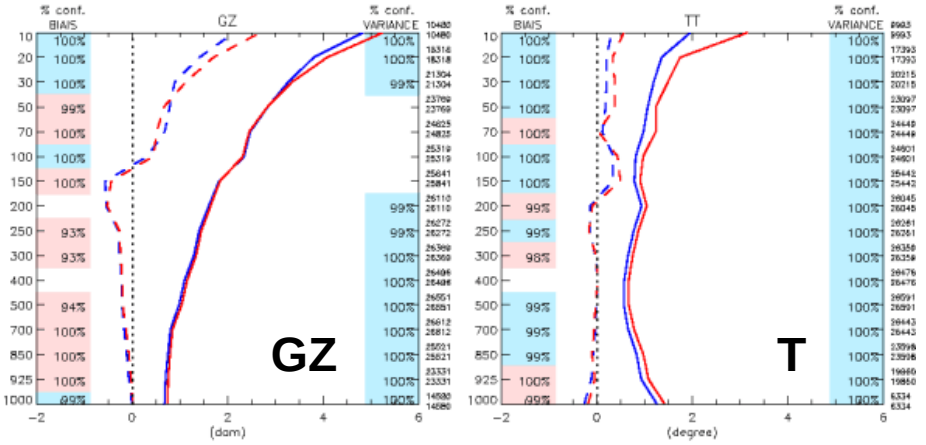


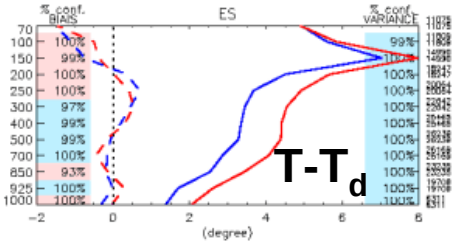




4D-Var Benkf
vs. 4D-Var Bnmc



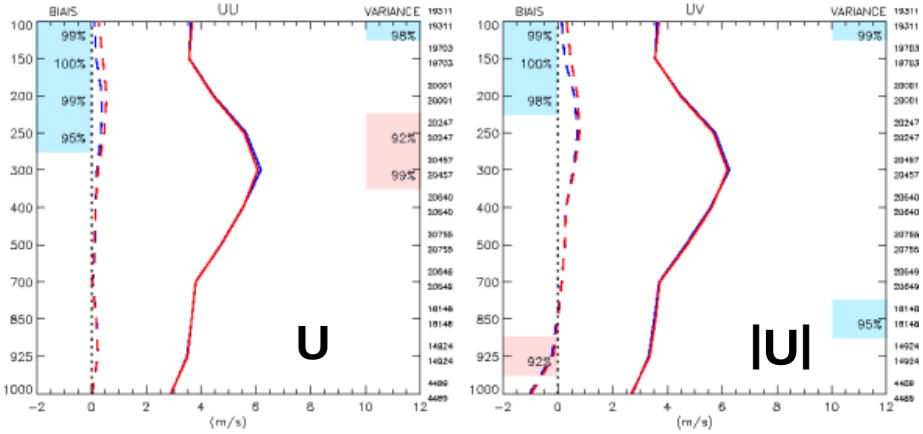


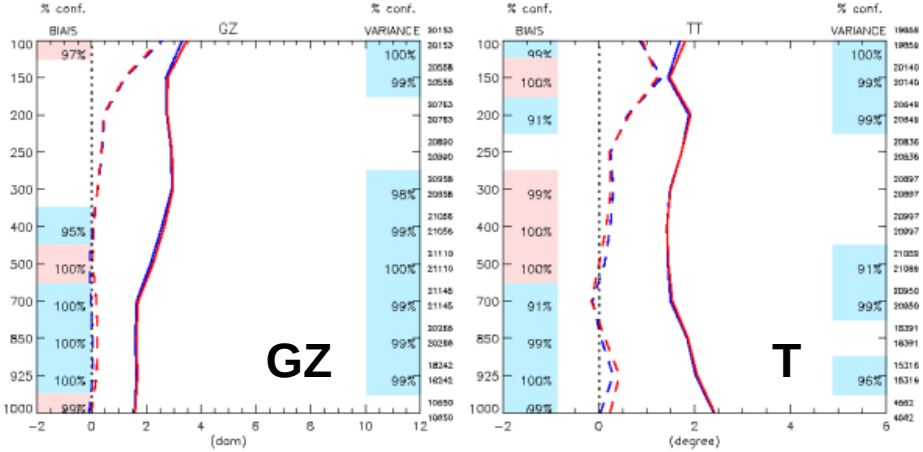


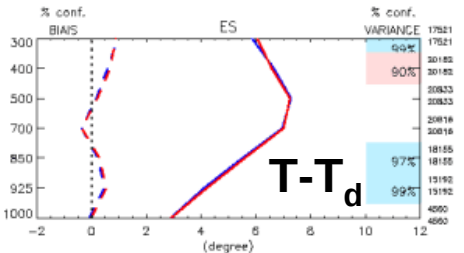
stddev & bias relative to radiosondes

Forecast Results – 48h northern hemisphere

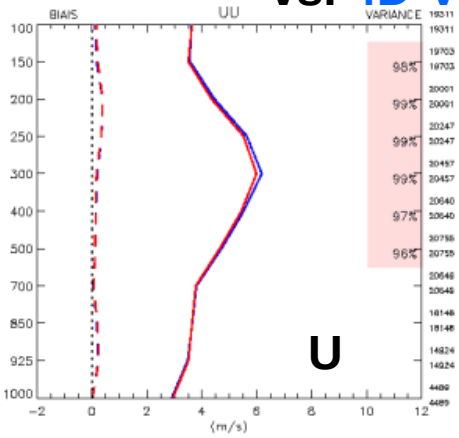
EnKF mean analysis
vs. 4D-Var Bnmc

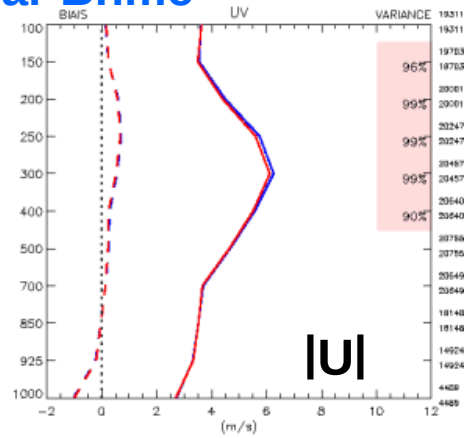


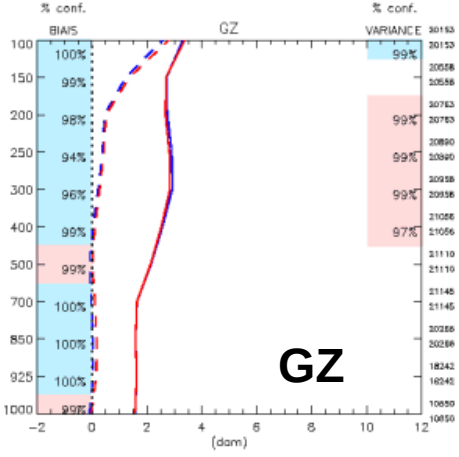


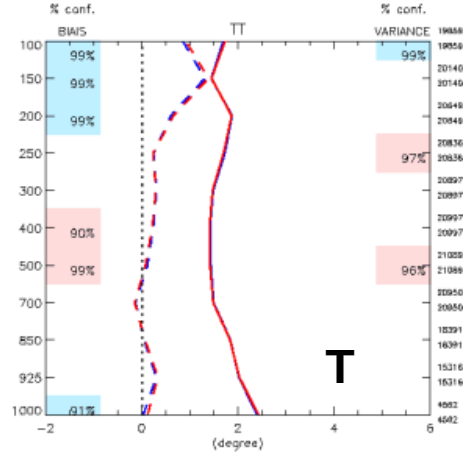


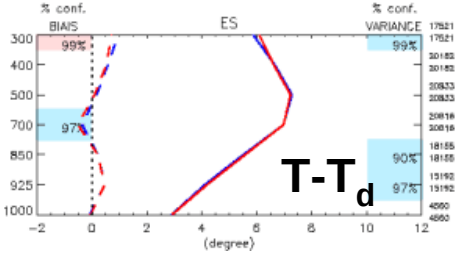
4D-Var Benkf
vs. 4D-Var Bnmc







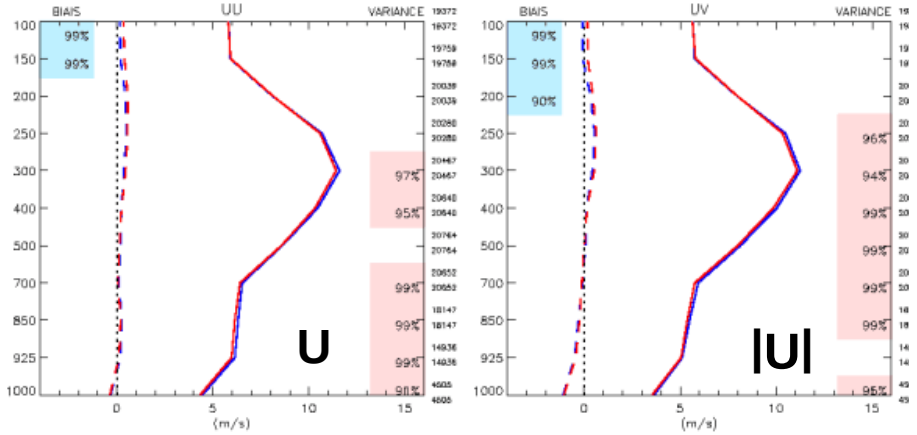


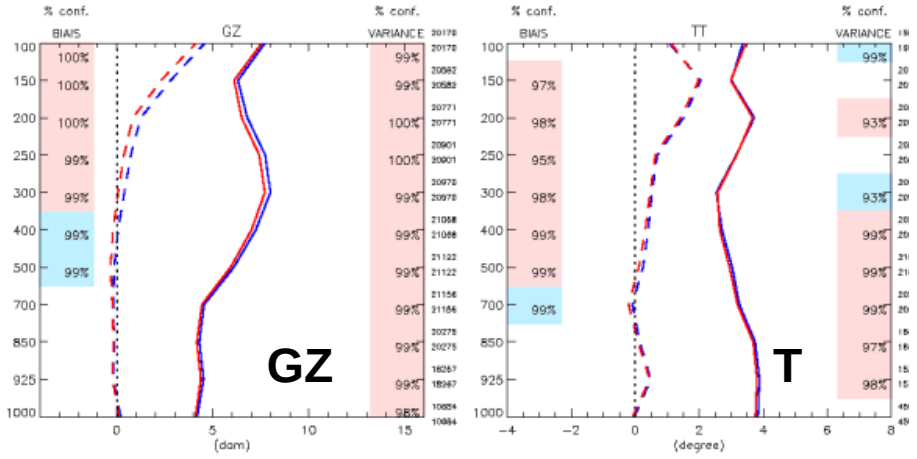


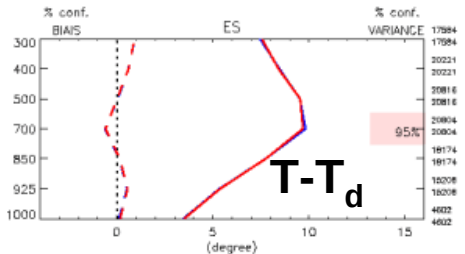
stddev & bias relative to radiosondes

Forecast Results – 120h northern hemisphere

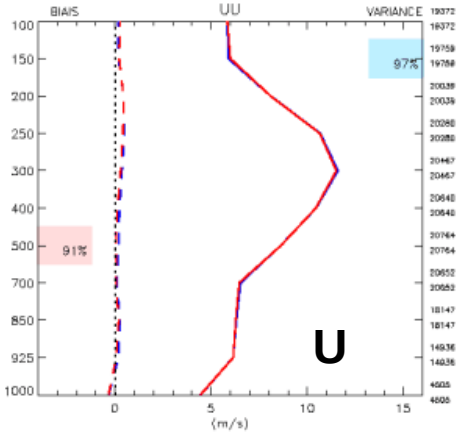
EnKF mean analysis
vs. 4D-Var Bnmc

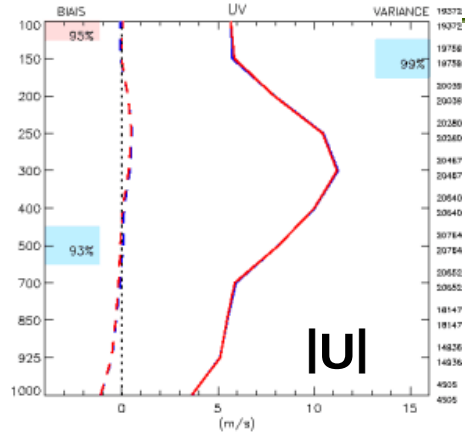


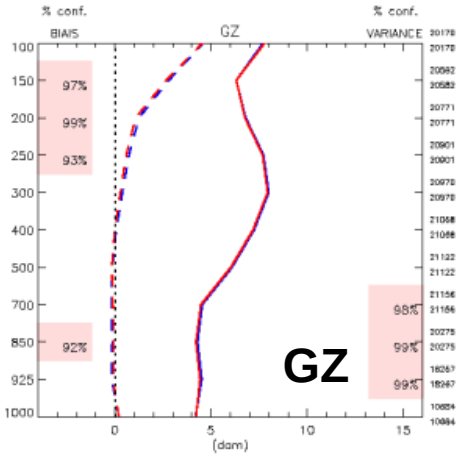


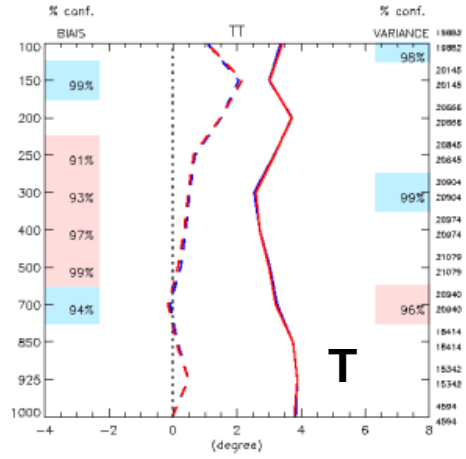


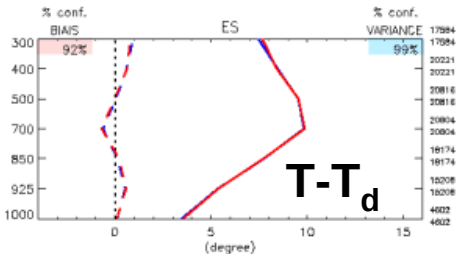
4D-Var Benkf
vs. 4D-Var Bnmc







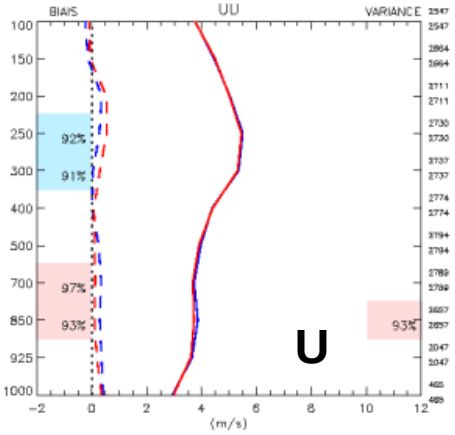


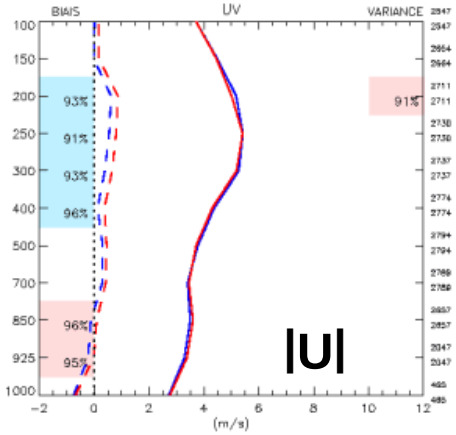


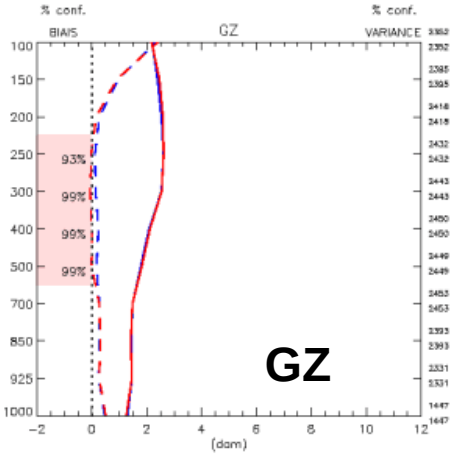
stddev & bias relative to radiosondes

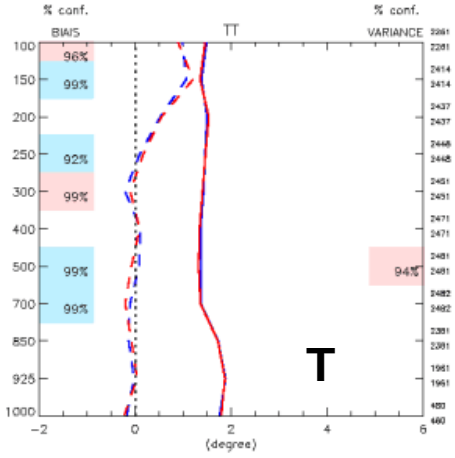
Forecast Results – 48h southern hemisphere

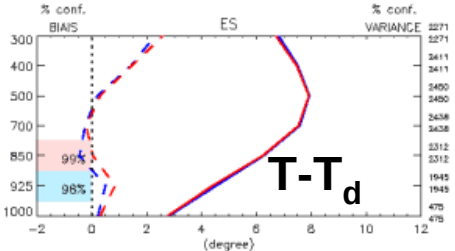
EnKF mean analysis
vs. 4D-Var Bnmc



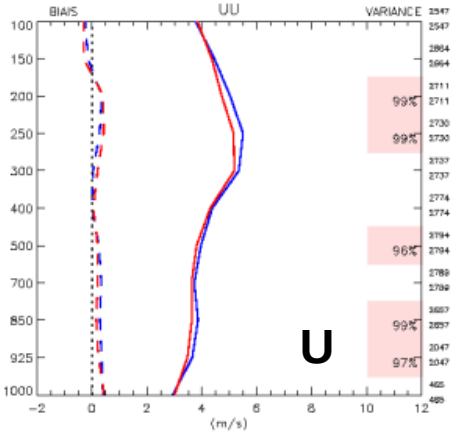


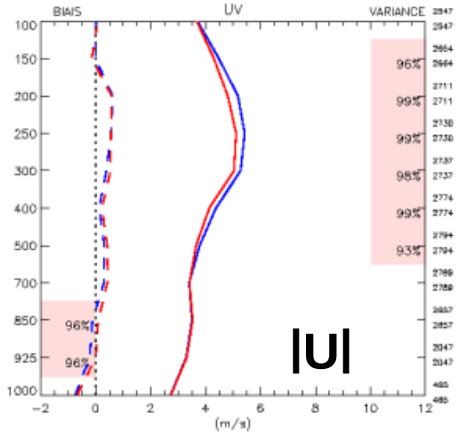


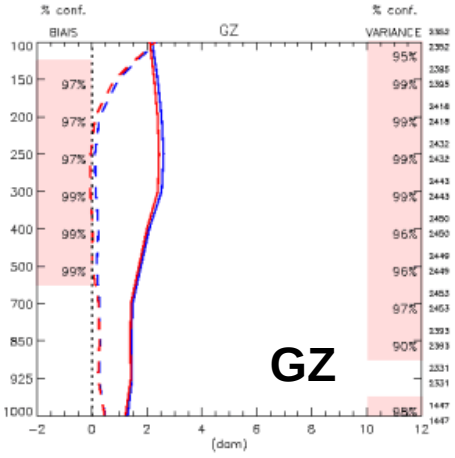


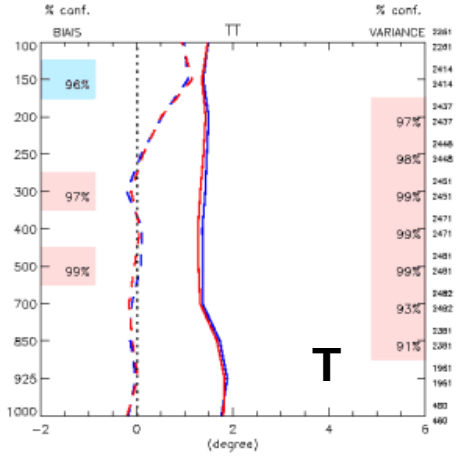


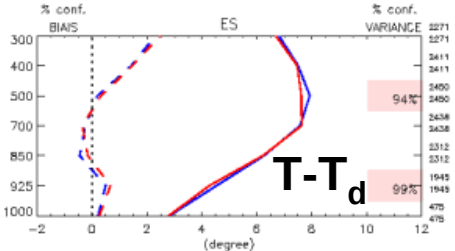
4D-Var Benkf
vs. 4D-Var Bnmc







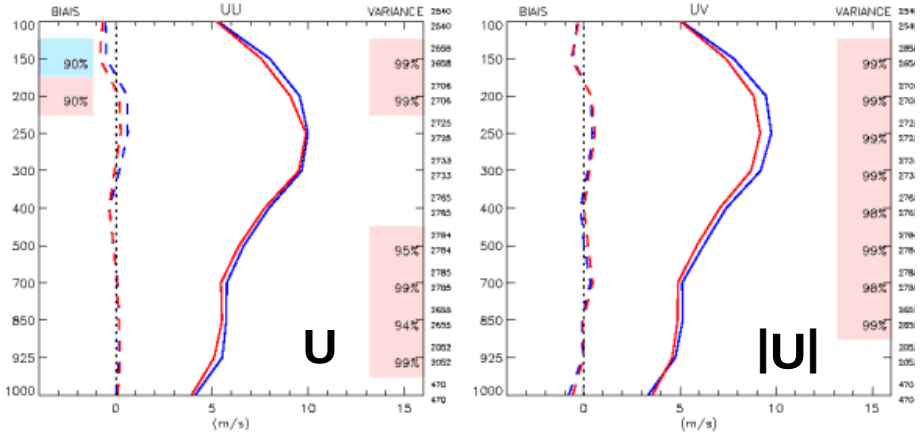


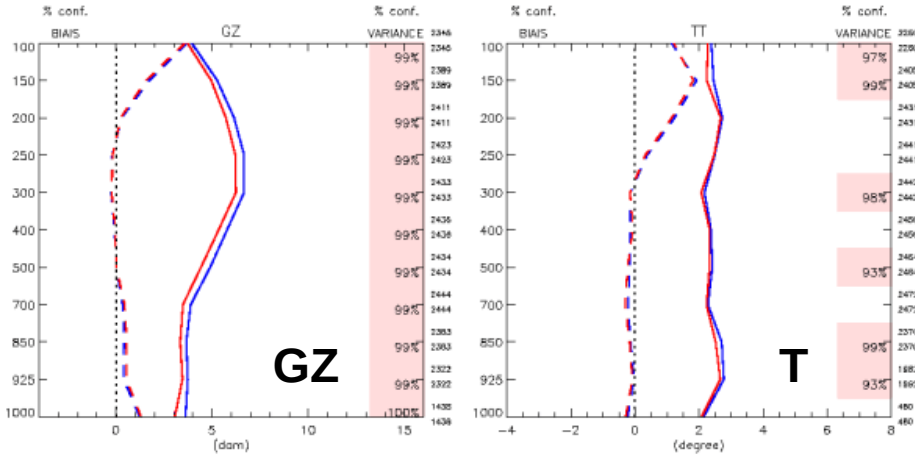


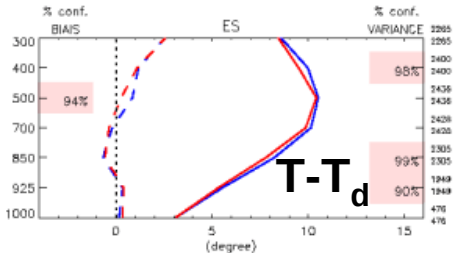
stddev & bias relative to radiosondes

Forecast Results – 120h southern hemisphere

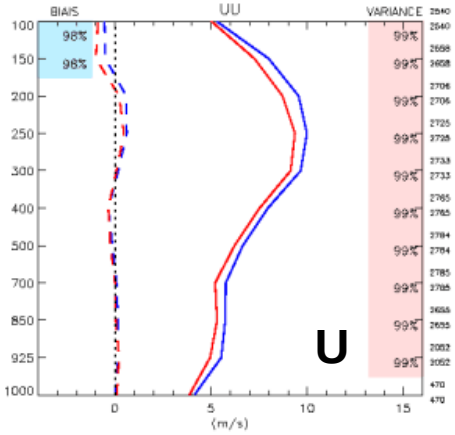
EnKF mean analysis
vs. 4D-Var Bnmc

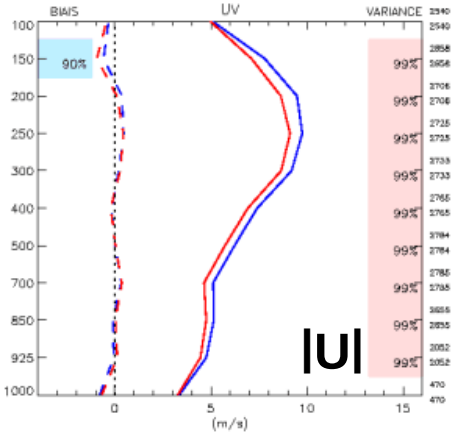


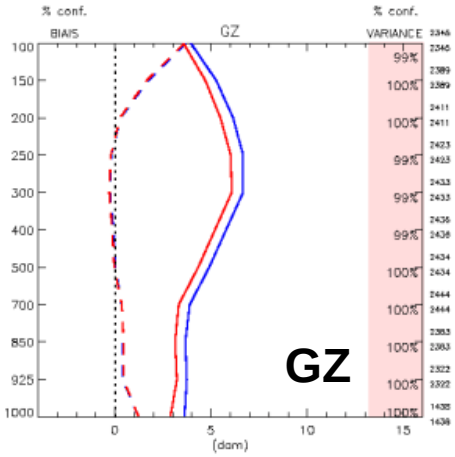


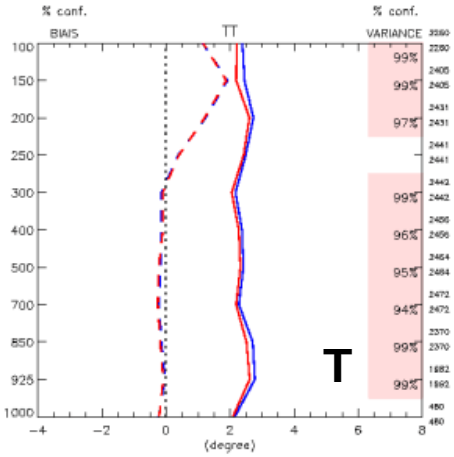


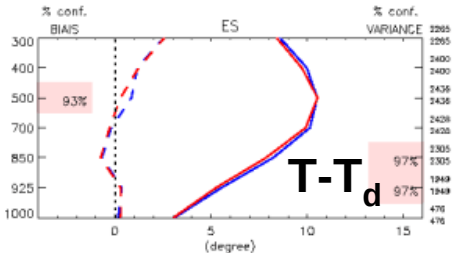
4D-Var Benkf
vs. 4D-Var Bnmc







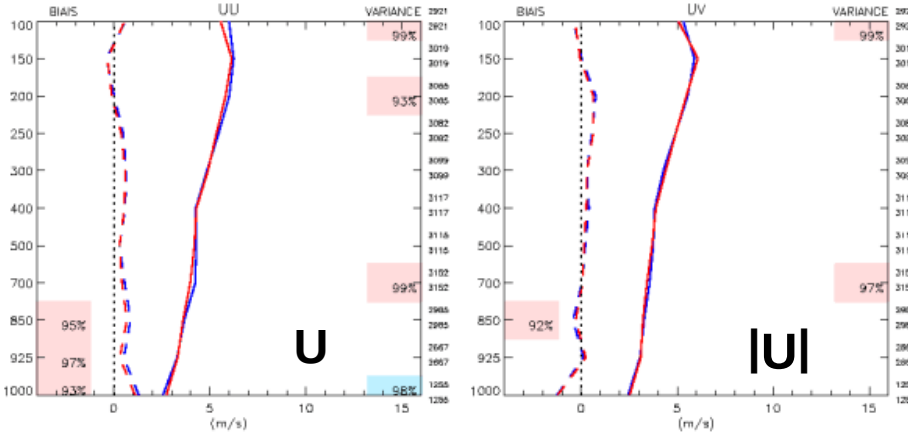


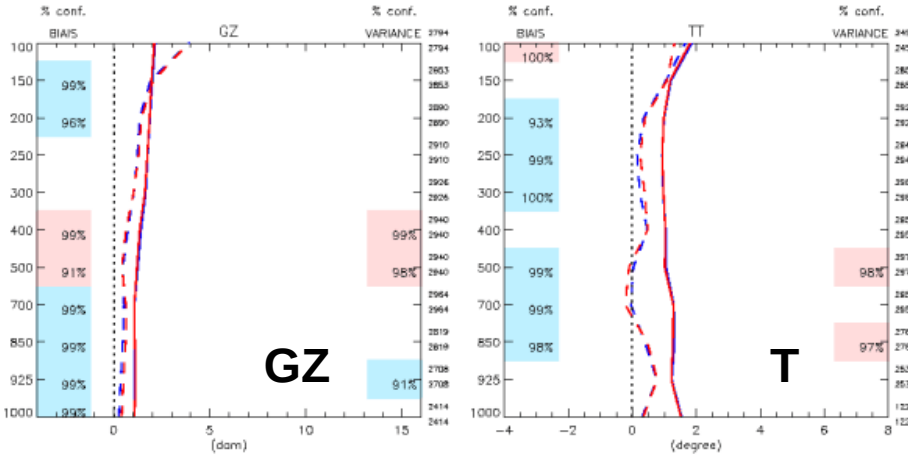


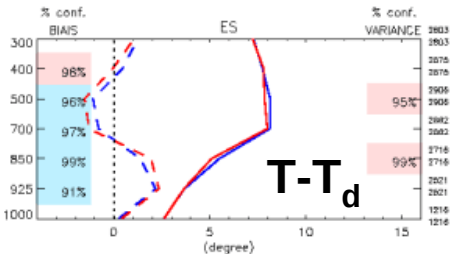
stddev & bias relative to radiosondes

Forecast Results – 72h tropics

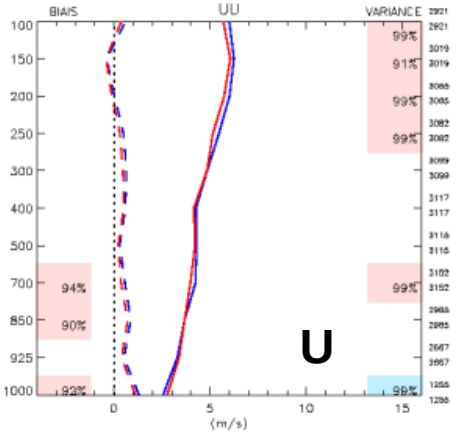
EnKF mean analysis
vs. 4D-Var Bnmc

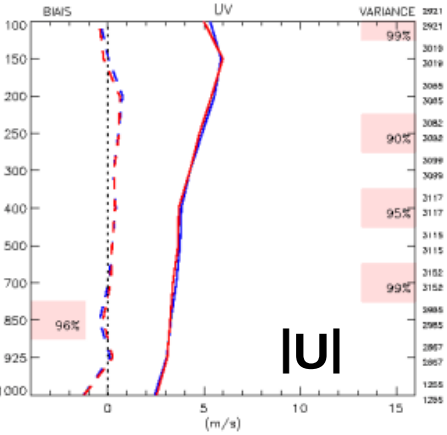


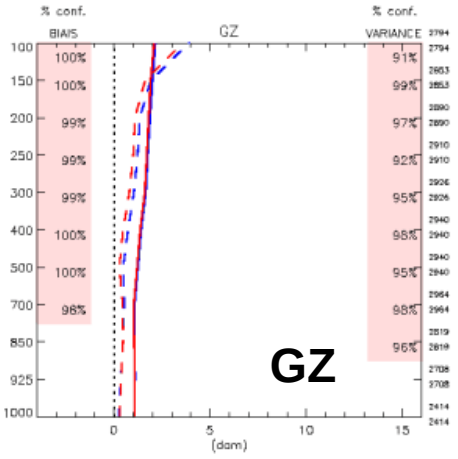


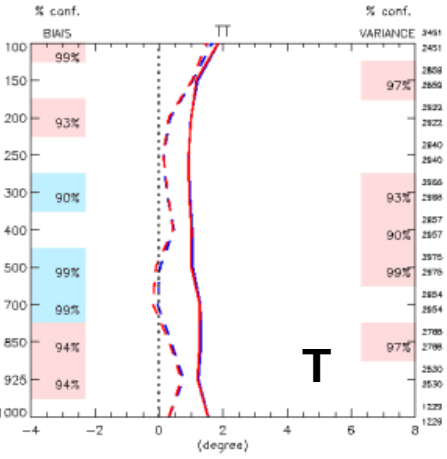


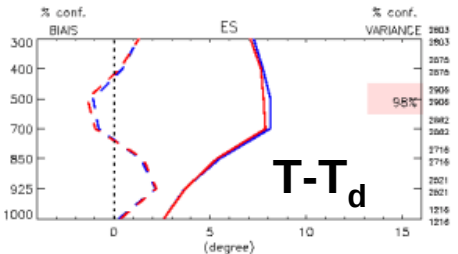
4D-Var Benkf
vs. 4D-Var Bnmc









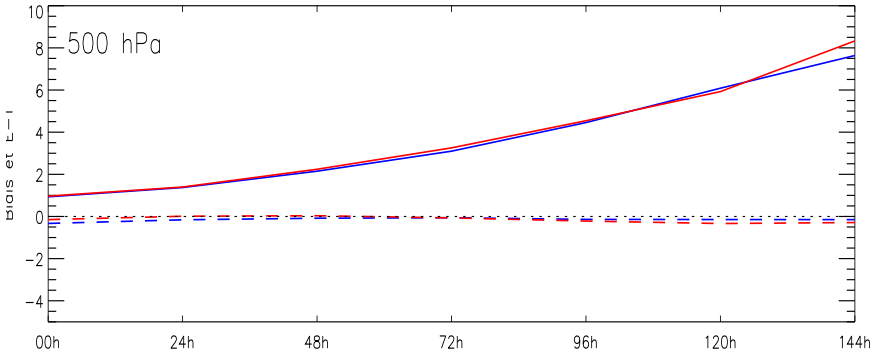


stddev & bias relative to radiosondes

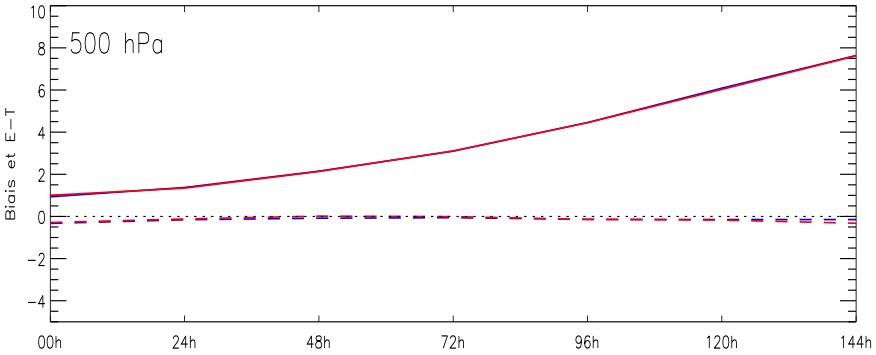
Forecast Results – 500 hPa GZ

Northern Hemisphere

EnKF Mean Analyses vs. 4D-Var Bnmc

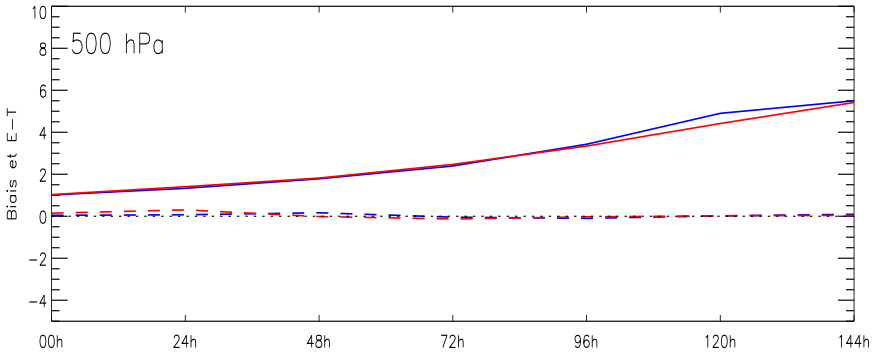


4D-Var with Benkf vs. 4D-Var Bnmc

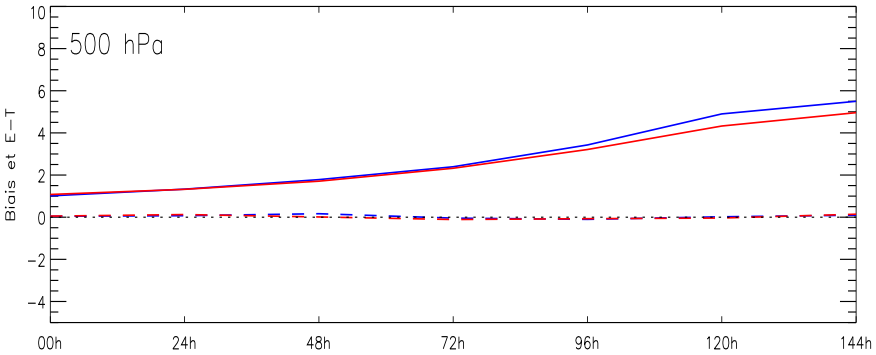


Southern Hemisphere

EnKF Mean Analyses vs. 4D-Var Bnmc



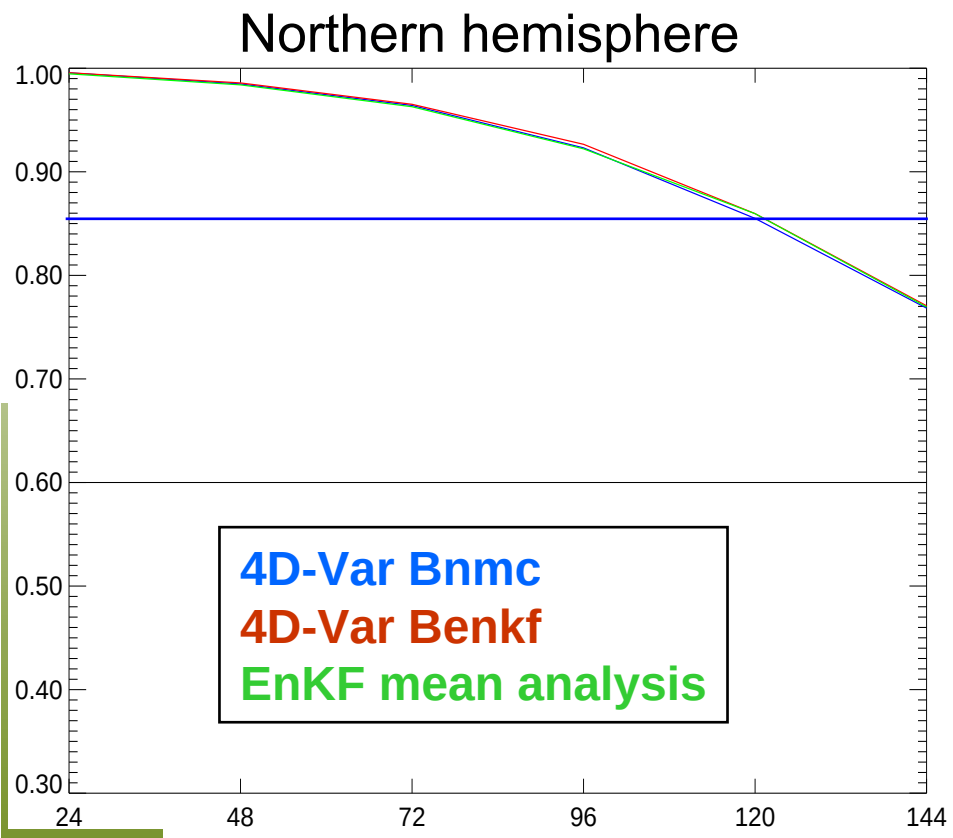
4D-Var with Benkf vs. 4D-Var Bnmc

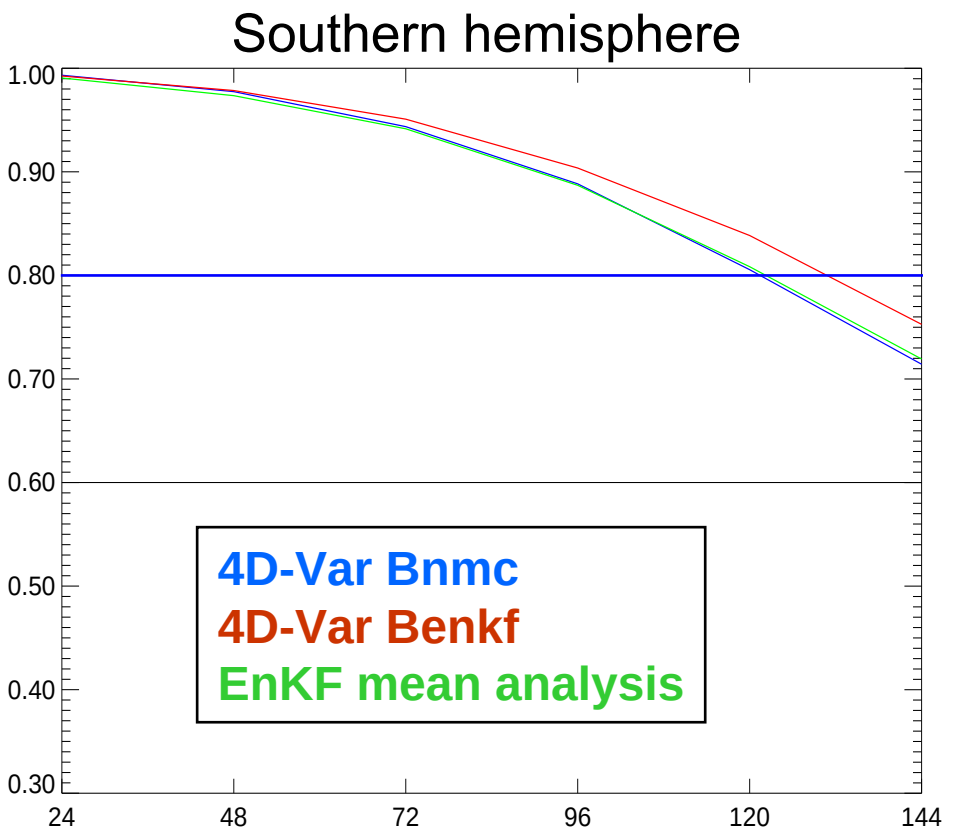


stddev & bias relative to radiosondes

Results – 500hPa GZ anomaly correlation

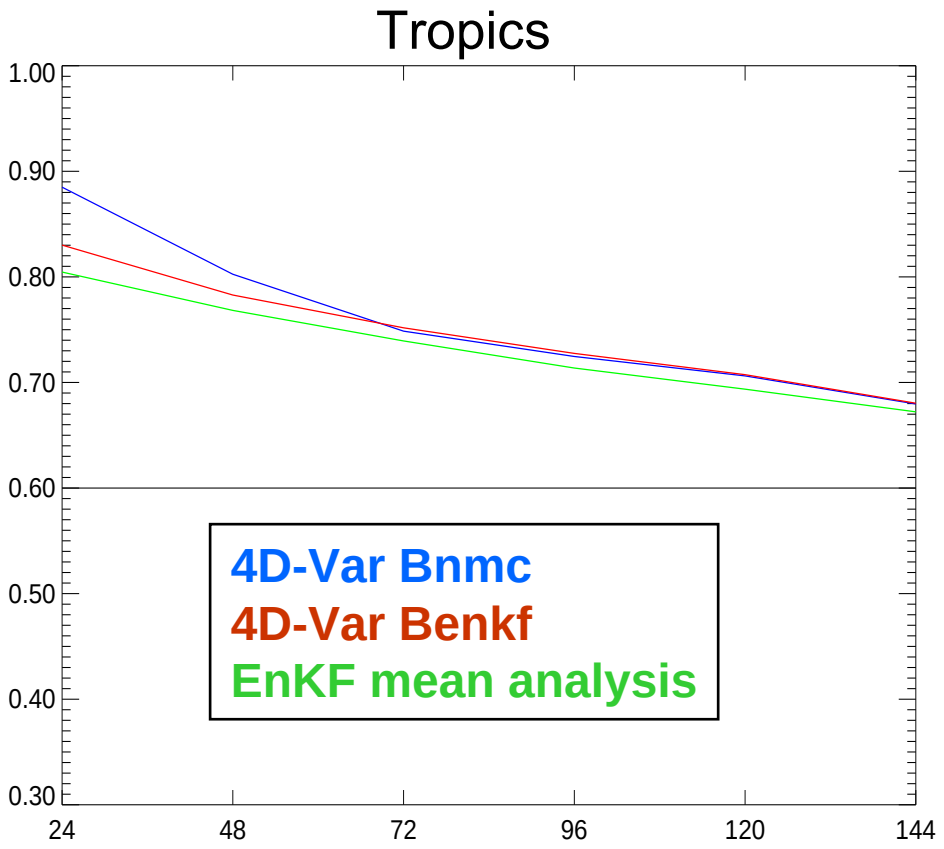
Verifying analyses from 4D-Var with Bnmc





Results – 850hPa T anomaly correlation

Verifying analyses from 4D-Var with Bnmc



Conclusions

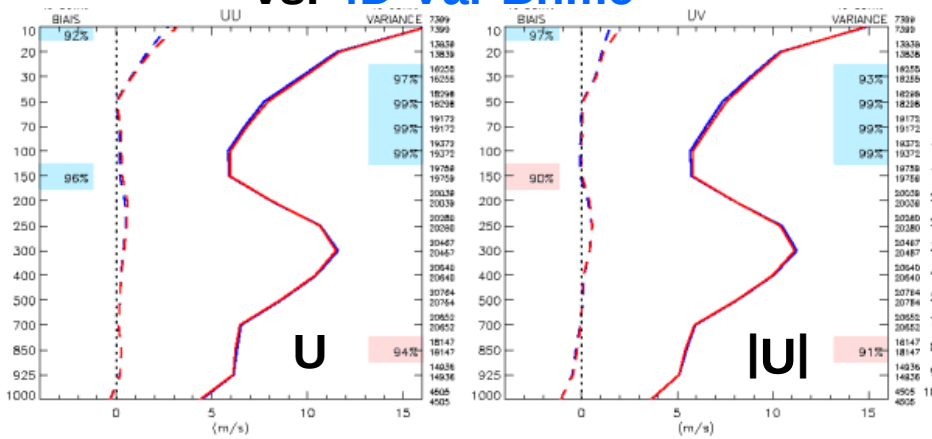
Based on 1-month data assimilation experiments (Feb 2007)

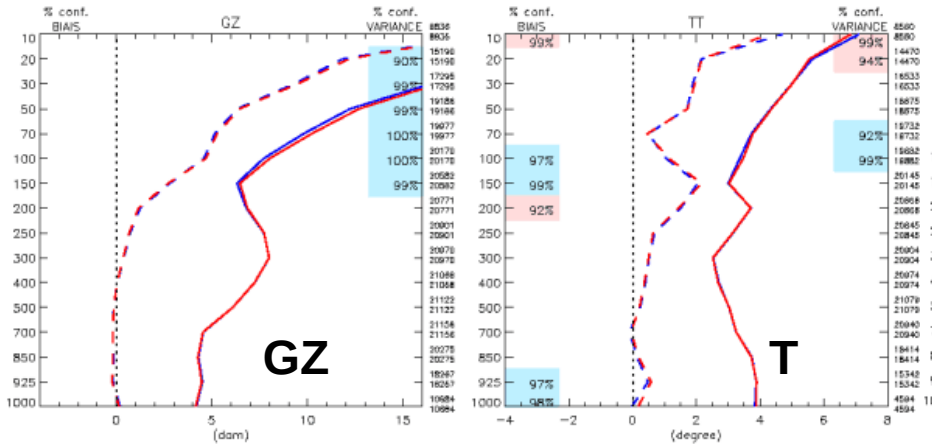
- High-resolution medium-range global deterministic forecasts initialized with:
  - 4D-Var (Bnmc) or EnKF (ensemble mean) analyses have comparable quality (both systems like operational approaches)
  - 4D-Var with flow-dependent EnKF covariances yields a gain of ~10 hours at day 5 in southern extra-tropics
- Still need to complete EnKF experiment using incremental approach to produce high-resolution deterministic analysis
- Also test impact of flow-dependent Benkf in 3D-Var

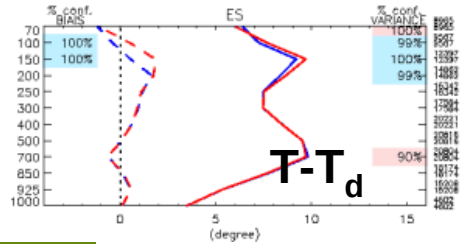
Extra Slides

Forecast Results – 120h Operational 4D-Var

Operational 4D-Var
vs. 4D-Var Bnmc

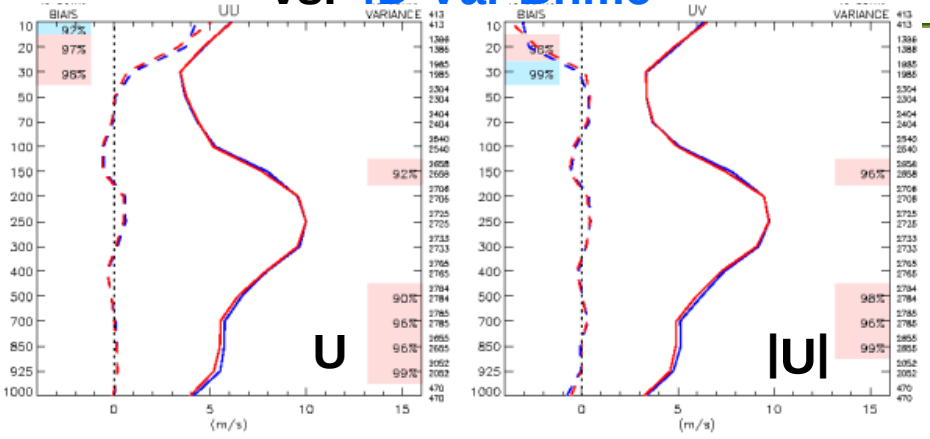


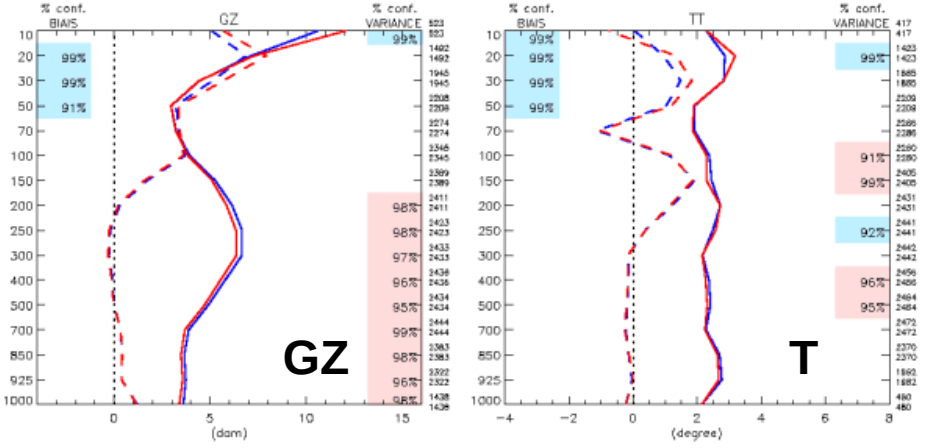


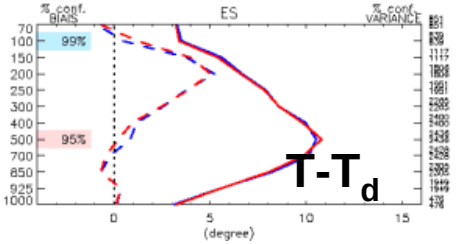


Northern hemisphere

Operational 4D-Var
vs. 4D-Var Bnmc



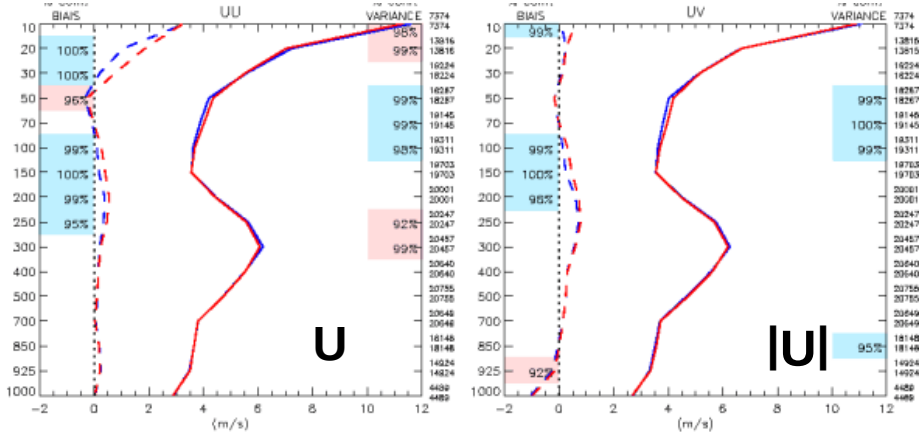




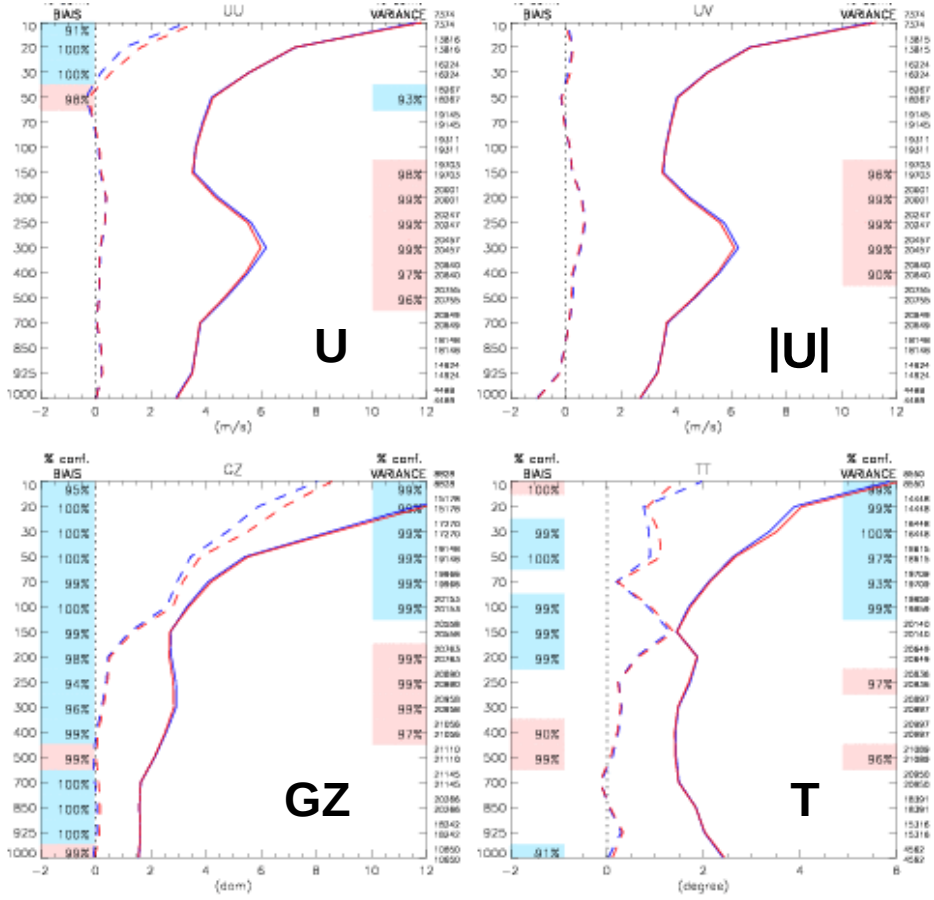
Southern hemisphere

Forecast Results – 48h northern hemisphere

EnKF mean analysis vs. 4D-Var Bnmc



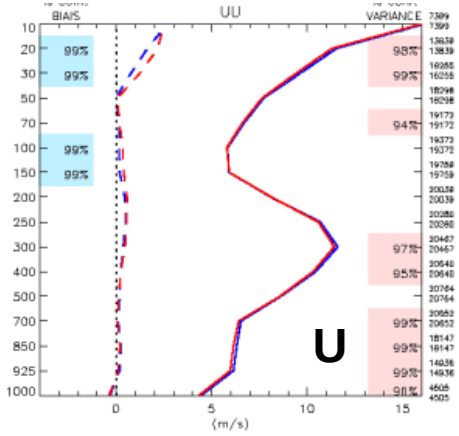
4D-Var Benkf vs. 4D-Var Bnmc

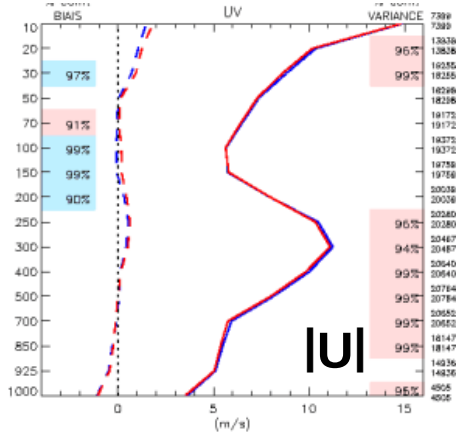


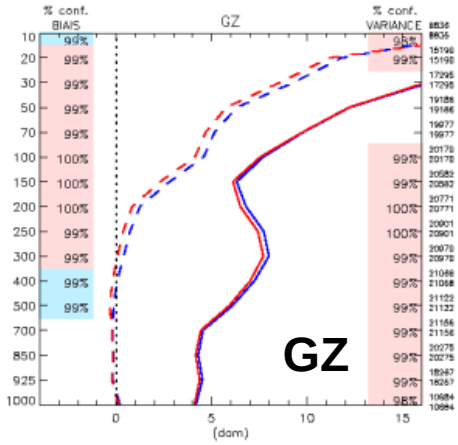
stddev & bias relative to radiosondes

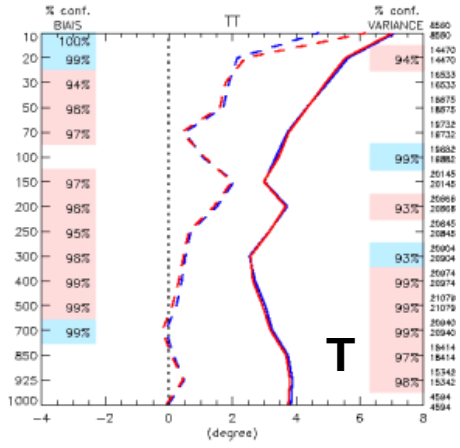
Forecast Results – 120h northern hemisphere

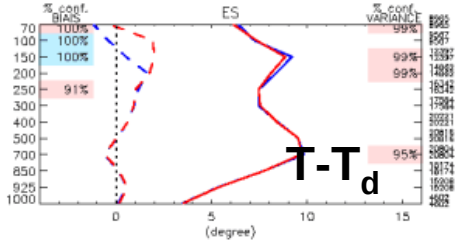
EnKF mean analysis vs. 4D-Var Bnmc



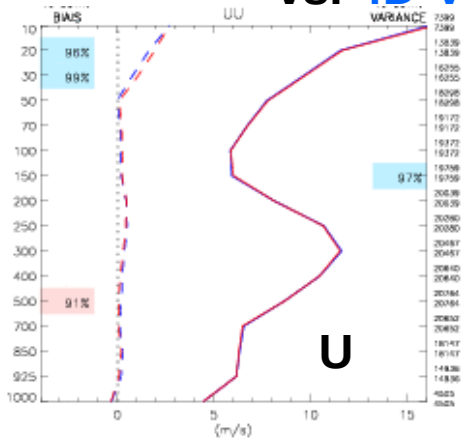


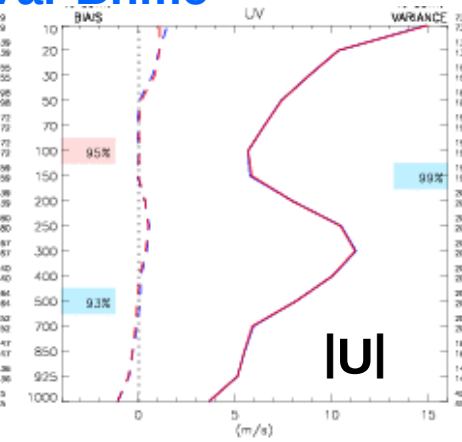


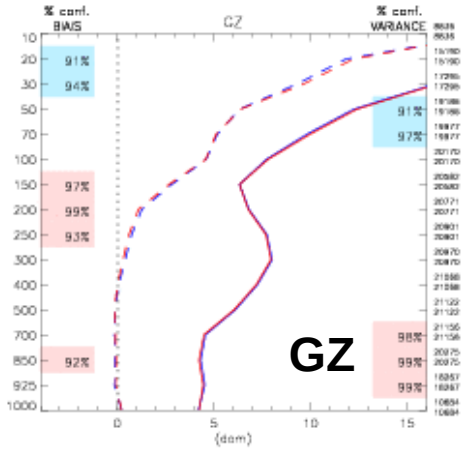


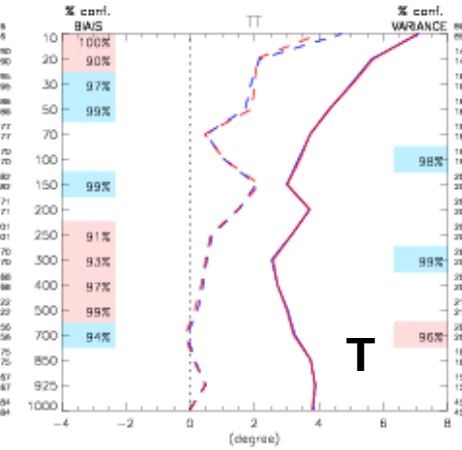


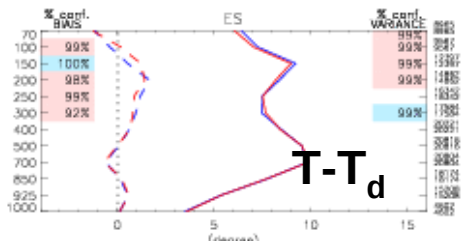
4D-Var Benkf vs. 4D-Var Bnmc







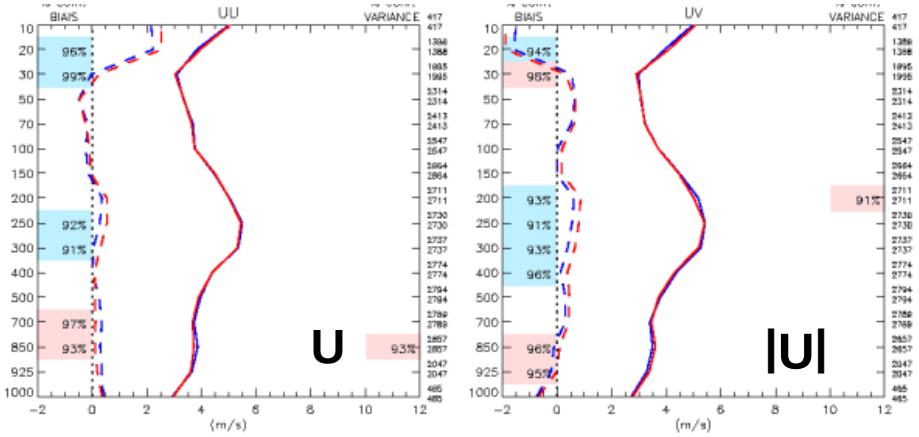


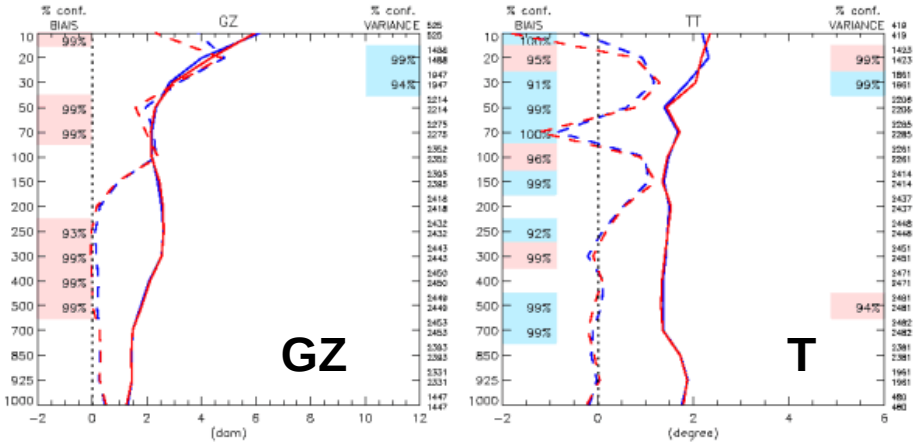


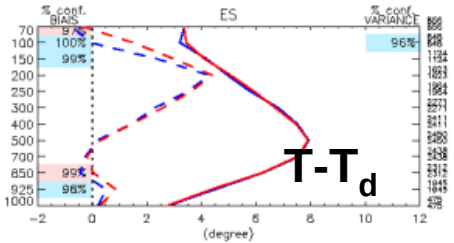
stddev & bias relative to radiosondes

Forecast Results – 48h southern hemisphere

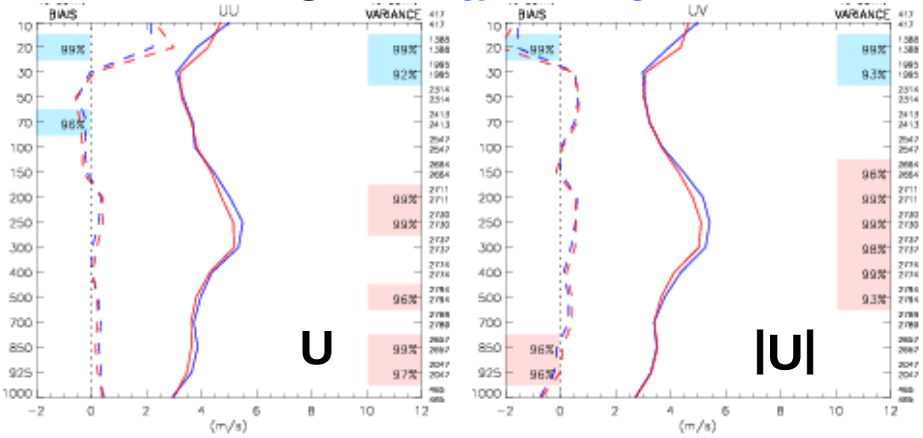
EnKF mean analysis vs. 4D-Var Bnmc

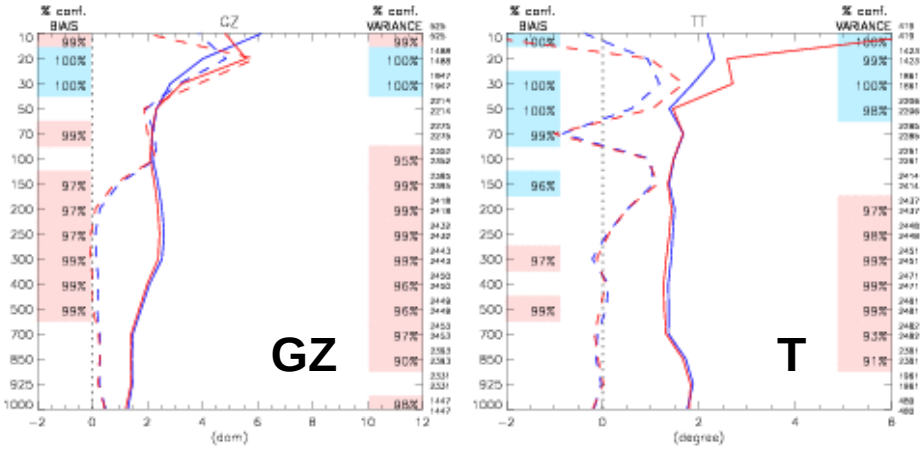


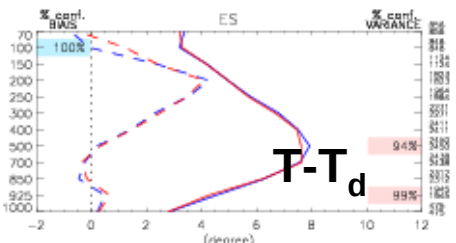




4D-Var Benkf vs. 4D-Var Bnmc



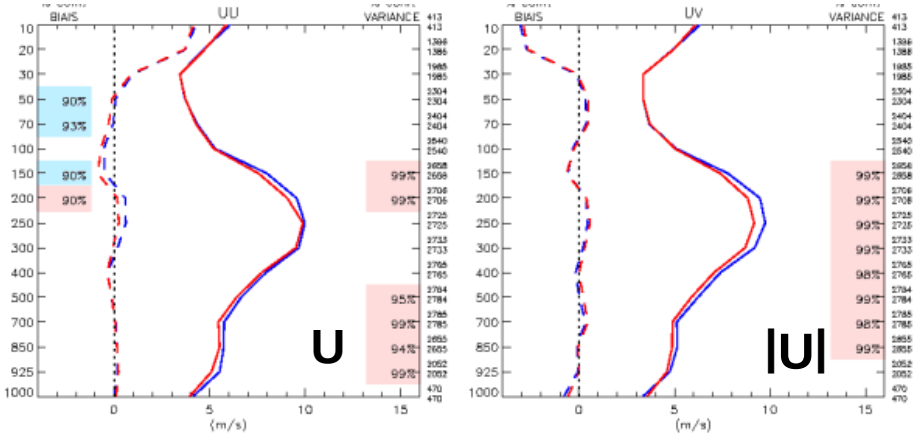


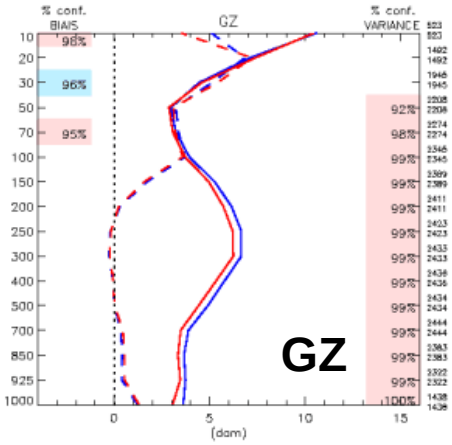


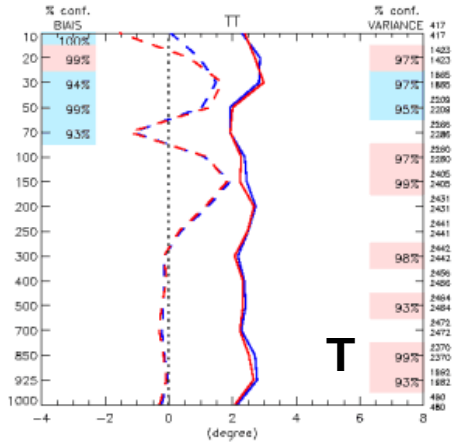
stddev & bias relative to radiosondes

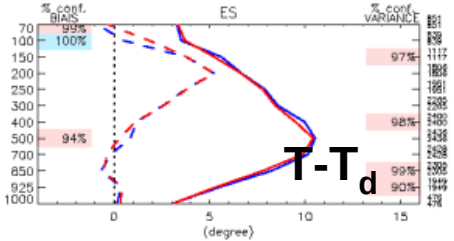
Forecast Results – 120h southern hemisphere

EnKF mean analysis vs. 4D-Var Bnmc

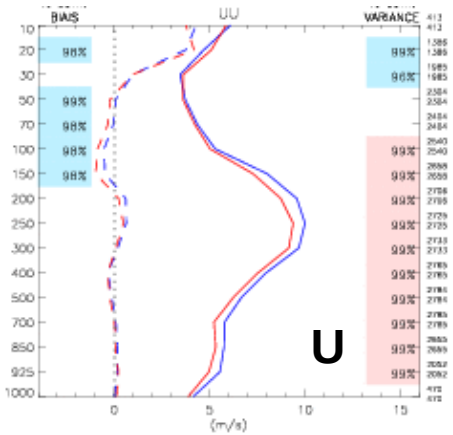


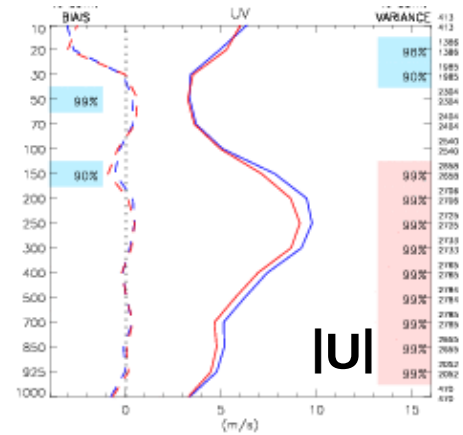


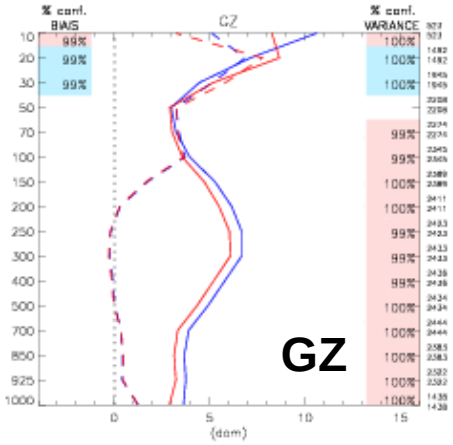


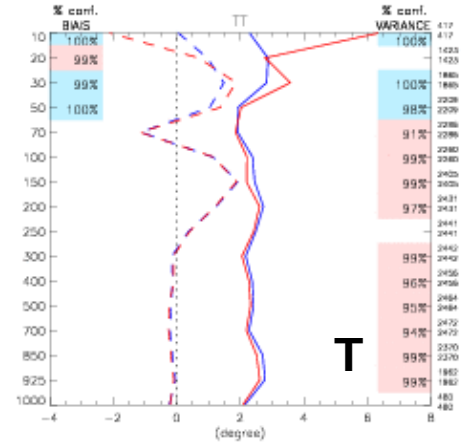


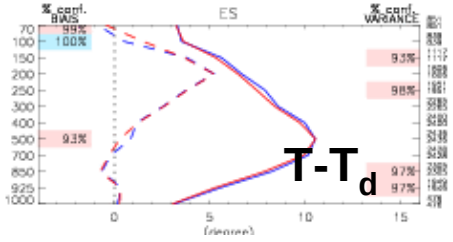
4D-Var Benkf vs. 4D-Var Bnmc







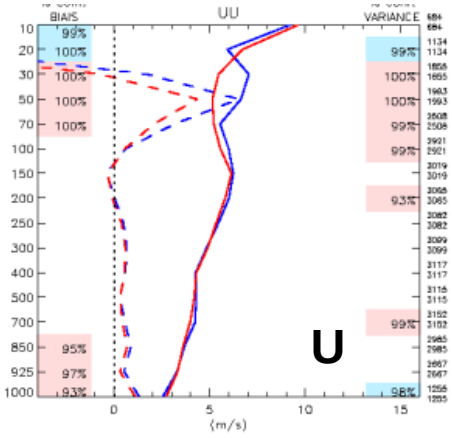


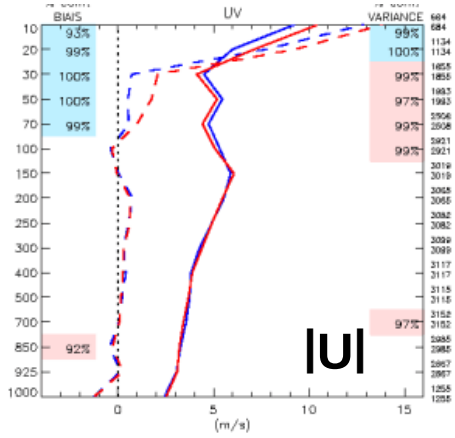


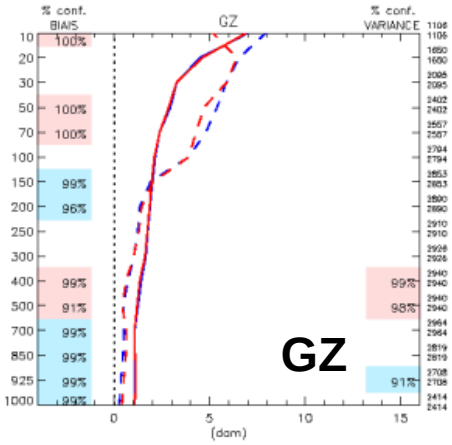
stddev & bias relative to radiosondes

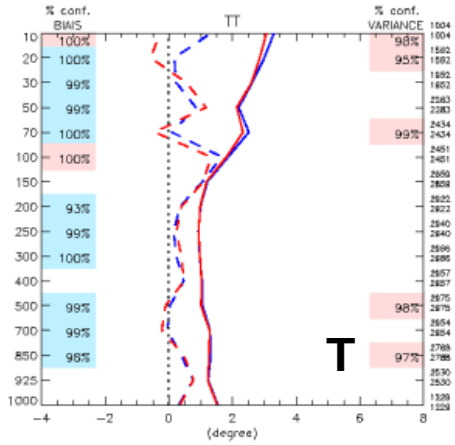
Forecast Results – 72h tropics

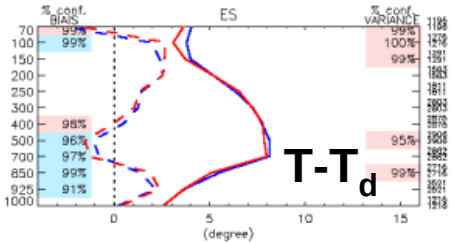
EnKF mean analysis
vs. 4D-Var Bnmc



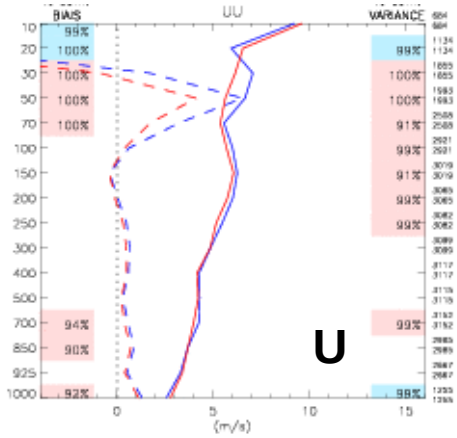


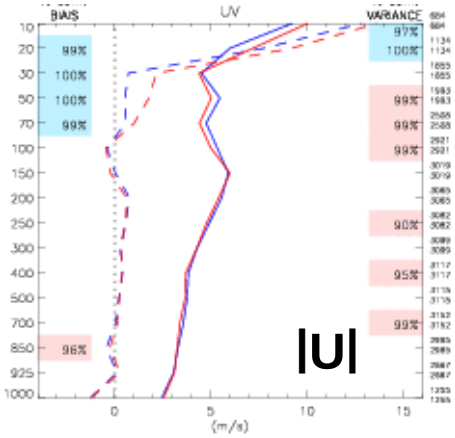


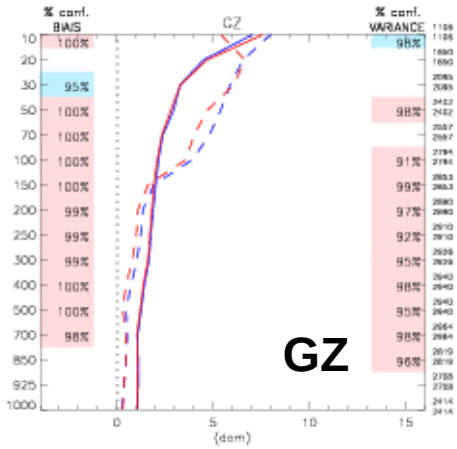


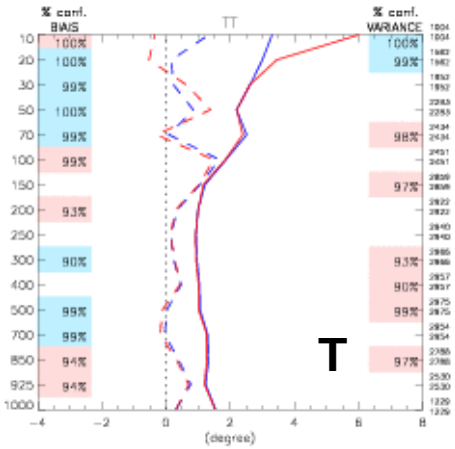


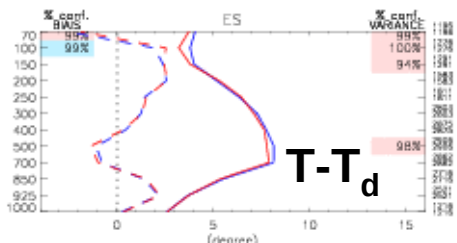
4D-Var Benkf
vs. 4D-Var Bnmc











stddev & bias relative to radiosondes