Assimilation of GPS delays with COSMO-DE/Kenda

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DWD
Deutscher Wetterdienst
Wetter und Klima aus einer Hand

6. December 2016

COSMO-DE, LETKF and STD-Operator

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COSMO-DE

Resolution: 2.8 km

Operational assimilation: nudging

Boundary conditions: ICON EU nest

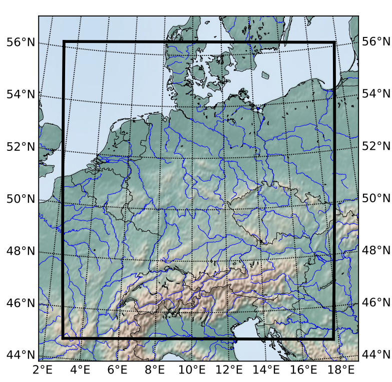
LETKF

The local transform ensemble Kalman Filter (LETKF) is in a pre-operational state and can be used for assimilation experiments.

STD-Operator

The STD/ZTD operator is called within each COSMO time step to compute the model equivalents of the observations.

COSMO-DE region



Kenda and LETKF

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1h COSMO-DE forecast, $\Delta t = 25$ s, observation operator $\mathcal{H}$:

$\mathbf{x}_a$, $\mathbf{y}$	$\mathbf{x}(t_1)$	$\mathbf{x}(t_2)$	$\xrightarrow{t}$	$\mathbf{x}(t_{n-1})$	$\mathbf{x}(t_n)$	$\mathbf{x}_f$
	$\Downarrow$	$\Downarrow$	$\cdots$	$\Downarrow$	$\Downarrow$	
	$\mathcal{H}(\mathbf{x}(t_1))$	$\mathcal{H}(\mathbf{x}(t_2))$	$\cdots$	$\mathcal{H}(\mathbf{x}(t_{n-1}))$	$\mathcal{H}(\mathbf{x}(t_n))$	$\Rightarrow$ $\mathcal{H}(\mathbf{x})$

Ensemble of 40 COSMO-DE 1 h forecasts:

member 1	member 2	$\cdots$	member 39	member 40
$\mathbf{x}_f^1, \mathbf{y}, \mathcal{H}(\mathbf{x}^1)$	$\mathbf{x}_f^2, \mathbf{y}, \mathcal{H}(\mathbf{x}^2)$	$\cdots$	$\mathbf{x}_f^{39}, \mathbf{y}, \mathcal{H}(\mathbf{x}^{39})$	$\mathbf{x}_f^{40}, \mathbf{y}, \mathcal{H}(\mathbf{x}^{40})$

$$\Downarrow$$

$$\text{LETKF} \left(\mathbf{x}_f^i, \ \mathbf{y} - \mathcal{H}(\mathbf{x}^i) \right)$$

$$\Downarrow$$

$\mathbf{x}_a^1$	$\mathbf{x}_a^2$	$\cdots$	$\mathbf{x}_a^{39}$	$\mathbf{x}_a^{40}$

$$\circlearrowleft$$

forecasts

STD Assimilation Operator

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The STD assimilation operator H_{STD} consists of 2 parts which are called by the ICON En-Var or COSMO interface:

1) Setup of the observation geometry

- Computes connecting line between satellite and reciver
- Definition of supporting points on the signal path

2) Signal path estimation and delay computation

- Interpolation/extrapolation of the model data on the supporting points
- Call of the raytracer, iterative estimation of the signal path
- Delay computation - integration of the refractive index along the signal path

The interface handles data I/O, load balancing, MPI data exchange, ...

Assimilation Experiment

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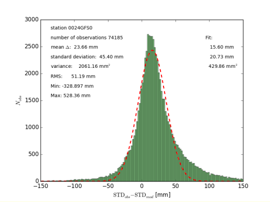
Experiment Summer 2014

Period	16.5.2014 – 1.6.2014
NWP system	COSMO-DE Kenda-LETKF
Initial conditions	ICON EU nest, 16.5.2014, 0:00 UTC
Boundary conditions	ICON EU nest, every 3 hours
Control experiment	assimilation of conventional observations, GPS STDs passive
GPS experiment	assimilation of conventional observations and GPS STD observations
Observation error	10 mm mapped on slant path
GPS data	STD data provided by GFZ, Potsdam
GPS stations	$\sim$ 300 within the COSMO-DE region
GPS observations	$\sim$ 50000 per hour, $20 \cdot 10^6$ total

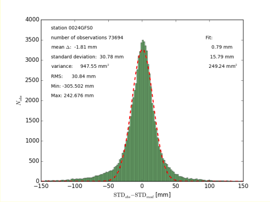
STD Observation Statistics

Station 0024 (SAPOS), Eberswalde, Germany, h = 24 m

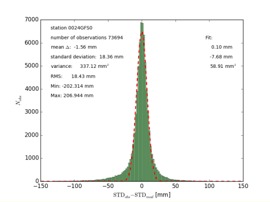
control experiment



obs. - first guess



observation - analysis



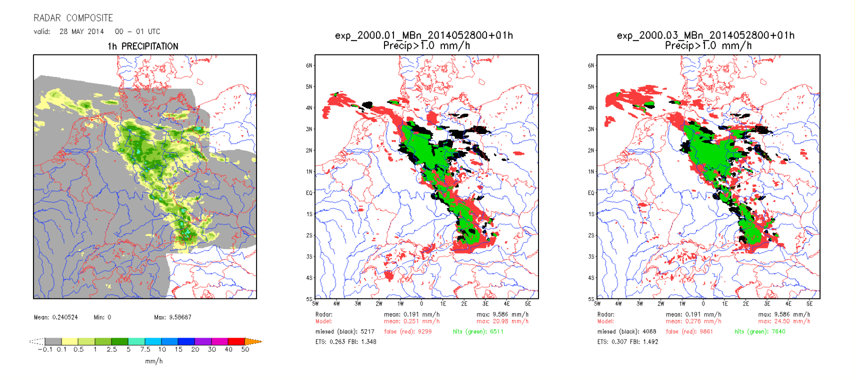
	control experiment	obs. - first guess	observation - analysis
N_{obs}	= 74185	= 73694	= 73694
bias	= 23.7 mm	= -1.8 mm	= -1.6 mm
σ	= 45.4 mm	= 30.8 mm	= 18.4 mm
N_{obs}	= 20178949	= 19966361	= 19966361
σ	= 41.6 mm	= 27.9 mm	= 17.3 mm
σ_{map}	= 13.6 mm	= 9.2 mm	= 5.4 mm

$\Longrightarrow$ allmost all STD data assimilated ($\sim$ 99 %)

Rain Forecast

28.5.2014, 1:00 UTC, 0:00 UTC forecast, 1 mm/h threshold

radar observations | control experiment | STD assimilation



	hit	miss	false	ETS
control experiment	6511	5217	9299	0.283
STD assimilation	7640	4088	9861	0.307

Radar Verification of Precipitation

12 UTC forecast, precipitation threshold 1.0 mm/h

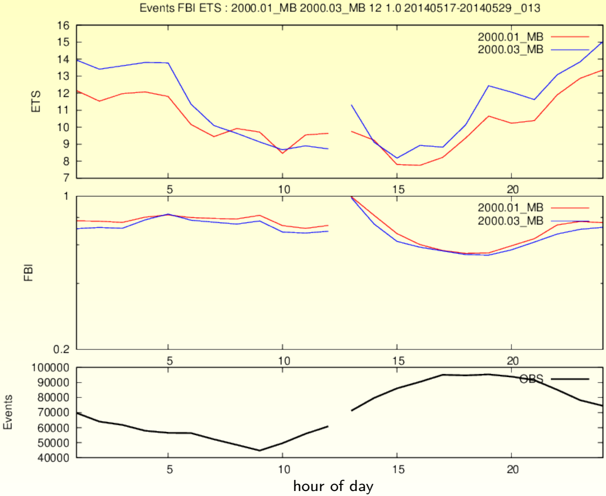
equitable threat score

$$ETS = \frac{A - A_r}{A + B + C - A_r}$$

frequency bias

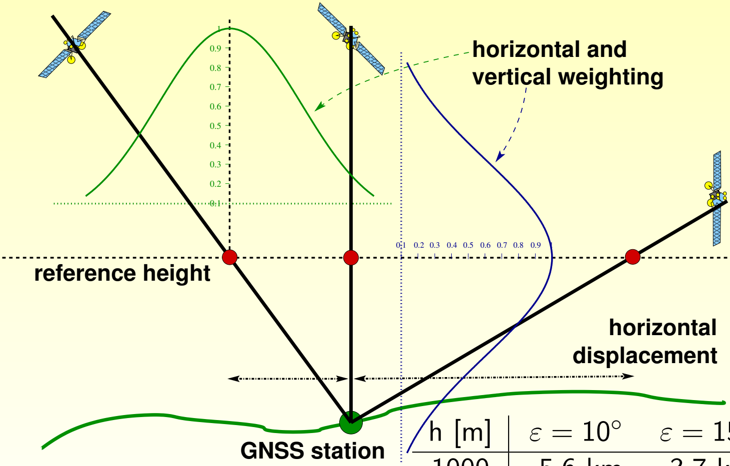
$$FBI = \frac{A + B}{A + C}$$

event - COSMO grid node with rain above threshold



Localisation of Slants

Local Transform Ensemble Kalman Filter→ localisation of STDs?



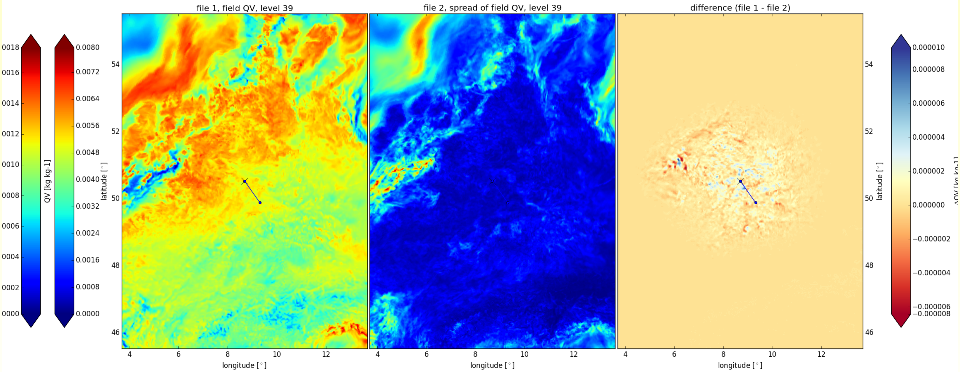
LETKF localisation length:
50 – 100 km horizontally

h [m]	$\varepsilon = 10^\circ$	$\varepsilon = 15^\circ$	$\varepsilon = 30^\circ$
1000	5.6 km	3.7 km	1.7 km
3000	16.9 km	11.2 km	5.2 km
5000	27.9 km	18.5 km	8.6 km

LETKF - Single Observation

Station Marburg – STD at station coordinates
Latitude: 8,685°, longitude: 50,533°, height ASL: 222 m
STD = 9.5403 m, azimuth = 148.4°, elevation = 14.15°

QV field spread increment



COSMO-DE QV field, 10 m layer

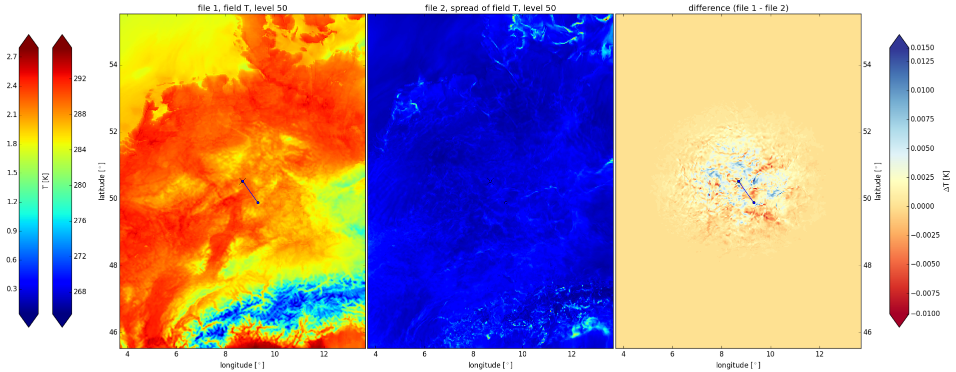
LETKF - Single Observation

Station Marburg – STD at station coordinates

Latitude: 8,685°, longitude: 50,533°, height ASL: 222 m

STD = 9.5403 m, azimuth = 148.4°, elevation = 14.15°

T field spread increment



COSMO-DE T field, 10 m layer

LETKF - Single Observation

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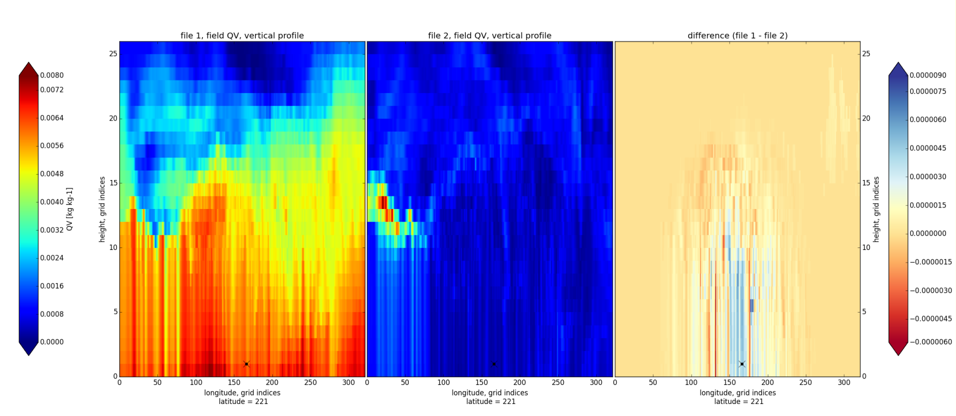

COSMO-DE QV field, vertical slice up to 5000 m (index 25), i12 = 990 m

LETKF - Single Observation

Station Marburg – STD at station coordinates
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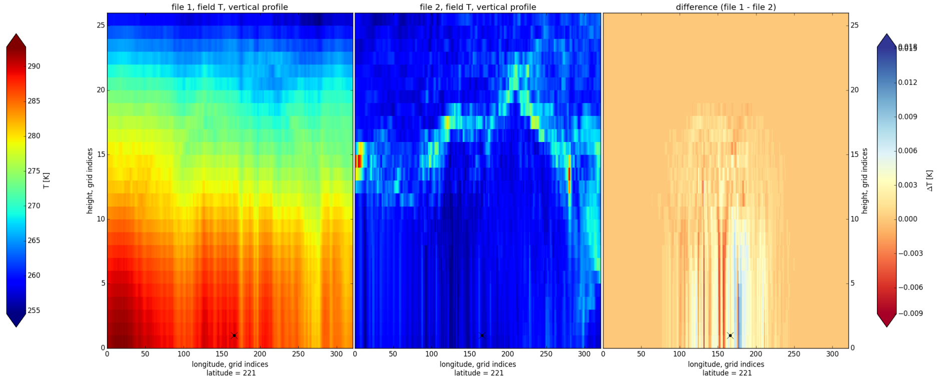
T field — spread — increment

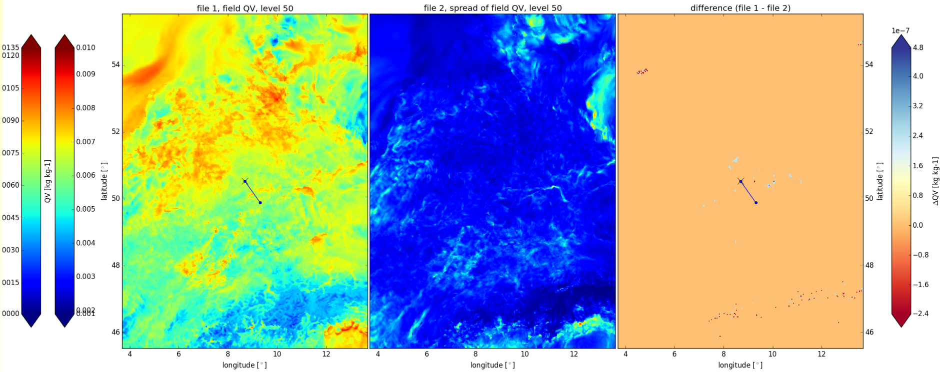


COSMO-DE T field, vertical slice up to 5000 m (index 25), i12 = 990 m

LETKF - Single Observation

Station Marburg – STD 2000 m above station
Latitude: 8,685°, longitude: 50,533°, height ASL: 222 m
STD = 9.5403 m, azimuth = 148.4°, elevation = 14.15°

QV field spread increment



COSMO-DE QV field, 10 m layer

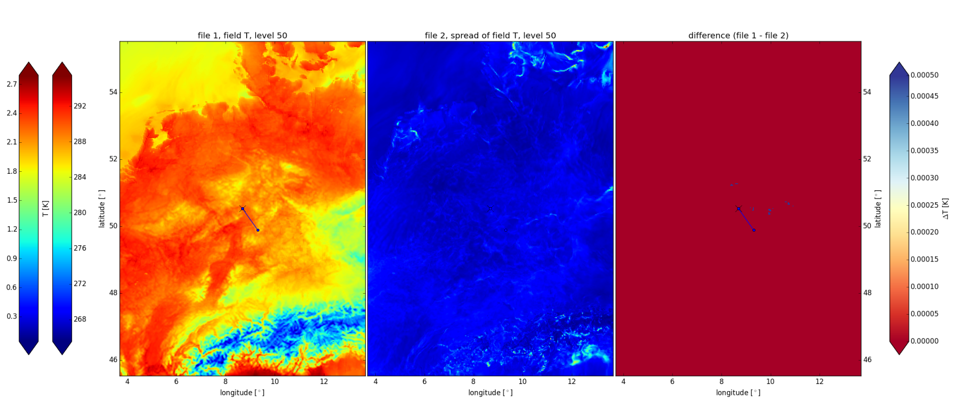
LETKF - Single Observation

Station Marburg – STD 2000 m above station

Latitude: 8,685°, longitude: 50,533°, height ASL: 222 m

STD = 9.5403 m, azimuth = 148.4°, elevation = 14.15°

T field spread increment



COSMO-DE T field, 10 m layer

LETKF - Single Observation

Station Marburg – STD 2000 m above station

Latitude: 8,685°, longitude: 50,533°, height ASL: 222 m

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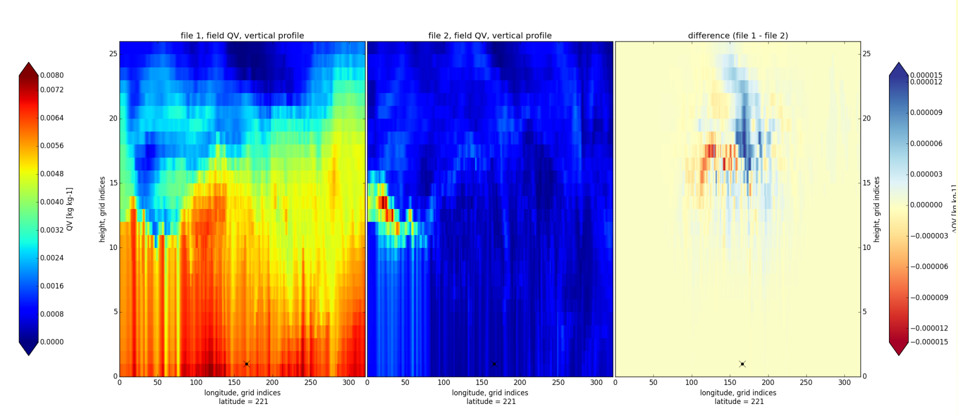
QV field spread increment



COSMO-DE QV field, vertical slice up to 5000 m (index 25), i17 = 2014 m

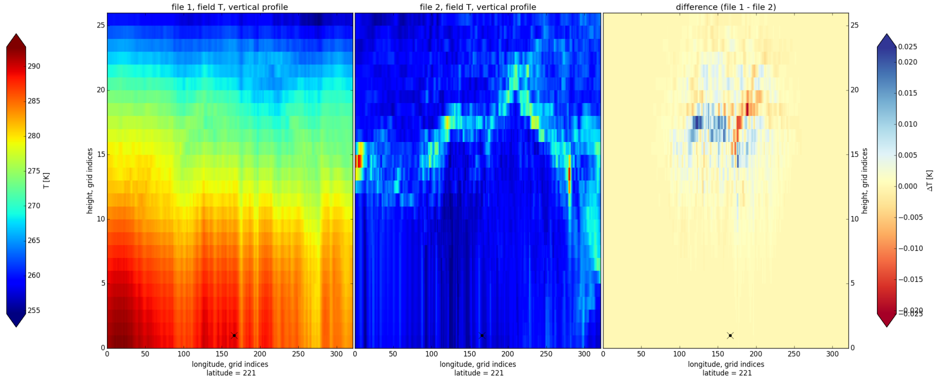
LETKF - Single Observation

Station Marburg – STD 2000 m above station

Latitude: 8,685°, longitude: 50,533°, height ASL: 222 m

STD = 9.5403 m, azimuth = 148.4°, elevation = 14.15°

T field spread increment



COSMO-DE T field, vertical slice up to 5000 m (index 25), i17 = 2014 m

Analysis Increments

Analysis $\mathbf{x}_a$:

$$\mathbf{x}_a = \mathbf{x}_b + \mathbf{K}\left(\mathbf{y}_0 - \mathcal{H}(\mathbf{x}_b)\right)$$

with the Kalman-Gain-Matrix $\mathbf{K}$

$$\begin{aligned}\mathbf{K} &= \left(\mathbf{B}^{-1} + \mathbf{H}^T\mathbf{R}^{-1}\mathbf{H}\right)^{-1}\mathbf{H}^T\mathbf{R}^{-1} \\ &= \mathbf{B}\mathbf{H}^T\left(\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{R}\right)^{-1}\end{aligned}$$

Analysis increments $\delta\mathbf{x}_a$

$$\boxed{\delta\mathbf{x}_a = \mathbf{B}\mathbf{H}^T\left(\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{R}\right)^{-1}\delta\mathbf{y}_0}$$

Increments $\delta\mathbf{x}_a$ are large, where $\mathbf{H}$ is large:

$$\mathbf{H} = (h_{ij}) \ , \qquad h_{ij} = \frac{\partial\mathcal{H}_i}{\partial x_j}$$

Analysis Increments for one STD

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$$\boxed{\delta \mathbf{x}_a = \mathbf{B}\mathbf{H}^T \left(\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{R}\right)^{-1} \delta \mathbf{y}_0}$$

For one single STD observation $\delta \mathbf{x}_a$ can be computed:

- $\delta \mathbf{y}_0 = \mathbf{y}_0 - \mathcal{H}(\mathbf{x}_b) = STD - \mathcal{H}(\mathbf{x}_b) \rightarrow$ real number
- $\mathbf{R} = \varepsilon_{\mathrm{STD}} \rightarrow$ real number
- $\mathbf{H} = \left(\frac{\partial STD}{\partial x_j}\right) \rightarrow$ vector, provided by adjoint operator
- $\mathbf{B} \rightarrow$ matrix, provided by ensemble

B is still a large matrix as p, T and qv on all grid nodes in the vicinity of the slant path need to be regarded $\rightarrow$ some GB.

Background Error Covariance Matrix $\mathbf{B}$

$\mathbf{B}$ can be estimated from an ensemble $\mathbf{x}^{b(k)}$ of state vectors

$$\mathbf{B} = \frac{1}{K-1} \sum_{k=1}^{K} \left(\mathbf{x}^{b(k)} - \bar{\mathbf{x}}^{b}\right) \left(\mathbf{x}^{b(k)} - \bar{\mathbf{x}}^{b}\right)^{T}$$

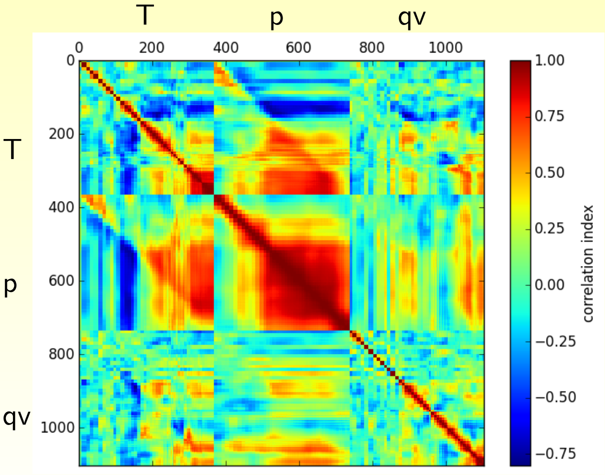
The matrix elements b_{ij} of $\mathbf{B}$ are given by

$$b_{ij} = \frac{1}{K-1} \sum_{k=1}^{K} \left(x_i^{b(k)} - \bar{x}_i^{b}\right) \left(x_j^{b(k)} - \bar{x}_j^{b}\right)$$

The correlation matrix $\mathbf{D}$ is much more descriptive and can be computed from $\mathbf{B}$:

$$d_{ij} = \frac{b_{ij}}{\sqrt{b_{ii} \cdot b_{jj}}}$$

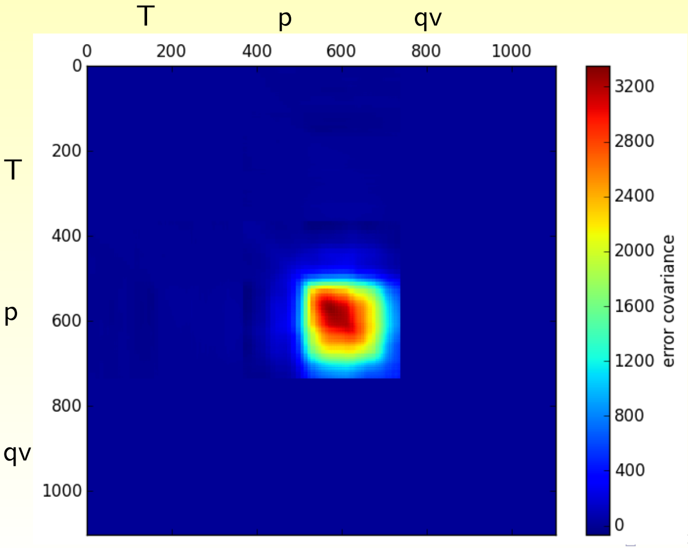
STD: 10.39 m, elevation = 13.35°, azimuth = 132.30°



$\mathcal{H}$ acts on
368 grid nodes
$\Downarrow$
3 values per node:
p, T, qv
$\Downarrow$
dimension of
state vector $\mathbf{x}$:
$368 \cdot 3 = 1104$

Background Error Covariance Matrix

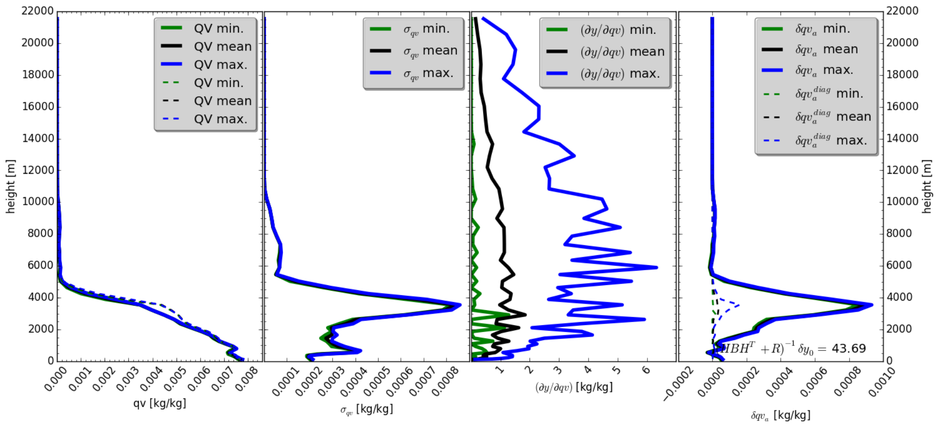
STD: 10.39 m, elevation $= 13.35^\circ$, azimuth $= 132.30^\circ$



Humidity Increments

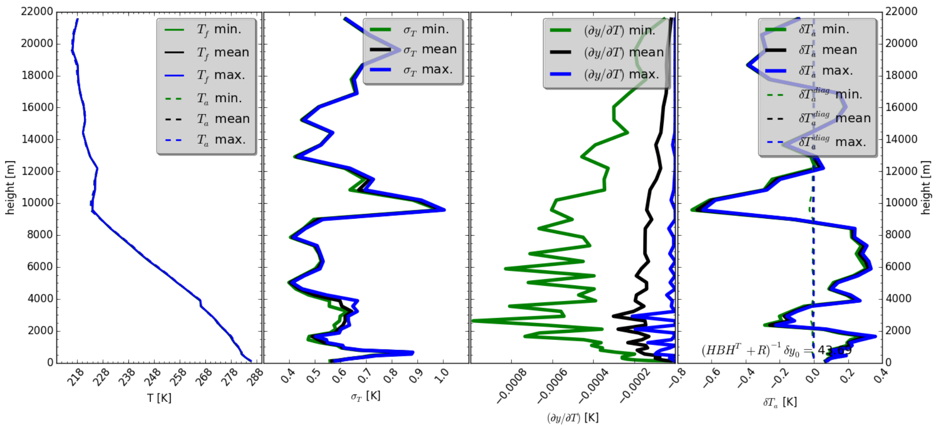
$$\delta \mathbf{x}_a = \mathbf{B}\mathbf{H}^T \left(\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{R}\right)^{-1} \delta \mathbf{y}_0$$

$\mathbf{x}_b,\ \mathbf{x}_a$ $\quad$ $\mathbf{B}_{\mathrm{diag}}$: qv $\quad$ $\mathbf{H} = \left(\frac{\partial\, STD}{\partial\, qv_j}\right)$ $\quad$ $\delta \mathbf{x}_a = \mathbf{B}\mathbf{H}^T \cdot c$



$$\delta \mathbf{x}_a = \mathbf{B}\mathbf{H}^T \left(\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{R}\right)^{-1} \delta \mathbf{y}_0$$

$\mathbf{x}_b,\ \mathbf{x}_a$ $\quad$ $\mathbf{B}_{\text{diag}}$: qv $\quad$ $\mathbf{H} = \left(\frac{\partial\, STD}{\partial\, T_j}\right)$ $\quad$ $\delta \mathbf{x}_a = \mathbf{B}\mathbf{H}^T \cdot c$



Pressure Increments

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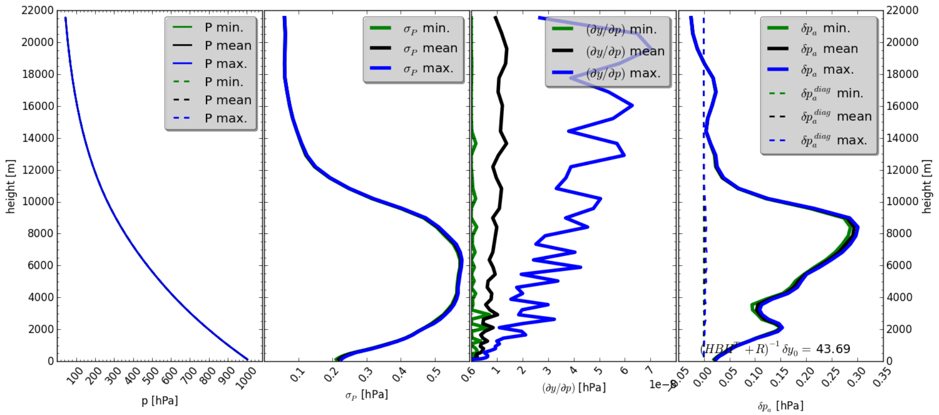
$$\delta \mathbf{x}_a = \mathbf{B}\mathbf{H}^T \left(\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{R}\right)^{-1} \delta \mathbf{y}_0$$

$\mathbf{x}_b,\ \mathbf{x}_a$ $\qquad$ $\mathbf{B}_{\mathrm{diag}}$: qv $\qquad$ $\mathbf{H} = \left(\dfrac{\partial\, STD}{\partial\, p_j}\right)$ $\qquad$ $\delta \mathbf{x}_a = \mathbf{B}\mathbf{H}^T \cdot c$



To Do

- Quality control, black listing
- Correction of some station heights
- Improved bias correction
- Data thinning
- LETKF tuning
  - Localisation of observations
  - Horizontal and vertical localization radii
  - Relative impact of different observation types
- Impact of ZTD, STD and ZTD+STD assimilation
- Combination with latent heat nudging and/or radar
- Observation errors