Assimilation of GNSS Delays with COSMO-D2/Kenda

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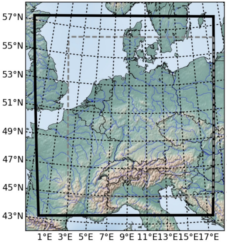
Waether Models at the DWD

ICON Global Model
Horizontal resolution: 13 km
Vertical levels: 90
Grid nodes: $2949120 \times 90 = 265420800$
Assimilation: En-Var - 3D-Var/LETKF hybrid system

European nest:
Horizontal resolution: 6.5 km
Vertical levels: 60
Grid nodes: $659156 \times 60 = 39549360$

COSMO-D2 Regional Model
Horizontal resolution: 2.2 km
Vertical levels: 65
Grid nodes: $651 \times 716 \times 65 = 30297540$
Assimilation: LETKF



LETKF

The Local Ensemble Transform Kalman Filter (LETKF) minimizes the cost function node by node (→ local) in ensemble space (→ transform).

Basic assumptions at each grid node:

$\boldsymbol{x}^a = \bar{\boldsymbol{x}}^b + \boldsymbol{X}^b \boldsymbol{w}$	analysis is linear combination of ensemble
$\mathcal{H}(\bar{\boldsymbol{x}}^b + \boldsymbol{X}^b \boldsymbol{w}) \approx \bar{\boldsymbol{y}}^b + \boldsymbol{Y}^b \boldsymbol{w}$	observations are also linear combinations

Cost function: $J = (k-1)\boldsymbol{w}\boldsymbol{w}^\intercal + [\boldsymbol{y}^0 - \bar{\boldsymbol{y}}^b - \boldsymbol{Y}^b \boldsymbol{w}]^\intercal \boldsymbol{R}^{-1} [\boldsymbol{y}^0 - \bar{\boldsymbol{y}}^b - \boldsymbol{Y}^b \boldsymbol{w}]$

Solution:

$$\bar{\boldsymbol{w}}^a = \boldsymbol{P}^a (\boldsymbol{Y}^b)^\intercal \boldsymbol{R}^{-1} (\boldsymbol{y}^0 - \bar{\boldsymbol{y}}^b) \qquad \text{vector of ensemble weights}$$

$$\boldsymbol{P}^a = \left[(k-1)\boldsymbol{I} + \boldsymbol{Y}^{b\intercal} \boldsymbol{R}^{-1} \boldsymbol{Y}^b\right]^{-1}$$

$\dim(\boldsymbol{x})$	- Number of model variables, $\mathcal{O}(10)$
$\dim(\boldsymbol{y})$	- Number of observations near grid node, $\mathcal{O}(100)$
$\dim(\boldsymbol{w})$	- k = ensemble size, $\mathcal{O}(100)$
$\dim(\boldsymbol{R})$	- Number of observations squared, $\mathcal{O}(100 \times 100)$
$\dim(\boldsymbol{P}^a)$	- $k \times k$, $\mathcal{O}(100 \times 100)$

Small number of floating point operations per grid node, efficient parallel processing as nodes are independent.

(See: Hunt et al., 2007, Physica D, **230**, 112-126)

Assimilation Cycle

Ensemble of 40 COSMO-D2 1 h forecasts:

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

$$\Downarrow$$

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

$$\Downarrow$$

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

$$\circlearrowleft$$

forecasts

1h COSMO-D2 forecast, $\Delta t = 25$ s, observation operator $\mathcal{H}$:

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

STD Assimilation Operator

The STD assimilation operator H_{STD} consists of 2 parts which are called by the COSMO interface:

1) Setup of the observation geometry

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

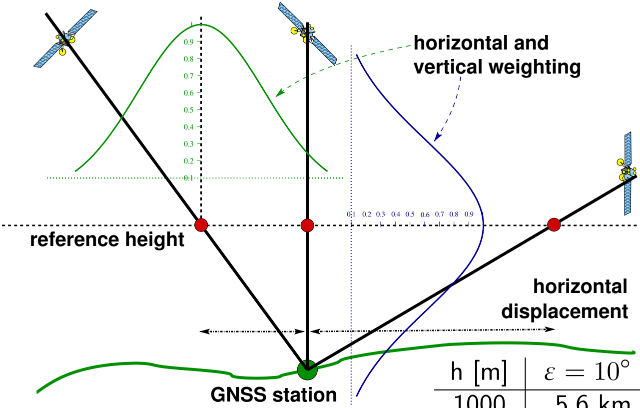
2) Signal path estimation and delay computation

- 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, ...

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

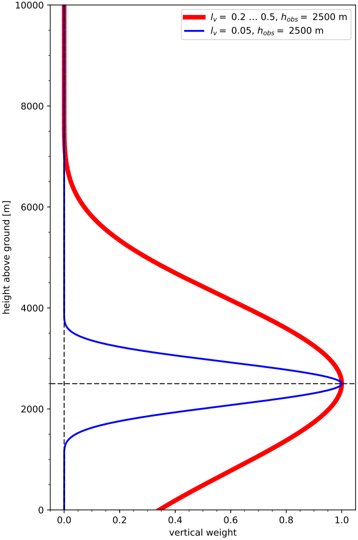
Vertical Localisation

Sharp localisation (`lv = 0.05`)
Vertical weights limited to a narrow layer near 1000 m

Weak localisation (`lv = 0.2`)
Vertical weights > 0 in the whole troposphere,
rather large weights near the surface.

Experiments with weak localisation

- Weights between $0.2 \lesssim \omega \lesssim 0.8$ near the surface are important for `RH2M` and `T2M`.
- Sharp localisation leads to distortions in the analyses.
- Weak localisation leads to better results than no localisation ($\omega = 1$).



Assimilation Experiment

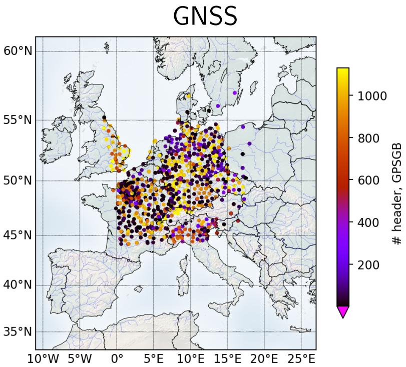
Experiment Spring 2019

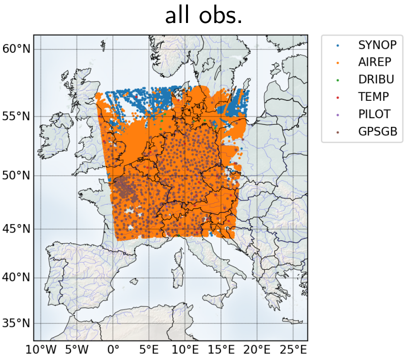
Period	14.4.2019 – 1.6.2019
NWP system	COSMO-D2 Kenda-LETKF
Forecasts	27 hour forecasts every 6 hours
Initial conditions	ICON EU nest
Boundary conditions	ICON EU nest, every 3 hours
Control experiment	assimilation of conventional observations,
GPS experiment	assimilation of conventional observations and GPS ZTD + STD observations
Observation error	12 mm mapped on slant path
GPS data	E-GVAP ZTDs, STDs provided by GFZ, Potsdam
GPS observations	323354 ZTDs + 674040 STDs total assimilated

GNSS Assimilation Strategy

- Temporal thinning: Last observation(s) within hour per station
- No spatial thinning
- Elevation thinning: Per station one ZTD and all STDs with $\varepsilon < 25^\circ$
- Horizontal localisation for LETKF: 20 km
- Weak vertical localisation for LETKF (see above)
- One constant ZTD error assumed for all stations (mapped for STDs)
- Bias correction per station/provider/product
- Ranking and whitelisting per product
- Blacklisting per station/provider/product

Assimilated GNSS Observations





Experiment: 47 days, 1 h assim. $\Rightarrow$ max. $47 \cdot 24 = 1128$ ZTDs per station

Radiosonde Forecast Verifikation

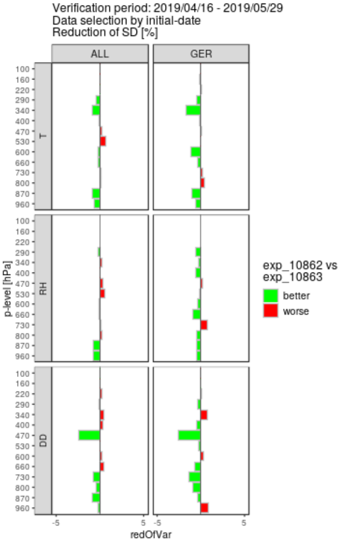
Standard deviation differences in %

Improvement by 1 - 2 %

T
temperature

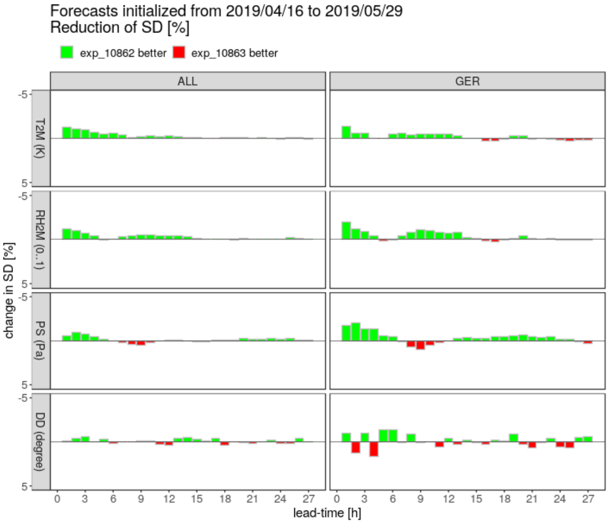
RH
relative
humidity

DD
wind
direction



Synop Forecast Verifikation

Deutscher Wetterdienst
Wetter und Klima aus einer Hand



Standard deviation differences in %

2 m temperature T2M

2m relative humidity RH2M

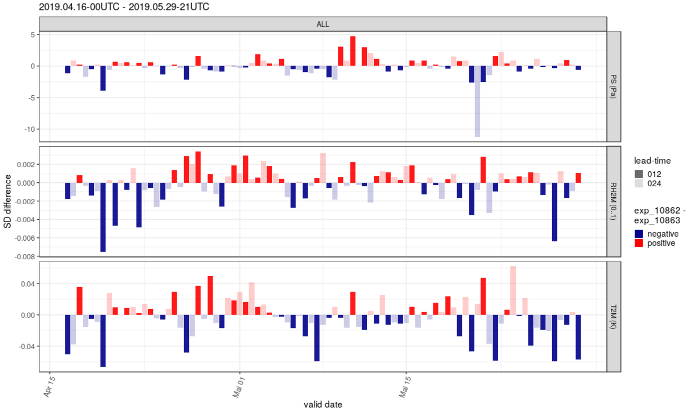
surface pressure PS

wind direction DD

Daily Synop Forecast Verifikation

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Synop verification for each day of the experiment:



Standard deviation differences %

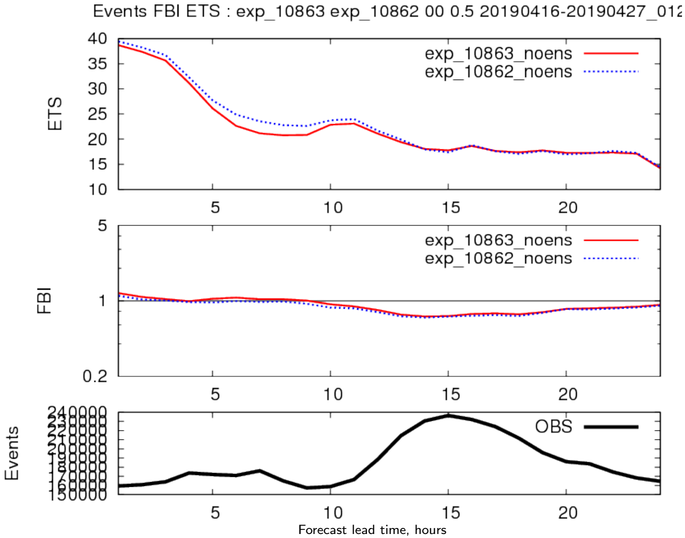
surface pressure PS

2m relative humidity RH2M

2 m temperature T2M

Two bars per day: solid bar - 12 h forecasts
shaded bar - 24 h forecasts

Radar Verification of Precipitation



Equitable threat score 100 is best

Frequency bias 1 is best

Number of rain events

ZTDs vs. STDs

Do STDs provide more information about the atmospheric state than ZTDs?

Three experiments for May/June 2016:

1. Reference experiment with conventional observations
2. ZTD assimilation experiment
3. Experiment with ZTDs and STDs at low elevations

- Same assimilation strategy than 2019 experiment
- But: COSMO-DE, 2.8 km horizontal resolution, smaller domain

Radiosonde Forecast Verifikation

ZTD + STD experiment
compared to
reference experiment

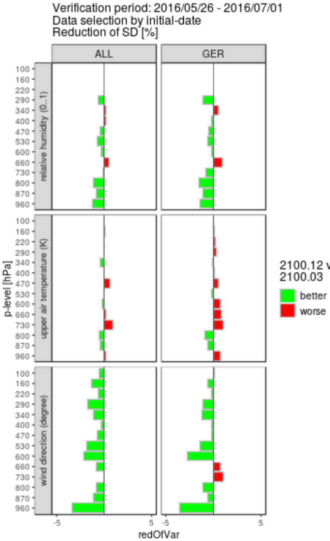
Standard deviation differences in %

Improvement by 1 - 4 %

RH
relative
humidity

T
temperature

DD
wind
direction



Radiosonde Forecast Verifikation

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

ZTD + STD experiment
compared to
ZTD experiment

green
ZTD + STD is better
smaller standard deviation

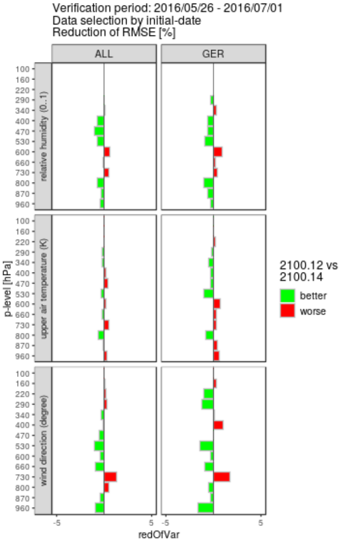
Standard deviation
differences in %

Improvement by 1 - 2 %

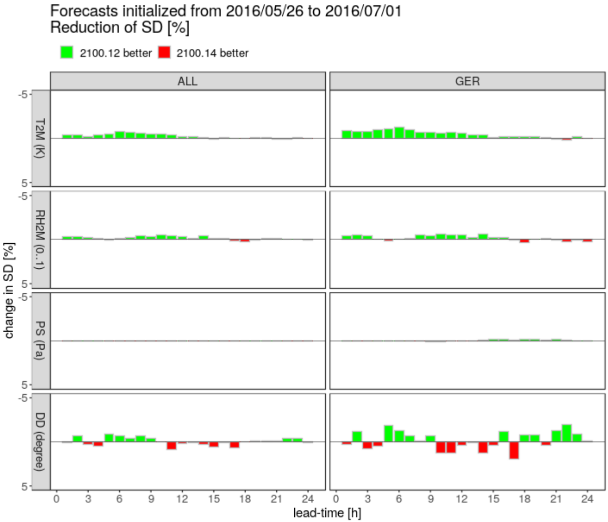
RH
relative
humidity

T
temperature

DD
wind
direction



Synop Forecast Verifikation



Standard deviation differences in %

2 m temperature T2M

2m relative humidity RH2M

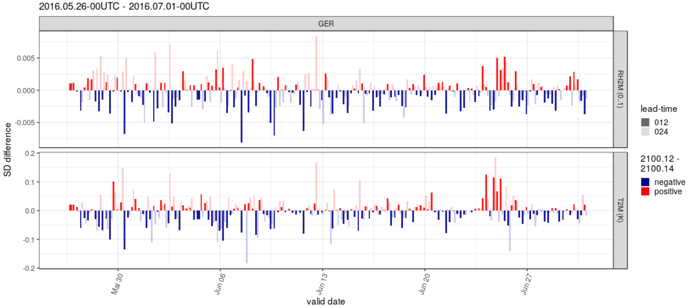
surface pressure PS

wind direction DD

Daily Synop Forecast Verifikation

Synop verification for each day of the experiment:

ZTD + STD assimilation is in general better (blue),
but there are days were ZTDs alone (red) lead to better results.



2m relative humidity RH2M

2 m temperature T2M

Two bars per day: solid bar - 12 h forecasts
shaded bar - 24 h forecasts

Conclusions

- The assimilation of ZTDs and STDs leads to improved analyses and forecasts in a regional weather model.
- Assimilating a combination of ZTDs and STDs leads to better results than the assimilation of ZTDs alone.
- The GNSS assimilation is not yet operational and further experiments are required to develop:
  - Improved (vertical) LETKF localisation strategies for GNSS delays.
  - Station specific observation errors
  - Improved STD bias correction