GNSS tomography and the impact of refractivity data assimilation on precipitation forecast

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Atmosphere as complex thermo-hydrodynamical system

- A „growth in understanding strongly depends on the improvement of the measurements and observing systems“ (Peixoto and Oort, 1991)
- Future evolution of atmospheric science leans on densified classical and new, more complex observation technologies (Bauer et al., 2015)

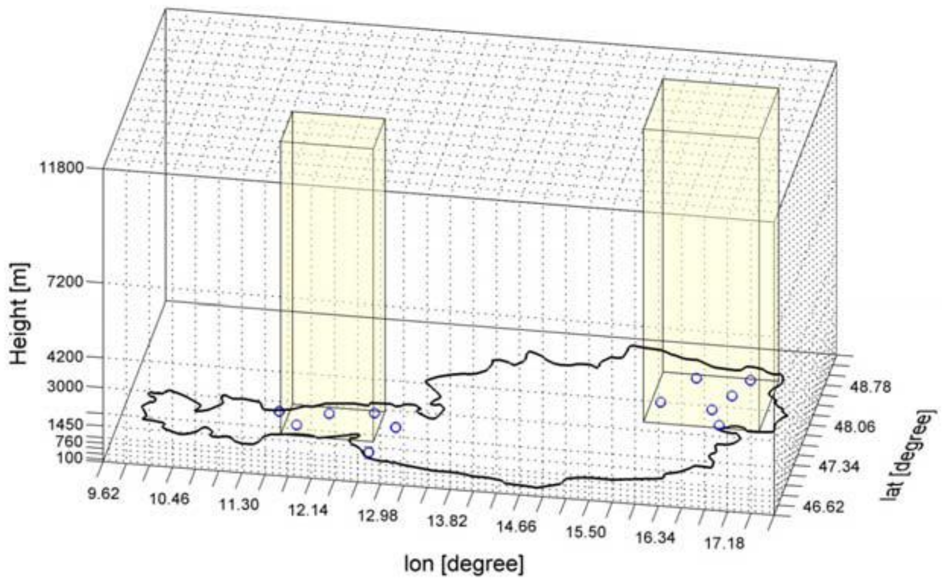
GNSS as atmospheric observing technique (occultation, meteorology, …)

- High accuracy and sensitivity to atmospheric constituents
- Since early 1990s GNSS mircowave signals are utilised to derive information about water vapour in the atmosphere (see Bevis et al., 1992)
- Station density, number of satellites and signals increases continously
  -> **new processing strategies** to exploit the full potential of future GNSS

Content

1. Principles of GNSS tomography
2. Tomography impact studies
3. Results using GNSS derived slant wet delays
4. Assimilation test cases during 2013 Europe floods
5. Conclusion/Challenges

Goal: Vertical structure of humidity (and temperature)



Wet refractivity on a three-dimensional grid

$$N_w = k_2 \frac{e}{T} + k_3 \frac{e}{T^2}$$

Smith and Weintraub, 1953

- Atmosphere (< 11 km) is divided into volume elements (voxels)
- Voxel size : 20km x 20km, 11 vertical layers (350m, 750m, ... 9750m)

Least squares adjustment: $N_w = (A^T \cdot P \cdot A)^+ \cdot A^T \cdot P \cdot SWD$

SWD ... slant wet delays [mm]

A ... design matrix with ray paths [km]

N_w ... wet refractivity field [ppm]

P ... observation weights

Pseudo inverse using singular value decomposition

$(A^T \cdot P \cdot A)^+ = V / S \cdot U$ S ... diagonal matrix of eigenvectors (EV)

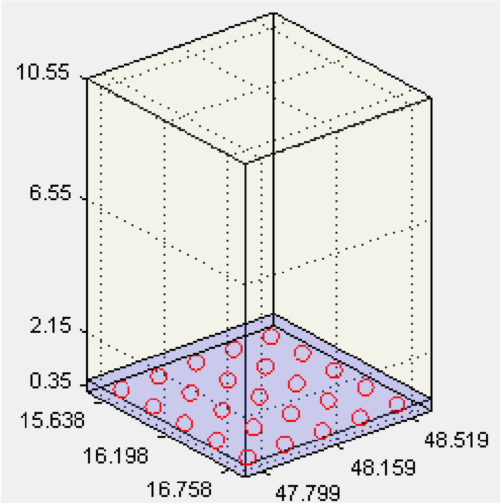
- Zero EV correspond to voxels not crossed by any ray path

- Other reconstrution methods: Algebraic reconstruction technique (ART), Kalman-Filter

Synthetic (ray-traced) slant wet delays (SWD)

- Vienna ray-tracer is adapted to voxel model
- Input: AROME model parameters (p, Q, T-> N)

AROME	Value
Resolution	2.5km (600x432), 60 levels
Epoch	25 May 2013, 00 UTC

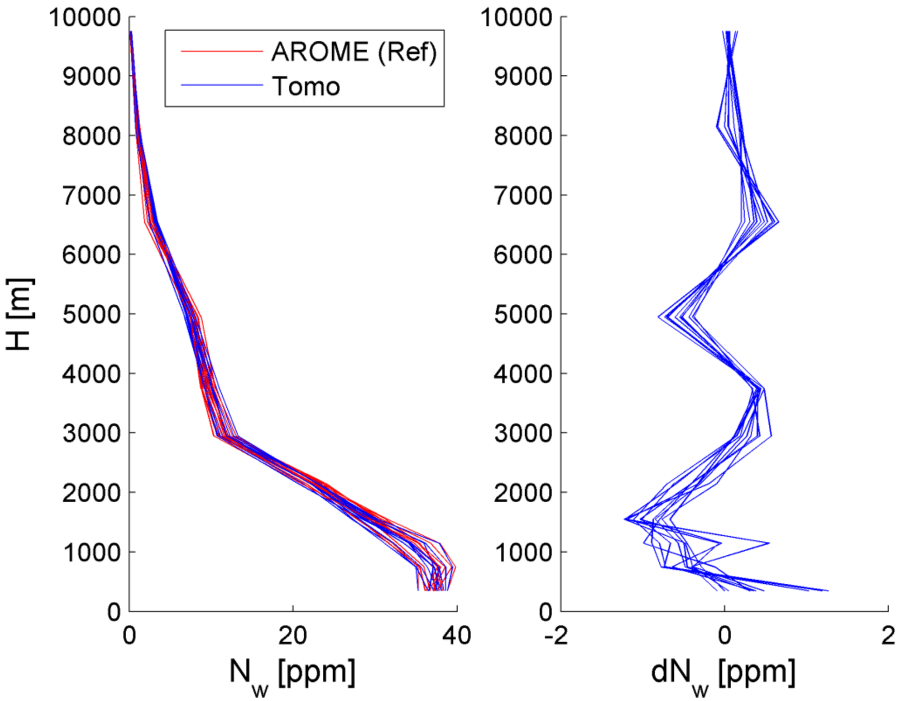


- Output: SWDs for 25 stations (see figure) incl. ray paths und bending
- Settings: Elev = 1, 2, 3, 5:5:85°, Azi = 0:10:350°
- #Observations: 25stations x 20Elev x 36Azi = 18000

Results (synthetic observations)

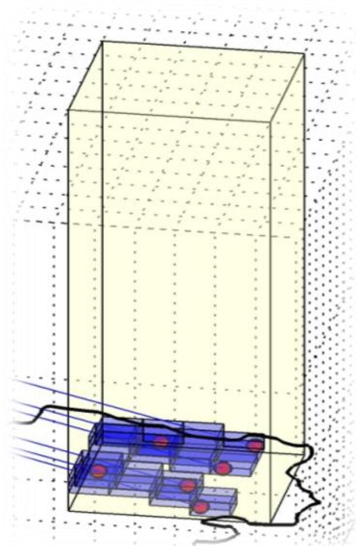
Parameter	Value
Number of observations	18000
Zero elements in A	96.2 %
Condition number	32
Rank (EV > 0.01 km^2)	275
Bias/Stddev of dN_{wet}	-0.12/0.57 ppm

Voxels: 25x11 = 275

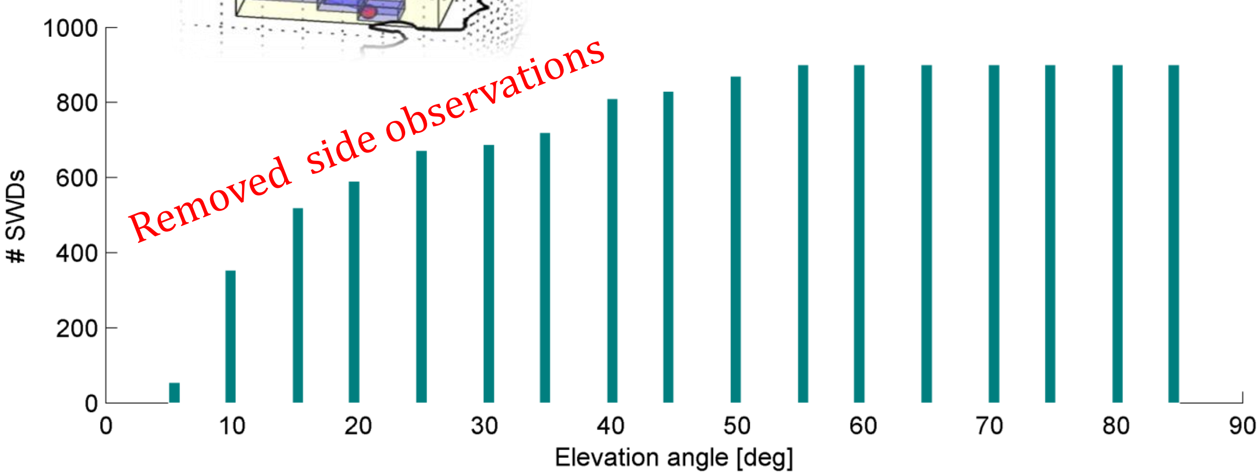


- N_{wet} estimated <u>without</u> any a priori information or constraints
- Bias and stddev computed from N_{wet} differences (AROME minus Tomo)

Side observations (which enter voxel model through a lateral surface)

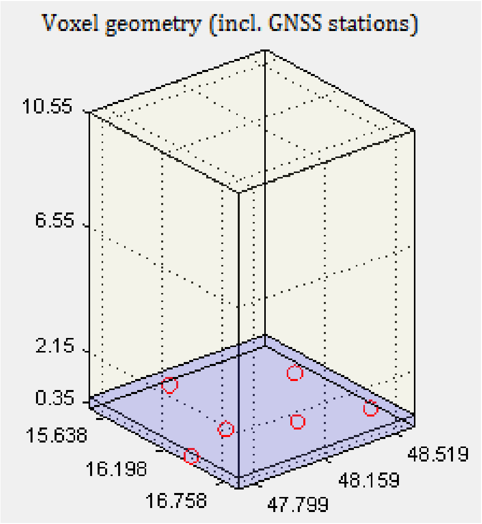


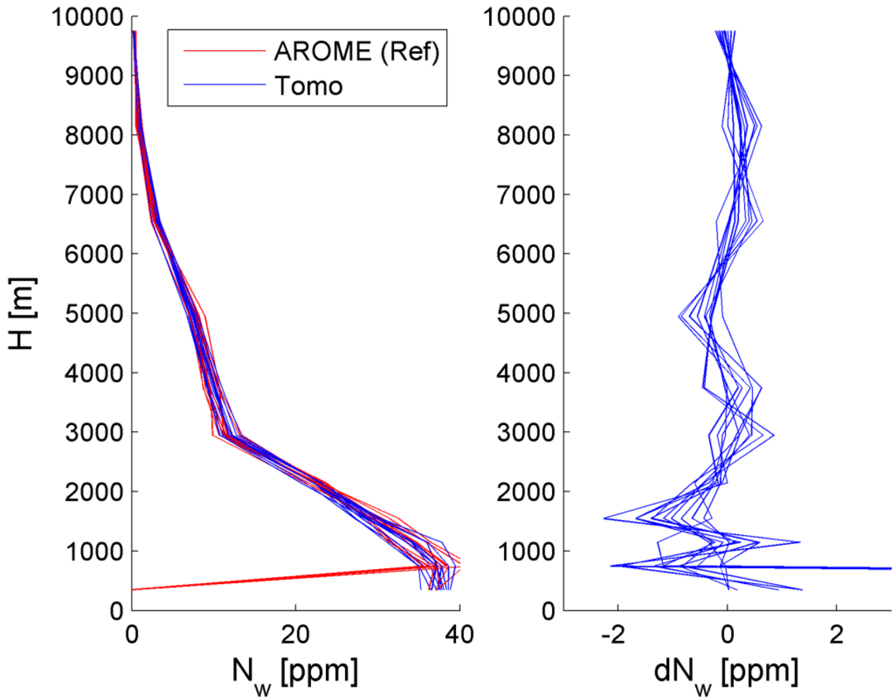
Parameter	Value (top)	Value (all)
Number of observations	12407	18000
Condition number	1200	32
Rank (EV > 0.01 km^2)	233	275
Mean formal error	0.59 ppm	0.03 ppm
Bias/Stddev of dN_{wet}	3.76/14.70 ppm	-0.12/0.57 ppm



Side observations cannot be used until the delay outside the voxel model is determined

Station density (6/25 stations)



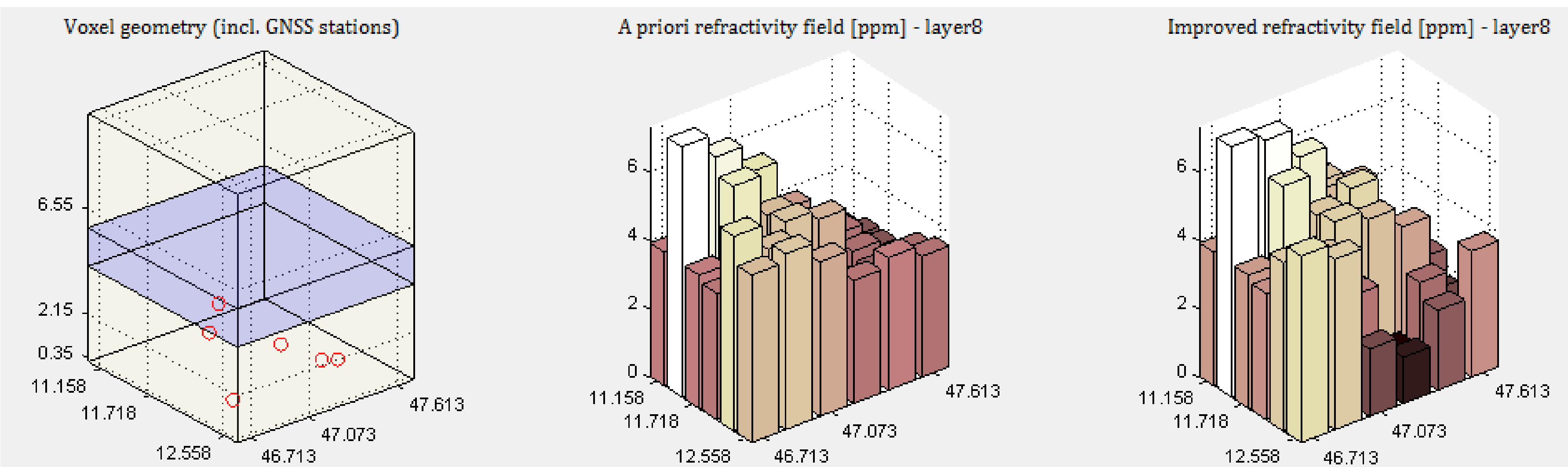


Parameter	Value (6 sites)	Value (all)
Number of observations	4320	18000
Condition number	187	32
Rank (EV > 0.01 km²)	267	275
Bias/Stddev of dN_{wet}	0.86/6.52 ppm	-0.12/0.57 ppm

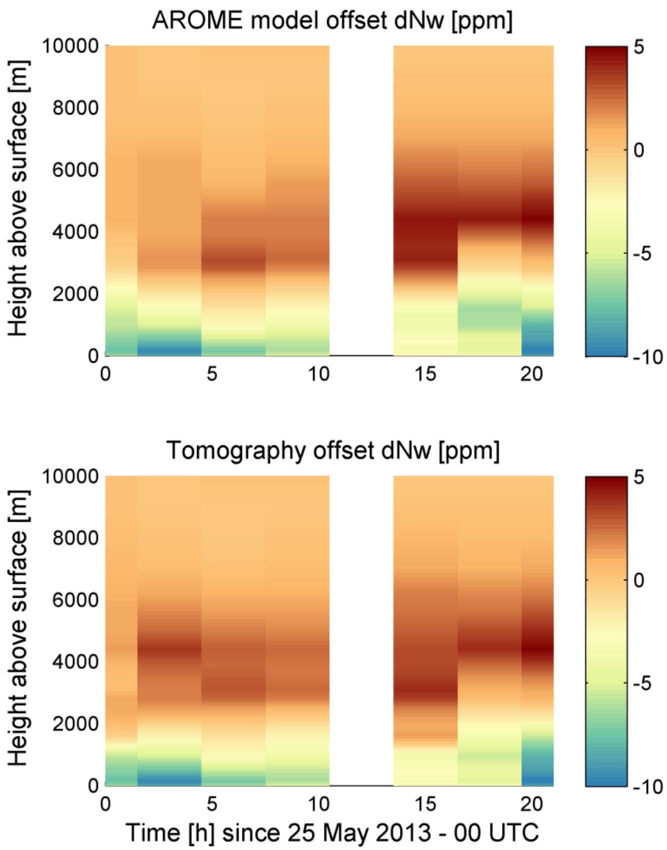
No solution for certain voxels at lower layers

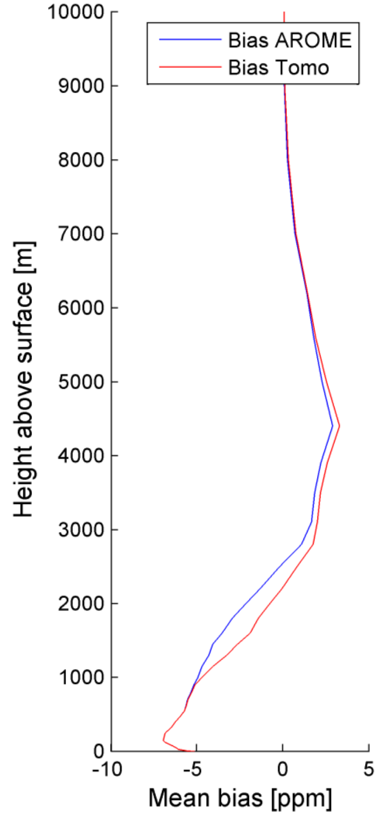
Solution with observed (GNSS derived) SWDs – 25 May 2013

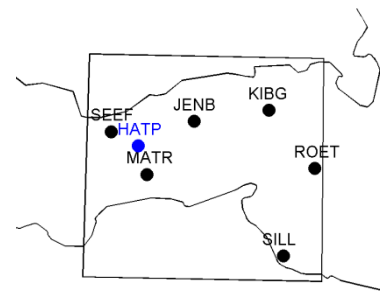
Inversion	LSQ	**Used SWD**	All > 3°, no side observations
A priori	AROME	**Weighting**	Elevation and height-dependent
Other	6 GNSS stations, +/- 5 min observation window		



Comparison with radiometer data - 25 May 2013 (Uni Innsbruck)





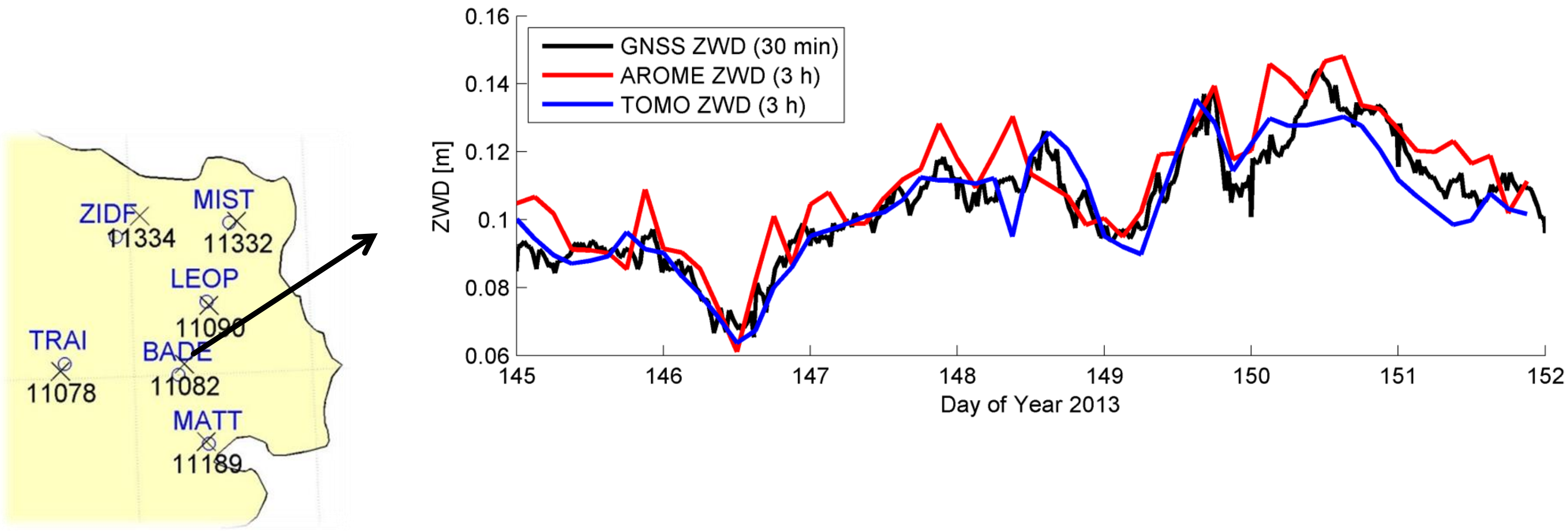


<u>Radiometer (HATPRO)</u>
lat: 47.26 °
lon: 11.38 °
H: 612 m

T ~ 0.5 K, rh ~5 %

Evaluation of estimated refractivity fields (East Austria)

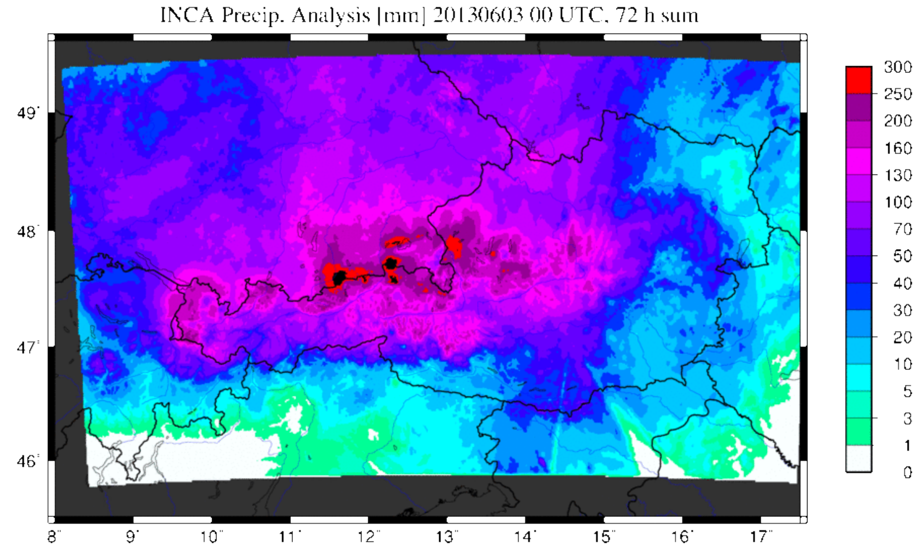
- vertical integration $ZWD_v = 10^{-6} \int N_{wet} \cdot ds$
- comparison of ZWD_v with ZWD estimated at GNSS site



4 Assimilation test cases

Heavy precipitation events

- Period: 21.05. – 03.06. 2013
- Large area was affected, local extremes of up to 300 mm precipitation in 72 h



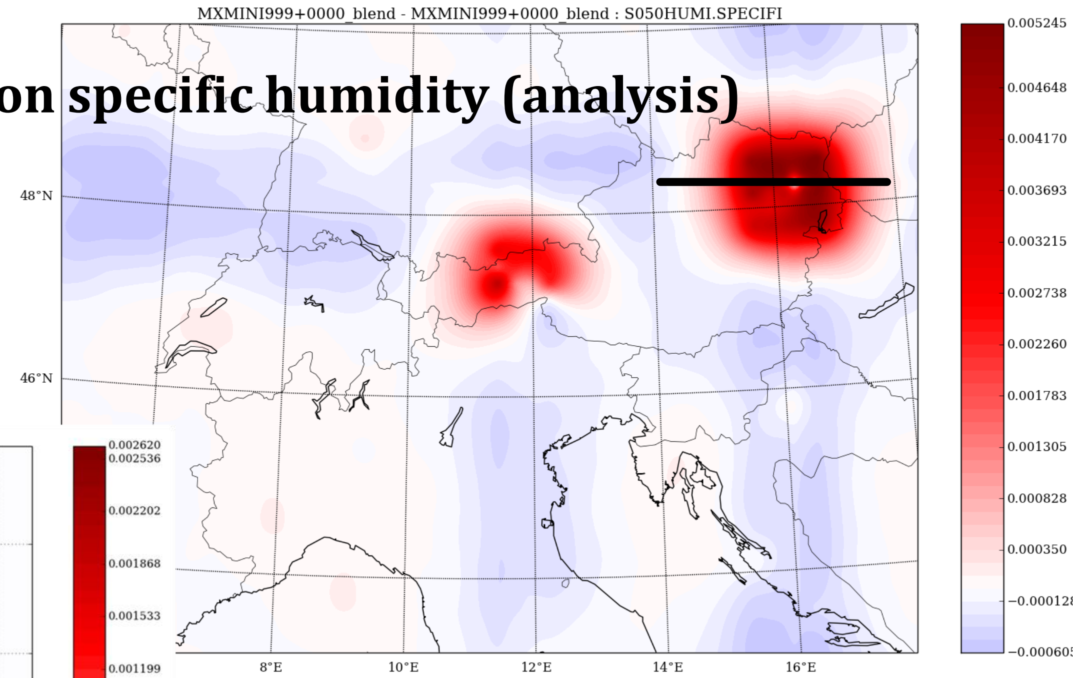
Assimilation of GNSS derived refractivity fields

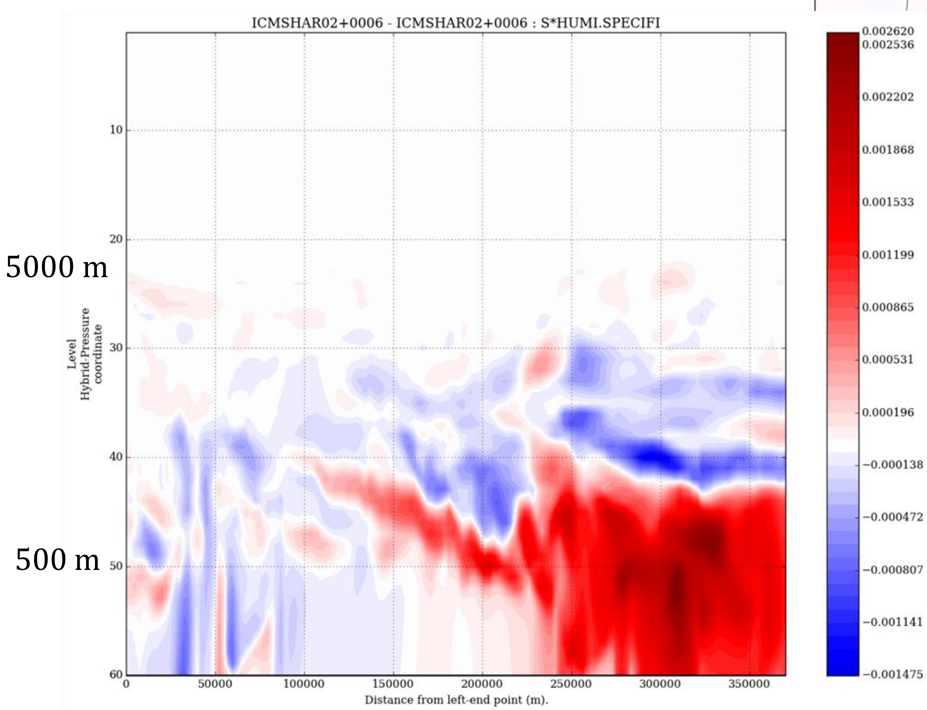
- Convert N_{wet} into specific humidity and temperature (1DVAR)
- Assimilation in AROME (3DVAR) like radiosonde profiles

experiment name	description	a-priori for refractivity
ZG01	reference run	none
ZG02	refractivity assimilation	ALARO
ZG03	ZTD assimilation	none
ZG04	refractivity assimilation	AROME
ZG05	ZTD assim. (no bias corr.)	AROME

Impact of refractivity fields on specific humidity (analysis)

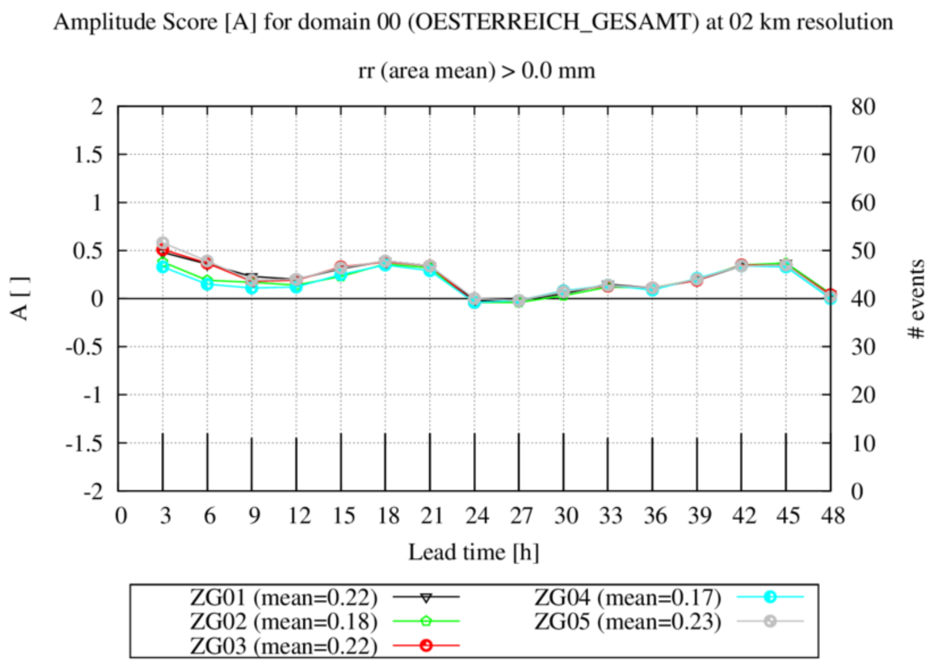
Model level 50 (right), East-West cross section (bottom)





Drying effect visible at lower levels, less impact on higher levels

Impact on precipitation forecast



A = 0: perfect forecast (wrt. analysis)

A > 0: overestimation (wrt. analysis)

AROME tends to overestimate precipitation during the test period

Refractivity data (ZG02 and ZG04) help to reduce the forecast error (< 15 h)

Larger impact than ZTD data (ZG03 and ZG05), particular in the alpine region

5 Conclusion/Challenges

- GNSS tomography can provide good results but is very sensitive to input data
  - especially to missing observations at low elevation angles
  - very much affected by the a priori model
- Assimilated refractivities have a strong impact on AROME forecast over complex orography, deteriorate over flat terrain.

Challenges

- Modelling of side observations
- Improved weighting (remove dependency on a priori model)
- Combination with other observations (MultiGNSS) and observation types

References

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[Bauer et al., 2015] P. Bauer, A. Thorpe, G. Brunet, The quiet revolution of numerical weather prediction, Nature, Vol. 525, No. 7567. (2 September 2015), pp. 47-55, doi:10.1038/nature14956

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[Smith and Weintraub, 1953] E. K. Smith, S. Weintraub, The Constants in the Equation for Atmospheric Refractive Index at Radio Frequencies. Proceedings of the Institute of Radio Engineers (I.R.E.), 41: 1035-1037, 1953

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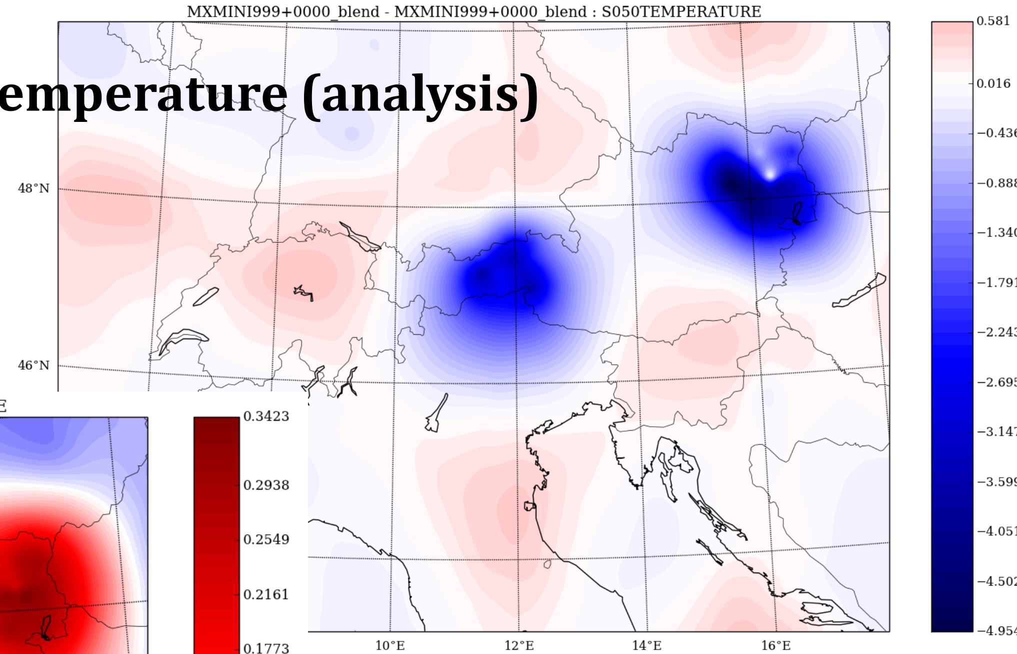
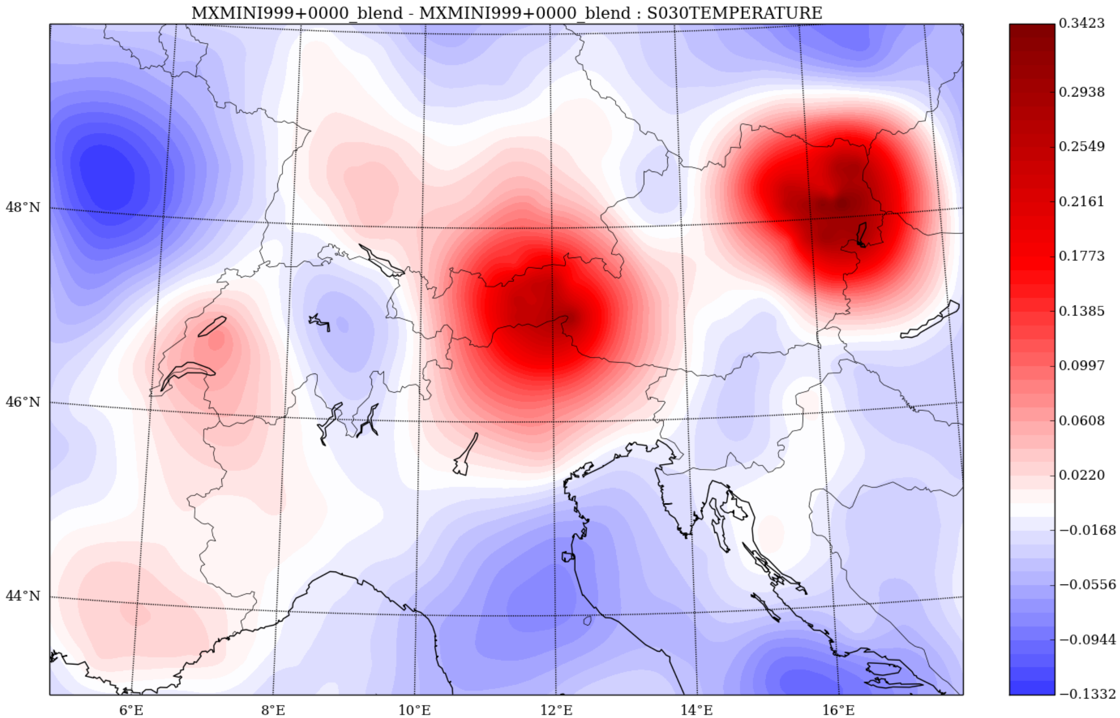
Impact of refractivity fields on temperature (analysis)

Model level 50 (right) and 30 (bottom)





Heating effect visible at lower levels, less impact on higher levels

AROME - assimilated observations

Observation type	assimilated fields	data source
SYNOP+TAWES	T2m,RH2m,U10m,V10m,f	ZAMG+OPLACE
AMDAR (airplanes)	U,V,T	ZAMG+OPLACE
GEOWIND (SAT-Winde) MSG3	U,V	OPLACE
TEMP (radiosondes)	U,V,T,Q,f	ZAMG+OPLACE
~~PILOT~~	~~U,V~~	~~ZAMG~~
~~WINDPROFILER*)~~	~~U,V~~	~~ECMWF MARSARCHIV/OPLACE~~
MSG3-SEVIRI	WV-radiances	OPLACE
NOAA16/18/19+MetOp-A-B AMSU-A,-B,MHS,HIRS	radiances	OPLACE
MetOp-A-B IASI	radiances	OPLACE
ASCAT wind	U10m,V10m (25km)	ZAMG/EUMETSAT
GNSS ZTD	zenith total delay (ZTD)	TU-Wien
GNSS 3D refractivity	humidity/temperature profiles	TU-Wien
~~RADAR*)~~	~~reflectivity / radial winds~~	~~Austrocontrol/Remote Sensing~~
~~MODIS-Schneebedeckung *)~~	~~snow yes / no~~	~~ENVEO-CRYOLAND~~

Appendix

Results (all observations; outliers removed)

Observations with large residuals (> 30rms) were removed

Parameter	Value (all)	Value (3sig)
Number of observations	18000	17160
Zero elements in A	96.2 %	96.2 %
Condition number	32	30
Rank (EV > 0.01 km^2)	275	275
Mean formal error	0.03 ppm	0.03 ppm
Mean error/Stddev of dN_{wet}	-0.12/0.57 ppm	-0.09/0.48 ppm

No effect on mean formal error but better fit of estimated N_{wet}

(smaller bias and standard deviation wrt. AROME data)