GPS-ZTD and radar data assimilation using a convection permitting WRF 3DVAR-RUC configuration

Thomas Schwitalla and Volker Wulfmeyer
Institute of Physics and Meteorology (IPM)
University of Hohenheim (UHOH)
Stuttgart, Germany
Outline

• Variational data assimilation techniques in Numerical Weather Prediction (NWP)
• Remote sensing data for nowcasting applications: GPS & Radar
  • Assimilation of GPS & Radar in WRF
• Summary
• Outlook
Why data assimilation?
Some aspects of data assimilation

• Think about crossing the street - this is data assimilation!
  ➢ Estimating the current state using observations and your background

• A classical method is the Four-dimensional data assimilation (e.g. applied for the operational COSMO models)
  • Model fields are adjusted by adding a weighting term to the prognostic equations
  • Allows only assimilation of model’s “prognostic observations“

• More recent methods are deterministic variational schemes like 3DVAR and 4DVAR
  • Use observation error matrices (R)
  • Include model background errors representing meteorological and model variability (B)
  • Allow non-prognostic observations (Radar, GPS, radiances...)
  • Uses the (full) forecast model in case of 4DVAR
Some aspects of data assimilation (2)

• Requires a forward operator (H) and its adjoint

• New initial state (x) is determined by minimizing a “cost function” (J), describing differences between observations (y) and background (x_b)

\[
J(x) = (x - x_b)^T B^{-1} (x - x_b) + (y - H(x))^T R^{-1} (y - H(x))
\]

• B would be a $10^7 \times 10^7$ matrix, therefore control variables are introduced to reduce the size of B to $10^7$ elements

• R is usually a diagonal matrix describing the observation errors. Cross correlations are neglected (except for high-resolution satellite data).

• 3DVAR rapid update cycle (RUC) used by several meteorological centers

• High-resolution 4DVAR is often in development state

• Requires lots of computing resources
In a 3DVAR RUC, the full complex model can be applied between the assimilation steps, but $B$ matrix remains constant and the adjoint of $H$ required.
Some informations about $B$

- $B$ must spread information both vertically & horizontally with proper weights to observations and first guess.
- Contains correlations and cross correlations between control variables
WRF model setup

- Convection permitting resolution of 3km
- 691*682*57 grid boxes (COSMO-IT 502*604*50@2.8km)
- Two-Moment microphysics
- Digital Filter initialization
- New vegetation fraction from MODIS
- Boundaries from ECMWF
- Shallow convection
- 3DVAR RUC
- Simulations are performed on a Cray XE6/XC30 system using 960 cores
Rapid Update Cycle approach with WRF used at IPM

Lateral boundary conditions from ECMWF analyses/forecast

Time:

- 00Z: Forecast
- 03Z: Forecast
- 06Z: Forecast
- 09Z: Forecast
- 12Z: Forecast

- T + 0h: ECMWF analysis + DFI
- T + 3h: 3DVAR
- T + 6h: 3DVAR
- T + 9h: 3DVAR
- T + 12h: 3DVAR
- T + xx hours: Free forecast

Update low boundary
Update lateral boundary conditions

ECMWF analysis + DFI

Obs

ECMWF analysis

Update lateral boundary conditions

Obs

Free forecast

Obs

Free forecast
Available observations

• Conventional observations (SYNOP, AMDAR, TEMP...)
• MSG Atmospheric Motion Vectors from IR, WV and HRV channels
• QuickScat sea winds (12.5km resolution)
• GPS-ZTD data (~950 stations in our domain, over land only!)
• Radar radial velocities and reflectivities (only French and German data used -> OPERA?)
• Satellite radiances from polar orbiting satellites (HIRS, AMSUA/B, AIRS, IASI, MHS)
• Raman Lidar data (experimental)

• Conventional observations are obtained via the ECMWF MARS
• AMV and QSCAT data are retrieved from EUMETSAT UMARF archive
• GPS-ZTD are downloaded from EGVAP
• Radar data have been received directly from Météo France and DWD during COPS
• Satellite data are received from the NCEP archive (dss 735.0)
GPS data assimilation

• Water vapor information can be derived from GPS by measuring the signal delay between satellite and receiver.
• GPS provides data with large spatial coverage and high time resolution (15 minutes) under all weather conditions.
• A large impact of GPS data assimilation on the improvement of the initial water vapor field is expected.
• Complex STD operator required for low elevations.
GPS-ZTD data assimilation experiment

Observations rejected where $h_{\text{model}} - h_{\text{obs}} > 100$ m
GPS-ZTD data assimilation experiment (2)
STD difference model-observation
Radar data coverage during COPS

- 15 Doppler radar in total
  - 10 from France
  - 5 from Germany
- S- and C-Band radars
- Scanning radius up to 250km
- Range resolution 1km
- $R_{u_{\text{max}}} = 60\text{m/s and 32m/s}$
- 3D volume data

Mostly NO clear air data!
Assimilation of radar data in WRF

Radial velocity assimilation:

\[ v_r = \frac{x-x_i}{r_i} \cdot u + \frac{y-y_i}{r_i} \cdot v + \frac{z-z_i}{r_i} \cdot (w-v_T) \]

Terminal velocity \( v_T \) represents the fall speed of rain. It depends on the rain water mixing ratio \( q_r \) under the assumption of a laminar flow (\( R_e \approx 300 \)).

Reflectivities (dBZ) are assimilated applying the following operator:

\[ Z = 43.1 + 17.5 \log \left( \frac{\rho_{\text{air}} q_r}{1 \text{ kg/m}^3} \right) \]

Derived from a Marshall-Palmer distribution with \( N_0 = 8 \times 10^6 \text{ m}^{-4} \)

Only based on rain water mixing ratio!
Quality control and data thinning

Raw observations amount is too large and data are noisy

Data thinning and filtering prior to its use in a data assimilation scheme

Applied filtering procedure for e.g. German radar data:

1) According to quality flags, the raw observation is set to missing value
2) Calculation of a 3x3 average value
3) Calculation of variance for every raw observation
4) Variance rejection threshold 50dBZ² for reflectivity and 60m²/s² for radial velocity (Xiao, WRF Workshop 2008)
5) Additional smoothing along the ray and azimuth

Radial wind observation error = f(range)
Reflectivity error set to 5dBZ
Reflectivities are discarded above 4000m AGL
Quality control and data thinning

\[ V_r \]

\[ \text{RF} \]
Improvement of precipitation nowcasting after RUC from 6-9 UTC:

Simulation with radar DA

„No-radar“ – Obs.

„Radar-DA“ – Obs.

Promising reduction of precipitation bias by 50 %. Improvement of spatial distribution (Schwitalla et al. submitted to Meteorol. Z. 2013).
Integrated (Ensemble) Simulation Model

Boundaries (deterministic or ensemble prediction system)

Convection permitting NWP model simulations (WRF, Arome, COSMO...) of $X^b$ with error covariance $B$

VAR or EnKFs providing state vector $X^a$ and analysis error covariance $A$

Forecast or reanalysis ensemble, update of $B$

Model observation forward operators $H(X)$

Observation vector $Y$ with error covariance $R$

Soil-land-surface obs.: - Streamflow - In-situ soil and veg. - Hyperspectral obs.

Atmospheric obs.: - In-situ - GPS ZTD and STD - Radar radial velocities and reflectivities - Lidar - Polarimetric radar - Passive rem. sens.

Verification and Calibration

Data of meteorological services and research institutes

Coupling of hydrological model with WRF-NOAH: Samaniego et al. AGU 2012
Streamflow DA: Warrach-Sagi and Wulfmeyer GMD 2012
Summary

- Setup of a unique WRF Rapid Update Cycle over central Europe applying a convection permitting resolution
- Beneficial impact of GPS-ZTD data
- First steps to assimilate 3D volume radar data from two different networks with WRF over Europe
- Results are promising, but still deficiencies due to model imbalances, deficits in clear air dynamics
- Quality issues of reflectivities – bias correction or new Z-q_r relation required to adopt for European radar systems?
Outlook

- Harmonize radar data quality and interpolation procedures
  - OPERA European radar data base (work in progress)
- Utilize polarization radar data (www.caos-project.de)
- Comparison of 3DVAR-RUC and 4DVAR (challenging....)
- Testing (hybrid) ensemble data assimilation methods (EnKF, 3DVAR-ETKF, Ensemble-3DVAR)
- Use of MODE-S aircraft data (Clear air data!)
- Incorporate GPS slant total delays to further improve the water vapor fields
- GPS data data over the Ocean?