Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Assimilation of GPS Radio-Occultations at DWD

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NWP Models at DWD

GME

Global model, hydrostatic

Triangular grid, mesh size: 20 km
60 levels (top: 5 hPa)
(1474562×60 grid points)

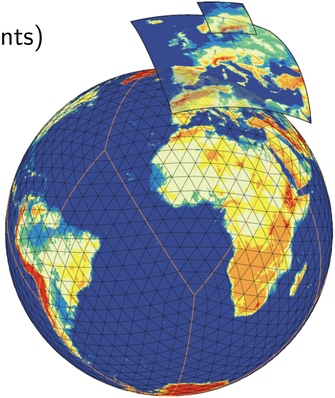
Forecast times:
174h from 00Z, 12Z;
48h from 06Z, 18Z

COSMO-EU

Non-hydrostatic

Mesh size: 7 km
40 levels

Forecast times:
78h from 00Z, 12Z;
48h from 06Z, 18Z



COSMO-DE

Non-hydrostatic,
"convection allowing"

Mesh size: 2.8 km
50 levels

Forecast times:
21h from 00Z, 03Z, . . . , 21Z

COSMO-DE-EPS

(Pre-operational)
Ensemble prediction system
20 ensemble members
(operationally: 40 members)

Forecast times:
21h from 00Z, 03Z, . . . , 21Z

Global Data Assimilation System at DWD

- **3D-Var-PSAS**, 3-hourly update cycle
- **Available Forward models for GPSRO**
  - 1d bending angle operator (Implementation by Michael Gorbunov); fixed/effective tangent point for profile or individual tangent point
  - 3d ray tracer (Michael Gorbunov)
- Implementations tested and evaluated in collaboration with GFZ using data from CHAMP and GRACE (Pingel and Rhodin, 2009)
  - Ray tracer: best in terms of std.dev. of OBS-FG, numerically expensive! Ray tracer also needs additional data not provided in BUFR messages (satellite positions and velocities)
  - 1d-operator (Abel integral) with effective location of occultation probably good enough for initial operational implementation (still needed major optimization efforts for the NEC SX-9)
- **Refractivity**

  3-term expression as recommended by GRAS-SAF
- **"Initialization"**

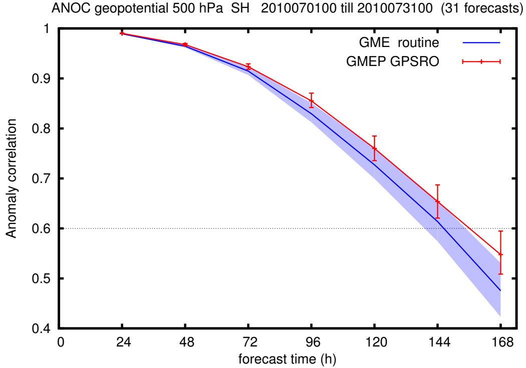
  MSIS-90 climatology matched at model top ($\sim 36\,\mathrm{km}$)

Assimilation of GPS Radio-Occultations

- **Observation errors** (S. Healy):
  - Linear decrease from 10% to 1% for impact height from 0 to 10 km
  - 1% from 10 km to 30 km
- **Quality control** of observations:
  - Consistency checks of profiles
  - Observation-minus-first guess check: 4σ (should be made stricter)
  - B.a. < 0.02 rad to avoid ducting (replace by condition on refractivity)
  - Clip lowest section of GPS-RO profiles when non-monotonous
- **Vertical thinning** to model resolution, exponential smoothing
- Use **impact heights** 3 km–30 km
- Exclude occultations starting above 20 km
- **GPS Radio-Occultations operationally used since 2010-08-03**
  - COSMIC/FORMOSAT-3 FM 1-2, 4-6 (FM-3 dead since 2010-08-01)
  - GRACE-A
  - GRAS on METOP-A
  - TerraSAR-X (since 2010-12-09)
  - C/NOFS, SAC-C (since 2012-02-29)

Impact of the Assimilation of GPSRO

- Better fit to radiosondes in upper troposphere/lower stratosphere, esp. southern hemisphere (but mixed results in Antarctic)
- Significant forecast improvements with assimilation of GPSRO



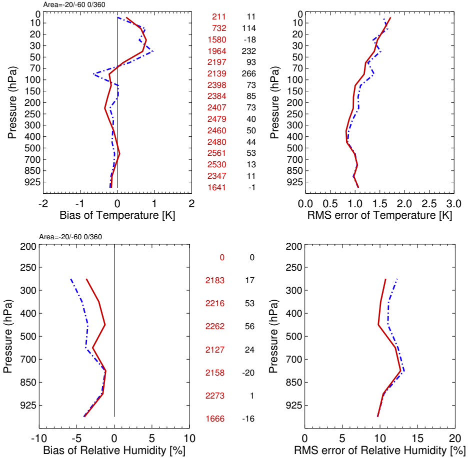
(90% c.l.)

H. Anlauf et al., Atmos. Meas. Tech., 4, 1105–1113

Anomaly Correlation of Geopotential 500 hPa, Southern Hemisphere for July 2010 ⇒ gain of several hours vs. operational system

Comparison to Radiosondes

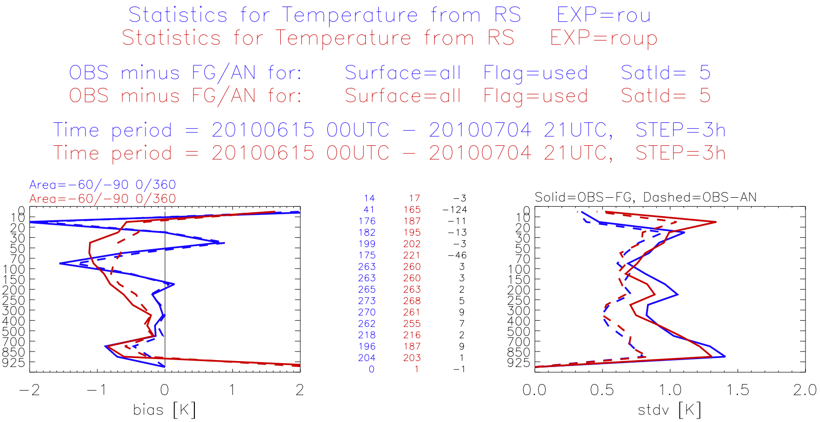
- Mean departures of temperature and rel. humidity observations from radiosondes to 3-h forecasts, Southern Hemisphere



H. Anlauf et al., Atmos. Meas. Tech., 4, 1105–1113

(blue: ctrl (operational), red: GPSRO experiment)

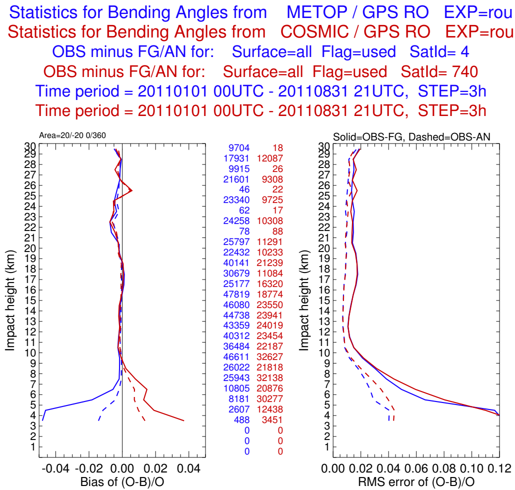
Problems with the Assimilation of GPSRO over Antarctic



- Large temperature bias, got even worse with assimilation of GPSRO!
- Partially understood: poor representation of vertical correlations in operational assimilation system, revised in December 2010
- Some issues with the forecast model, but investigations ongoing

Issues with Assimilation of GPSRO Data (I)

- Bias, RMS differences for different satellites (processing, model, ...)
- Lower troposphere: largest bias in the tropics, smaller in extratropics



Tropics

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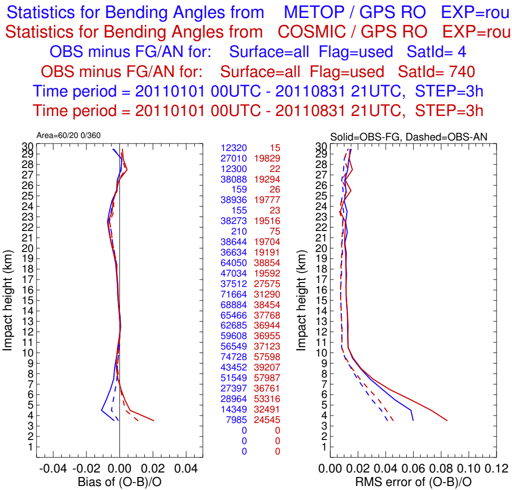

Northern Extratropics

Issues with Assimilation of GPSRO Data (II)

- Apparent positive bias for non-GRAS data due to bugs in *first-guess check implementation* (non-symmetric w.r.t. OBS and FG!)
- Current GRAS data are (known to be) biased below $\sim 8\,\mathrm{km}$
  - Rising occultations (globally)
  - Setting occultations (notably tropics, lower troposphere)

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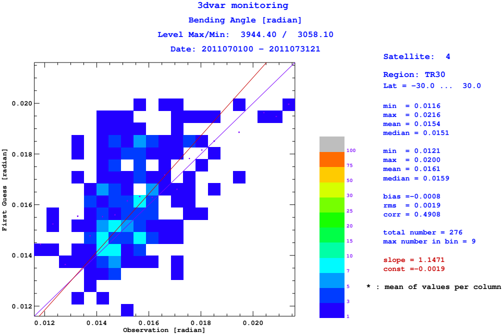
GRAS, 30°S–30°N, 3-4 km



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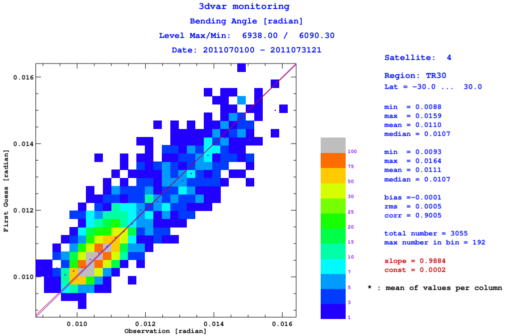

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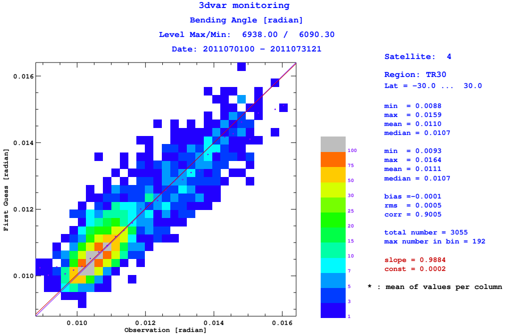


Bias might be tolerable for small bending angles ($\lesssim 15\,\mathrm{mrad}$)

Issues with Assimilation of GPSRO Data (III)

- Occasionally poor convergence of the 3D-Var
  - Forward operator was evaluated outside domain of validity, e.g.
    - $\mathrm{d}(r \cdot n(r))/\mathrm{d}r < 0$ for some r, or
    - rays were extrapolated below model orography (mostly Antarctic) in line-search during minimization
  - Extend forward operator and first-guess checks (not yet operational)
    - minimum geometric height of rays above orography (1 km)
    - require $\mathrm{d}(r \cdot n(r))/\mathrm{d}r > 0.5$
  - Enhance optimization algorithm to enable detection and removal of bad rays during minimization
  - Variational Quality Control (VQC) scheme initially used for surface pressure observations (Gaussian+Flat) while using an approximate (modified) Huber-function for the other observations didn't work well

Variational Quality Control

- In variational assimilation schemes, VQC enables dealing with bad observations during minimization
  - Observational cost function for Gaussian error distribution (p)

$$J_o(y - \mathcal{H}(x)) = -\log(p(y - \mathcal{H}(x))) = \frac{1}{2}(y - \mathcal{H}(x))^{\mathsf{T}}\mathbf{R}^{-1}(y - \mathcal{H}(x))$$

    $\Rightarrow$ Pull of outliers same as for good observations
  - Gaussian+Flat: large outliers have zero impact, but strong non-linearities, possible multiple minima, slow convergence
  - 'Huber norm' (ECMWF): quadratic/linear for small/large departures; outliers have small impact, but better convergence, no multiple minima
  - **Approximate (modified) Huber-function**

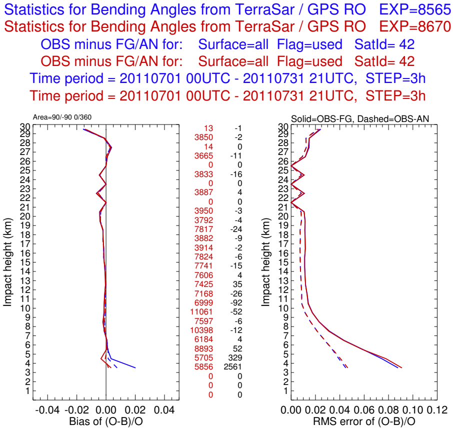
$$J_{qc} \sim \alpha \cdot \left(\sqrt{\frac{x^2}{\beta} + 1} - 1 \right) , \quad \text{with parameters} \quad \alpha,\ \beta = \beta(\mathbf{R}, \ldots)$$

    $\Rightarrow$ Similar to Huber norm, but smooth gradient, 2nd derivative

    We now use the approximate (modified) Huber-function approach for all observations

Results from revised first-guess checks and QC

- Bias for lower troposphere reduced, more rays used (except GRAS)
- Example: TerraSAR-X (blue: control, red: experiment)



Global

(blue: ctrl, red: experiment)

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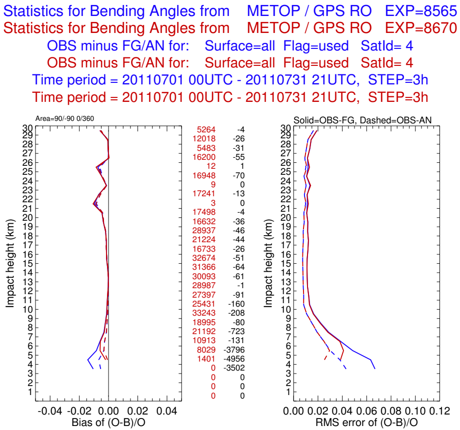

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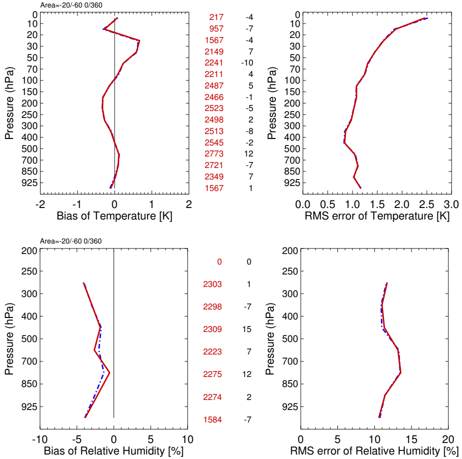
Comparison to Radiosondes

- Mean departures of T, rH obs. to 3-h forecasts, Southern Hemisphere



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Only small improvements w.r.t. radiosondes, neutral on forecasts ☹

Summary and Outlook

- GPS Radio-Occultations are a useful component of the global observing system for Numerical Weather Prediction at DWD
  - Improved analyses and forecasts in particular in data-sparse regions
  - Improved stability of (static) bias correction for satellite radiances
  - Exhibit deficiencies in the data assimilation (e.g. background error model)
  - Help locating forecast model deficiencies
  - Strong non-linearity of forward operator poses challenges for quality control in data assimilation
- Future developments
  - Optimize and test impact of forward operator with tangent point drift
  - Implement ROPP 2d forward operator
  - Evaluate options to re-activate 3d ray tracer
    (needs satellite positions and velocities missing in BUFR!)

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A big Thank You to all involved
in making data available in Near Real-Time!