Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Experiences from implementing GPS Radio Occultations in Data Assimilation for ICON

Harald Anlauf

Research and Development, Data Assimilation Section
Deutscher Wetterdienst, Offenbach, Germany

IROWG 4th Workshop, Melbourne, Australia
16–22 April 2015

Outline

Latest Developments in Global NWP at DWD

ICON

- Joint project by DWD and MPI-M (Hamburg)
  - Unified framework for NWP and climate modeling
  - **ICO**sahedral-triangular (Arakawa C) grid, **N**on-hydrostatic core
  - unstructured mesh, local refinement options
    global/regional mode, self-nesting, 1- and 2-way nesting
    (G. Zängl et al., doi:10.1002/qj.2378)
- Global NWP version operational since 2015-01-20:
  13 km avg. mesh size, 90 levels (top: 75 km)

  replaces former GME model
- Europe nest (mid-2015):
  mesh size 6.5 km, 60 levels
  2-way horizontal/vertical
  nesting with feedback

History of GPS Radio Occultations at DWD

- **Bending angle** operator, based on code by Michael Gorbunov
  - 2000: 3d ray tracer for ECHAM
  - 2002: adapted 3d ray tracer to GME grid, non-operational 3D-Var
  - 2006: 1d operator (Abel integral) based on ray tracer code
    - fixed/effective tangent point for whole profile, or
    - individual tangent point for each ray
- Evaluation (monitoring) in collaboration with GFZ using CHAMP and GRACE data
  - Ray tracer needs (drifting) satellite positions and velocities

    Processing using CT2 was done at DWD (Pingel and Rhodin, 2009).
  - Ray tracer best in terms of std.dev.(obs-fg), numerically expensive!

History of GPS Radio Occultations at DWD

- 2008: DWD's 3D-Var-PSAS for GME becomes operational
  - Replaces former OI
- **2010**: operational implementation of GPSRO
  - 1d-operator with effective location of occultation

    (H. Anlauf et al., doi:10.5194/amt-4-1105-2011,
    some later refinements, see my IROWG-2 talk)
  - only affordable option on former NEC SX-9 computer
- 2015: evaluate operator variants accounting for tangent point drift
  - More important for ICON than for GME due to:
    - ★ increased model top, horizontal resolution
    - ★ major overhaul of model physics
  - We have another computer (Cray XC40) and can afford it now

The Utility of GPSRO in Model Development

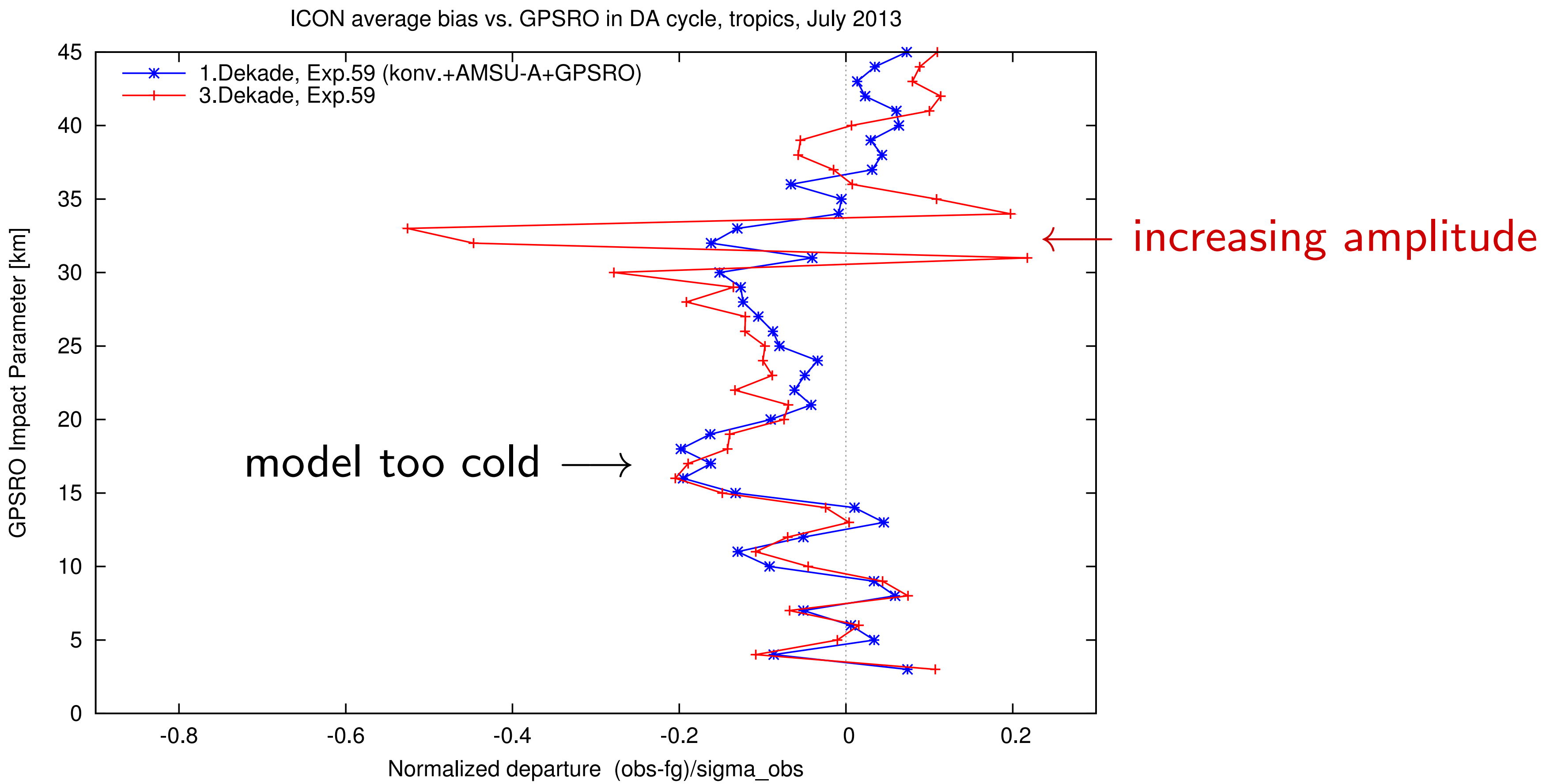
- **Promises** of GPSRO:
  - High vertical resolution (in UT/LS better than most NWP models)
  - Globally distributed, with almost uniform coverage
  - Essentially bias-free $\Rightarrow$ assimilate without bias correction
  - Well understood error characteristics (really?) of disseminated data

- By-product of data assimilation: "feedback files" with comparisons of observational data to first guess (O-B) and to analysis (O-A).
  - Assessment of model bias (relative to observations)
  - Diagnostics of performance and of problems in data assimilation
  - Statistical inference of (parts of) background and observation error covariances, **B** and **R**
    - ⋆ May require additional assumptions, as e.g. in Desroziers' method
    - ⋆ Optimality for non-linear systems, non-gaussian errors?

- Understanding/control of biases and proper choice of **B** and **R** are prerequisite to optimal utilization of data

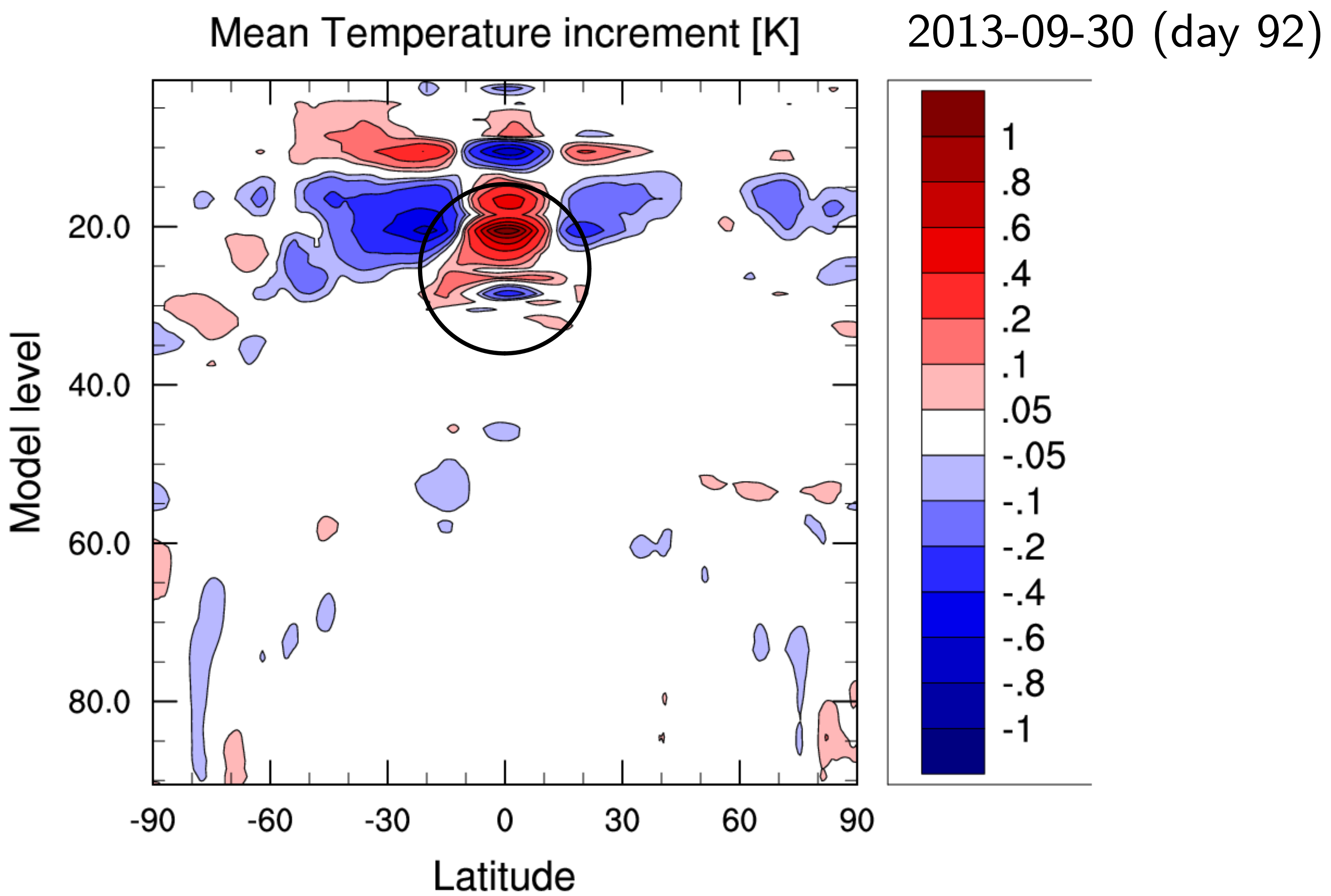
Diagnosing Model Biases and Data Assimilation Problems

- Early tests with ICON and cycled data assimilation
  - Negative bias of (O-FG) in tropical stratosphere (model too cold)
  - Emerging oscillatory pattern in (O-FG) at higher altitudes, tropics only, amplitude increasing over time



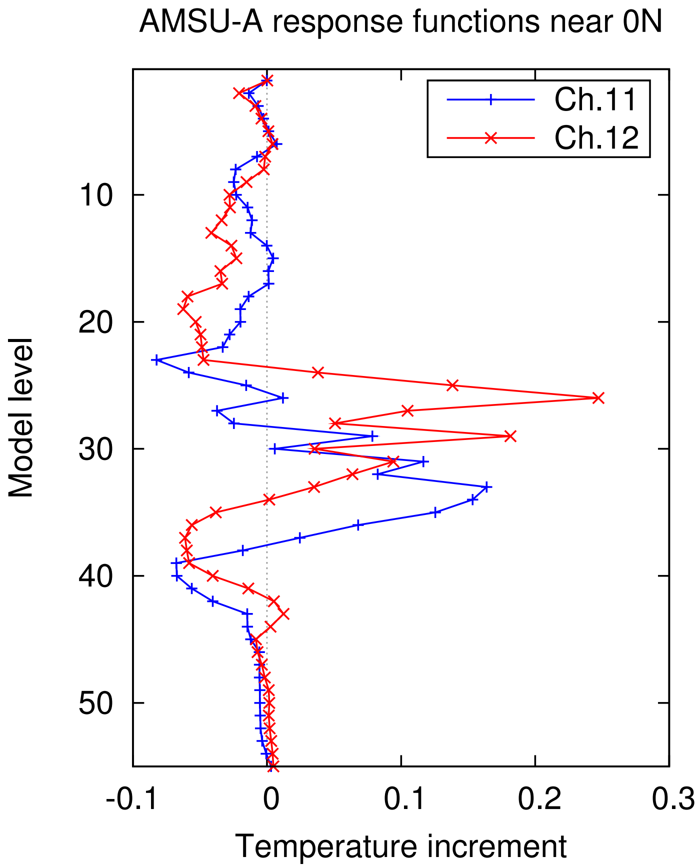
Diagnosing Model Biases and Data Assimilation Problems

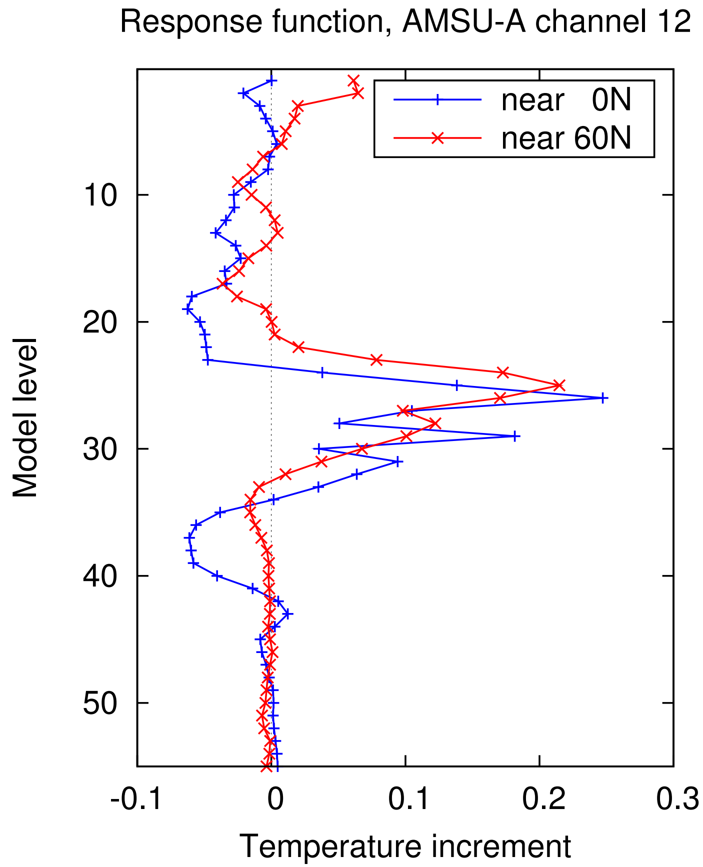
- Analysis increments on model levels developed sharp pattern
  - Quality control started to reject good observations which are sensitive to this pattern (GPSRO)!



Explanation and Solution, Part I

- Analysis increments on model levels, simulated single observations
  - Strange patterns induced mainly by AMSU-A channels 11 & 12
  - Most pronounced in the tropics (**B**: shorter vertical correlations!)
  - $\Delta x^a \sim \mathbf{B}\mathbf{H}^T(\ldots)$ involves different vertical grids: model, **B**, RTTOV





Explanation and Solution, Part II

Y. Rochon et al., QJRMS 133, 1547–1558 (2007)

- Vertical resolution mismatch: NWP model ⇔ fast radiative transfer code (e.g. RTTOV)
- Smoothing of Jacobian profiles by **B** ineffective for model vertical resolution much higher than RTTOV coefficient set
- Replacing interpolation from nearest model levels by suitable weighted layer average (available in RTTOV10) solved the sharp pattern issue!

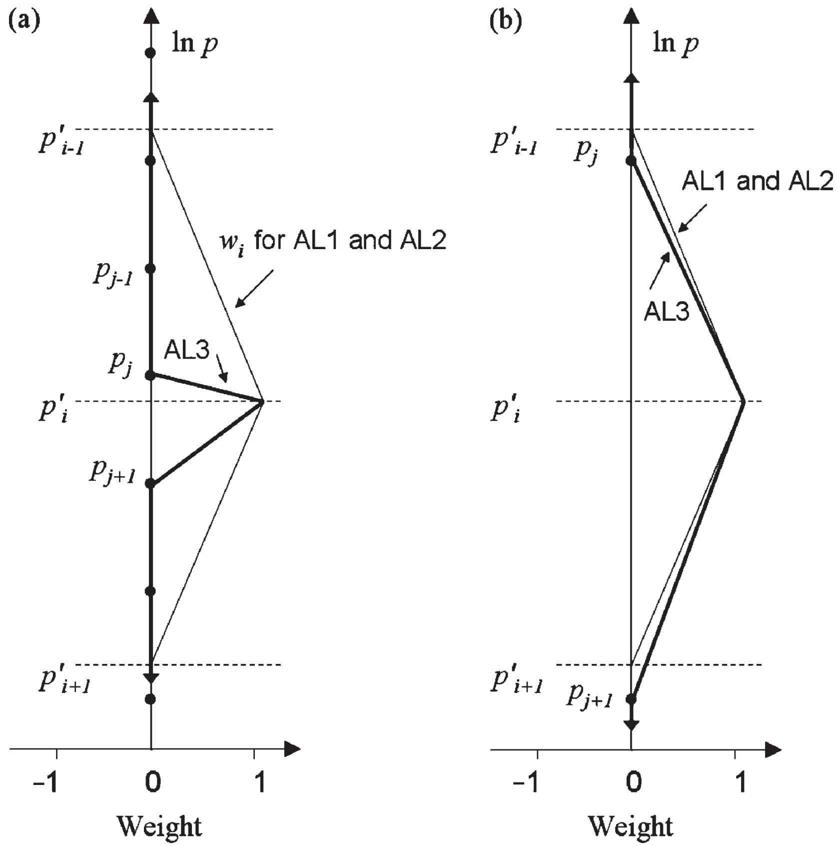
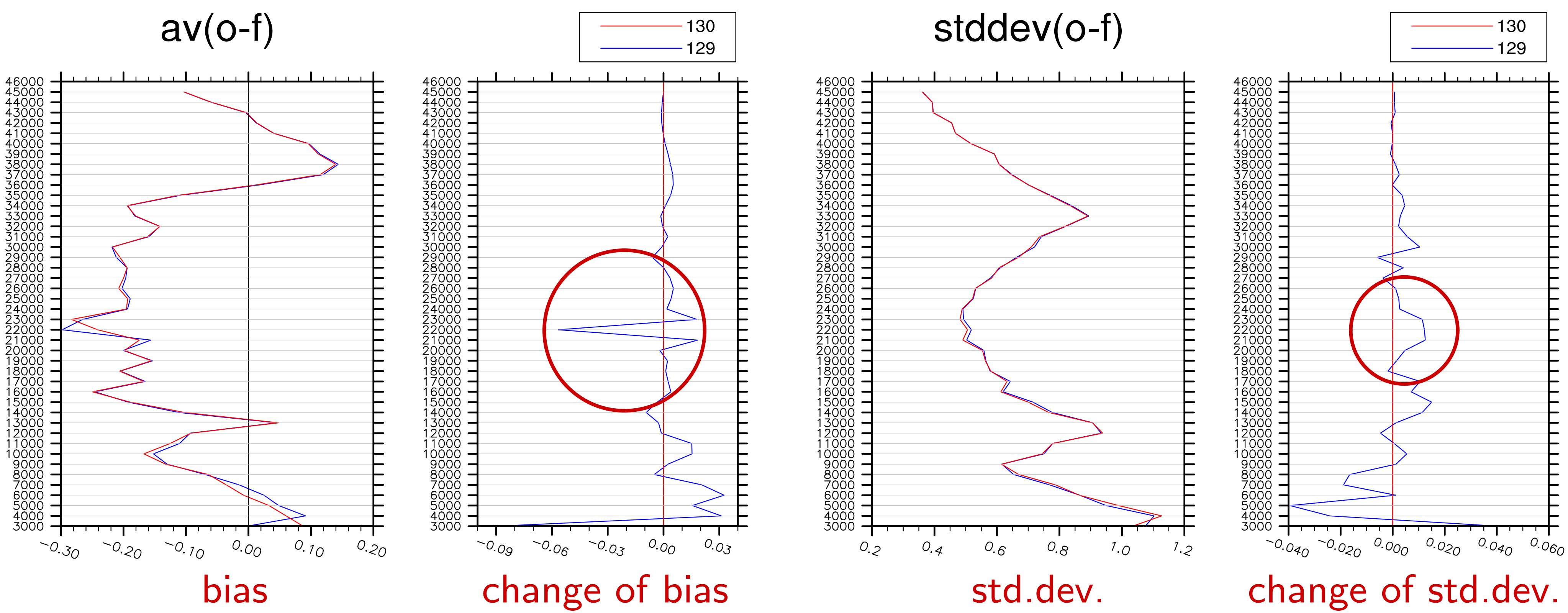


Figure A.1. Weighting functions w_i of the AL1 and AL2 weighted averaging interpolators (Equation (5); thin lines) and the AL3 log-linear interpolator using nearest points (Equation (A.5); thick lines). (a) and (b) show weighting functions for two different distributions of NWP levels.

A Problem in ICON's Vertical Nest Interface

- Comparison of bending angles against model over Europe
  - Reduction of standard deviation of observation minus FG in troposphere, but increase around vertical interface levels
  - Sharp structure in bias at vertical interface levels (~ 22 km): Inconsistencies in radiation fluxes – solved in newer ICON releases

129=nest exp. 130=control (no nest)



Tuning of Observation and Background Error Covariances

- **First-guess, analysis departures in observation space:**

$$d_b^o := y^o - H(x^b)\ , \quad d_a^o := y^o - H(x^a)\ , \quad d_b^a := d_b^o - d_a^o$$

Assuming no biases:

$$\mathrm{E}\left\{d_b^o (d_b^o)^t\right\} \;=\; \mathbf{R} + \mathbf{HBH}^t$$

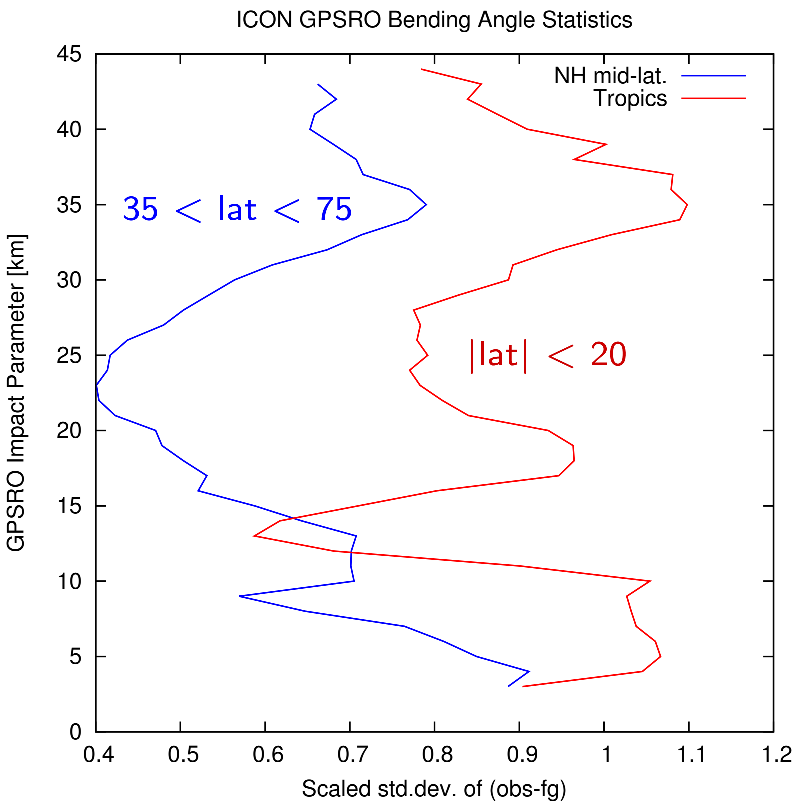
and for an optimal linear DA system (c.f. Desroziers et al., 2005):

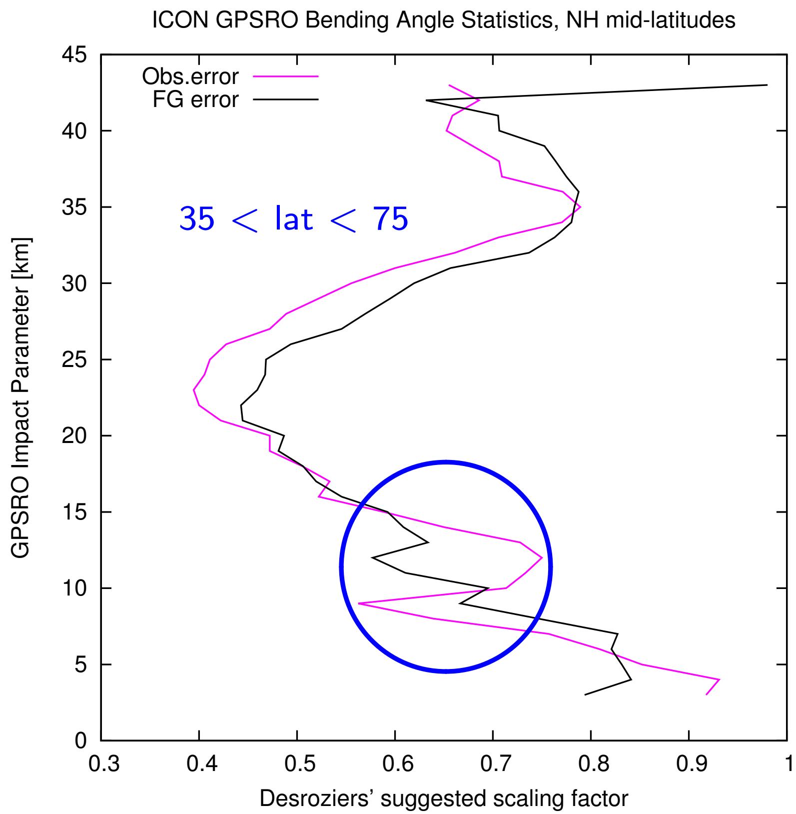
$$\begin{aligned}\mathrm{E}\left\{d_b^a (d_b^o)^t\right\} &= \mathbf{HBH}^t \\ \mathrm{E}\left\{d_a^o (d_b^o)^t\right\} &= \mathbf{R}\end{aligned}$$

- Beware that:
  - Above estimators for **R** and $\mathbf{HBH}^t$ are not positive definite!
  - Off-diagonal elements less reliable than the diagonals (variances)
  - Cross-validation with non-assimilated data may be crucial
  - Long-term aim: situation-dependent errors (model and data!)

Assessment of operationally used error statistics

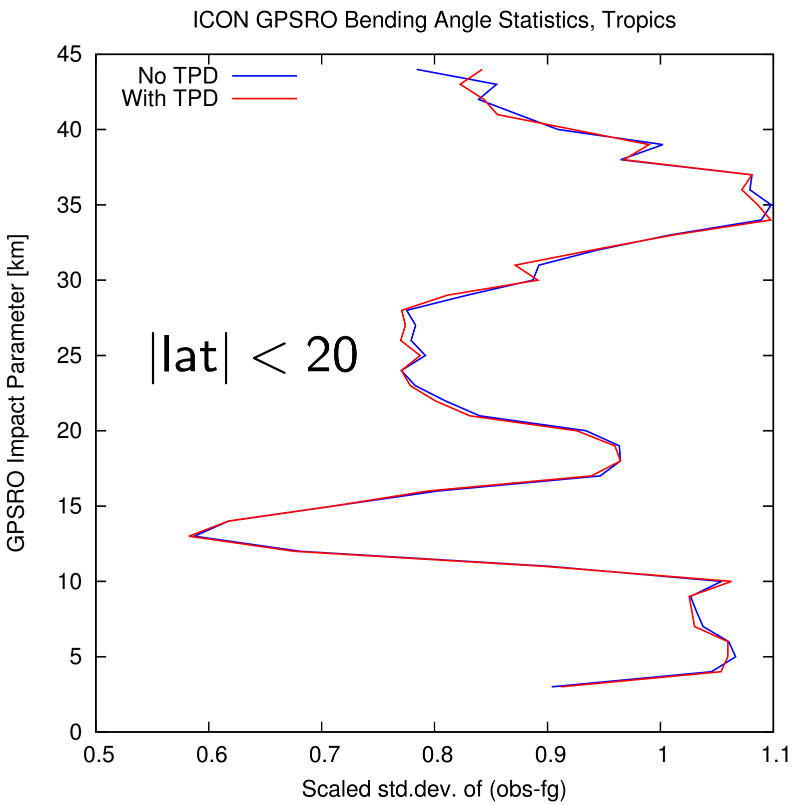
- Compare std.dev. of obs-fg to "expected error" $\sqrt{\sigma_o^2 + \sigma_b^2}$
  - Actual std.dev. much smaller than expected error in extra-tropics
- Derive scaling factors for assumed errors using e.g. Desroziers method
  - Scaling factors depend on latitude, impact parameter
  - Currently used observation error model poor near tropopause

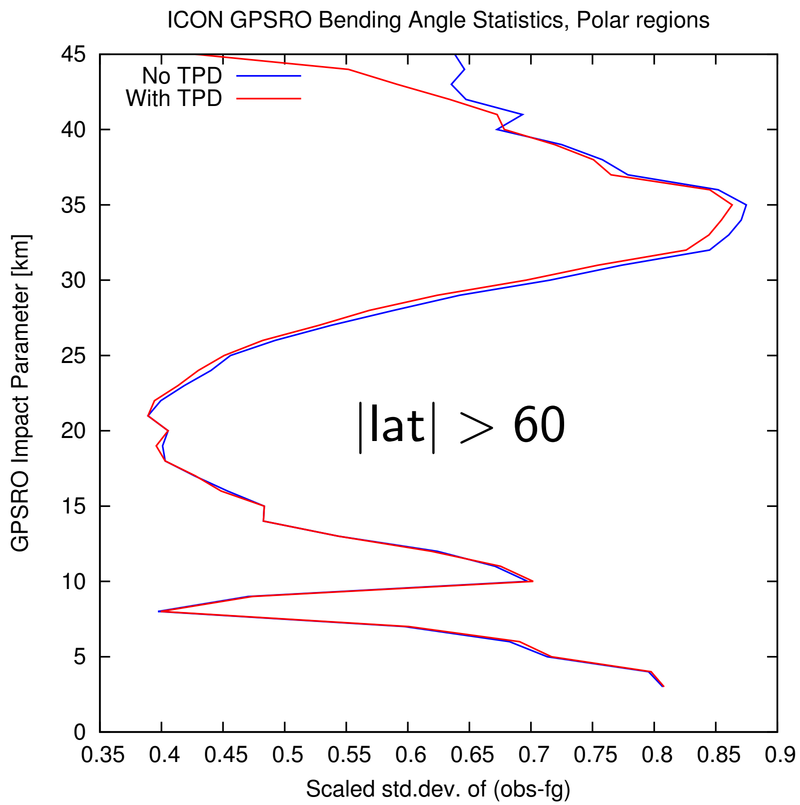




Observation Modeling: Tangent Point Drift

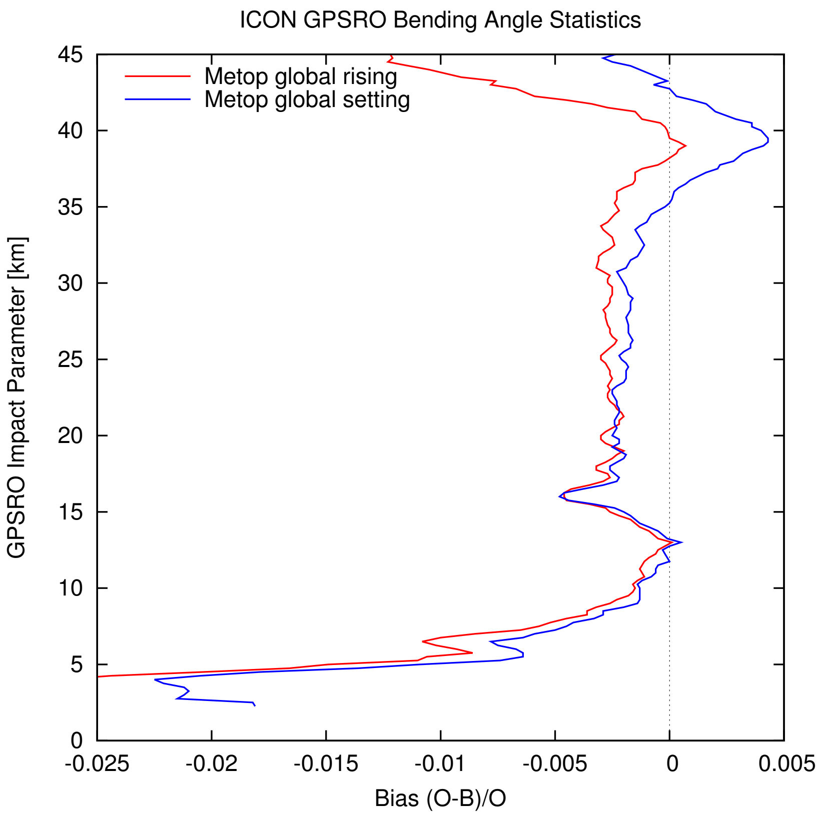
- Test period: 1–15 June 2014
- ICON, 13 km horizontal resolution
- "Optimized" 1d operator for tangent point drift: assign each ray to nearest model column, then batch model-column-wise
  - Small but systematic improvement in obs-fg statistics

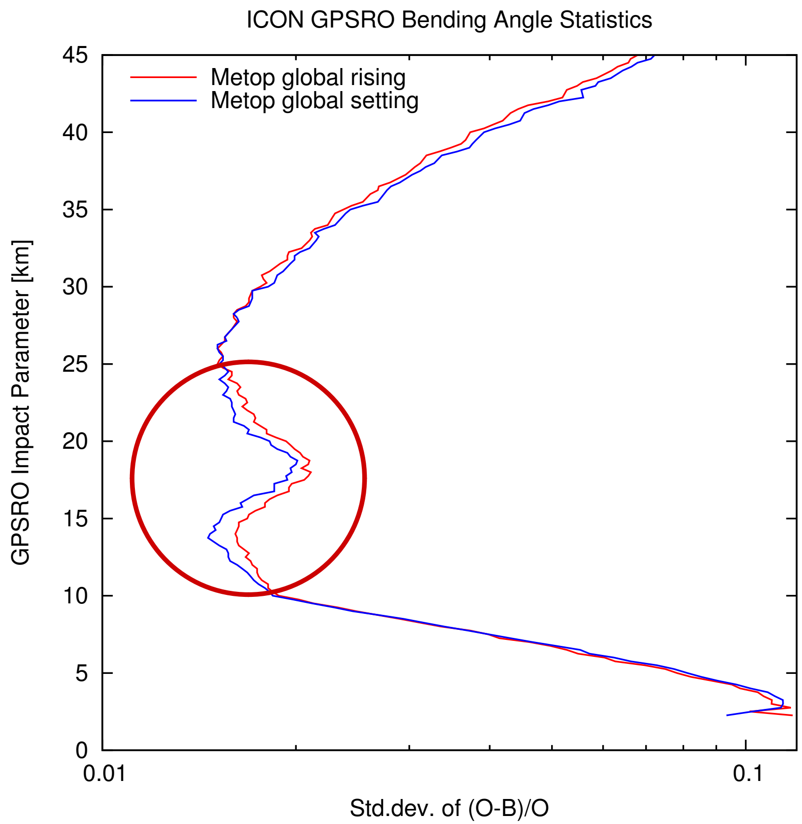




Quality of Available Observational Data: Metop/GRAS

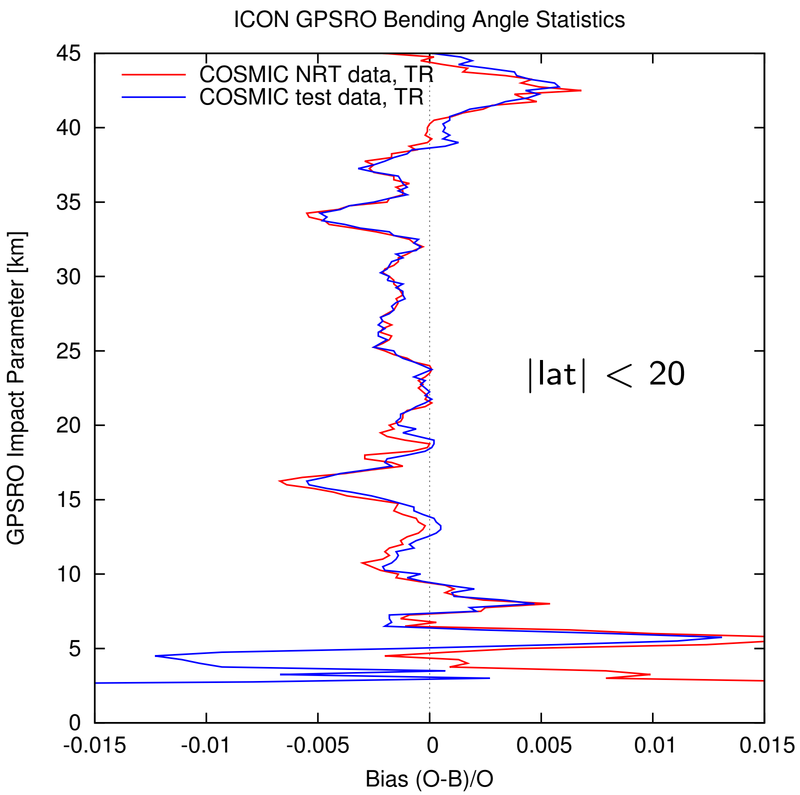
- Test period: 1–15 June 2014; ICON, 13 km horizontal resolution
- Simplified QC: only FG check + BUFR quality flags
- Metop-A/B bending angles, global region
  - Systematically different bias between rising and setting occs.
  - Systematically different data quality (standard deviation)

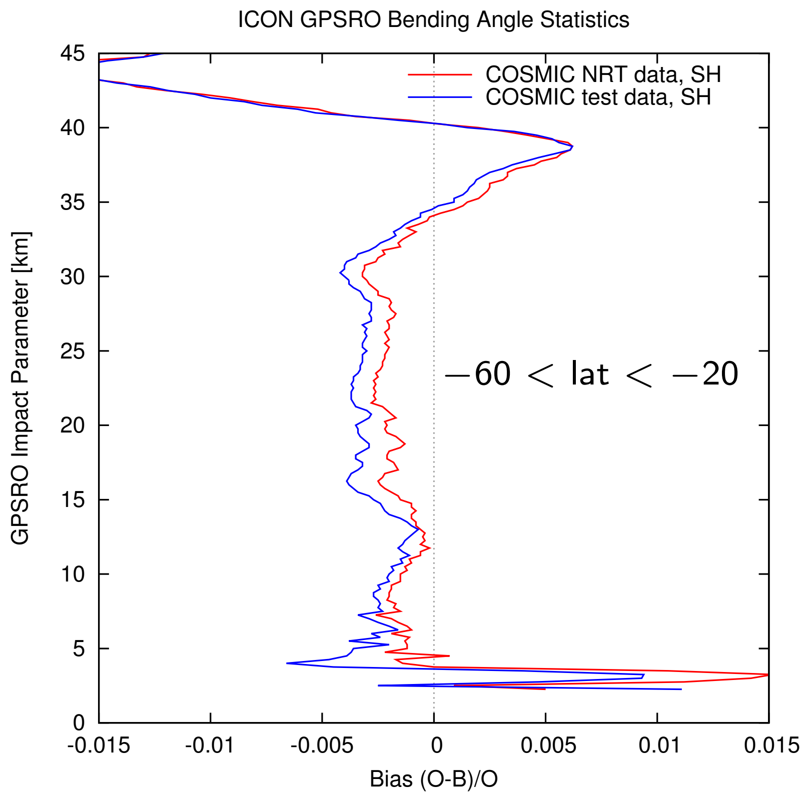




COSMIC: NRT Data vs. Test Data

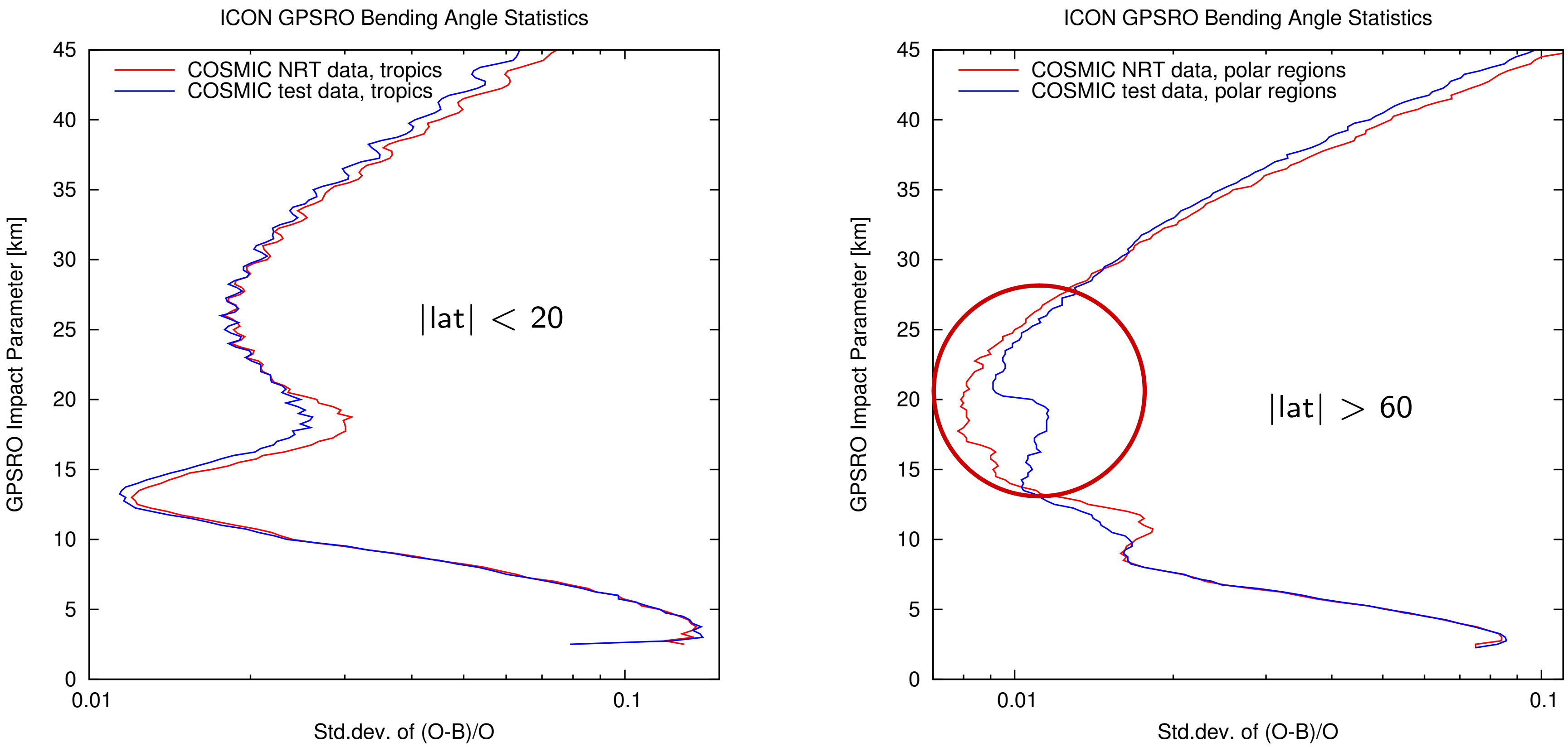
- Test period: 1–15 June 2014; ICON, 13 km horizontal resolution
- Comparison of COSMIC NRT data and test data from new inversion
- Small but systematic changes in bias, e.g.
  - Tropics: most significant change below 20 km
  - Southern mid-latitudes: significant changes up to ∼40 km





COSMIC: NRT Data vs. Test Data

- Test period: 1–15 June 2014; ICON, 13 km horizontal resolution
- Comparison of COSMIC NRT data and test data from new inversion
  - Reduced standard deviation near tropopause and in upper stratosphere
  - Increased standard deviation in polar stratosphere between 15–25 km



Conclusions

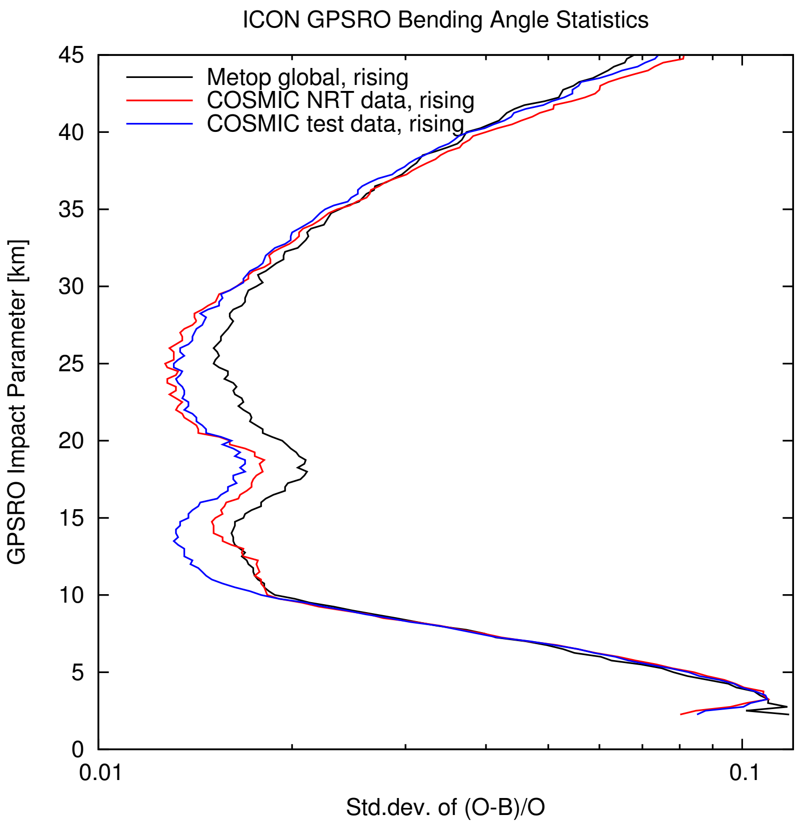
- GPS Radio-Occultations are a useful component of the global observing system for Numerical Weather Prediction
  - Good global coverage, almost uniform, high vertical resolution
  - Significant positive impact on forecast scores seen at all NWP centers
  - Very valuable for diagnosing model deficiencies (e.g. biases) and problems in data assimilation
- We do not yet make optimal use of observations!
  - Data assimilation needs proper specification of error covariances ($\mathbf{R}$,$\mathbf{B}$)
  - Higher model resolution benefits from forward operator improvements
    - ★ tangent point drift (already used by several centers)
    - ★ 2d forward operator (soon to be used at ECMWF)
    - ★ 3d ray tracer? (need to recreate ancillary data not provided in BUFR)
  - Quality of NRT data still far from optimal
    - ★ Differences between rising and setting occs. for some satellites
    - ★ New processing at CDAAC suggests general potential for improvements
    - ★ Will we ever see GRAS data from wave optics processing in NRT?

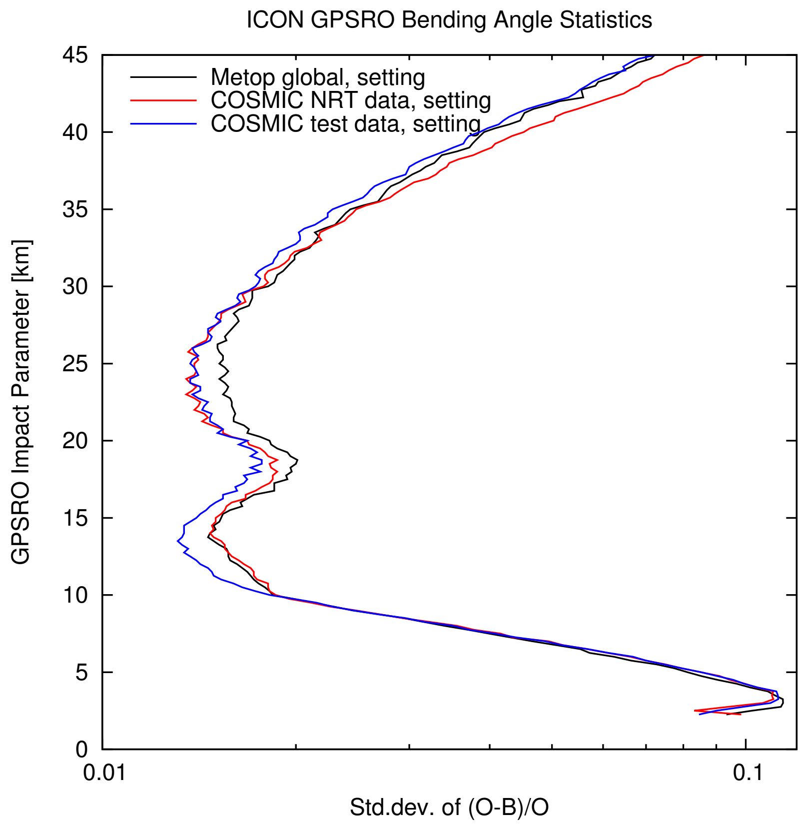

Thank you
for listening!

Backup Slides

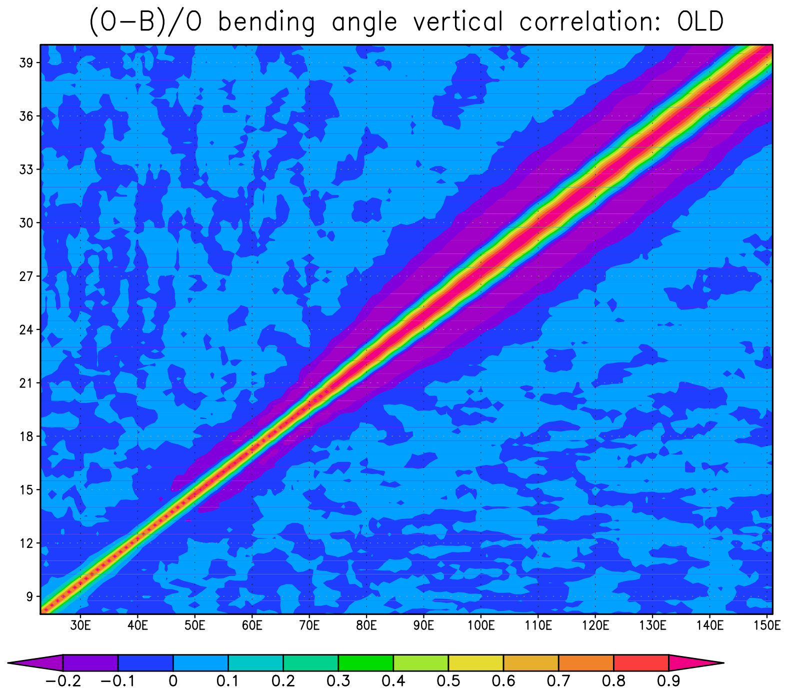
Metop vs. COSMIC NRT vs. COSMIC Test Data

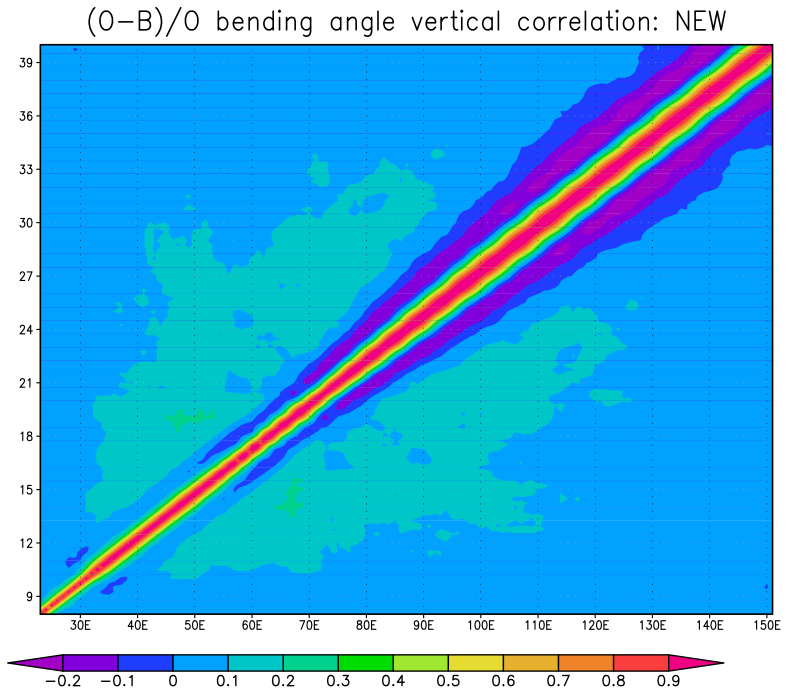
- Test period: 1–15 June 2014; ICON, 13 km horizontal resolution
- Comparison of Metop-A/B vs. COSMIC NRT vs. COSMIC test data
  - Global data: obs-fg standard deviation of rising and setting occs.

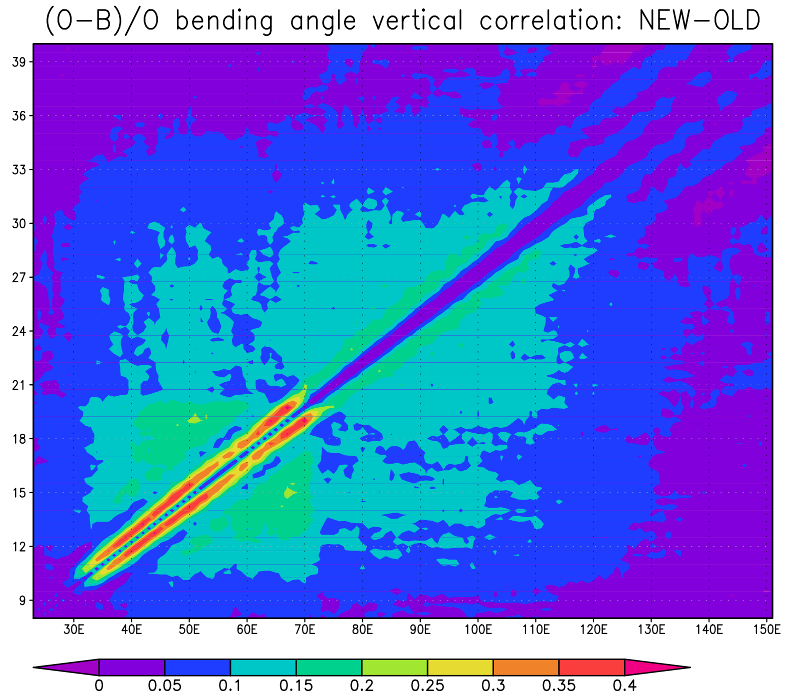




Vertical Correlations: COSMIC NRT vs. new inversion







- Test period: 1–15 June 2014
- ICON @ 13 km
- Vertical correlation of $(O - B)$ between 8–40 km impact height, binned to 0.25 km intervals
- **Increased vertical correlations** between 10–30 km with new inversion!