

Experiences from implementing GPS Radio Occultations in Data Assimilation for ICON

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



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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 $\text{std.dev.}(\text{obs-fg})$, numerically expensive!

History of GPS Radio Occultations at DWD

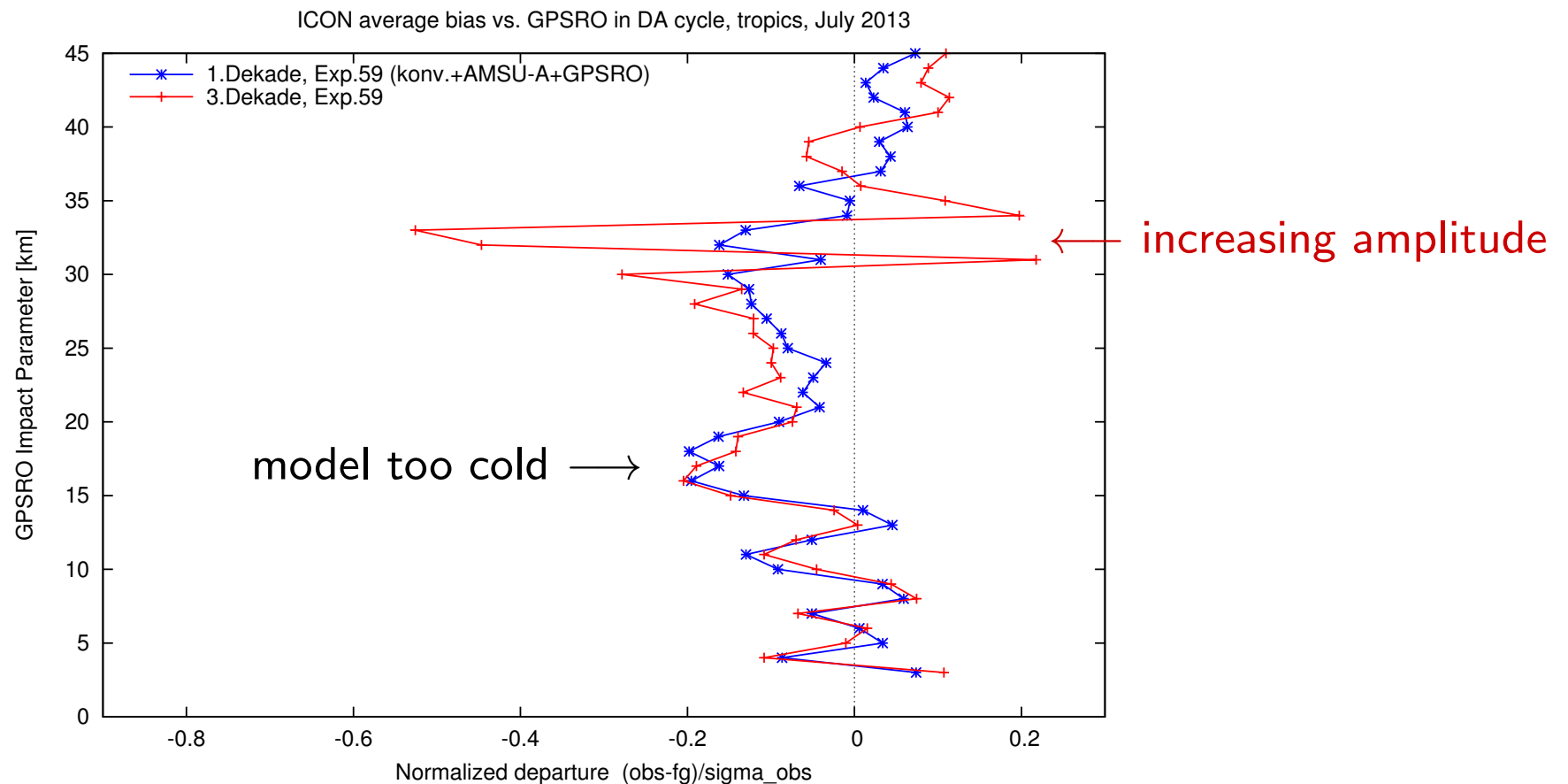
- 2008: DWD's 3D-Var-PSAS for GME becomes operational
 - ▶ Replaces former OI
- **2010**: operational implementation of GPSRO
 - ▶ 1d-operator with effective location of occultation
(H. Anlauf et al., doi:10.5194/amt-4-1105-2011, some later refinements, see my IROWG-2 talk)
 - ▶ only affordable option 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

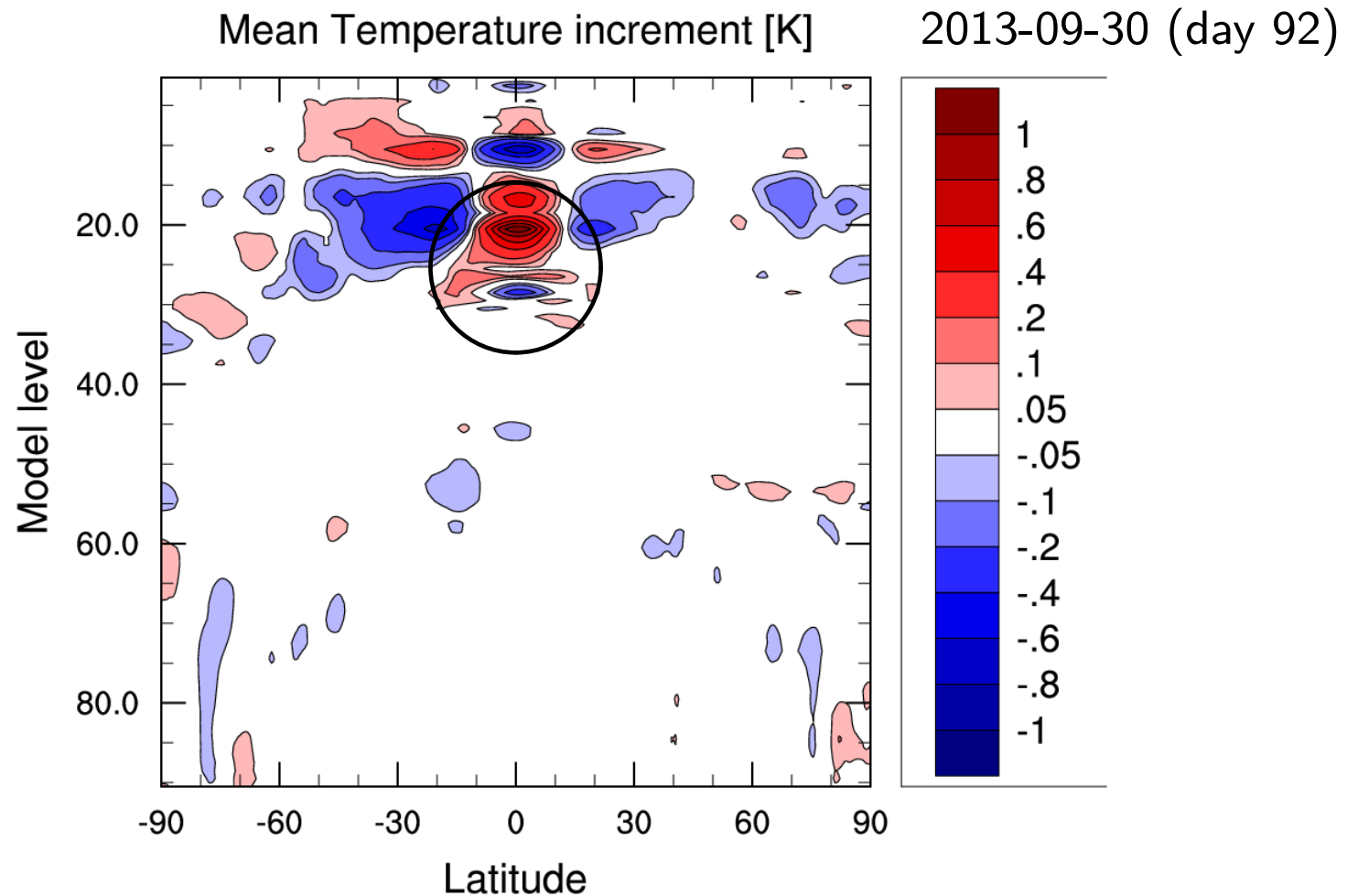
Diagnosing Model Biases and Data Assimilation Problems

- 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



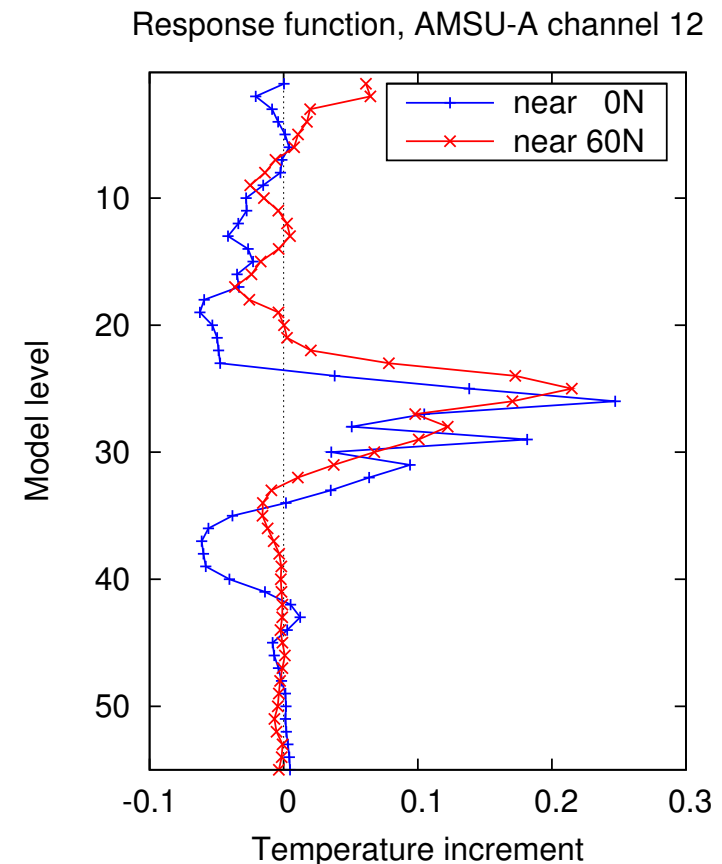
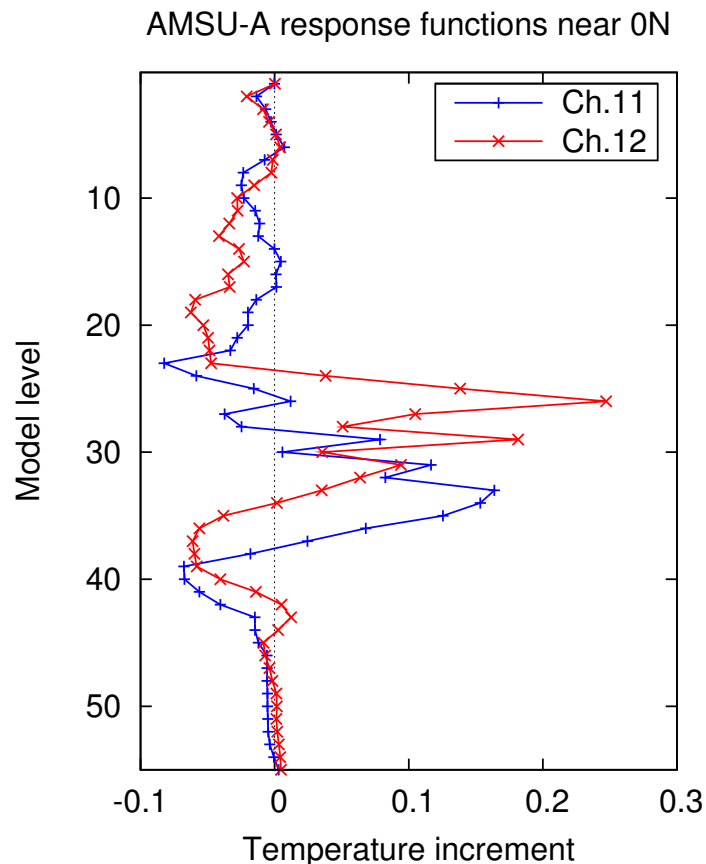
Diagnosing Model Biases and Data Assimilation Problems

- 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!)
 - ▶ $\Delta x^a \sim \mathbf{B}\mathbf{H}^T(\dots)$ 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 \Leftrightarrow 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!

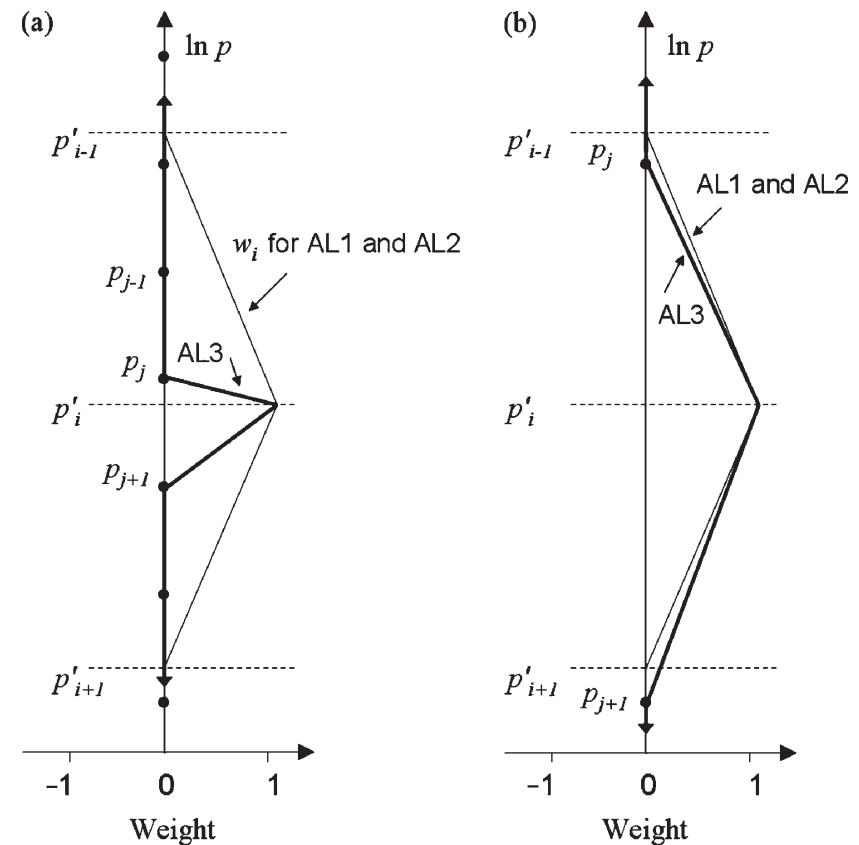
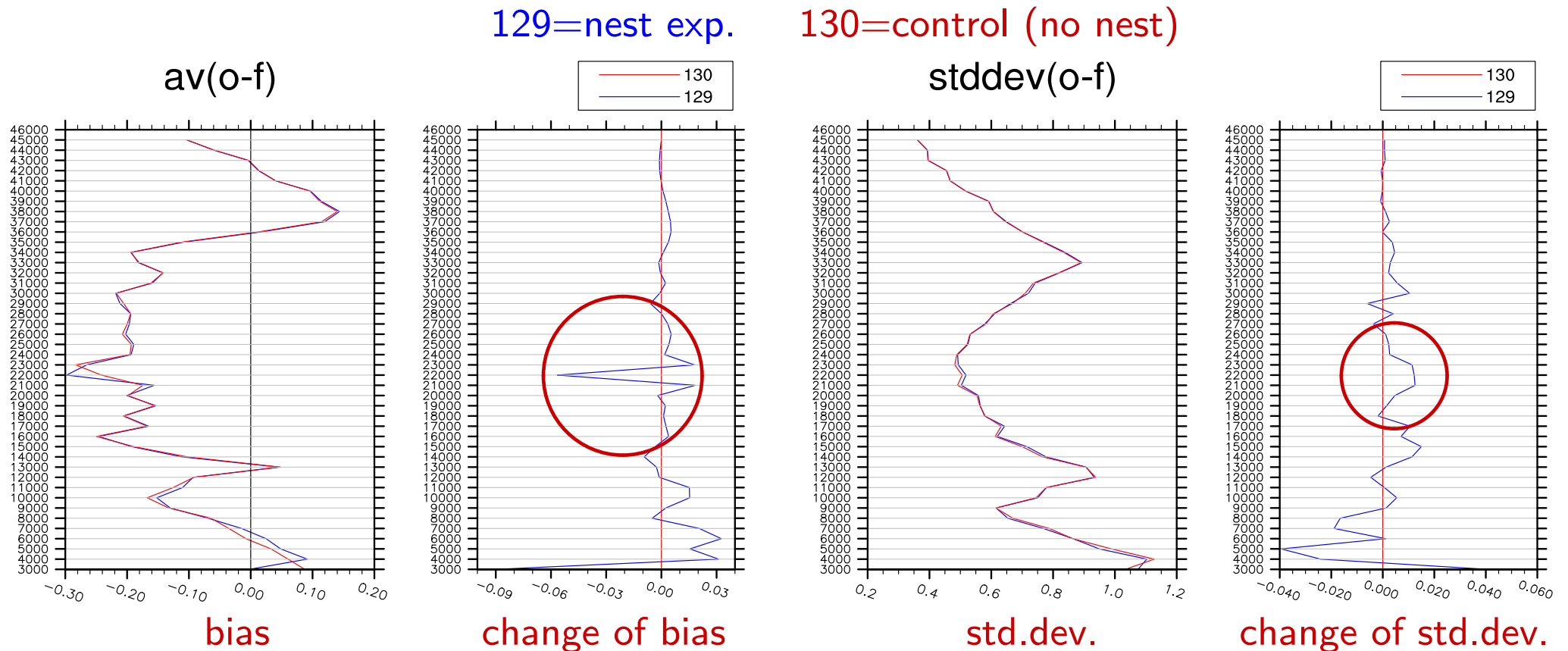


Figure A.1. Weighting functions w_i of the AL1 and AL2 weighted averaging interpolators (Equation (5); thin lines) and the AL3 log-linear interpolator using nearest points (Equation (A.5); thick lines). (a) and (b) show weighting functions for two different distributions of NWP levels.

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



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:

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

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

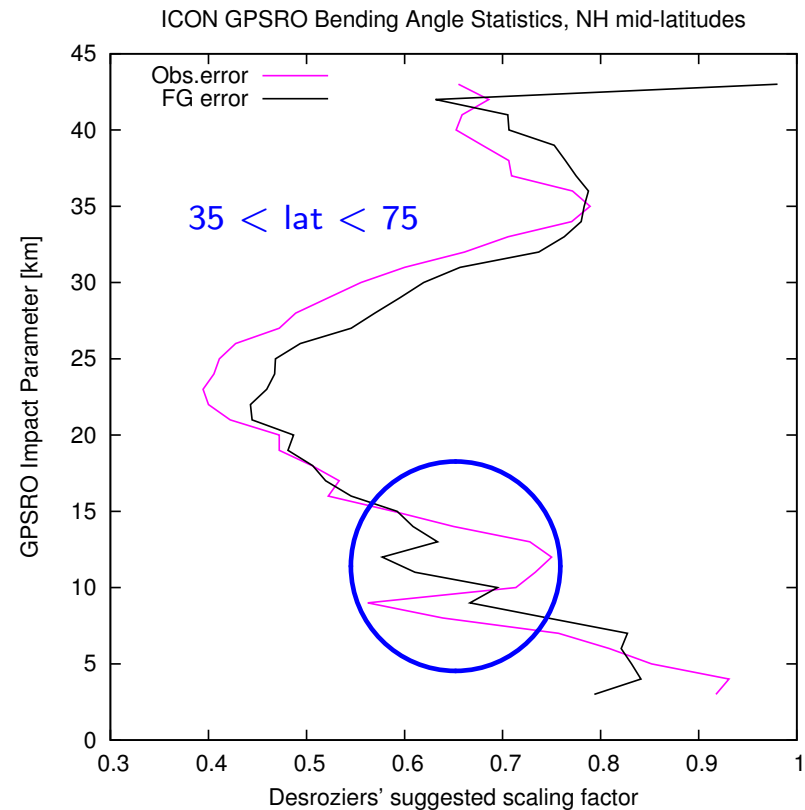
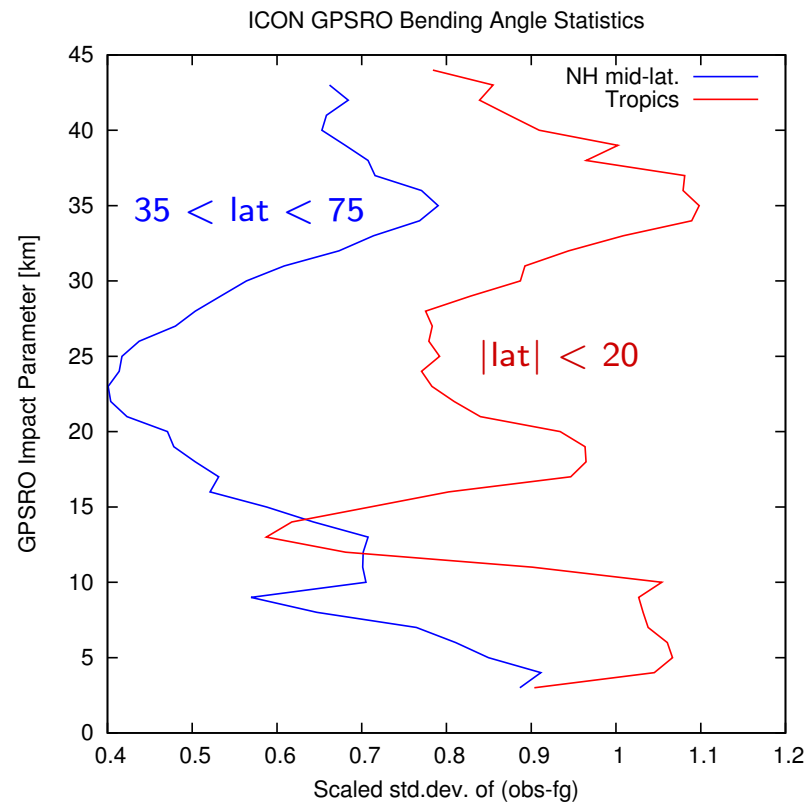
$$E \{ d_b^a (d_b^o)^t \} = \mathbf{HBH}^t$$

$$E \{ d_a^o (d_b^o)^t \} = \mathbf{R}$$

- Beware that:
 - ▶ Above estimators for \mathbf{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!)

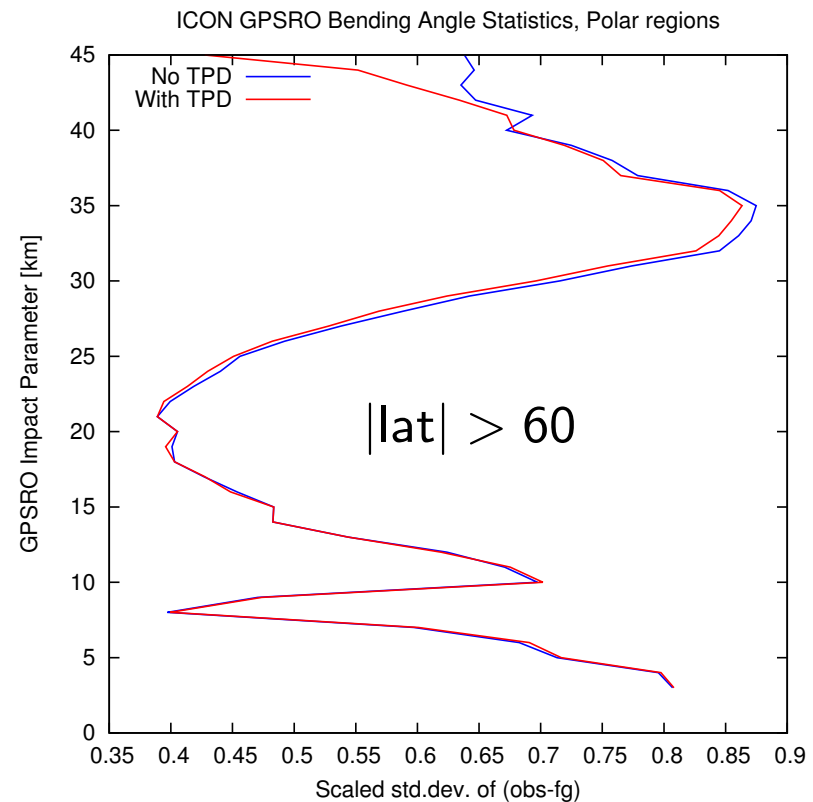
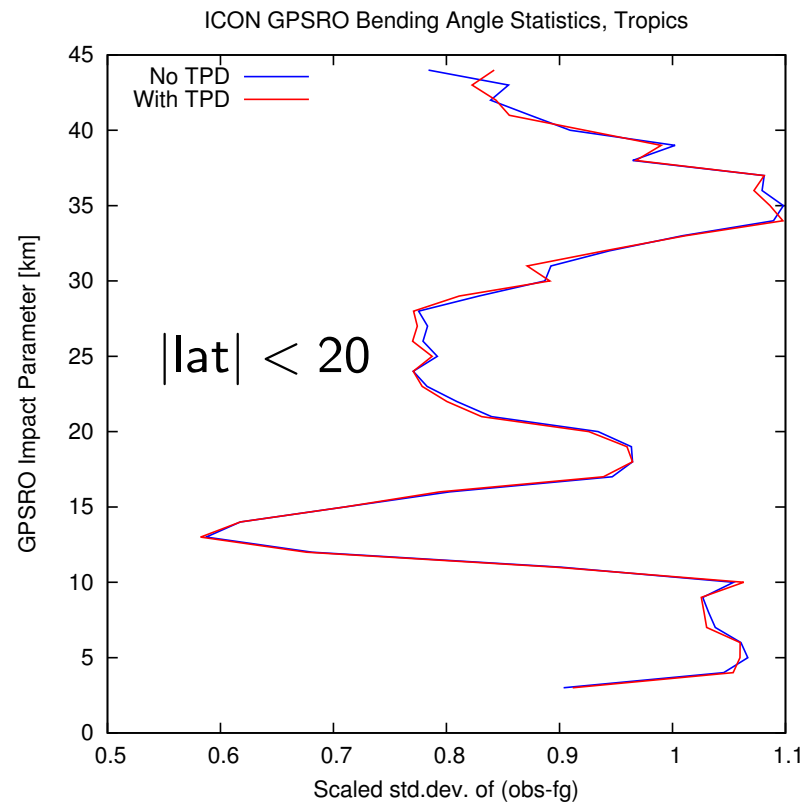
Assessment of operationally used error statistics

- 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



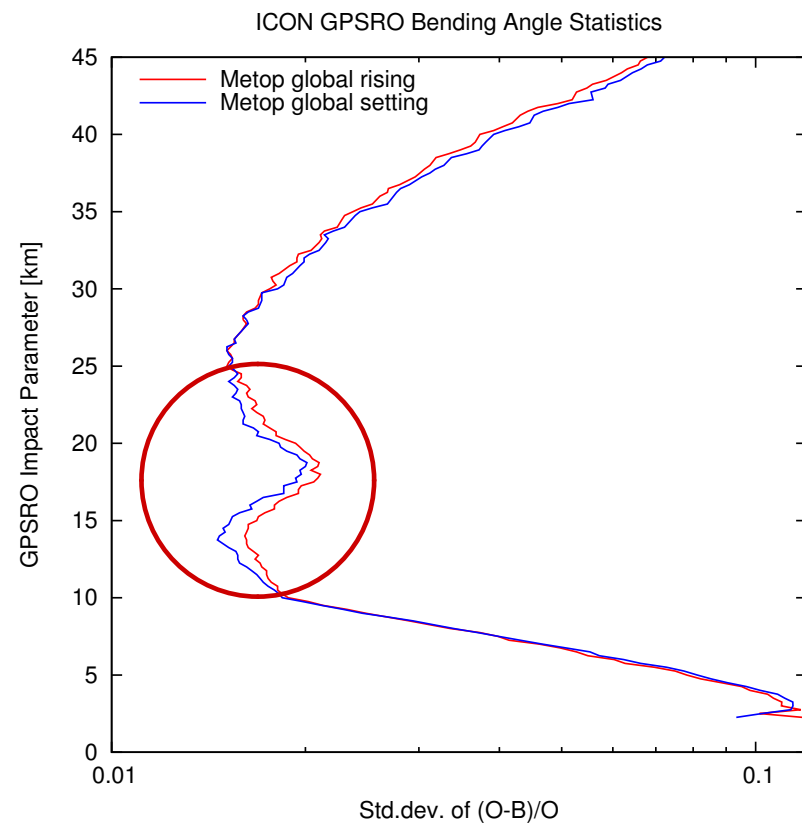
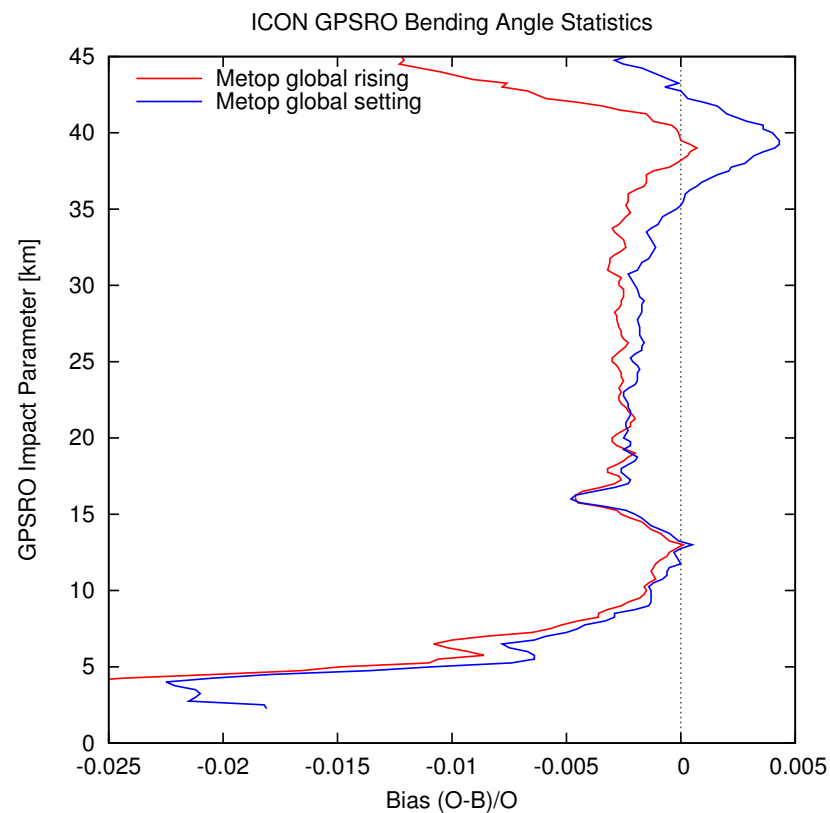
Observation Modeling: Tangent Point Drift

- 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



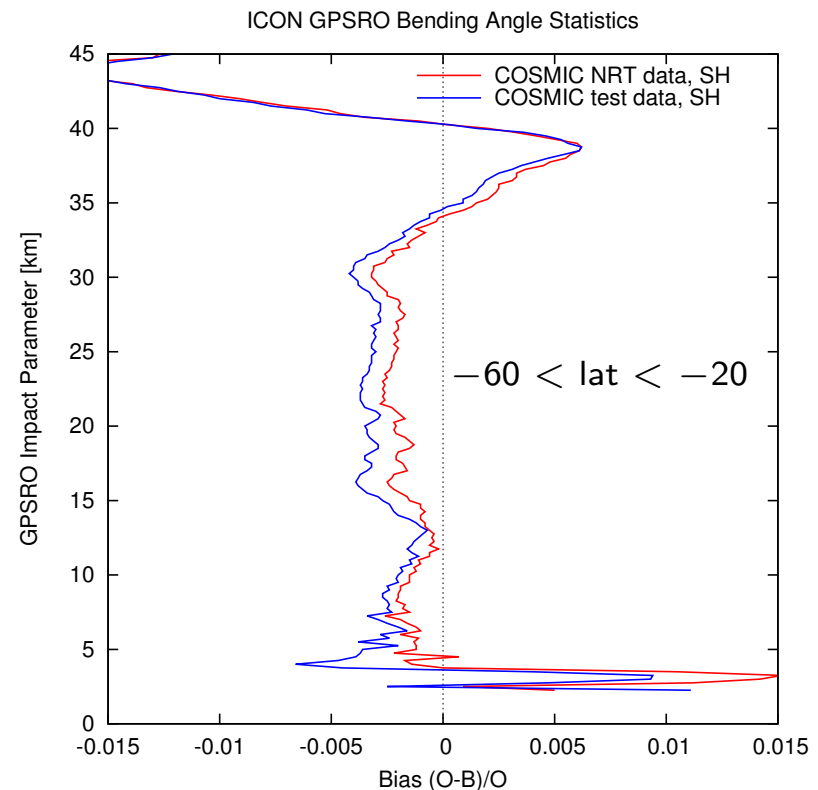
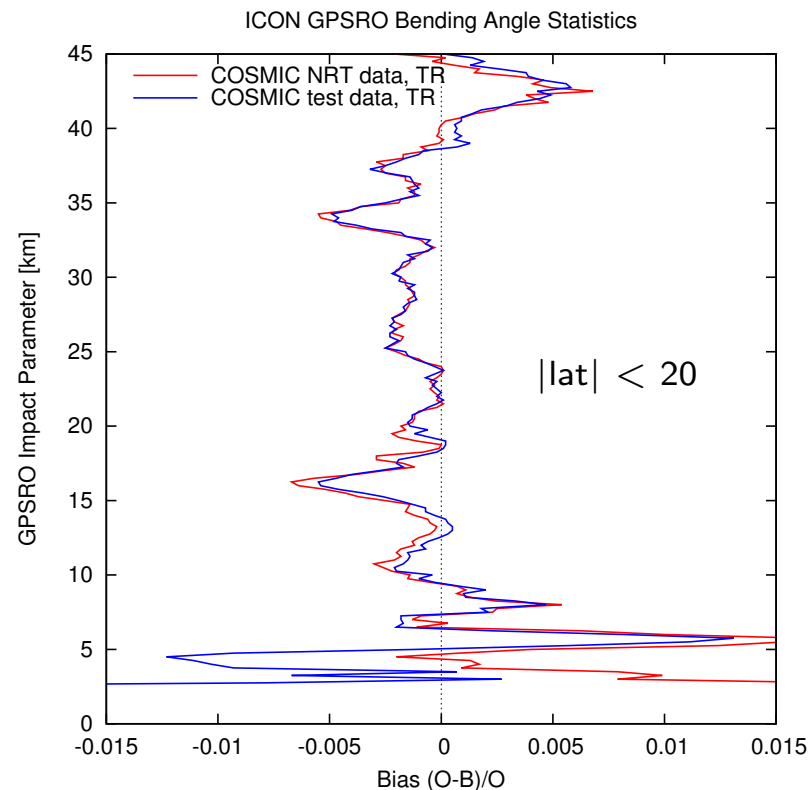
Quality of Available Observational Data: Metop/GRAS

- 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)



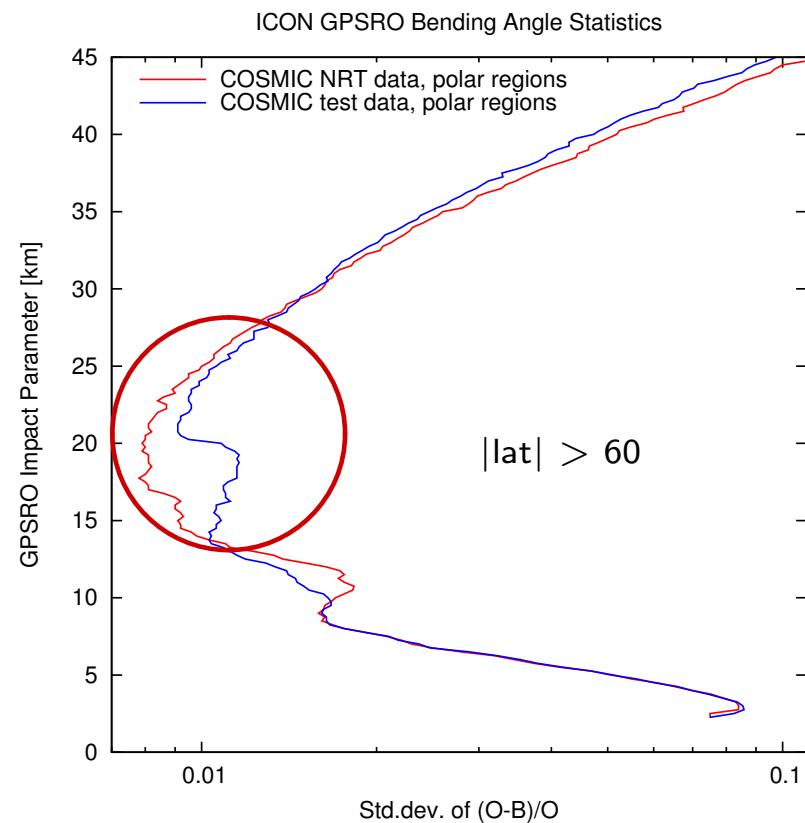
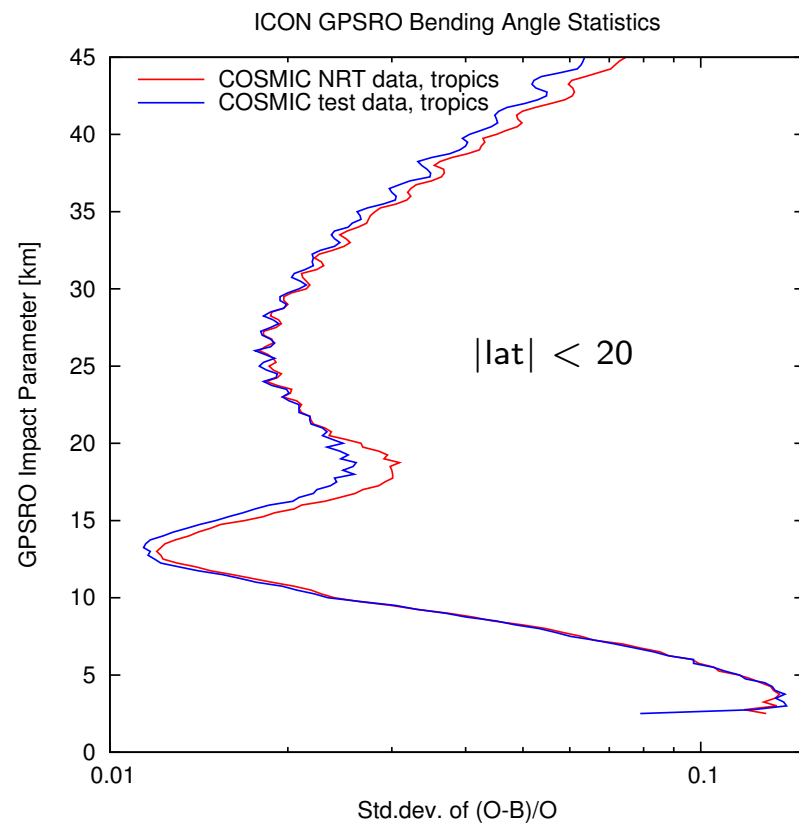
COSMIC: NRT Data vs. Test Data

- 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 (**R,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?

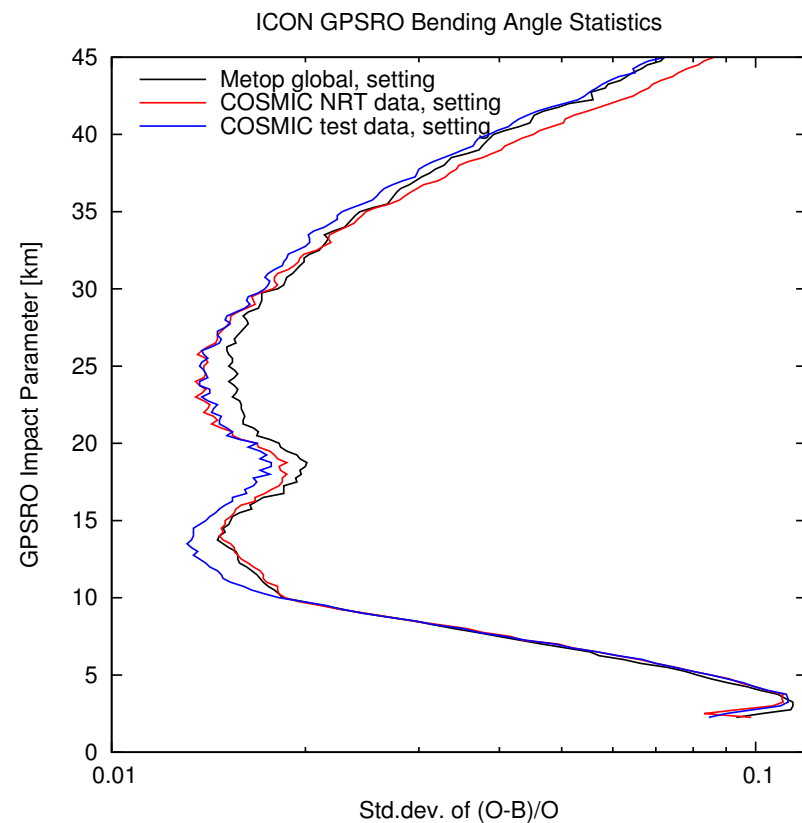
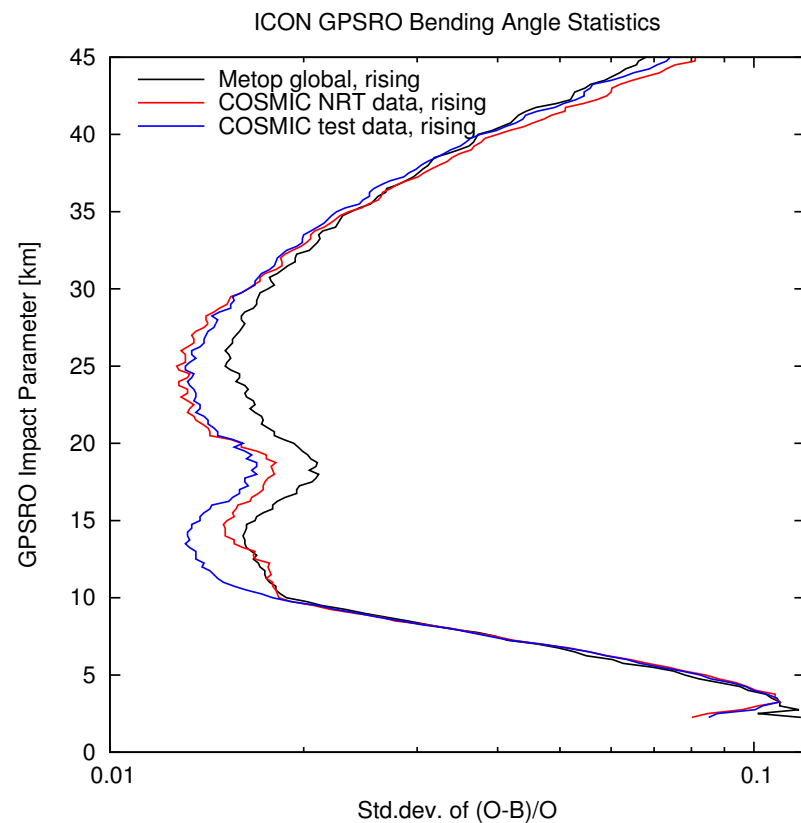
A photograph of a wooden structure, possibly a porch or a small building, with a corrugated metal roof. The structure is silhouetted against a bright, warm sunset sky. The sun is visible in the lower right corner, creating a lens flare effect. The overall color palette is dominated by warm oranges, yellows, and browns.

**Thank you
for listening!**

Backup Slides

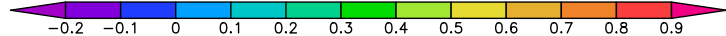
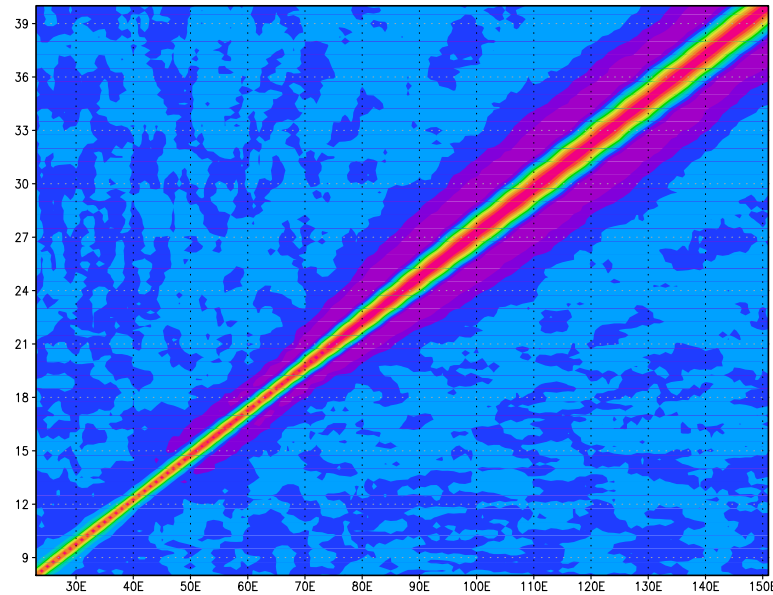
Metop vs. COSMIC NRT vs. COSMIC Test Data

- 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.

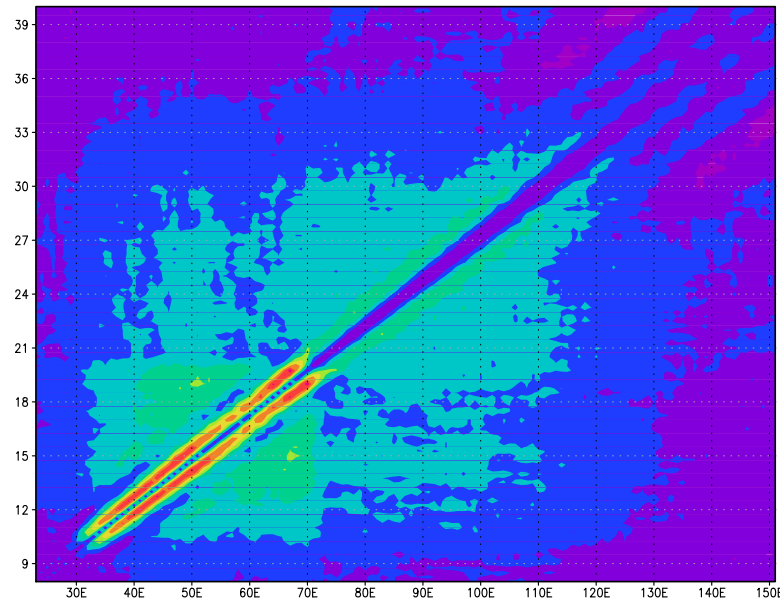


Vertical Correlations: COSMIC NRT vs. new inversion

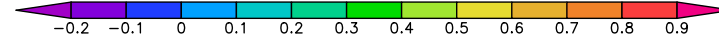
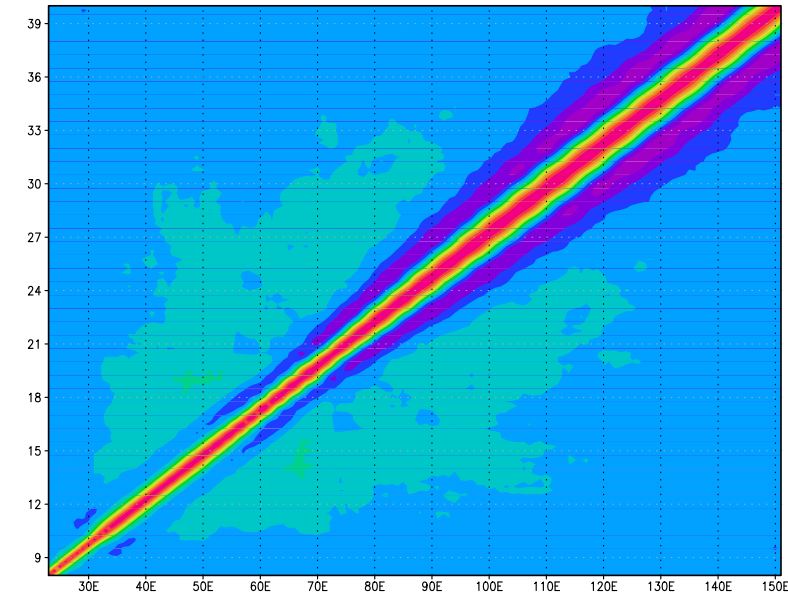
($O-B$)/ O bending angle vertical correlation: OLD



($O-B$)/ O bending angle vertical correlation: NEW-OLD



($O-B$)/ O bending angle vertical correlation: NEW



- 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!