Potential of the radio occultation mission

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The EUMETSAT Network of Satellite Application Facilities

GRAS SAF
GRAS Meteorology

ECMWF

Outline

- GPS Radio Occultation (GPS-RO) technique.

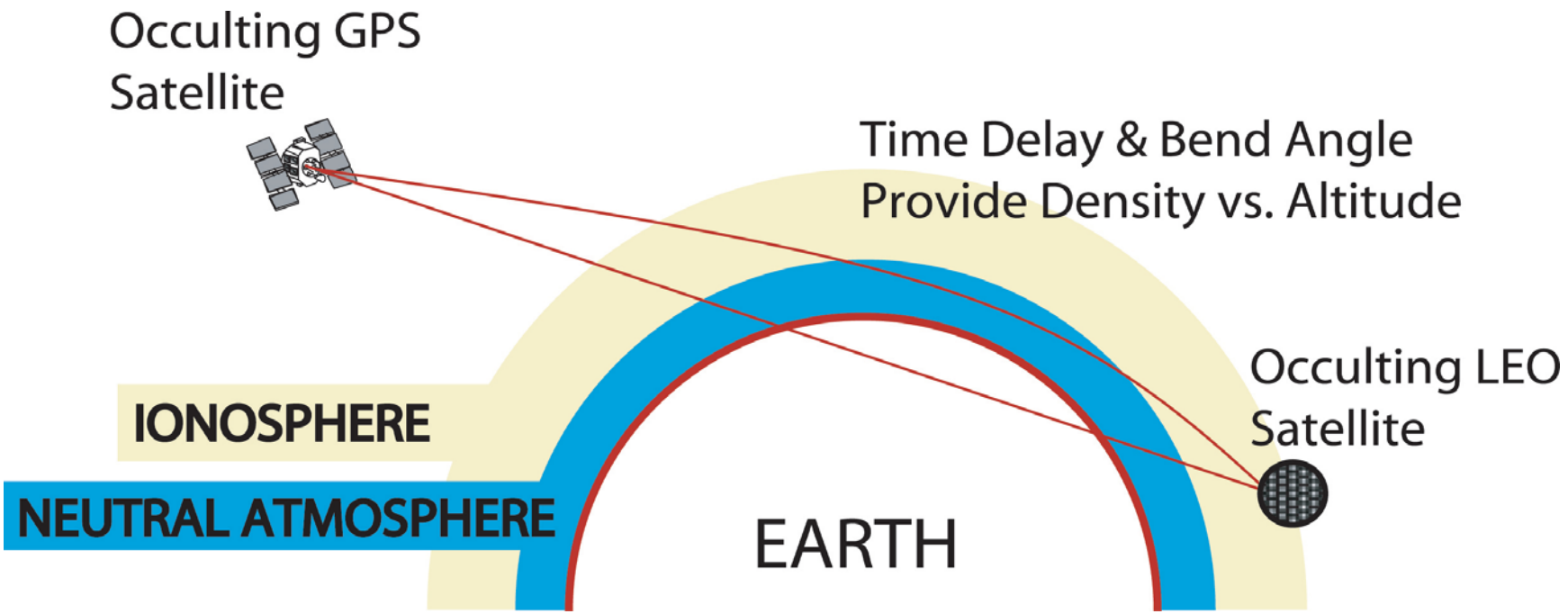
- User perspective on "**Why is GPS-RO are an important component of the Global Observing System?**".

  - Summarise the use/impact of GPS-RO in NWP.
  - Climate monitoring/reanalysis applications.

- The benefits of having a fully operational "GRAS-like **reference instrument**".

- **Areas of potential improvement for the next generation**
  - Use of Galileo, GLONASS signals.
  - Better tracking and exploitation in lower troposphere.

GPS radio occultation concept



Key measurement characteristics

- **Sharp weightings function provide good vertical resolution**. Horizontal resolution ~300-400 km.

- Fundamental measurement based on a time-delay with an atomic clock.

  - **The derived products (bending angle, refractivity) can be used without bias correction.**

- Globally distributed.

Use of GPS-RO in NWP

- **All the major Global NWP centres now assimilate GPS-RO measurements from GRAS, COSMIC and some research missions (eg, TSX, GRACE-A).**

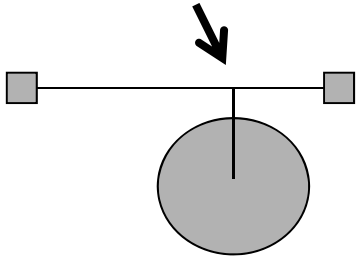
- NWP centres assimilate either:
  - Bending angle profiles (ECMWF, MF, Met Office, DWD, NRL)
  - Refractivity (NCEP, EC, JMA)

- **NWP centres assimilate the measurements without bias correction.**

- Essentially treat the information as a profile, not a 2D, limb measurement. **NWP centres have generally very found good impact on temperatures between ~7-35 km.**

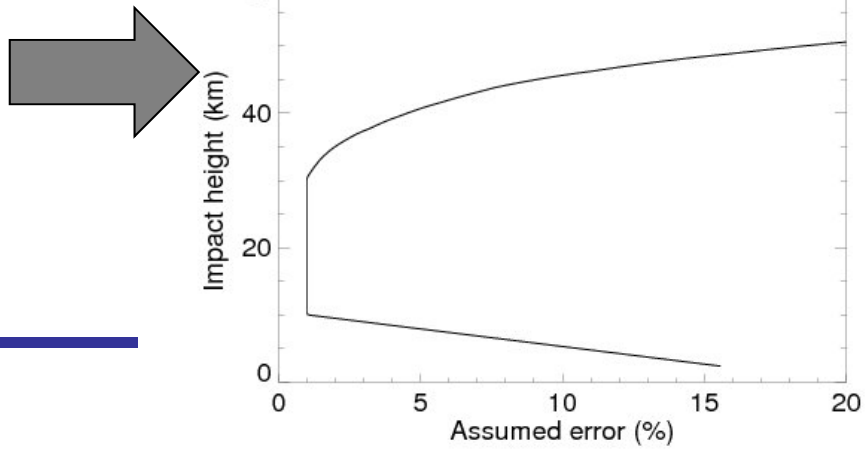
Assimilation approach at ECMWF

- We assimilate bending angles with a 1D operator. We ignore the 2D nature of the measurement and integrate



$$\alpha(a) = -2a\int_{a}^{\infty} \frac{d\ln n / dx}{\sqrt{x^2 - a^2}}\, dx$$

- The forward model is quite simple in comparison with RT codes **(Code in GRAS SAF's ROPP)**:
- Observation errors.



Impact at ECMWF

- ECMWF has assimilated GPS-RO bending angles operationally since December 12, 2006.

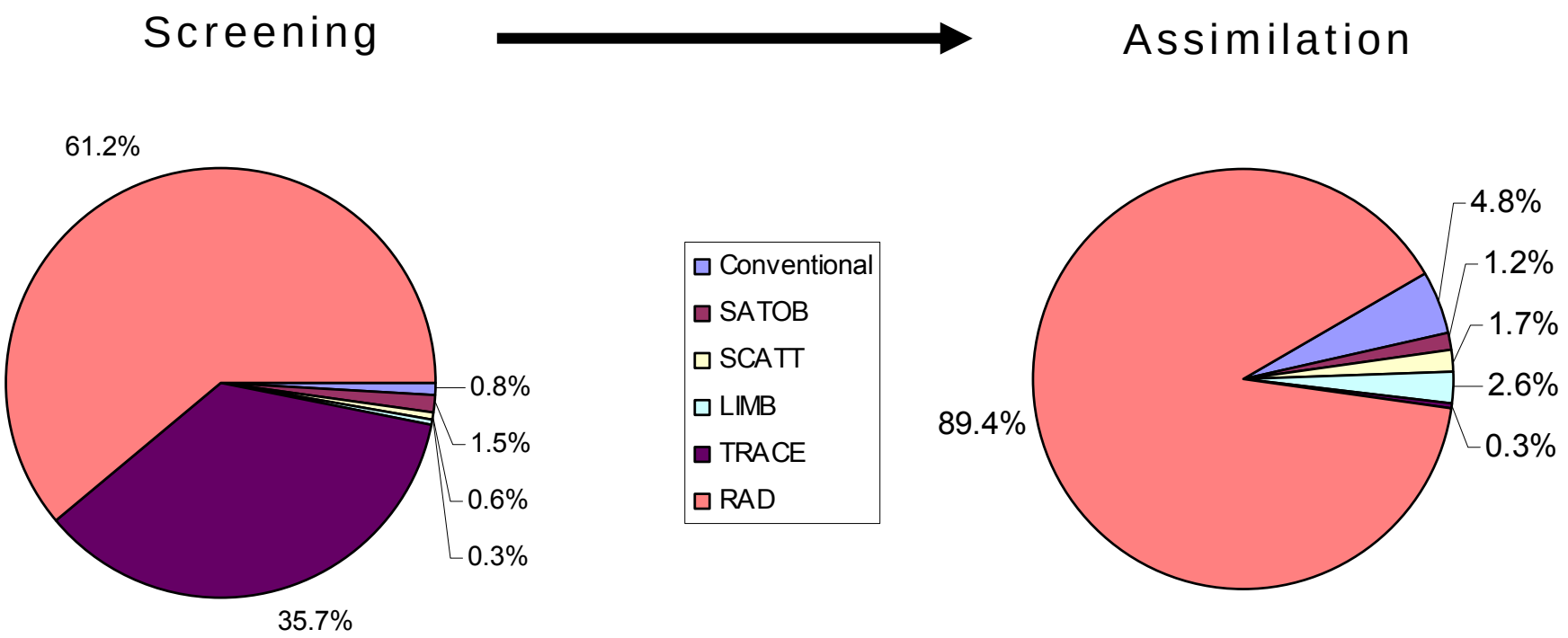
- **Success!** **Despite low observation numbers** – in comparison with the number of radiances – the impact has been very good.

- Main impact on upper-tropospheric and lower/mid stratospheric temperatures.

  - **GPS-RO measurements are assimilated without bias correction, so they can correct (some) model biases.**

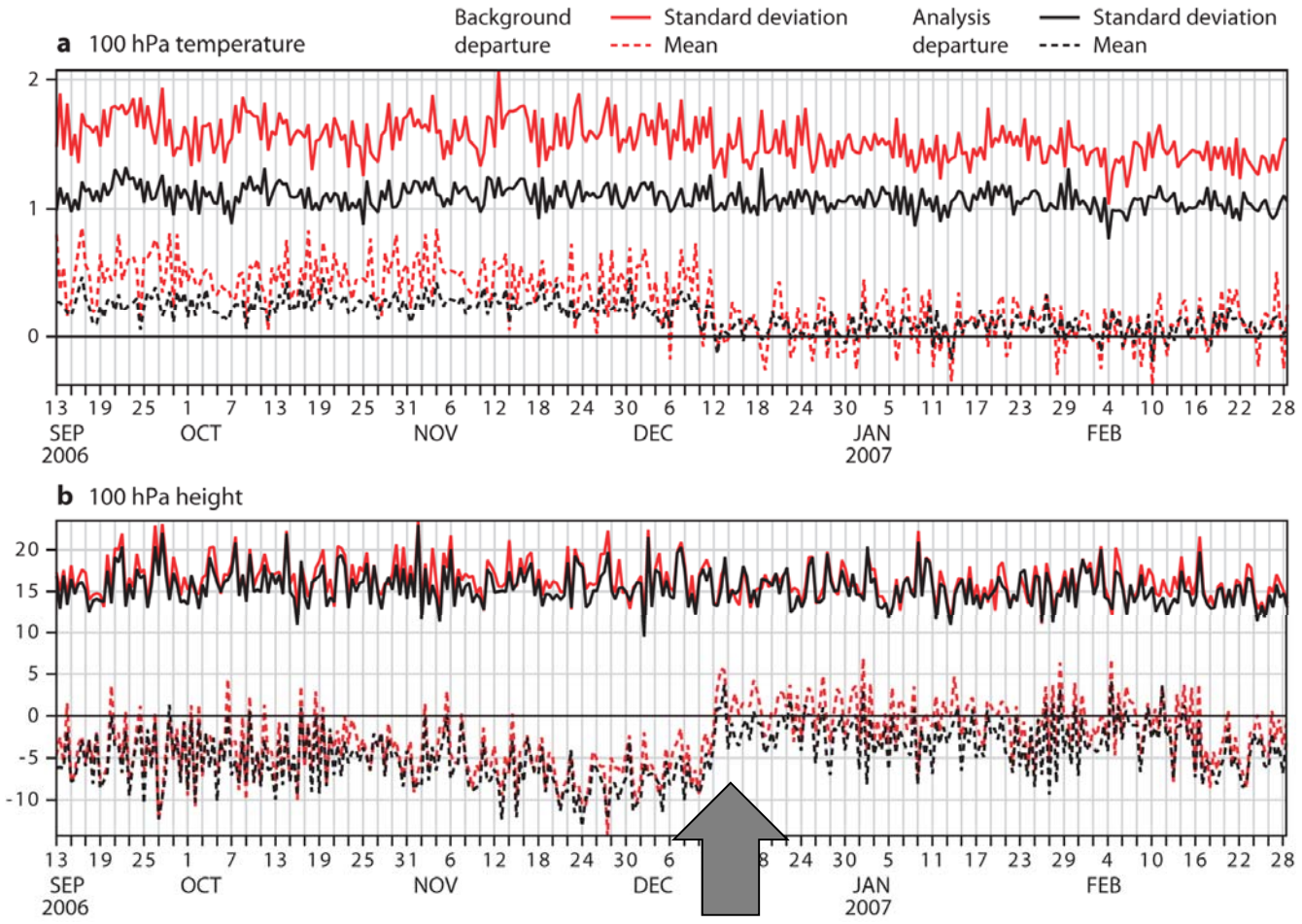
  - **Very good vertical resolution, so they can correct errors in the "null space" of the radiance measurements.**

Data types



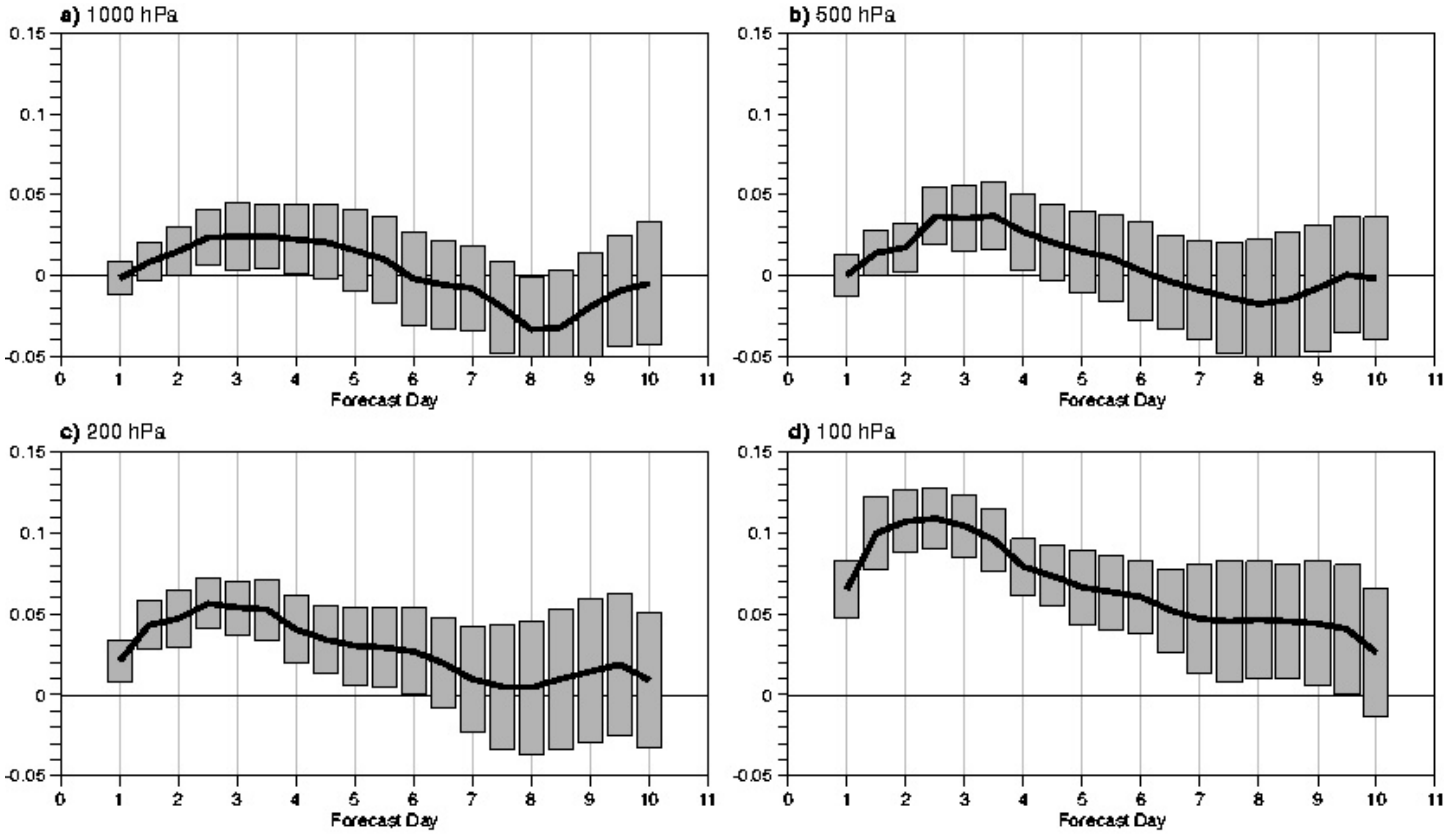
- Satellite data amounts to 99% in screening and 95% in assimilation.
- Radiance data dominates assimilation with 90%.
- **GPS-RO data contributes only ~2-3 % of the assimilated observations .**

Impact of GPS-RO on ECMWF operational biases against radiosonde measurements



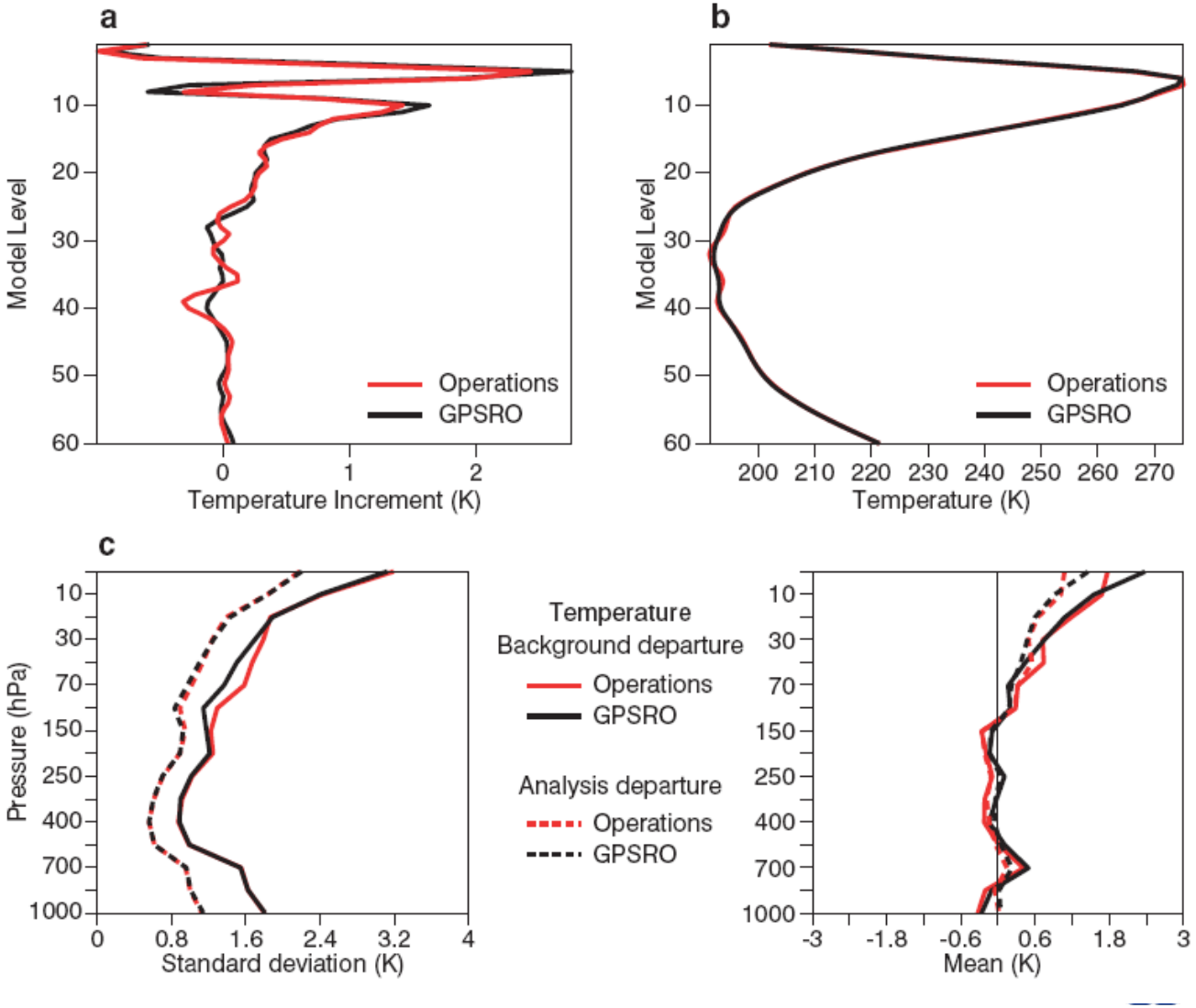
Operational implementation

Fractional improvement in the southern hemisphere geopotential height RMS scores



Similar results obtained at the other major NWP centres.

Stratospheric ringing problem over Antarctica solved by assimilating GPS-RO



Adjoint-based data assimilation diagnostics (ECMWF work by Carla Cardinali)

- Data assimilation scientists at NWPcentres have developed sophisticated techniques to estimate which observing systems (e.g. all AMSU-A) contribute most in reducing the ***24 hour forecast errors***.

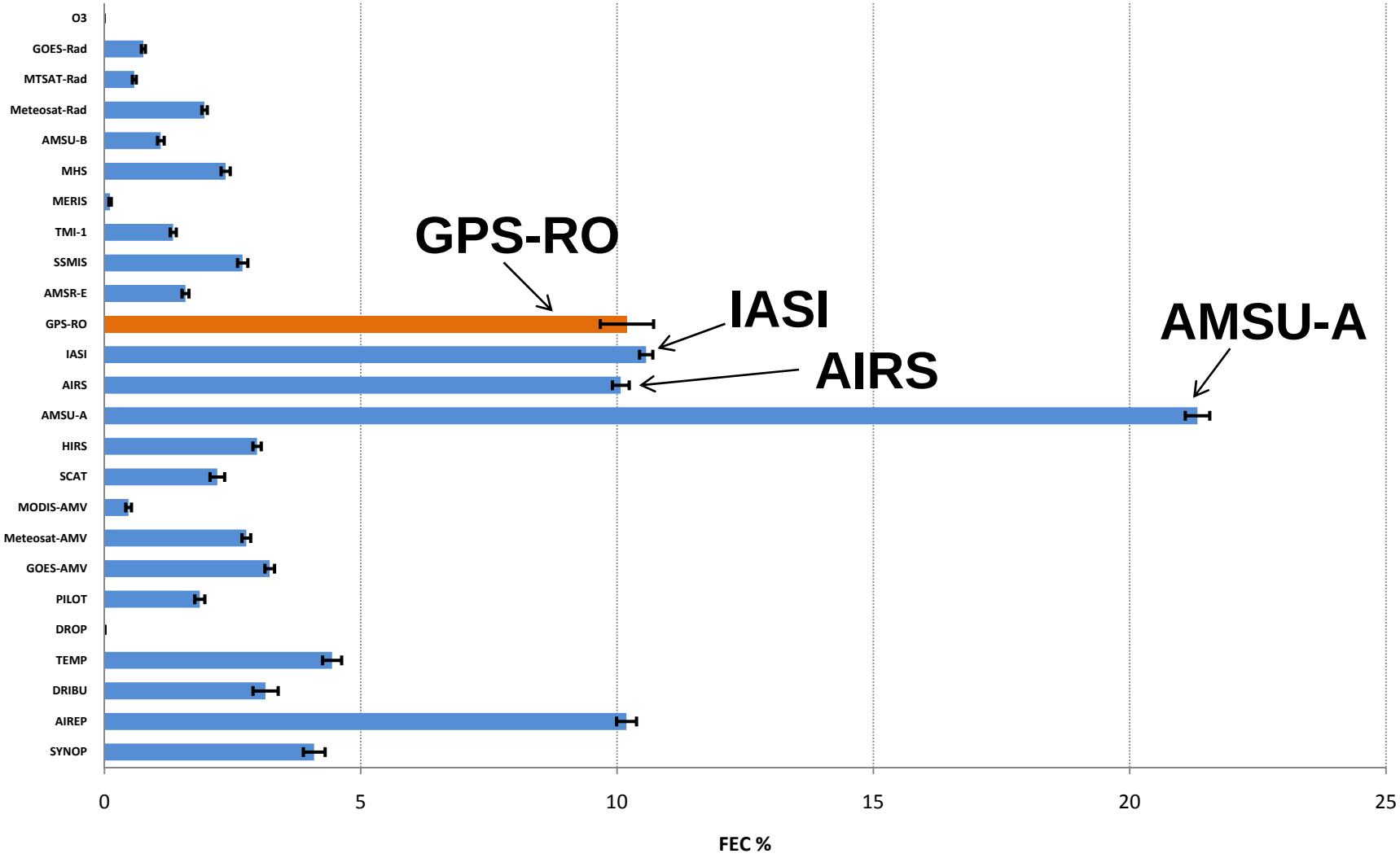
- The mathematics can be found in ECMWF Tech Memo 599 (http://www.ecmwf.int/publications/library/do/references/list/14).

- Essentially, they look at how the observing systems reduce the 24hr errrors in a **weighted average** of (*surface pressure, tropospheric and* ***stratospheric*** *temperatures and winds*).

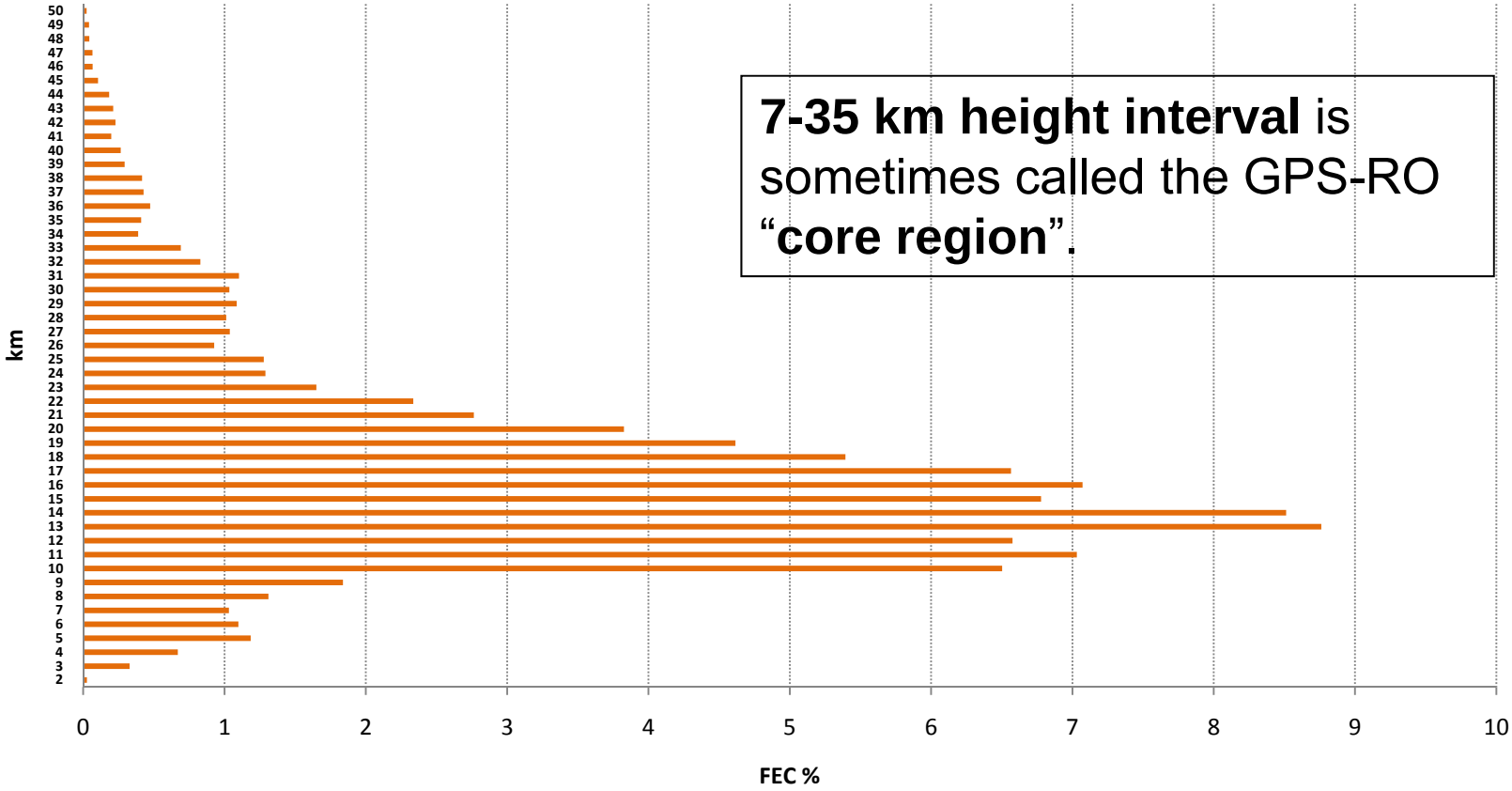
- **Latest ECMWF results from June 2011. GPS-RO scores well because of its impact in the stratosphere.**

ECMWF

ECMWF System (June 2011)



Heights where GPS-RO is reducing the 24hr errors



Remark: Agrees with early 1D-Var information content studies.

GPS-RO and the bias correction of radiances

- "**Bias correction schemes need to be grounded by a reference.**" The reference measurements are often called **"anchor"** measurements.

- "**Recommendation to NWP Centres** to identify part of global observing system (e.g. high quality Radio-sondes, GPS Radio Occultation) as reference network which is actively assimilated but NOT bias corrected against an NWP system."

Working group 3, ECMWF/EUMETSAT NWP-SAF Workshop on "Bias estimation and correction in data assimilation" (2005).

http://www.ecmwf.int/newsevents/meetings/workshops/2005/NWP_SAF/index.html

VarBC is used at ECMWF

Dee, QJRMS (2007), **131**, pp 3323-3343

- Bias corrected radiances are assimilated.

$$\tilde{\mathbf{y}} = \mathbf{y} - \mathbf{b}(\boldsymbol{\beta}, \mathbf{x})$$

$$\mathbf{b}(\boldsymbol{\beta}, \mathbf{x}) = \sum_i \beta_i \mathbf{p}(\mathbf{x})$$

$$J(\mathbf{x}, \boldsymbol{\beta}) = (\mathbf{x_b} - \mathbf{x})^{\mathrm{T}} \mathbf{B}_{\mathbf{x}}^{-1} (\mathbf{x_b} - \mathbf{x})$$

$$+ (\boldsymbol{\beta}_{\mathbf{b}} - \boldsymbol{\beta})^{\mathrm{T}} \mathbf{B}_{\boldsymbol{\beta}}^{-1} (\boldsymbol{\beta}_{\mathbf{b}} - \boldsymbol{\beta}) +$$

$$(\mathbf{y} - \mathbf{b}(\boldsymbol{\beta}, \mathbf{x}) - H(\mathbf{x}))^{\mathrm{T}} \mathbf{R}^{-1} (\mathbf{y} - \mathbf{b}(\boldsymbol{\beta}, \mathbf{x}) - H(\mathbf{x}))$$

In the 4D-Var, we minimize an augmented cost function, where the bias coefficients are estimated.

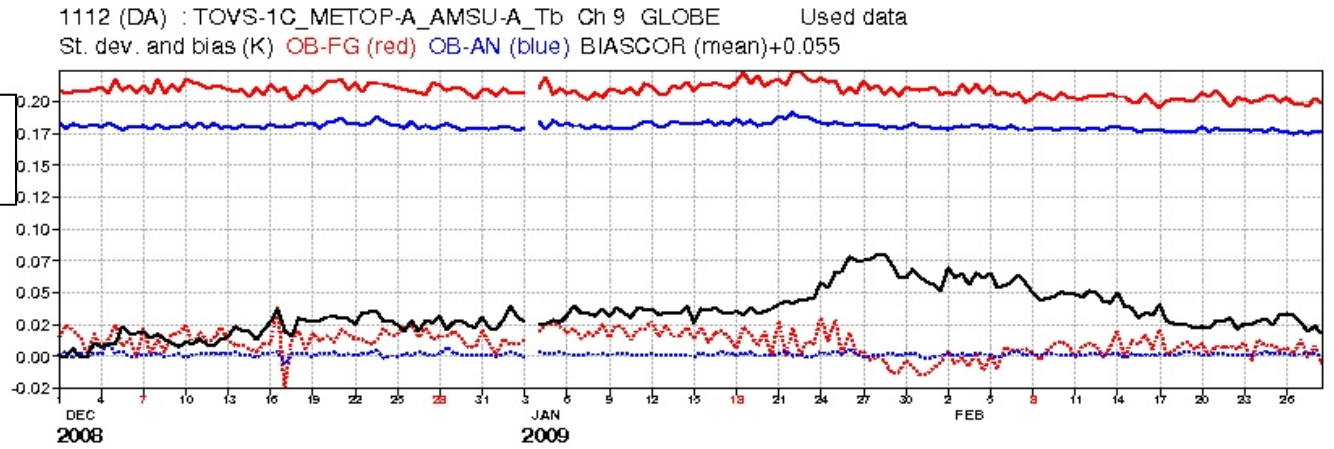
- **VarBC assumes an unbiased model.**

ECMWF

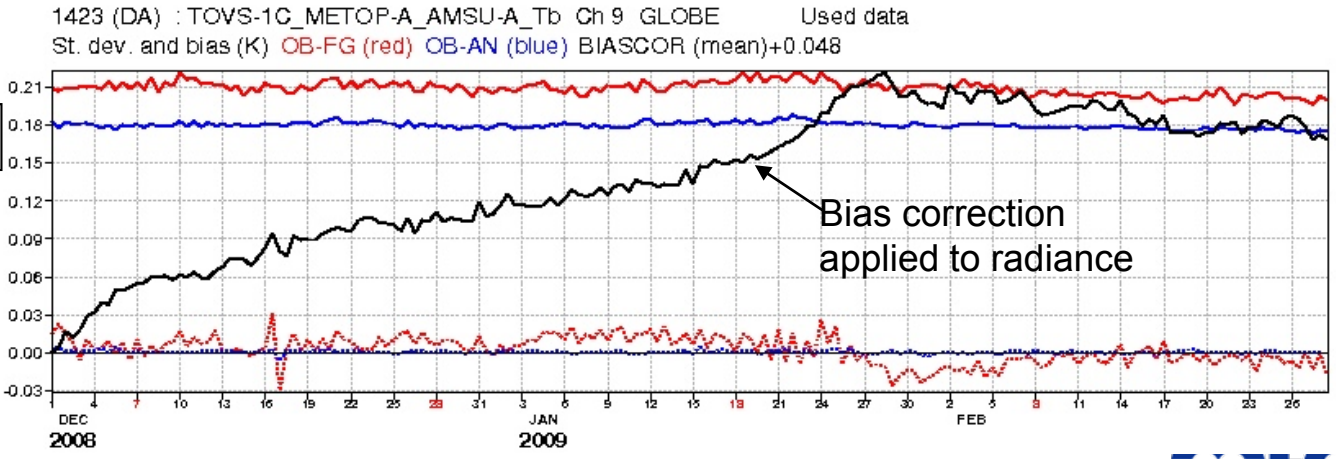
Recent experiment removing GPS-RO from ERA-Interim (Dec. 08, Jan-Feb 09)

- Impact on bias correction. E.g., globally averaged **MetOP-A**, **AMSU-A channel 9 bias correction**.

GPSRO assimilated



No GPSRO



A future developments in data assimilation perspective

- **Weak constraint 4D-Var** estimates the NWP model error during the assimilation window.
  - The model error estimate is derived from the observations.
  - **Similar arguments to VarBC**, measurements that do not require bias correction to the model, should be especially valuable for estimating model errors/biases.
- **Ensemble Kalman Filters (EKFs).** Current experience suggests it is easier to use GPS-RO in EKFs than radiances because of the width of the radiance weighting functions. Fewer vertical localization issues.

Climate/re-analysis applications

- **RO is likely to become more useful for climate monitoring as the time-series lengthens (*see also work by RoTrends project*).**

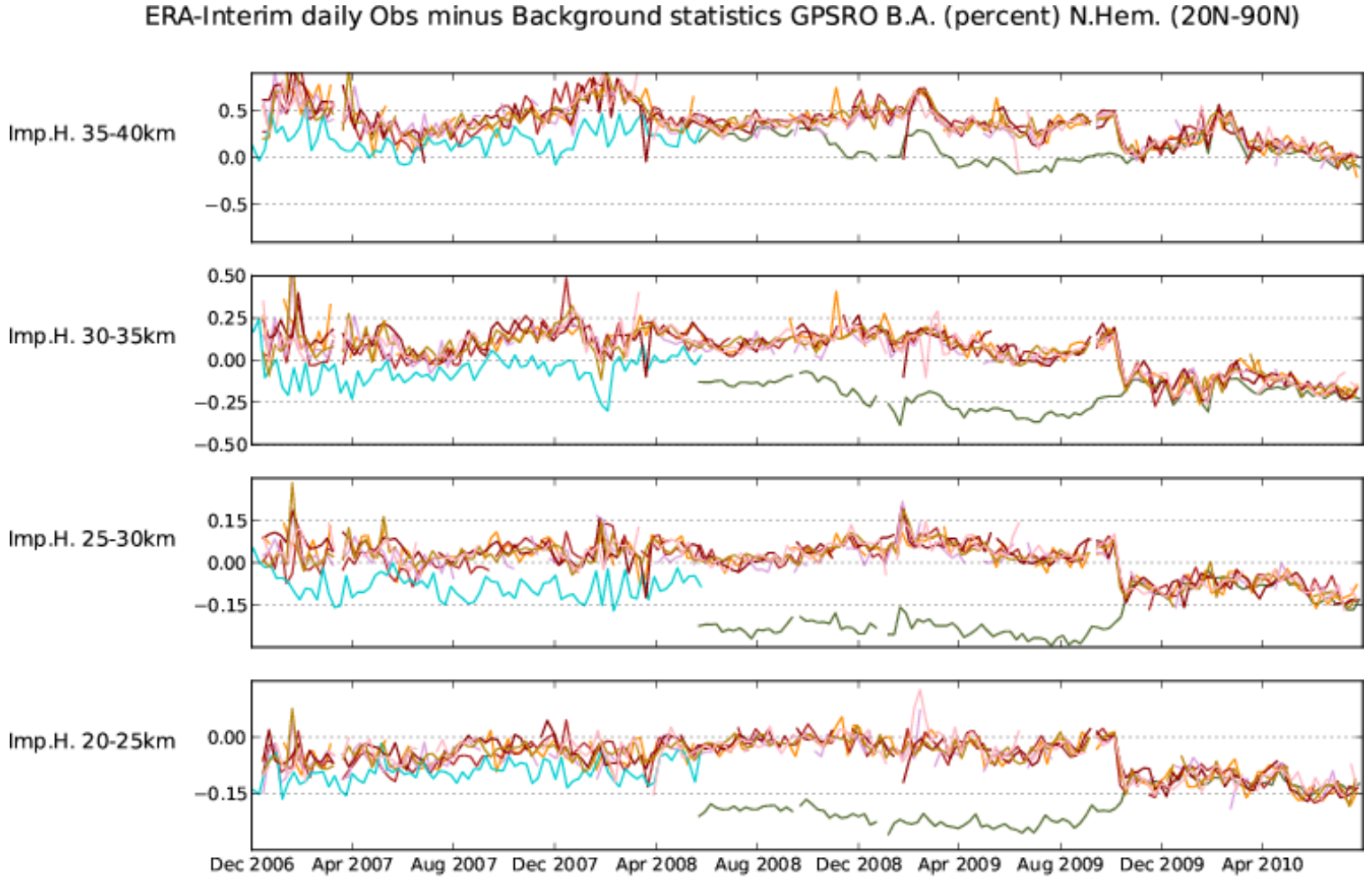
- Claim: GPS-RO measurements should not be biased.

  – It should be possible to introduce data from new instruments without overlap periods for calibration.

  – No discontinuities in time-series as a result of interchange of GPS-RO instruments.

- **Bending angle departure statistics derived from the ERA-Interim reanalysis can be used to investigate this claim.**

Consistency of GPS-RO bending angles (ERA-Interim Reanalysis, Paul Poli)



GPS-RO for climate monitoring

Simulation study using the Hadley Centre climate model

Simulation studies to assess:

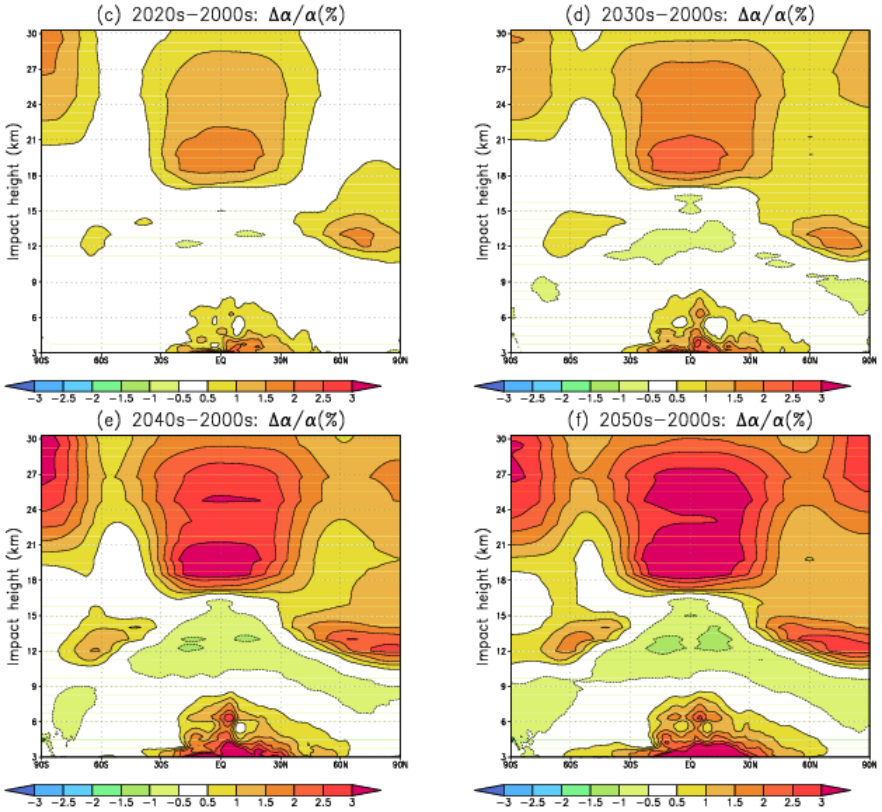
- potential of GPS-RO for detecting climate trends
- information content of GPS-RO in relation to other sensors

Simulations use:

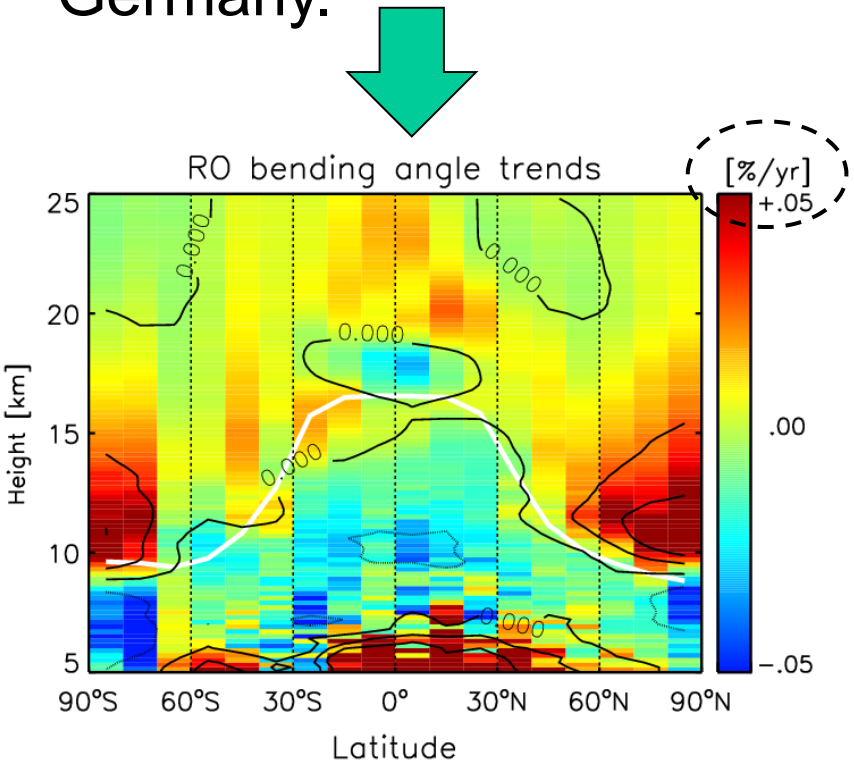
- Met Office Hadley Centre coupled climate model (HadGEM1)
- Climate change scenario (A1B) for 2000 – 2100
- Forward modelling of the GPS-RO bending angles
- Forward modelling of MSU/AMSU brightness temperatures

Provided by Mark Ringer (Hadley Centre)

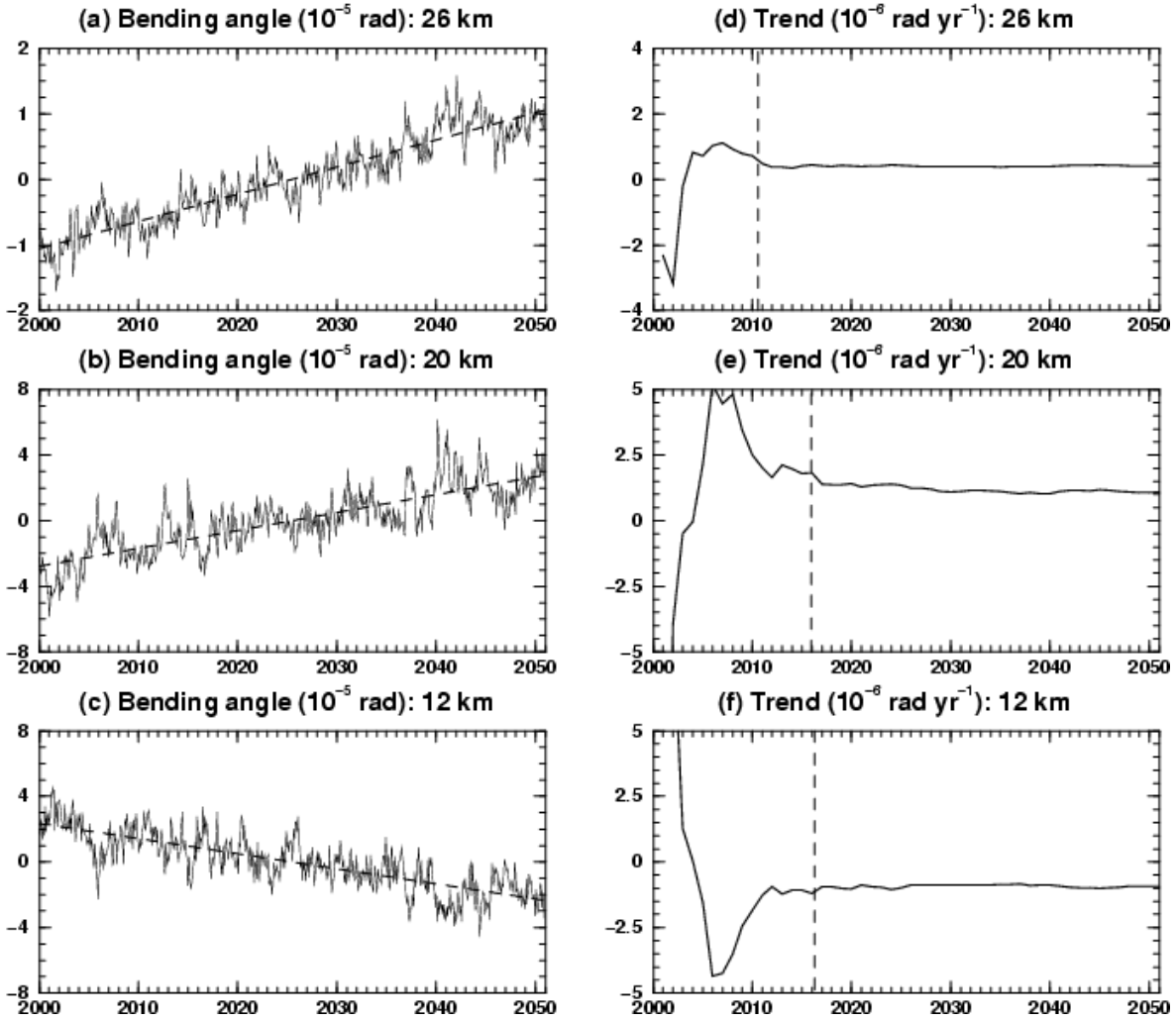
Initial comparison with observations



Bending angle trends 2001 – 2011. Courtesy of Torsten Schmidt, GFZ, Potsdam, Germany.



Trends in the tropics may be detectable in about ~15 years



Detection times

(95% confidence intervals)

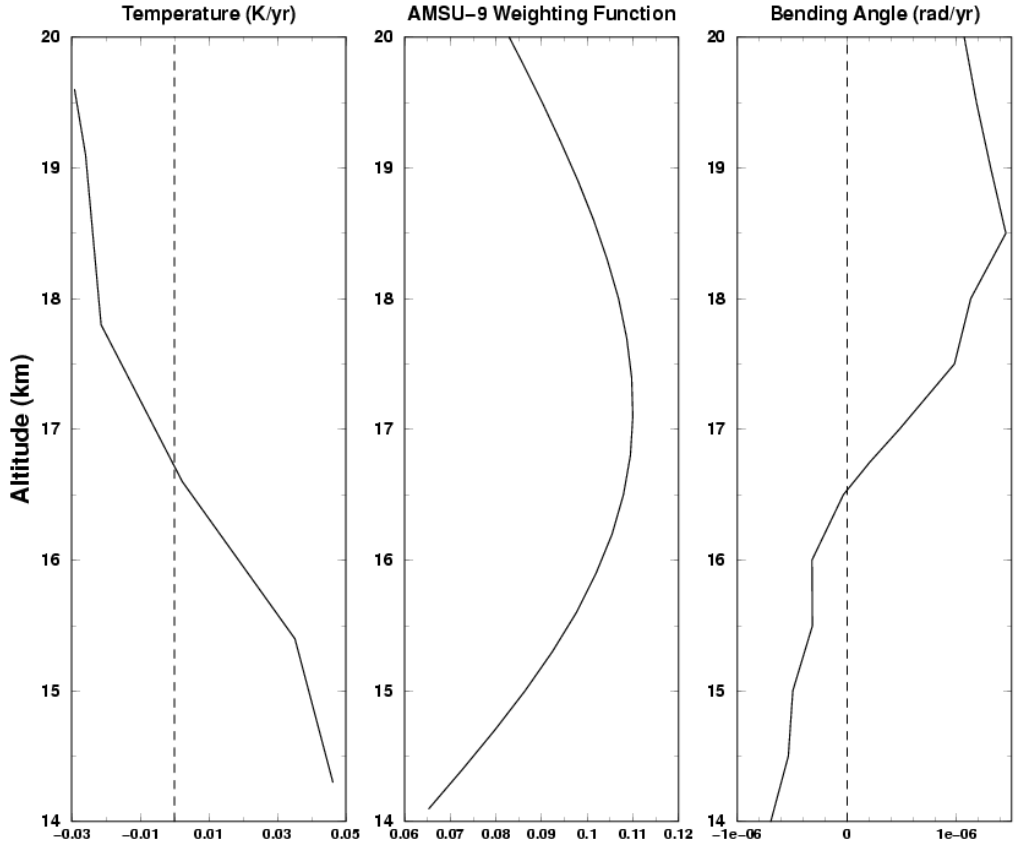
26 km: 9.4 – 11.7 years

20 km: 13.6 – 18.7 years

12 km: 14.6 – 18.2 years

ECMWF

Difficult to see any signal with AMSU-A channel 9 in the tropics because of width of the weighting function



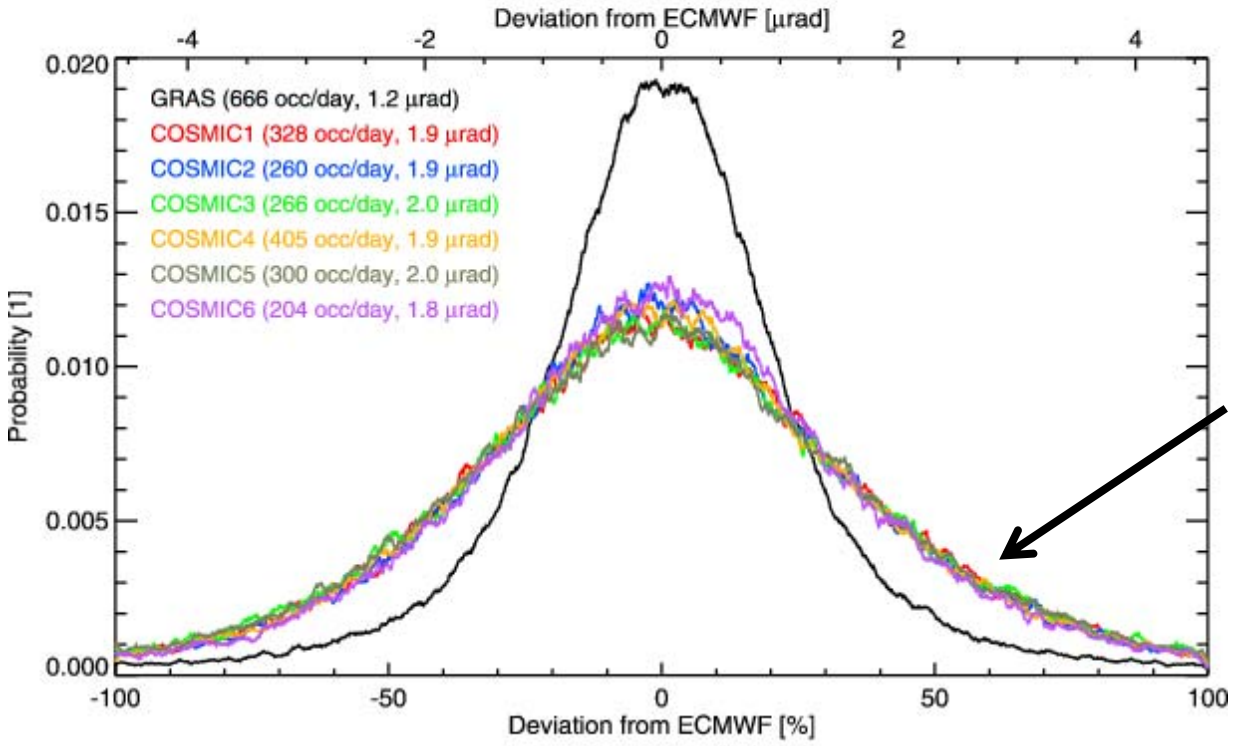
Climate signal in tropics is in the "null-space" of the AMSU-A measurement!

ECMWF

GRAS is the only fully operational GPS-RO instrument

- We can see clear advantages of having a fully operational instrument.
  - Noise characteristics.
  - Consistent, stable data numbers.
  - **GRAS has 1000 Hz sampling in open-loop mode, but we have not yet exploited this because of geometrical optics processing.**

GRAS has significantly lower noise than COSMIC measurements [(o-b)'s at 60 km]



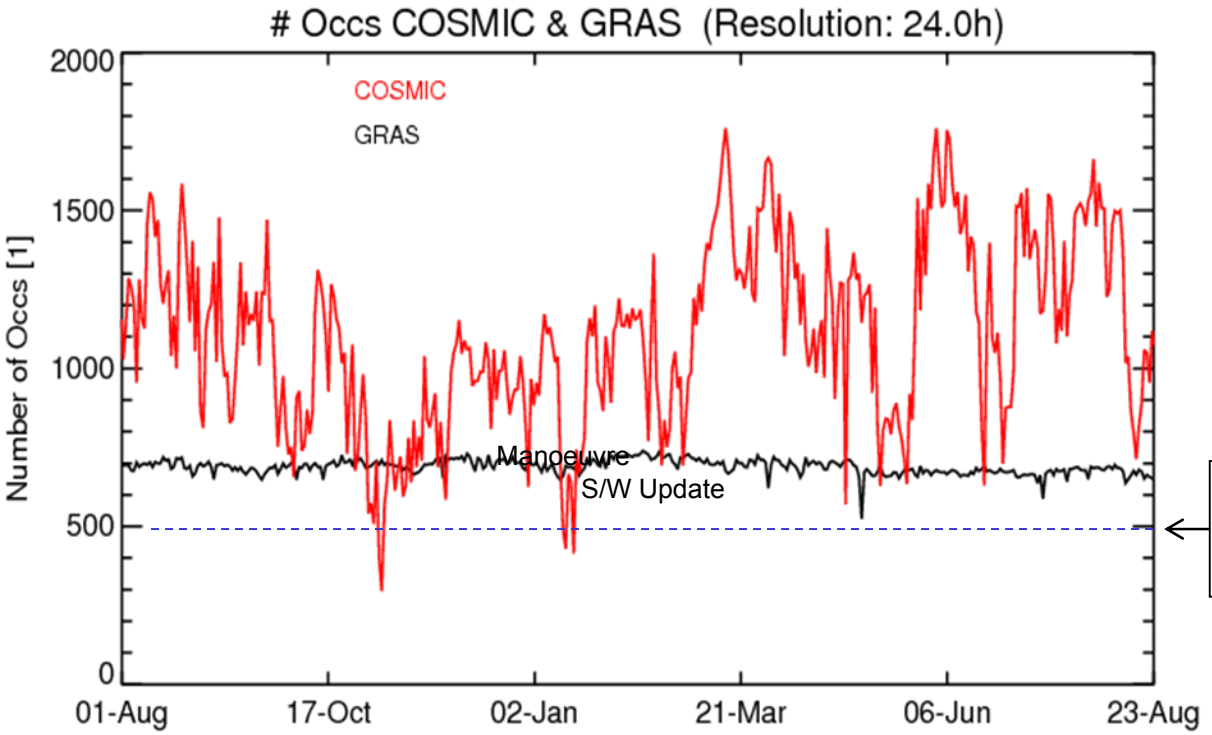
Before GRAS some thought that the COSMIC noise was limited by the residual ionospheric noise.

Ie, a retrieval issue.

(**von Engeln *et al* GRL 2009**)

GRAS performance: number of observations per day is consistently ~650-700

- **GRAS shows very solid performance, very few instrument issues detected and potential software updates are evaluated.**



I was expecting this number

Post-EPS RO

- **Post-EPS RO mission is extremely important to ensure RO continuity, particularly given the COSMIC-2 funding problems.**
- **We want more high quality, operational radio occultation data.**
  - Exploitation of other GNSS signals.
- Improved noise characteristics
  - Can we extend the impact of GPS-RO out of the ~7-30km “core region”.
  - Improve the impact on tropospheric humidity?

Potential improvements: Data numbers

- Data numbers: Example, On 25th September 2011, ECMWF received **2070 GPS-RO profiles in total**, 667 from GRAS. **No evidence that GPS-RO impact is saturated at this level – users want more data!**

- Post-EPS RO missions will exploit GNSS signals from Galileo, and possibly GLONASS, … BEIDOU.

- Post –EPS MRD defines (for each satellite)
  - > 1000 per day (Threshold)
  - > **1500 per day (Breakthrough)**

- **ECMWF will conduct OSSEs to investigate the impact of up to 64000 observations per day. (Funded by ESA).**

Observation error requirements

Impact height interval (km)	Errors currently assumed at ECMWF	Post-EPS "threshold"	Post-EPS "breakthrough"
Surface to 10 km	**20%** falling to 1% at 10 km	**10%** falling to 1% at 10 km	**5%** falling to 0.5% at 10 km
10 km to 35 km	Max(1%, 3 μ rad)	1% falling to 0.4% at 35 km.	0.5% falling to 0.2% at 35 km
35 km to 80 km	3 μrad	Max(1 μrad,0.4%)	Max(0.5 μrad, 0.2%)

Post-EPS error specifications in troposphere

- Potentially important step forward.
- **NWP centres have not been able to demonstrate much impact on tropospheric humidity fields.**
  - **Measurement errors too large?**
    - Improve receiver tracking in lower troposphere.
  - **Assimilation problem? NWP users will investigate:**
    - Assumed errors too conservative?
    - Fundamental limitation of 1D assimilation methods?

Summary

- Radio Occultation is now established in global NWP, and it likely to become more important in climate monitoring as the time series lengthens.

- Post-EPS RO mission is crucial for ensuring the continuity of operational quality RO measurements for NWP and climate monitoring.

- **Clear impact with relatively few measurements.** We need more measurements, making use of Galileo and GLONASS signals.

- Post-EPS error specifications offer the possibility of extending the GPS-RO “core region” beyond ~7-35 km.

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