Role of GNSS radio occultation measurements constraining biases in NWP and reanalyses

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EUMETSAT ROM SAF
RADIO OCCULTATION METEOROLOGY

http://www.romsaf.org

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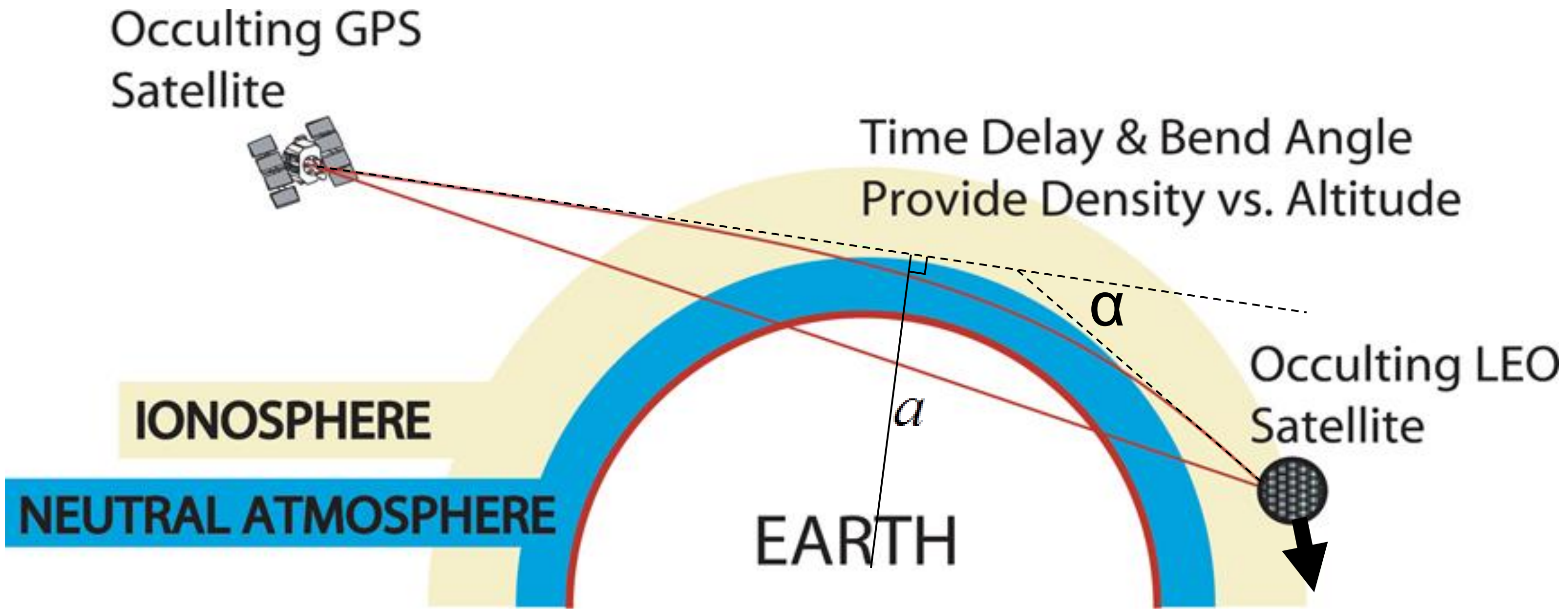
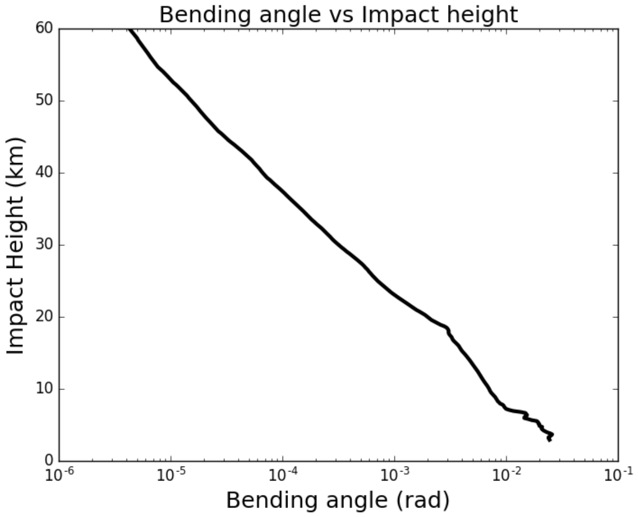
Outline

- **Why we treat GPS (now GNSS) radio occultation as an anchor measurement**
  - GPS radio occultation **measurement geometry**
  - GPS radio occultation and “**standard**” **GPS-RO retrieval** development.
  - Some **limitations, how biases can creep in**
- **Assimilation of GPS-RO data into NWP and reanalysis systems**
- **Questions, summary and conclusions**

GPS-RO geometry. "Bending angles"

(Classical mechanics: e.g, Compare this picture with the deflection of a charged particle by a spherical potential!)





Setting occultation: as the LEO moves behind the earth we obtain a **profile** of bending angles, **α**, as a function of impact parameter, **a**.
The impact parameter is the distance of closest approach for the straight line path. It is directly analogous to angular momentum of a particle.

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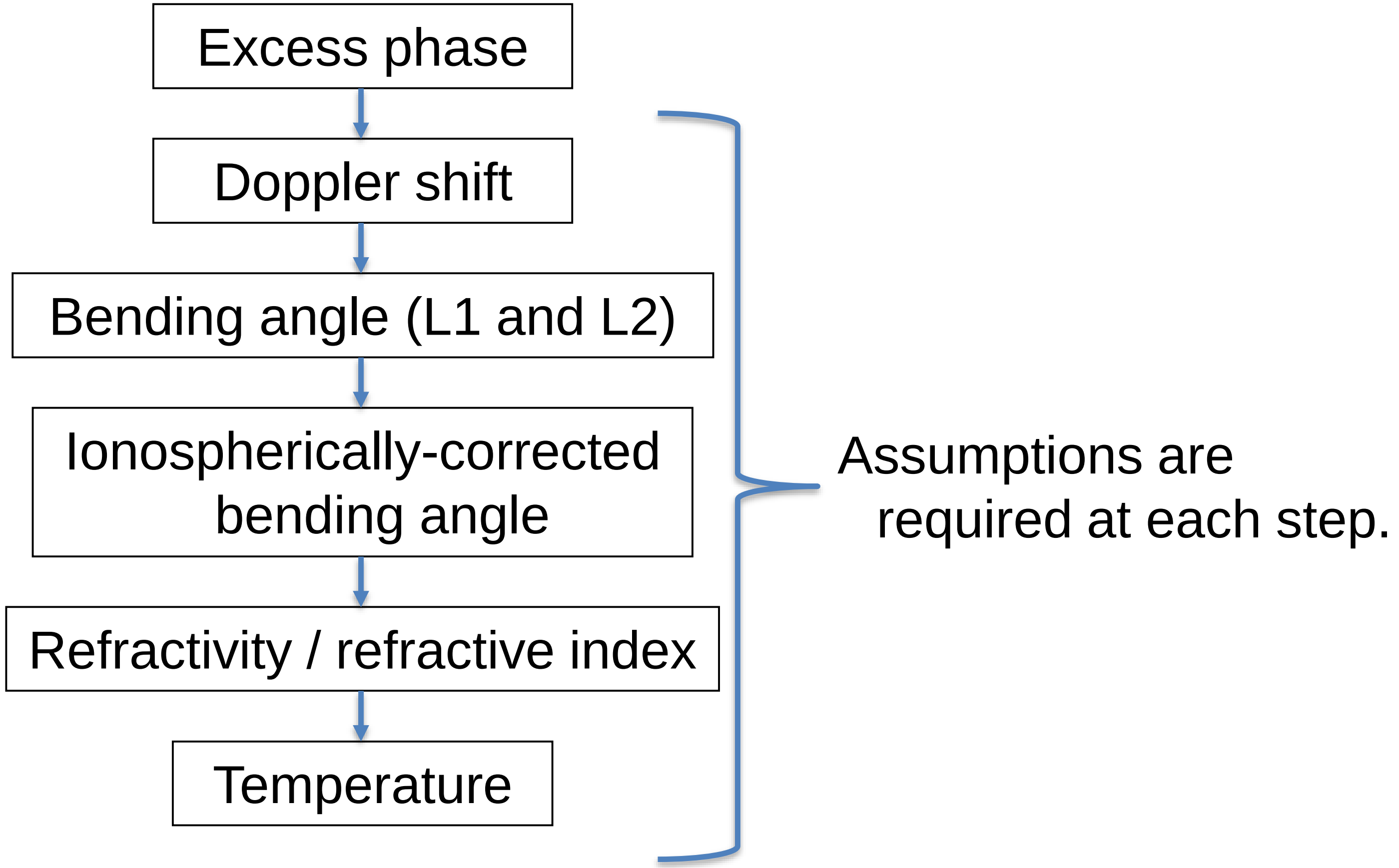
Retrieving atmospheric information

Process:



Geometrical Optics Processing of the **GPS**-RO Observations (1)

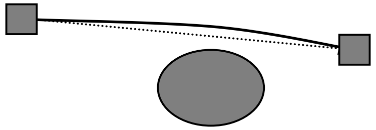
GPS receivers do not measure temperatures/ray bending directly!

The GPS receiver on the LEO satellite measures a time series of phase-delays $\phi(i-1)$, $\phi(i)$, $\phi(i+1)$,… at the two **GPS frequencies**:

L1 = 1.57542 GHz
L2 = 1.22760 GHz

The phase delays are "**calibrated**" to remove **special and general relativistic effects** and to remove the GPS and LEO clock errors – calibration is referenced to **atomic clocks**. ("**Differencing**", see Hajj et al. (2002), JASTP, **64**, 451 – 469).

We know accurately where the satellites are. Calculate **Excess phase delays**: i.e. remove straight line path delay, $\Delta\phi(i)$.



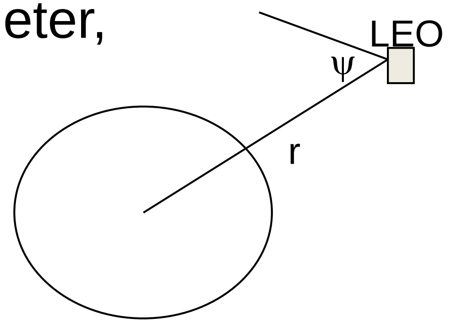
A time series of **Doppler shifts** at L1 and L2 are calculated by differentiating the **excess phase delays** with respect to time.

Processing of the GPS-RO observations (2)

The ray bending that is caused by gradients in the atmosphere and **ionosphere** modify the L1 and L2 Doppler values, but **deriving the bending angles, α, from the Doppler values is an ill-posed problem** **(an infinite set of bending angles could produce the same Doppler)**.

The problem is made well posed by **assuming** the impact parameter, given by

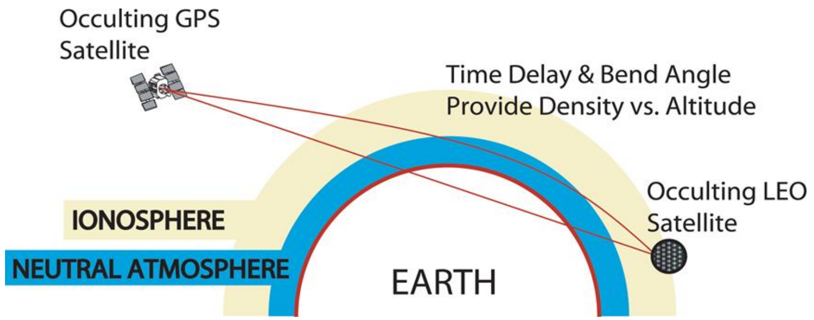
$$a = nr\sin\psi$$



has the same value at both the satellites.

Given accurate position and velocity estimates for the satellites, **and making the impact parameter assumption**, the bending angle, α, as a function of impact parameter **a** can be derived simultaneously from the Doppler shift.

The ionospheric correction



Every ray passes through the ionosphere!

We have to isolate the **atmospheric** component of the bending angle. **The ionosphere is dispersive, but the neutral atmosphere is not** and so we can take a linear combination of the L1 and L2 bending angles to obtain the "corrected" bending angle. See Vorob'ev + Krasil'nikov, (1994), Phys. Atmos. Ocean, **29**, 602-609.

$$\alpha(a) = c\alpha_{L1}(a) - (c-1)\alpha_{L2}(a)$$

$$c = \frac{f_{L1}^2}{\left(f_{L1}^2 - f_{L2}^2\right)}$$

"Corrected" bending angles

Constant given in terms of the L1 and L2 frequencies.

Does it introduce biases that vary in time with solar cycle?

YES, the retrieved temperatures are sensitive to this! Less important for bending angle assimilation.

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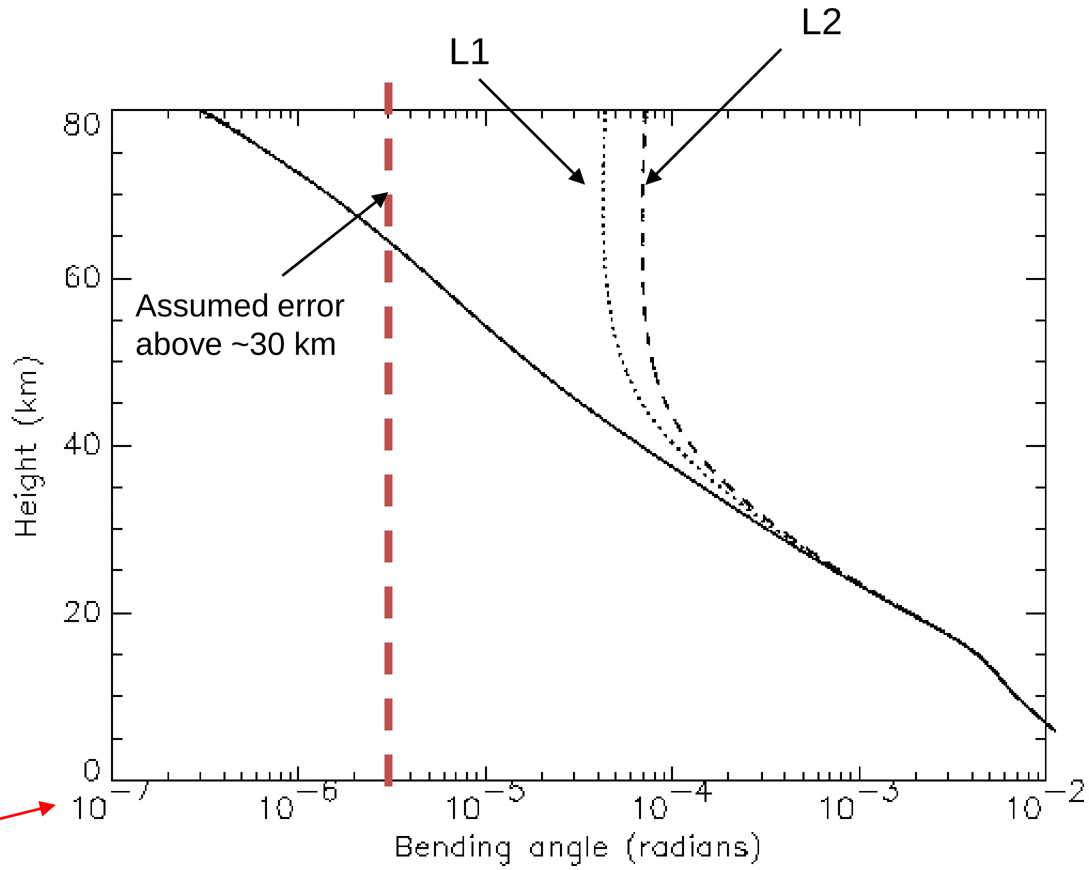
The ionospheric correction: a simulated example



Log scale

High up, the ionosphere dominates the L1 and L2 signals, **but they are affected differently to each other**.

Low down, the atmospheric signal dominates and the lines overlap.

The “correction” is very big!

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Deriving the refractive index profiles

Assuming local spherical symmetry, we can use an **Abel transform** to retrieve a refractive index profile

Note the upper-limit of the integral! <u>A priori</u> information needed to extrapolate to infinity.

$$n(x) = \exp\left(\frac{1}{\pi} \int_x^{\infty} \frac{\alpha(a)}{\sqrt{a^2 - x^2}} da \right)$$

The inverse Abel transform can be used to obtain the bending angle profile for a given refractive index profile (i.e. the inversion).

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

Corrected Bending angle as a function of impact parameter

Convenient variable ($x=nr$) (refractive index * radius)

GPS-RO limitations – upper stratosphere

In order to derive refractivity the **noisy**, **corrected** bending angle profiles must be extrapolated to infinity – **i.e., we have to introduce a-priori simulated bending angles**.

This blending of the observed and simulated bending angles is called "**statistical optimisation**". Consider the (**matrix**) equation:

$$\boldsymbol{\alpha}_{\mathbf{so}} = \boldsymbol{\alpha}_{\mathbf{m}} + \mathbf{K}\left(\boldsymbol{\alpha} - \boldsymbol{\alpha}_{\mathbf{m}}\right)$$

We use this "blended" profile in the Abel transform to get refractivity!

Model (e.g. MSIS)

"Corrected" BA

It's a linear combination of simulated bending angles from a climatology model (e.g., MSIS)

The gain matrix, **K**, determines the relative contribution of the model. **By ~60 km the merged profile is dominated by the model contribution.**

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Determining profiles of density (dry atmosphere only)

The refractive index (or refractivity) is related to the pressure, temperature and vapour pressure using two experimentally-determined constants (from the 1950s and 1960s!)

N= refractivity
n= refractive index
c1,c2 refractivity constants
P= pressure
T= Temperature
Pw= partial pressure of water vapour
ρ= density
R= gas constant

$$N = 10^6 (n - 1)$$

$$= \frac{c_1 P}{T} + \frac{c_2 P_w}{T^2}$$

This two-term expression is probably the simplest formulation for refractivity, but it is widely used in GPS-RO.

We now use an alternative three term formulation, including non-ideal gas effects

If the water vapour is negligible, the 2nd term = 0, and the refractivity is proportional to the density

$$N \approx \frac{c_1 P}{T} = c_1 R \rho$$

So, although we don't know the values of P and T, we can use the ideal gas equation to retrieve a vertical profile of density!

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Early work on the GPS RO uncertainty model

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 102, NO. D19, PAGES 23,429–23,465, OCTOBER 20, 1997

Observing Earth's atmosphere with radio occultation measurements using the Global Positioning System

E. R. Kursinski[1]

Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena

G. A. Hajj, J. T. Schofield, and R. P. Linfield

Jet Propulsion Laboratory, California Institute of Technology, Pasadena

K. R. Hardy

AS&T, Palo Alto, California

Propagating Phase errors -> Doppler -> Refractivity

KURSINSKI ET AL.: OBSERVING EARTH'S ATMOSPHERE BY OCCULTATION USING GPS 23,439

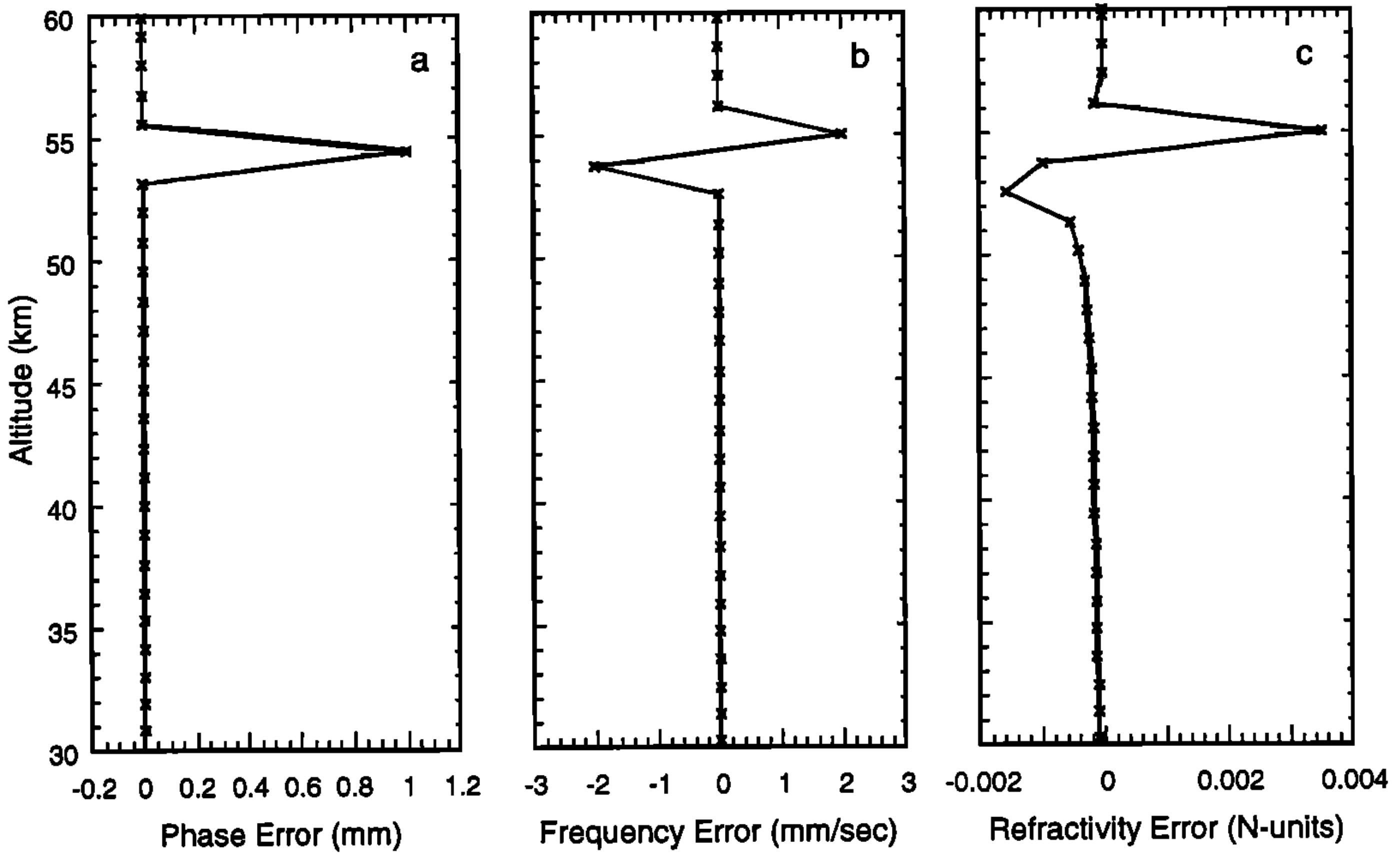


Figure 7. (a) Single phase error. (b) Frequency error resulting from Figure 7a. (c) Refractivity error response to frequency error in Figure 7b.

Kursinski: Refractivity error statistics

23,444 KURSINSKI ET AL.: OBSERVING EARTH'S ATMOSPHERE BY OCCULTATION USING GPS

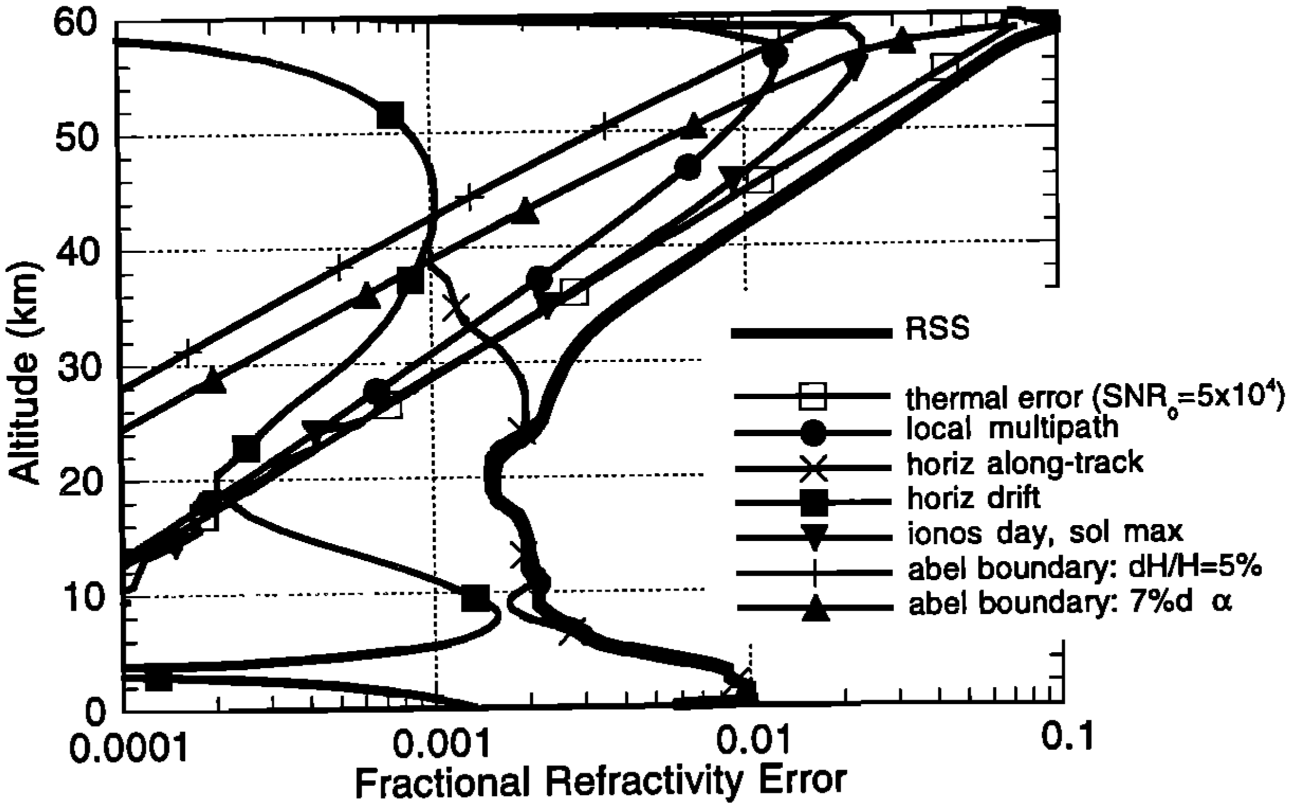
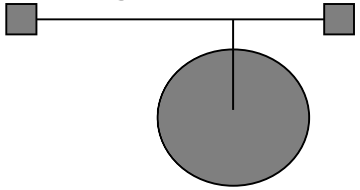


Figure 10. Summary of refractivity errors versus height. Thermal error, 1 s SNR=5 x 10^4; local multipath, 10 mm rms spread over 0.01 Hz; horizontal refractivity structure, along track from simulation and horizontal motion of ray path tangent point from tropospheric and stratospheric climatologies near 30°S for June-July-August; ionosphere error, daytime, solar maximum conditions; Abel boundary errors, 7% in α, 5% in H_α.

1D bending angle assimilation

- **Most centres assimilate bending angles with a 1D operator**: ignore the 2D nature of the measurement and use a **single model column** to integrate

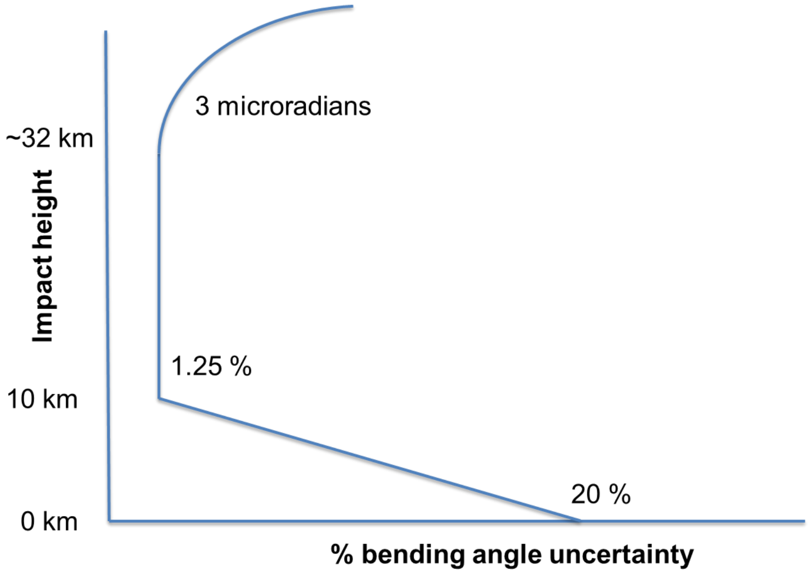


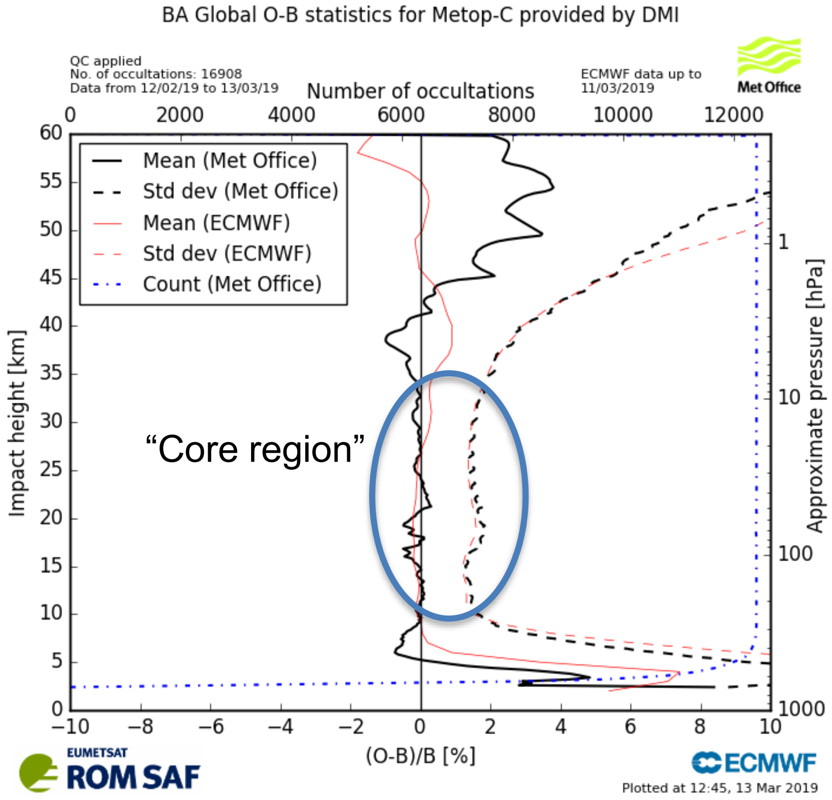
$$\alpha(a) = -2a \int_a^{\infty} \frac{d \ln n / dx}{\sqrt{x^2 - a^2}} \, dx$$

Convenient variable (x=nr) (refractive index * radius)

- The forward model, H(x) is quite simple:
  - **evaluate geopotential heights of model levels**
  - convert geopotential height to geometric height and radius values
  - evaluate the refractivity, N, on model levels **from P,T and Q**.
  - Integrate, assuming refractivity varies ~(*exponentially*quadratic)* between model levels. (*Solution in terms of the Gaussian error function*).
  - **Include tangent point drift (Poli, Cucurull)**

Assumed (global) observation error statistics and actual (o-b) departure statistics



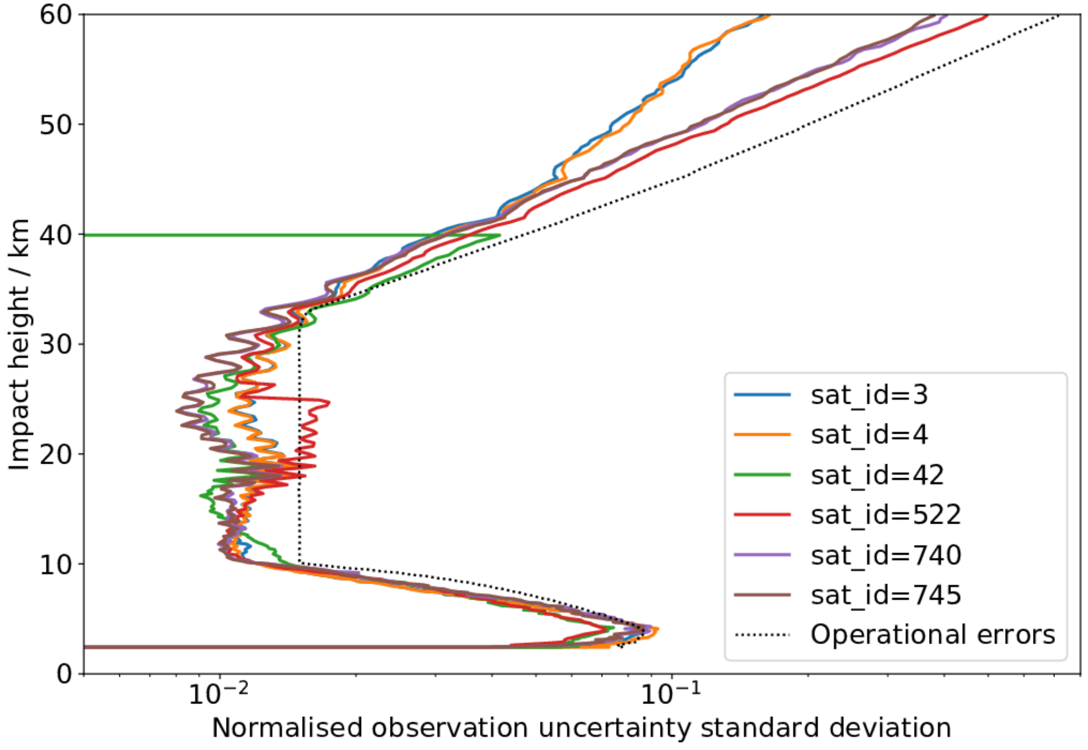


Consistent with global o-b stats
IGNORE VERT CORRELATIONS.

See **http://www.romsaf.org/monitoring/** for many plots of real-time RO statistics.

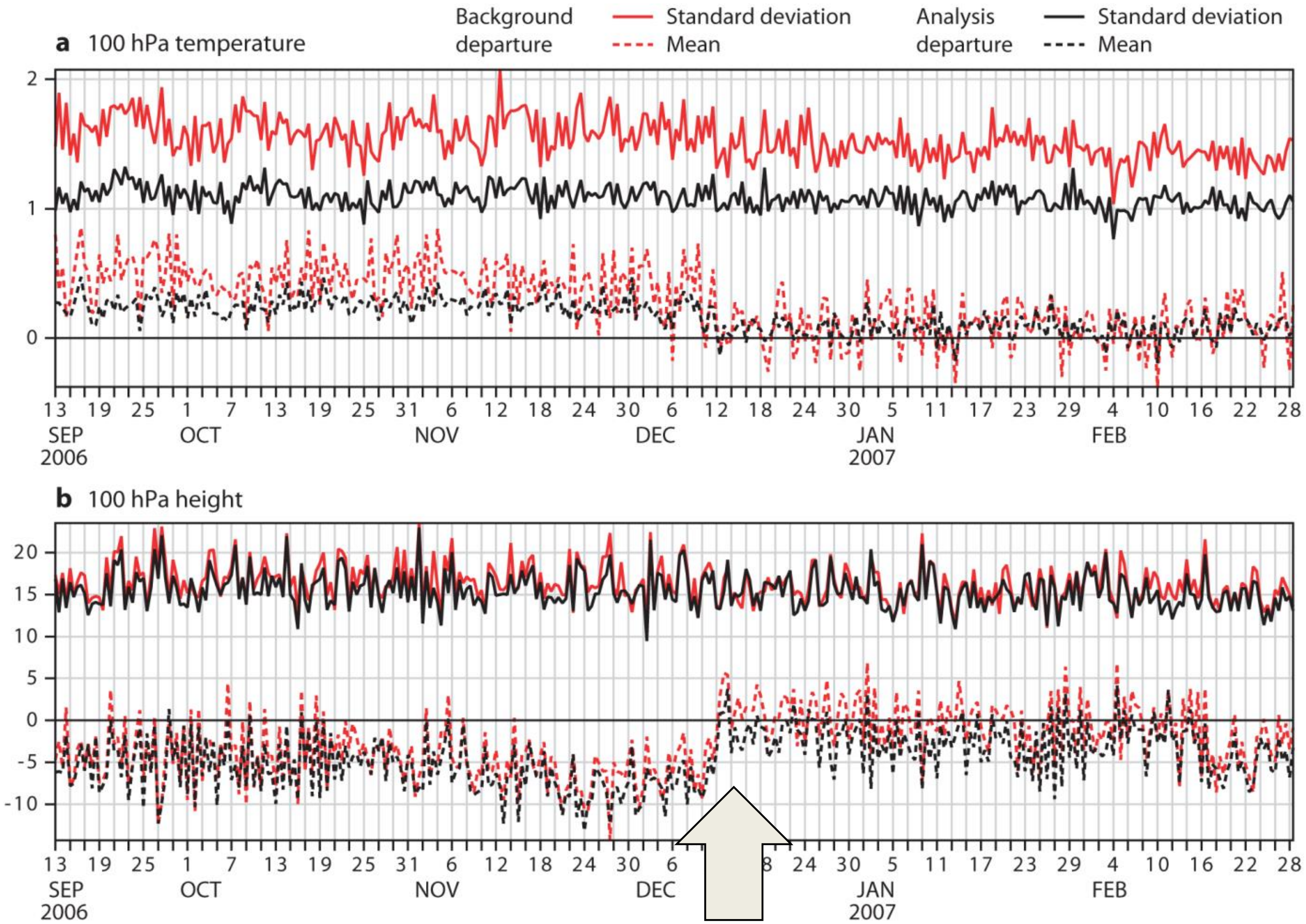
Met Office

Estimated uncertainties with satellite (Bowler, 2020, https://rmets.onlinelibrary.wiley.com/doi/full/10.1002/qj.3791)



- Observations from different satellites have different errors
- Metop satellites very accurate at high levels
- Different levels of smoothing lead to different uncertainties

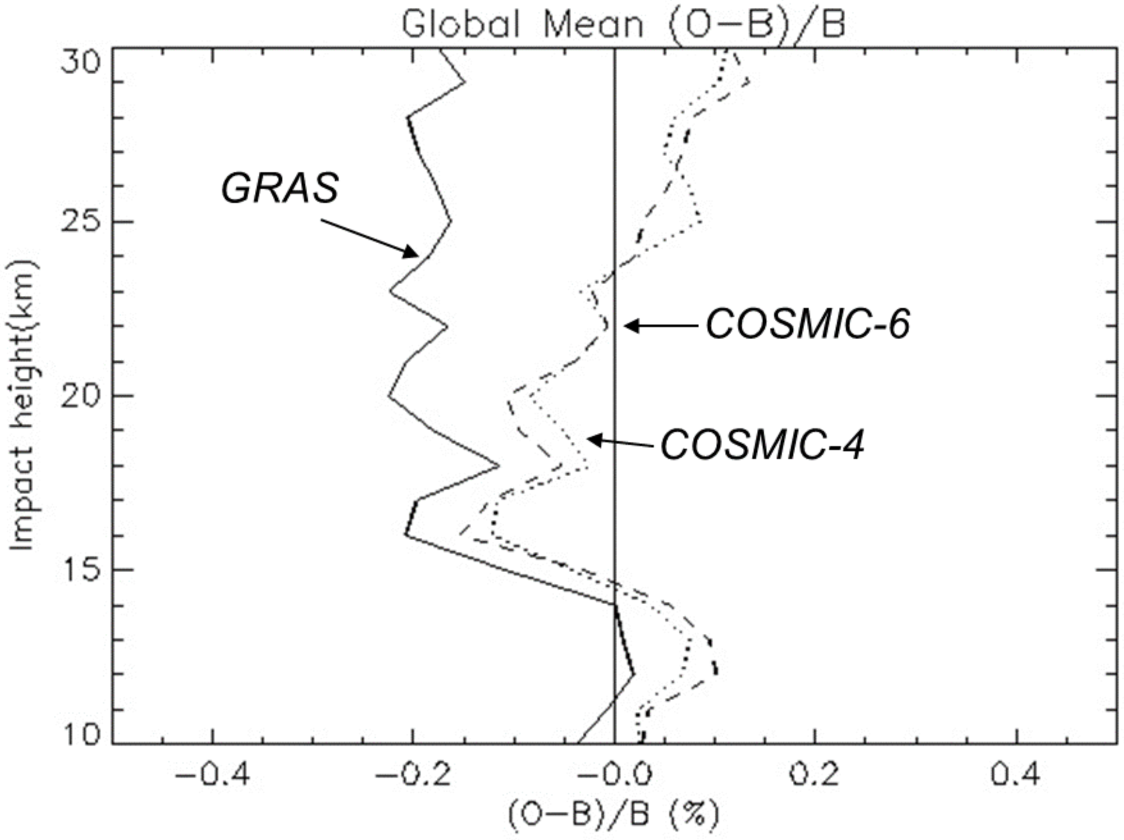
Impact of GPS-RO on ECMWF operational biases against radiosonde measurements in 2006



Operational implementation (COSMIC 1-6 and CHAMP)

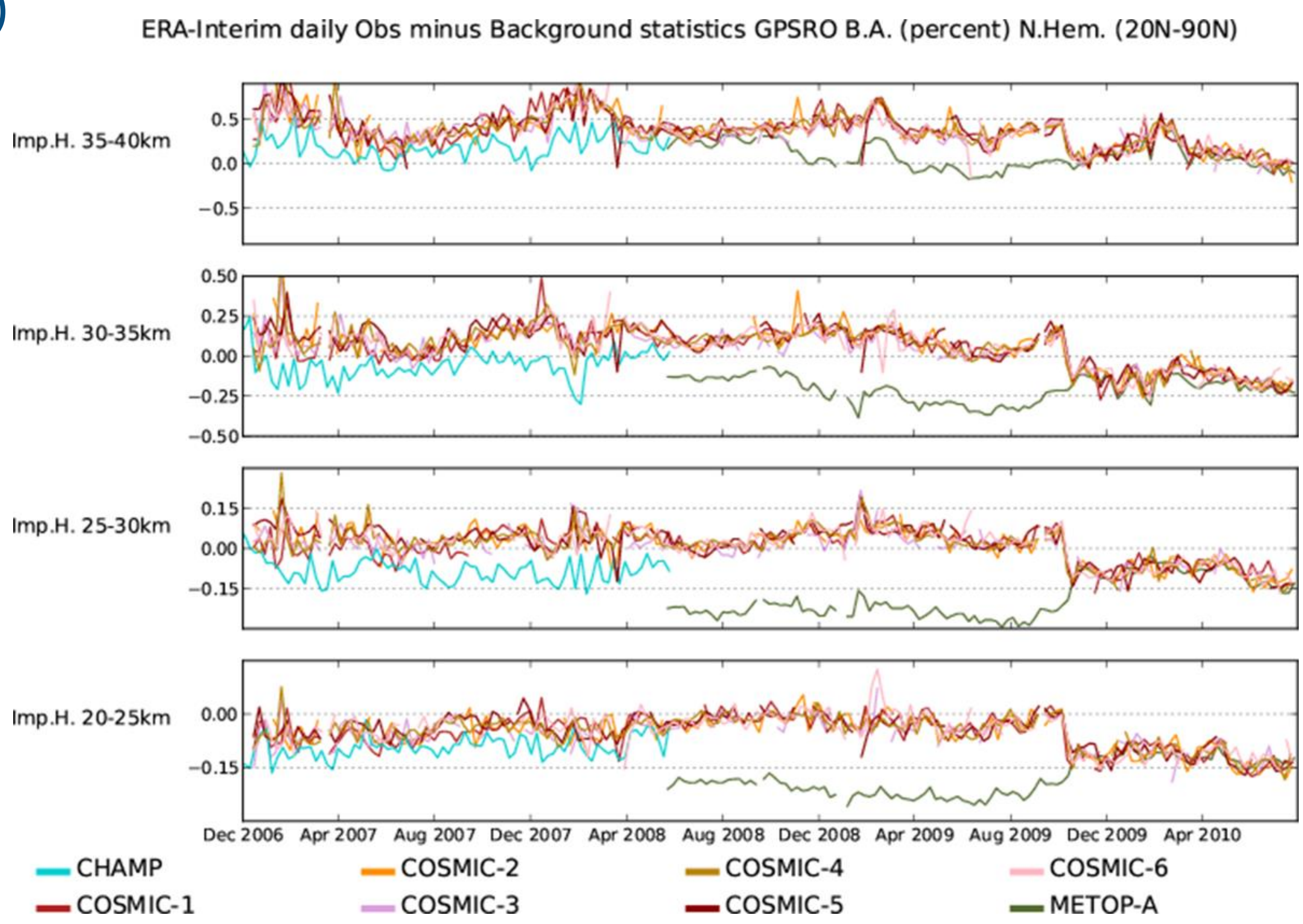
BUT processing differences can introduce biases

Global bending angle (O-B)/B departure statistics from ECMWF operations for Aug.20 to Sept. 20, 2009



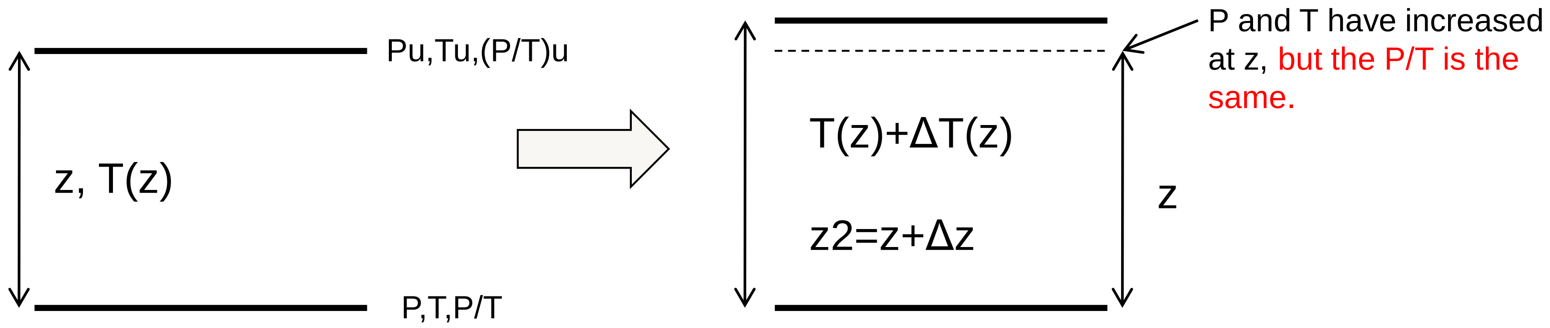
Timeseries from ERA-Interim. UCAR processing change in Nov 2009.

(Paul Poli)



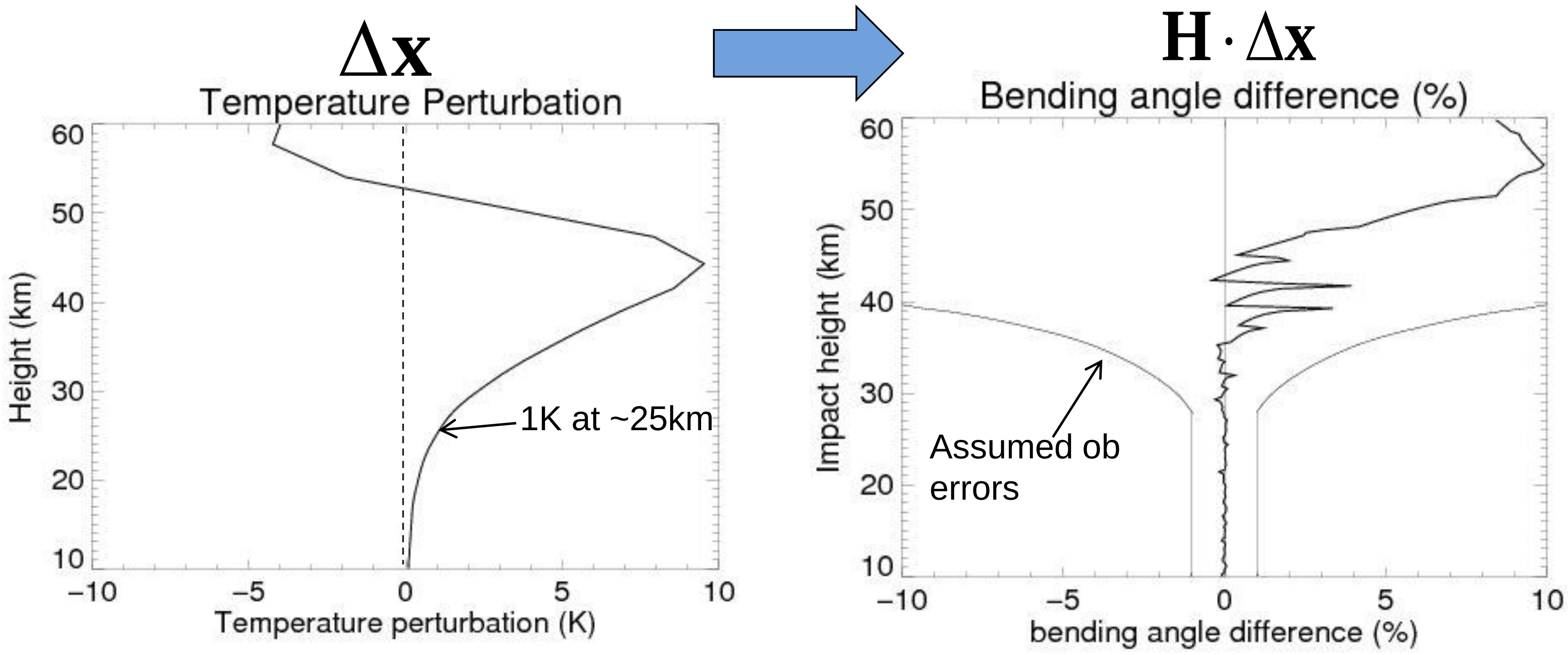
GPS-RO has a “null space”

The measurement is related to density (~P/T) on height levels and this ambiguity means that the effect of some temperature perturbations **can’t be measured**. Assume two levels separated by z, with temperature variation T(z) between them. Now add positive perturbation $\Delta T(z) \sim \exp(z/H)$, where H is the density scale height



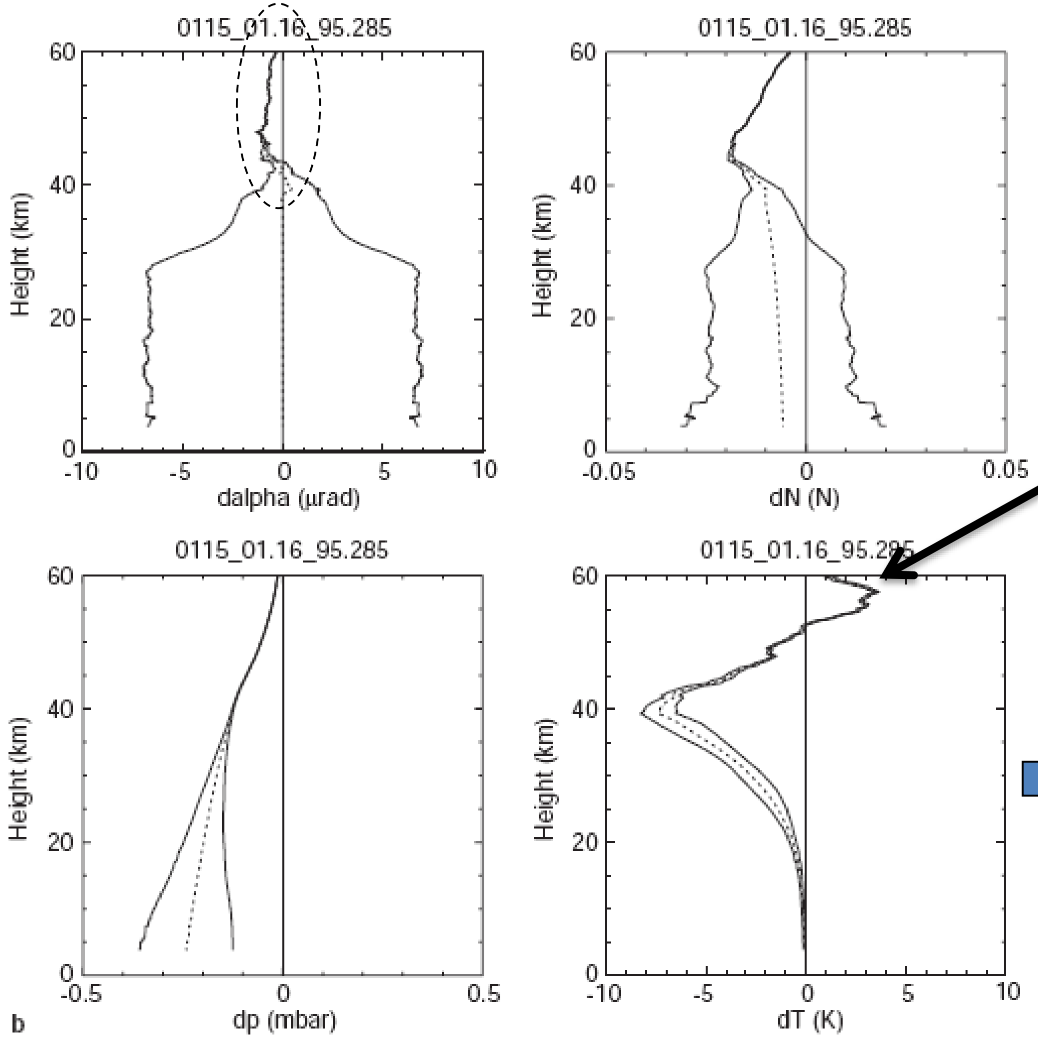
The density as a function of height is almost unchanged. **A priori information required to distinguish between these temperature profiles.** **This is the GPS-RO null space.**

Null space – how does a BIG temperature perturbation propagate through the bending angle observation operator?

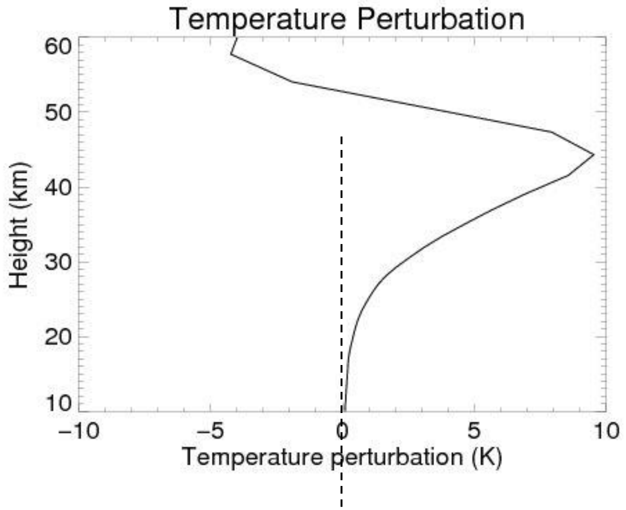


The null space arises because the measurements are sensitive to density as function of height (~P(z)/T(z)). A priori information is required to split this into T(z) and P(z). We can define a temperature perturbation ΔT(z)~exp(z/H) which is in the GPS-RO null space. Therefore, if the model background contains a bias of this form, the measurement can't see or correct it.

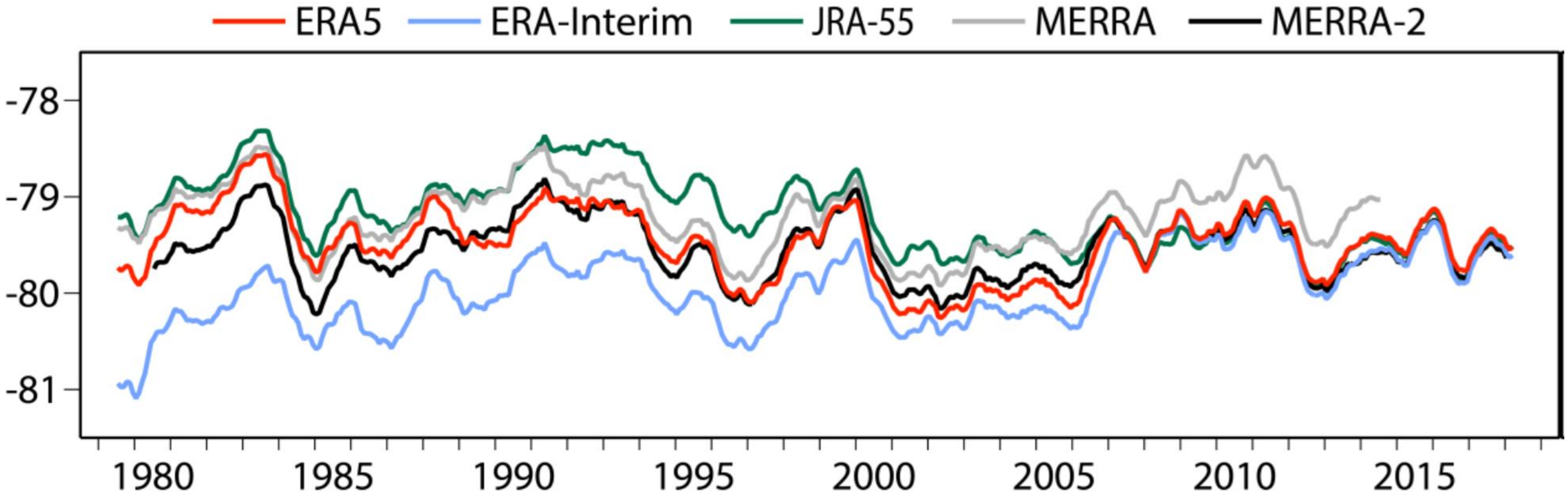
Compare with Steiner et al
(Ann.Geophs., 1999,17, 122-138)



Temperature retrieval error caused by a 5 % bias in the background bending angle used in the statistical optimization



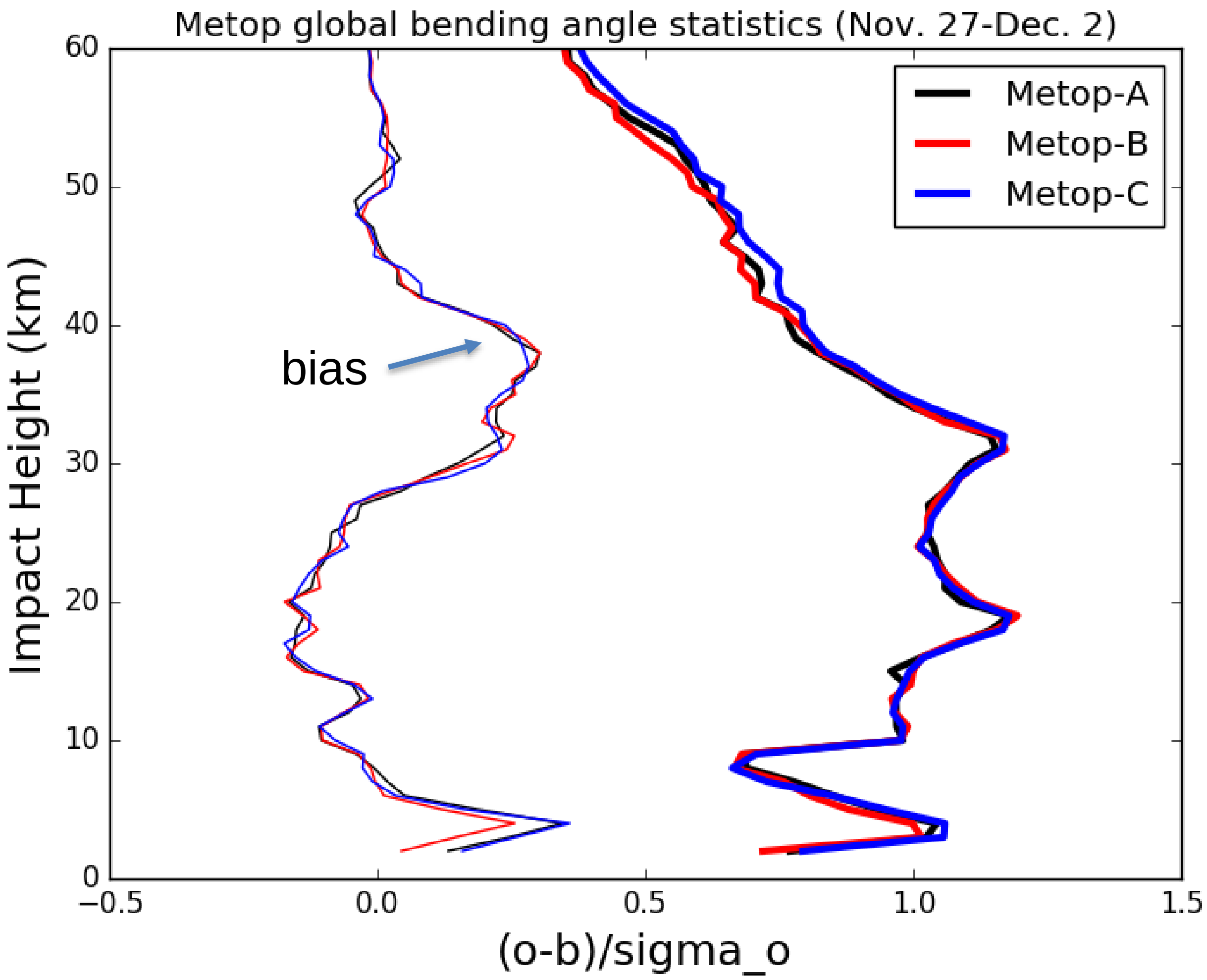
Impact on consistency of global temperature reanalyses (Simmons, Ho et al, 2020)



Timeseries of 12 month running averages of 100 hPa temperatures (Celsius) in the tropics (± 20 lat). **ERA5, ERA-Interim, JRA-55 and MERRA-2 assimilate GPS-RO data, but MERRA did not**.

The reanalyses converge in 2006 after the assimilation of COSMIC/FORMOSAT-3 data.

GRAS GPS-RO bending angle departure statistics (Global)



EUMETSAT produced bending angles just six days after launch (Nov. 13, 2018).

Quickly established that the Metop-C data has essentially the same departure statistics as Metop-A,B.

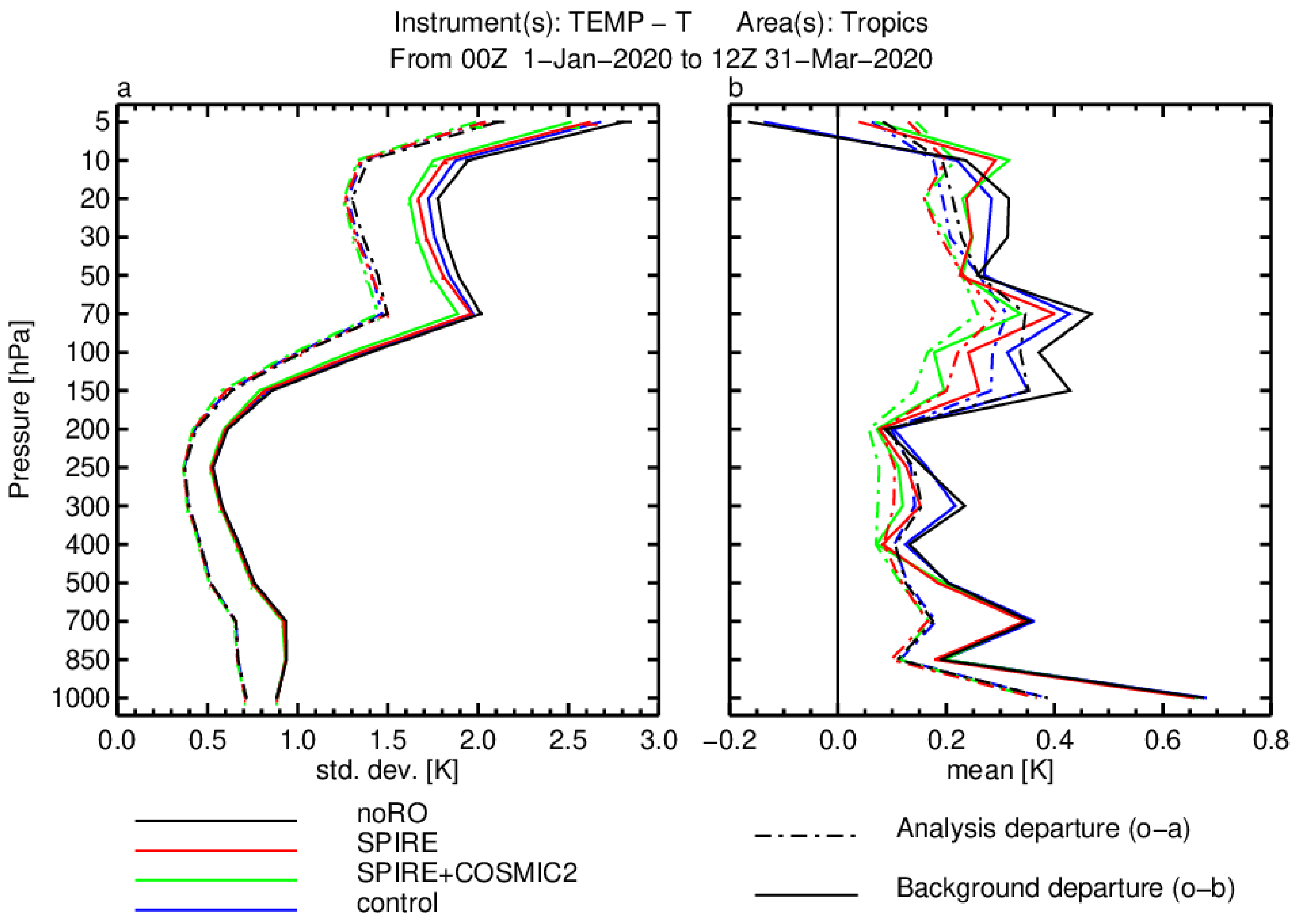
Similar results at the Met Office.

Metop-C increase GPS-RO numbers by 30%.

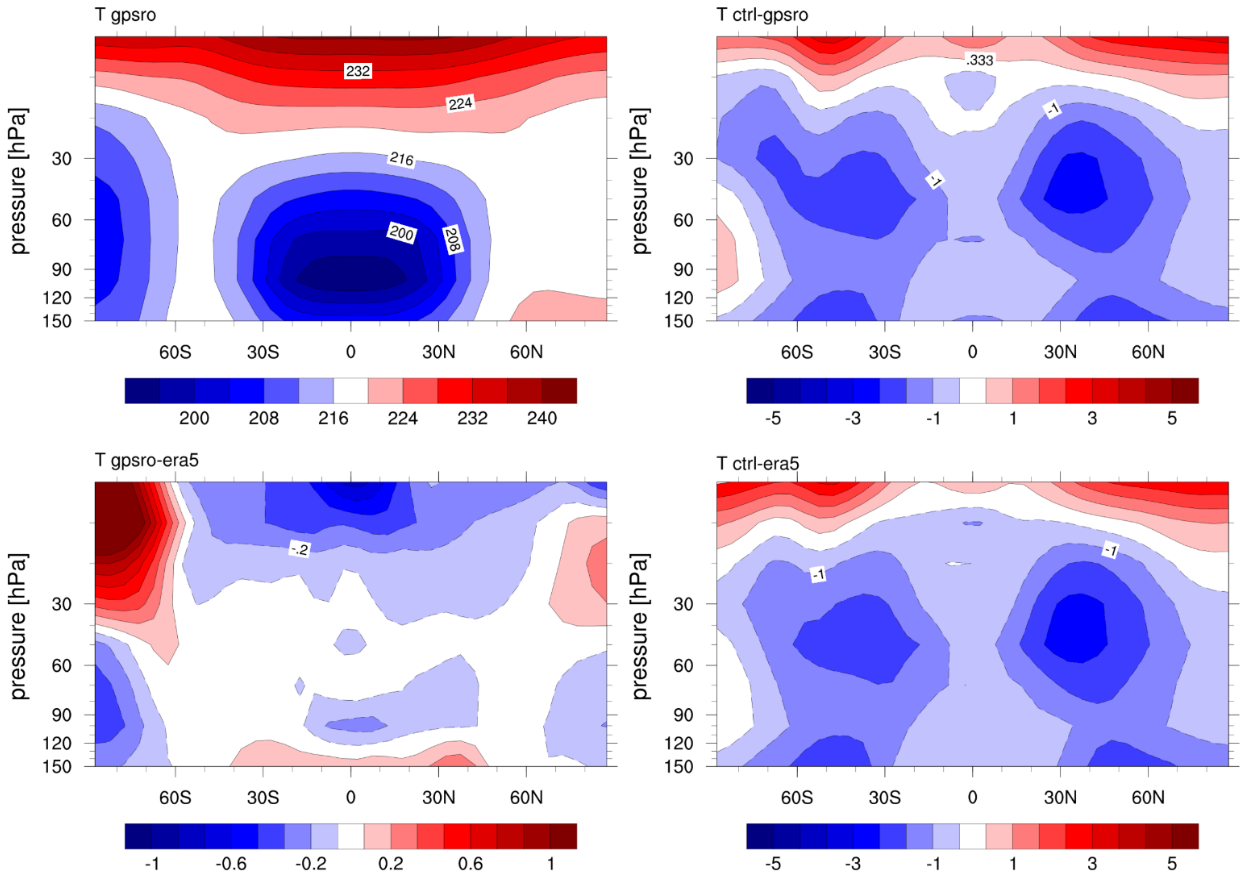
45R1 assimilation experiments from Nov. 27 to Feb. 28, 2019.

Metop-C treated the same as Metop-A,B.

Recent increase in GPS-RO data: impact on radiosondes



Model bias: *Free running model* vs ROM SAF monthly mean GPS-RO temp. climatologies and **ERA5** (Inna Politchouk)



Summary

- GPS-RO is assimilated without bias correction – an anchor measurement.

We need anchor measurements for VarBC and weak constraint 4D-Var. **How many?**

- The fundamental measurement (time/phase delay) can justify this approach, but processing differences can introduce biases even in bending angle space.

- BUT the consistency of stratospheric temperature reanalyses in the stratosphere since 2006 has improved.

- Metop-A,B,C departure statistics very consistent.

- Dataset for model developers

MSU-4/AMSU-9 anomalies