Assimilation in the upper troposphere/lower stratosphere: role of radio occultation

Sean Healy

Plus contributions from

Paul Poli, Carla Cardinali, Adrian Simmons, Michail Diamantakis, Mats Hamrud, Steve English, Peter Bauer, Niels Bormann, Florian Harnisch …

The EUMETSAT
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ROM SAF
Radio Occultation Meteorology

http://www.romsaf.org/

ECMWF

Outline

- GPS-RO technique: basic physics, measurement geometry.
  - *Processing of GPS-RO measurements, and the "standard" GPS-RO temperature retrieval*.

- Assimilation/impact of GPS-RO in NWP and reanalysis.
  - *Reduction of stratospheric temperature biases.*
  - *GPS-RO "null-space"*
  - *New dataset for model developers.*

- Estimate how the GPS-RO impact scales with observation number using and ensemble of data assimilations (EDA).

- Current/future work.

- Summary.

Radio Occultation: Some Background

- Radio occultation (RO) measurements have been used to study planetary atmospheres since 1960’s.

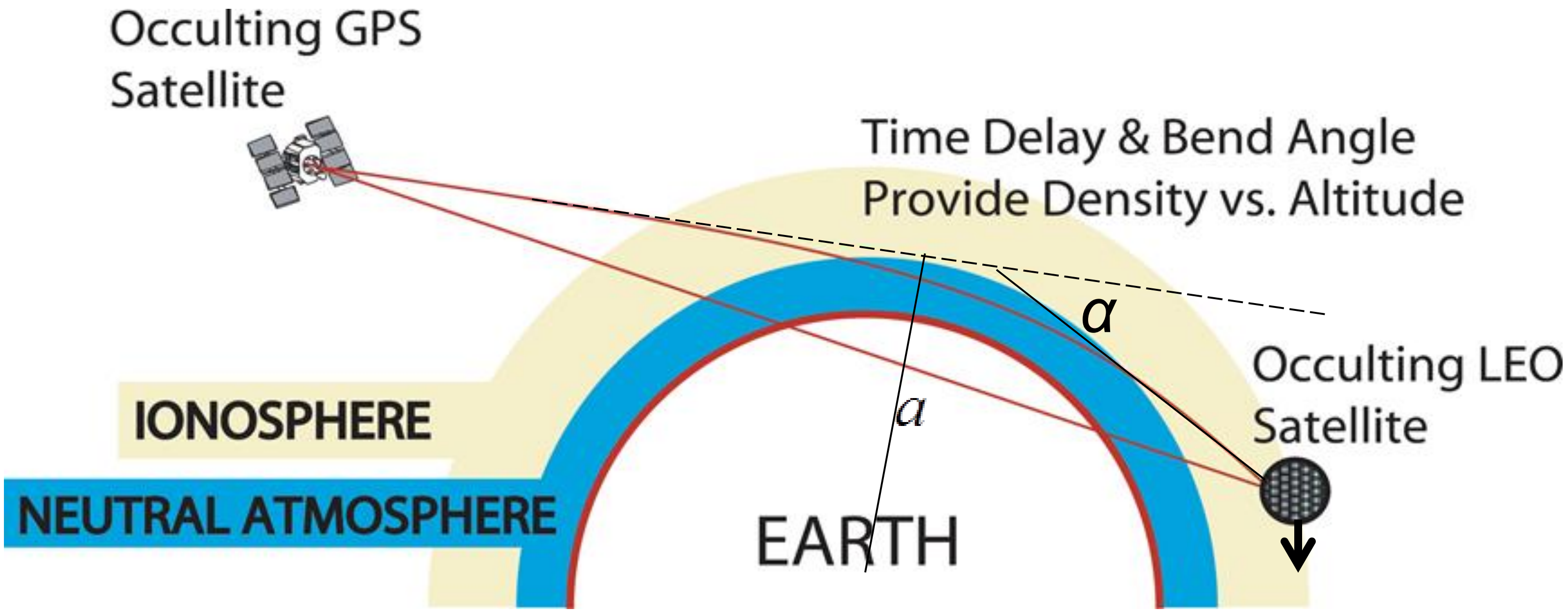
- **Active technique**: How the paths of radio signals are bent by refractive index gradients in an atmosphere **(Snel’s Law)**.

- Application to Earth’s atmosphere proposed in **1965**, but no obvious source of the radio signals.

- Use of **GPS** signals discussed at the Jet Propulsion Laboratory (JPL) in late 1980’s. In **1996** the “**GPS/MET experiment**” demonstrated useful temperature information could be retrieved from the GPS RO measurements. **GPS-RO.**

GPS-RO geometry

(*<u>Classical mechanics</u>*: deflection in a gravitational field/charged particle by a spherical potential!)



<u>Setting occultation</u>: LEO moves behind the earth.
We obtain a profile of bending angles, <u>α</u>, as a function of impact parameter, <u>a</u>.

*The **<u>impact parameter</u>** is the distance of closest approach for the straight line path. **<u>Determines tangent height, analogous to angular momentum</u>.***

GPS-RO characteristics

- **Good vertical resolution (*Show an example later*).**

- **Poor horizontal resolution**:~70% of the bending occurs over a **~450km** section of ray-path, centred on the tangent point *(point on path closest to surface)* – **broad horizontal weighting function, with a ~Gaussian shape *to first order*!**

- All weather capability: not directly affected by cloud or rain.

- The bending is ~1-2 degrees at the surface, falling exponentially with height. The scale-height of the decay is approximately the density scale-height.

- A profile of bending angles from ~60km tangent height to the surface takes about 2 minutes. Tangent point drifts in the horizontal by ~200-300 km during the measurement.

Ray Optics Processing of the GPS RO Observations

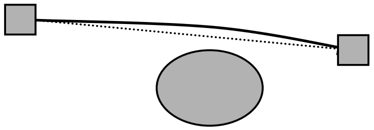
GPS receivers do not measure bending angle directly!

GPS receiver on the LEO satellite measures a series of phase-delays, ρ (i-1), ρ (i), ρ(i+1),… at 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 (“**Differencing**”, see Hajj et al. (2002), JASTP, **64**, 451 – 469).

Calculate **Excess phase delays**: remove straight line path delay, $\Delta\rho(i)$.



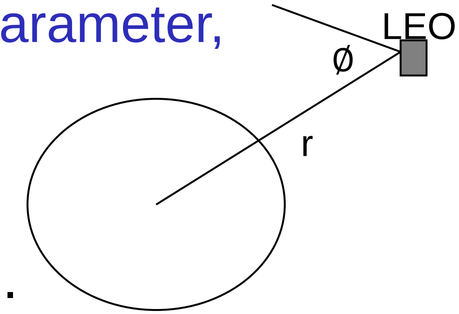
A time series of Doppler shifts at L1 and L2 are computed by differentiating the **excess phase delays** with respect to time.

Processing of the GPS-RO observations (2)

The ray bending 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 Doppler*)**.

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

$$\boxed{a = nr \sin \phi}$$



has the same value at both the satellites (spherical symmetry).

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

The ionospheric correction

We have to isolate the atmospheric component of the bending angle. **The ionosphere is dispersive.** **Compute 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*.

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

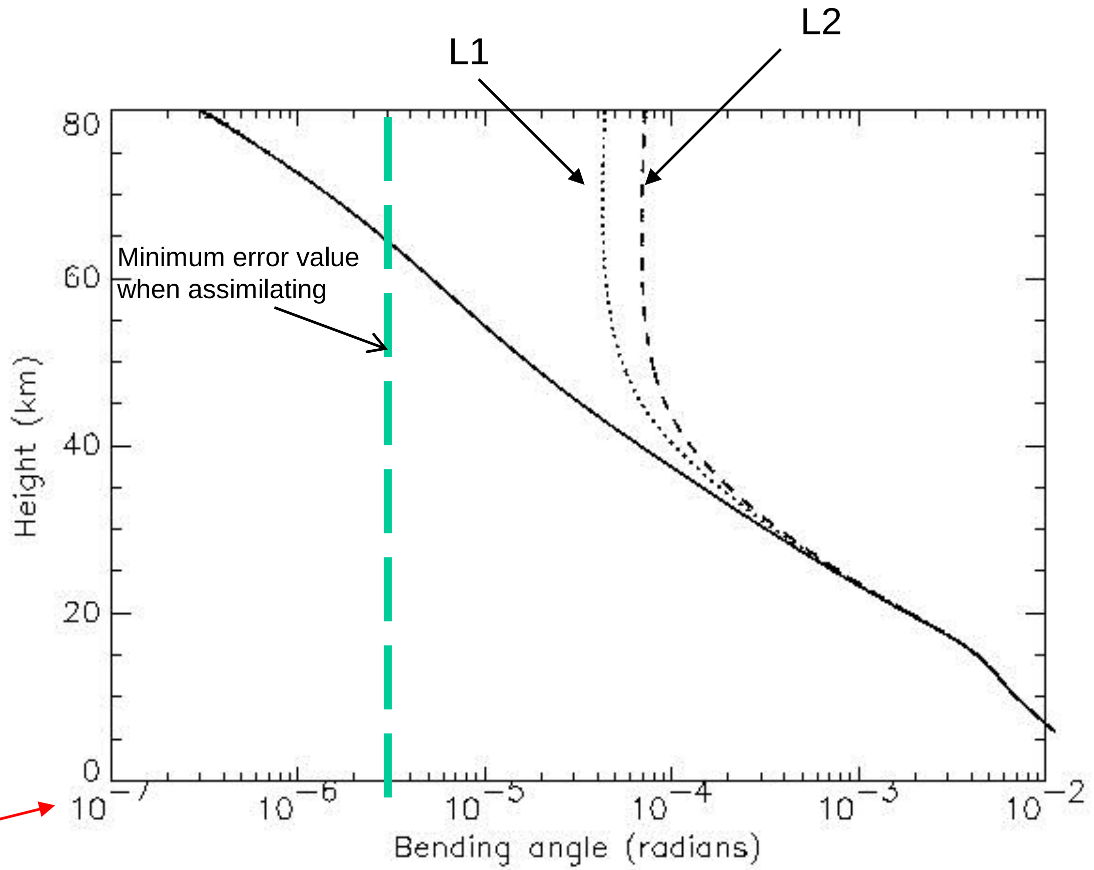
“Corrected” bending angles

Constant given in terms of the L1 and L2 frequencies.

$$\boxed{c = \frac{f_{l1}^{2}}{(f_{l1}^{2} - f_{l2}^{2})}}$$

How good is the correction? Does it introduce time varying biases? Impact on climate signal detection? I don’t think it’s a major problem in regions where the GPS-RO information content is largest.

Ionospheric correction: A simulated example



Log scale

The "correction" is large. ***Traceability of GPS-RO?***

Deriving the refractive index profiles

Assuming spherical symmetry the **ionospheric corrected** bending angle can be written as:

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

Corrected Bending angle
as a function of impact parameter

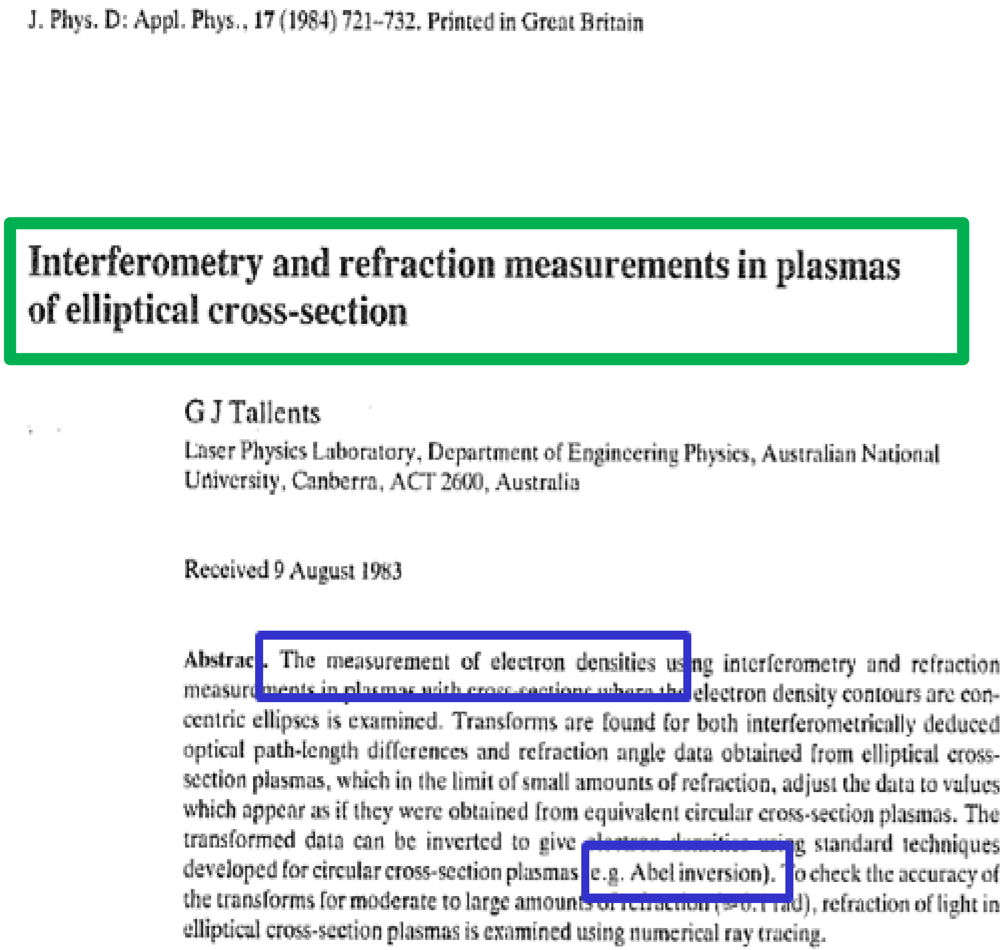
Convenient variable ($x = nr$)
*(refractive index * radius)*

We can use an **Abel transform** to derive a refractive index profile

Note the upper-limit of the integral! *A priori* information needed to extrapolate to infinity.

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

Aside: This kind of problem is not unique to GPS-RO



J. Phys. D: Appl. Phys., 17 (1984) 721–732. Printed in Great Britain

Interferometry and refraction measurements in plasmas of elliptical cross-section

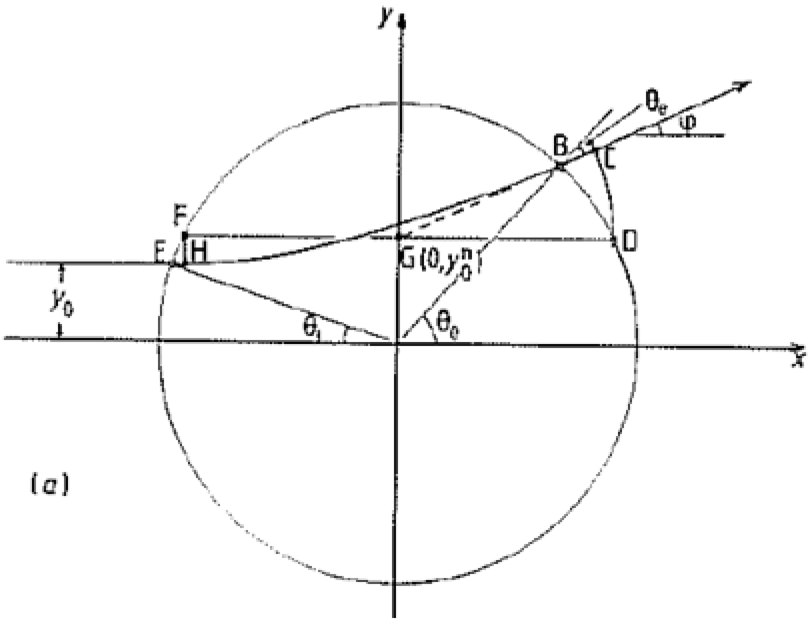
G J Tallents

Laser Physics Laboratory, Department of Engineering Physics, Australian National University, Canberra, ACT 2600, Australia

Received 9 August 1983

Abstrac. The measurement of electron densities using interferometry and refraction measurements in plasmas with cross-sections where the electron density contours are concentric ellipses is examined. Transforms are found for both interferometrically deduced optical path-length differences and refraction angle data obtained from elliptical cross-section plasmas, which in the limit of small amounts of refraction, adjust the data to values which appear as if they were obtained from equivalent circular cross-section plasmas. The transformed data can be inverted to give electron densities using standard techniques developed for circular cross-section plasmas e.g. Abel inversion). To check the accuracy of the transforms for moderate to large amounts of refraction (≥0.1 rad), refraction of light in elliptical cross-section plasmas is examined using numerical ray tracing.

Laser produced plasma paper from 1984.



Refractivity and Pressure/temperature profiles: “Standard or **Classical retrieval**”

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

refractivity

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

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

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 we have retrieved a vertical profile of density!

“Classical” retrieval

We can derive the pressure by integrating the **hydrostatic equation**

a priori

$$P(z) = P(z_u) - \frac{1}{c_1 R} \int_{Z}^{z_u} N(z) g(z) dz$$

The temperature profile can then be derived with the ideal gas law:

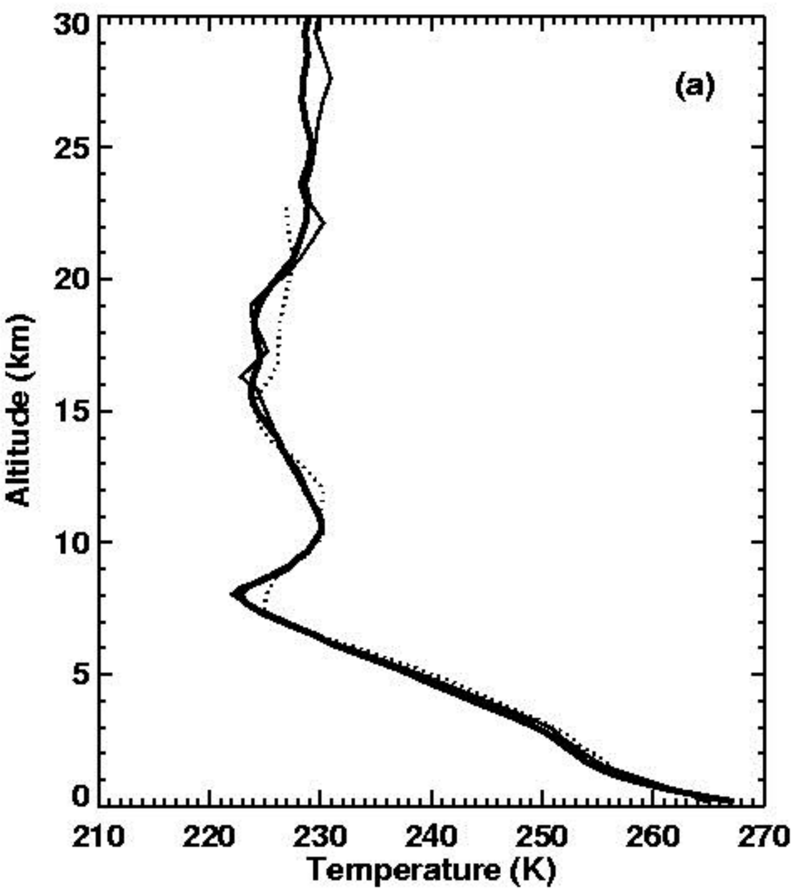
$$T(z) = c_1 \frac{P(z)}{N(z)}$$

GPSMET experiment (1996): Groups from JPL and UCAR demonstrated that the retrievals agreed with co-located analyses and radiosondes to within 1K between ~5-25km.

EG, See Rocken et al, 1997, JGR, 102, D25, 29849-29866.

GPS/MET Temperature Sounding

(Kursinski et al, 1996, Science, 271, 1107-1110, Fig2a)



*GPS/MET - **thick solid.***
Radiosonde – thin solid.
Dotted - ECMWF anal.

Results like this by JPL and UCAR in mid 1990's got the subject moving.

(Location 69N, 83W. 01.33 UT, 5th May, 1995)

GPS-RO limitations – upper stratosphere

In order to derive refractivity the **(noisy – e.g. residual ionospheric noise)** bending angle profiles must be extrapolated to infinity – **i.e., we have to introduce *a-priori***. This blending of the observed and simulated bending angles is called "**statistical optimization**". The refractivity profiles above ~35 km are sensitive to the choice of *a priori*.

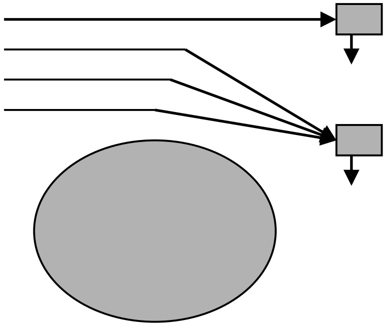
The temperature profiles require *a-priori* information to initialise the hydrostatic integration. Sometimes ECMWF temperature at 45km!

I would be sceptical about any GPS-RO temperature profile above ~35-40 km, derived with the *classical approach*. It will be very sensitive to the *a-priori*!

Limitations – lower troposphere

Horizontal gradient errors caused by the assumption of local spherical symmetry (variation of humidity over 100's km).

Atmospheric Multipath processing – more than one ray is measured by the receiver at a given time:



Single ray region – ray optics approach ok!

Multipath: More than one ray arrives at the receiver. They interfere.

Wave optics retrievals: *Full Spectral Inversion*. Jensen et al *2003, Radio Science*, **38**, *10.1029/2002RS002763.* *(Also improve vertical. res.)*

Improved GPS receiver software: Open-loop processing.

Use of GPS-RO in NWP

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

- NWP centres assimilate either:
  - Bending angle profiles (ECMWF, MF, NCEP, Met Office, DWD, NRL, JMA)
  - Refractivity (Env. Can., …?)

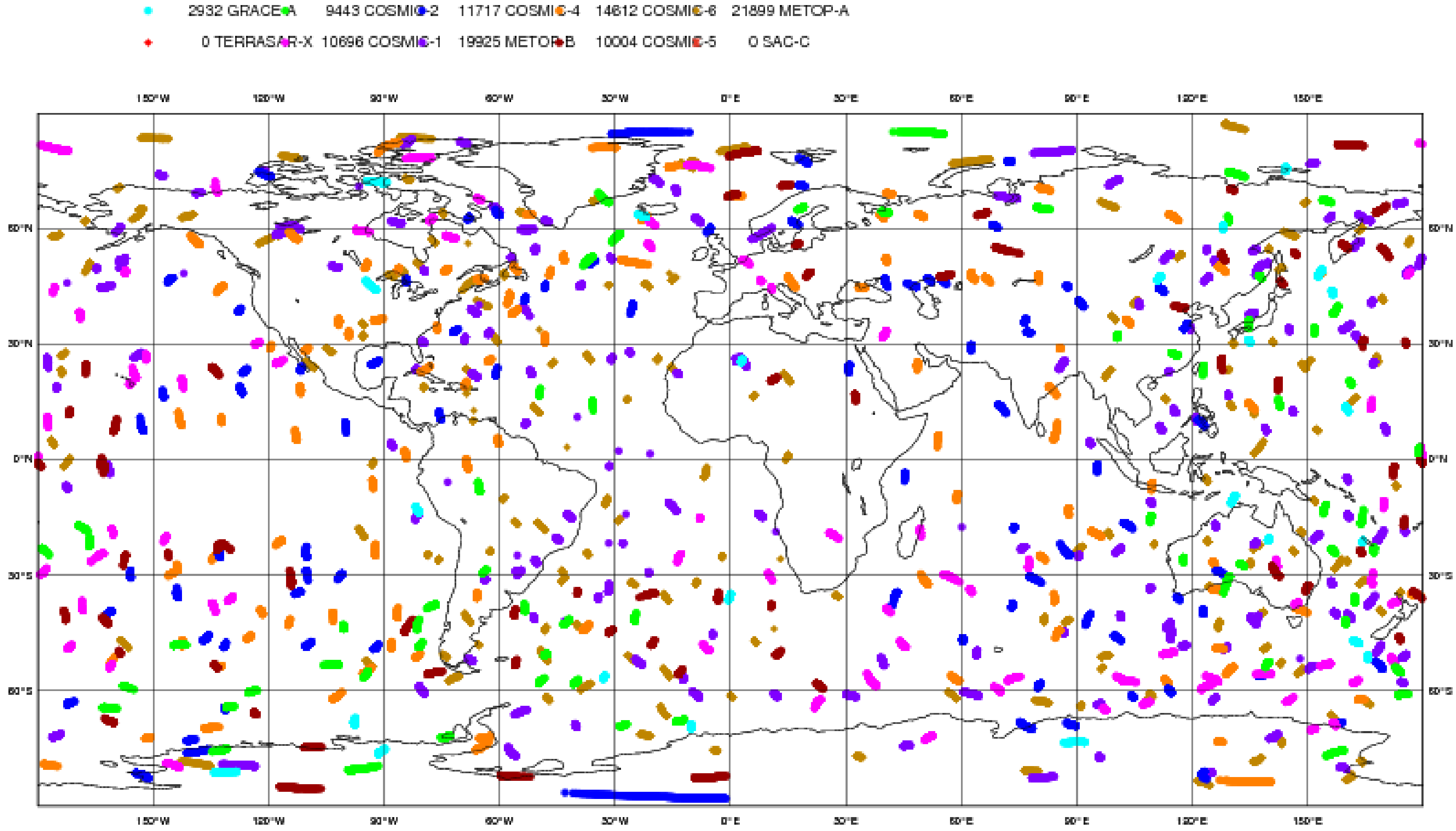
- **NWP centres assimilate the measurements without bias correction using a 1D operator.**

- 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**.

ECMWF Data Coverage (All obs DA) - GPSRO

18/Mar/2014; 00 UTC

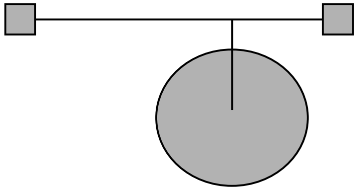
Total number of obs = 101228



Magics 2.14.4 (64 bit)

Current assimilation at ECMWF

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



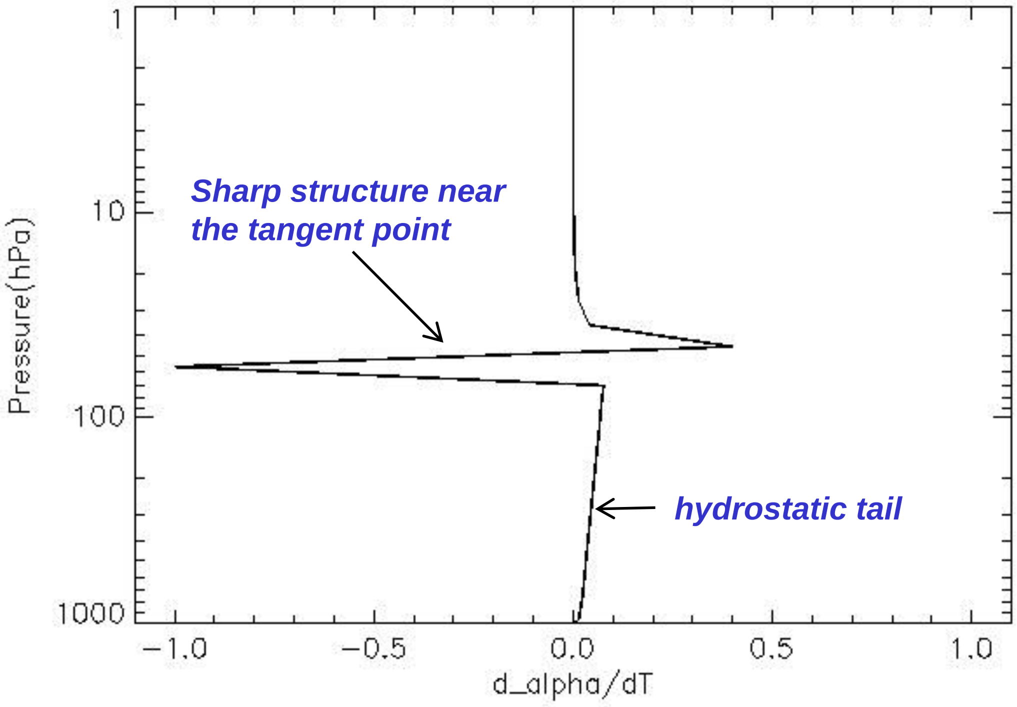
$$\alpha(a) = -2a\int_{a}^{\infty} \frac{d\ln n \big/ dx}{\sqrt{x^2 - a^2}}\,dx$$

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

- The forward model 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*: Gaussian error functions*).
  - **Following NCEP + MF, we now include tangent point (2011).**
  - **2D operator being tested currently at ECMWF (CY40R3).**

1D bending angle weighting function $\left(\frac{\partial\alpha}{\partial T}\right)$

(Normalised with the peak value)



Sharp structure near the tangent point

hydrostatic tail

(***See also Eyre, ECMWF Tech Memo. 199***.)

Weighting function peaks at the pressure levels above and below the ray tangent point. Bending related to vertical gradient of refractivity:

$$N = {c_1 P}/{T}$$

$$\Delta\alpha \propto (N_l - N_u)$$

Increase the T on the ***lower level*** *– reduce the N gradient – less bending!*

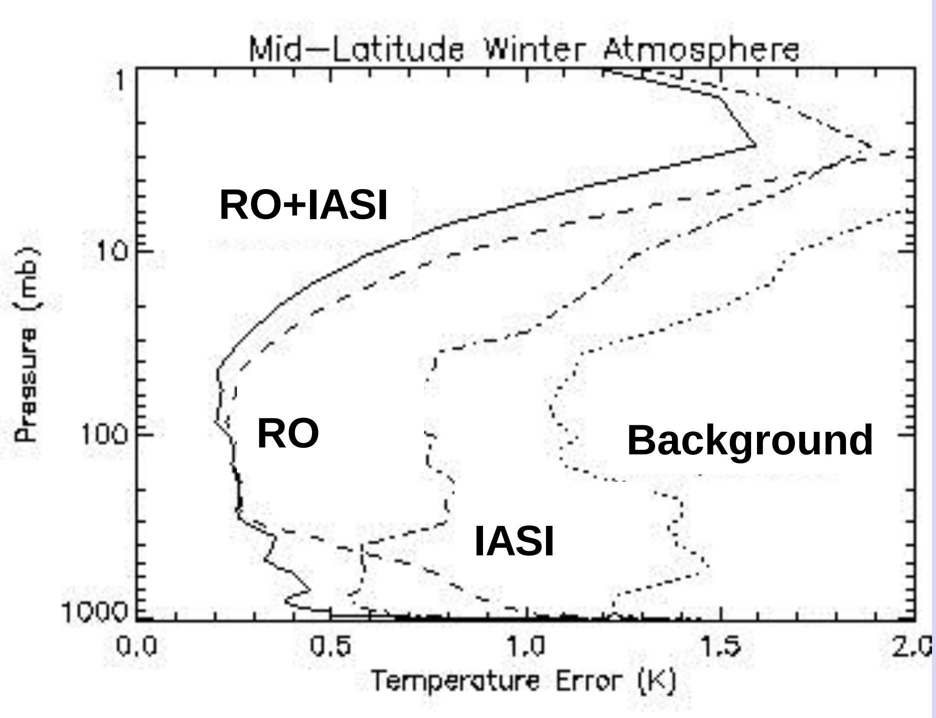
Increase the T on the ***upper level*** *– increase N gradient more bending!*

Very sharp weighting function in the vertical – we can resolve structures that nadir sounders cannot!

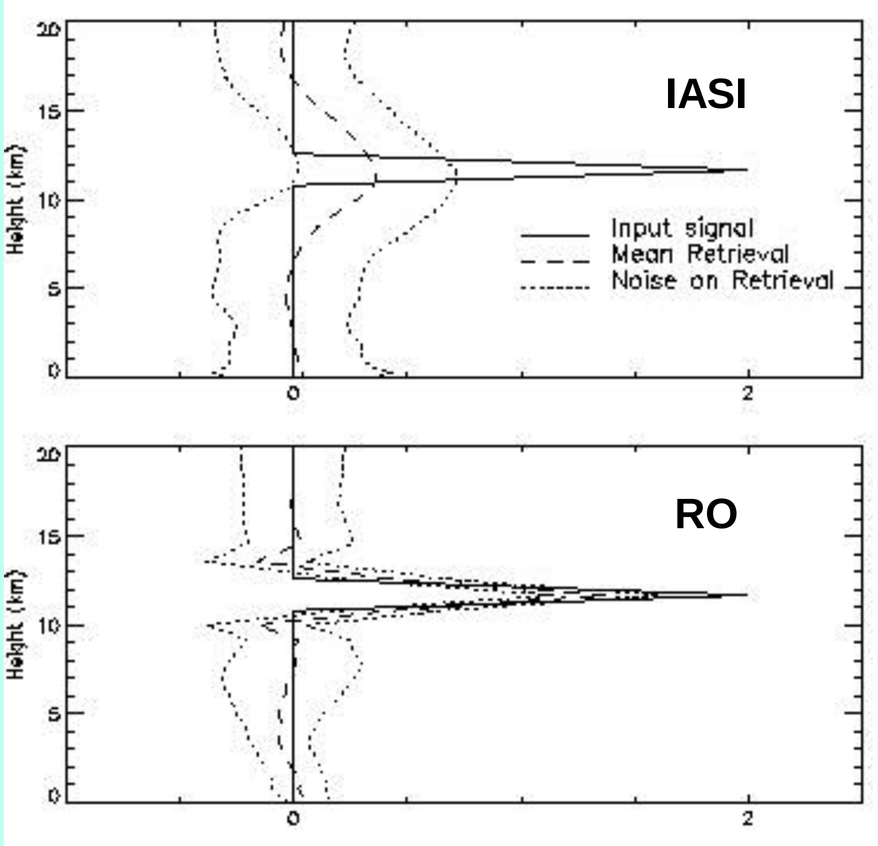
GPS-RO and IASI: 1DVAR simulations

Healy and Collard 2003, QJRMS:

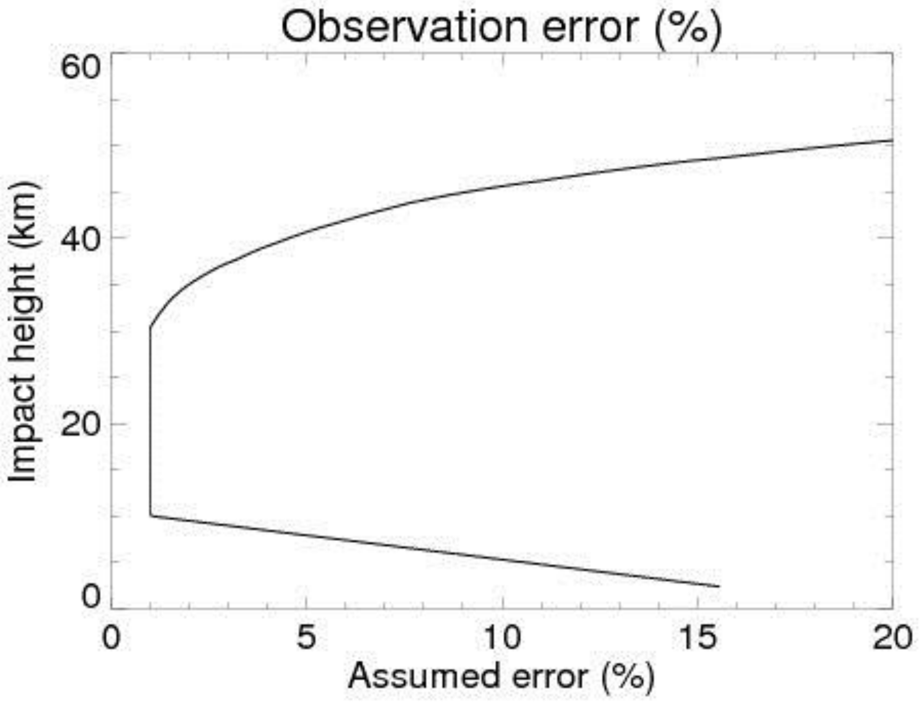
Expected retrieval error:

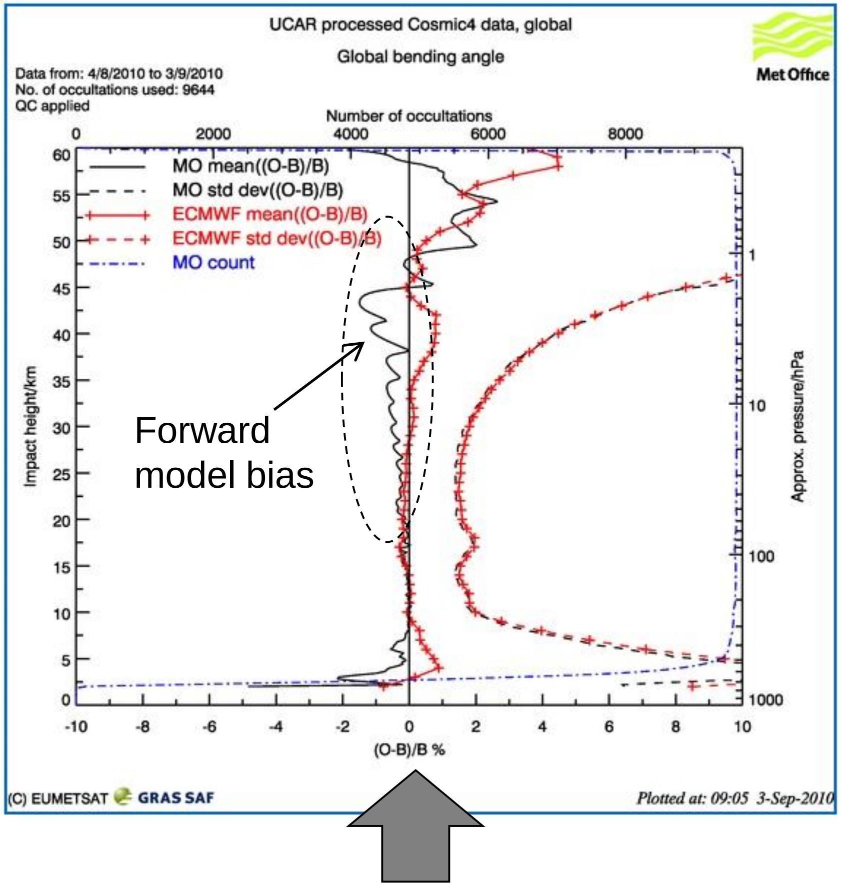


Power to resolve a peak-shaped error in background: Averaging Kernel.



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





Forward model bias

Consistent with (o-b) stats.

Met Office model varies with latitude.

See http://www.romsaf.org/monitoring/

Impact at ECMWF

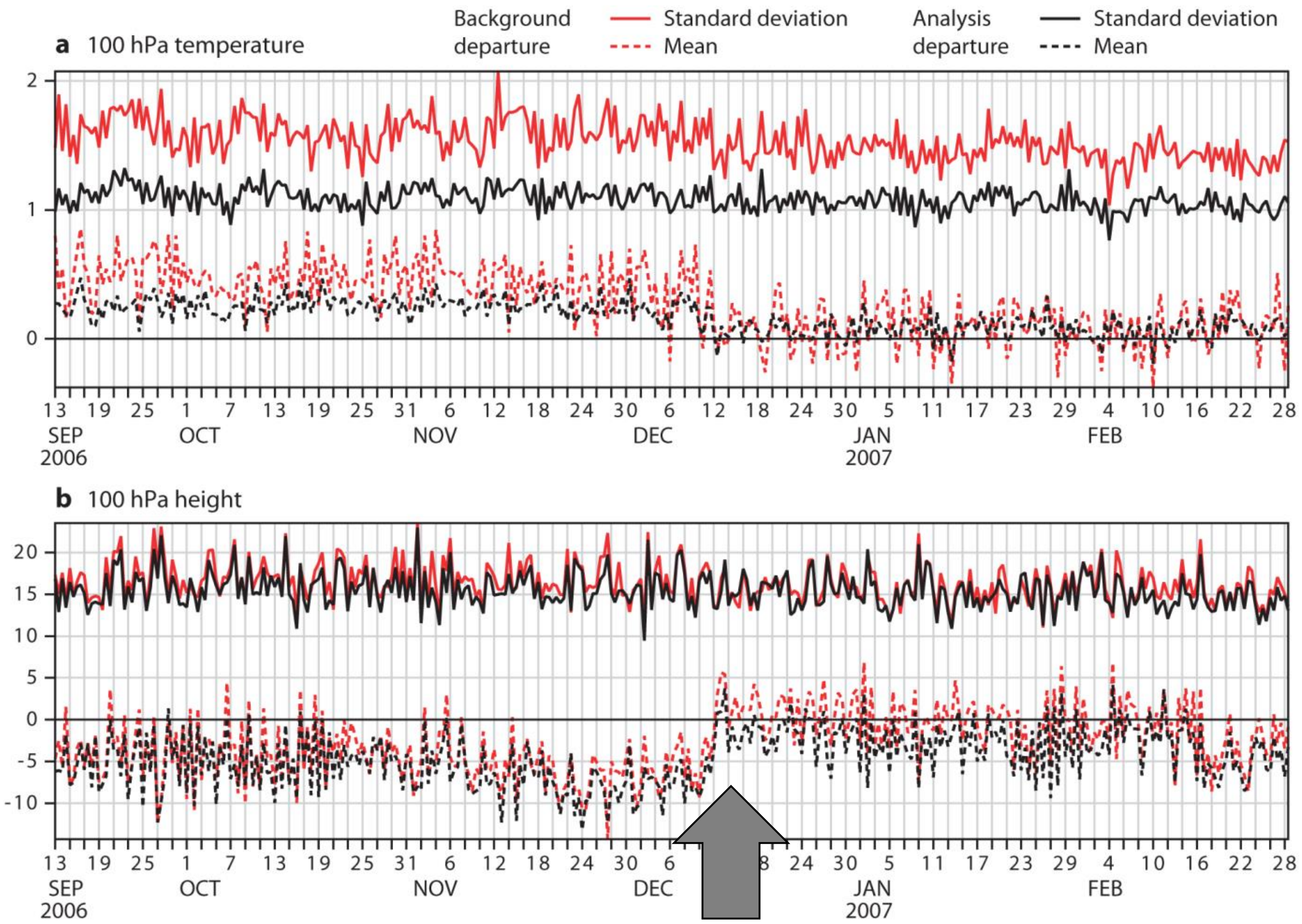
- ECMWF has assimilated GPS-RO bending angles operationally since December 12, 2006.

- 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.**

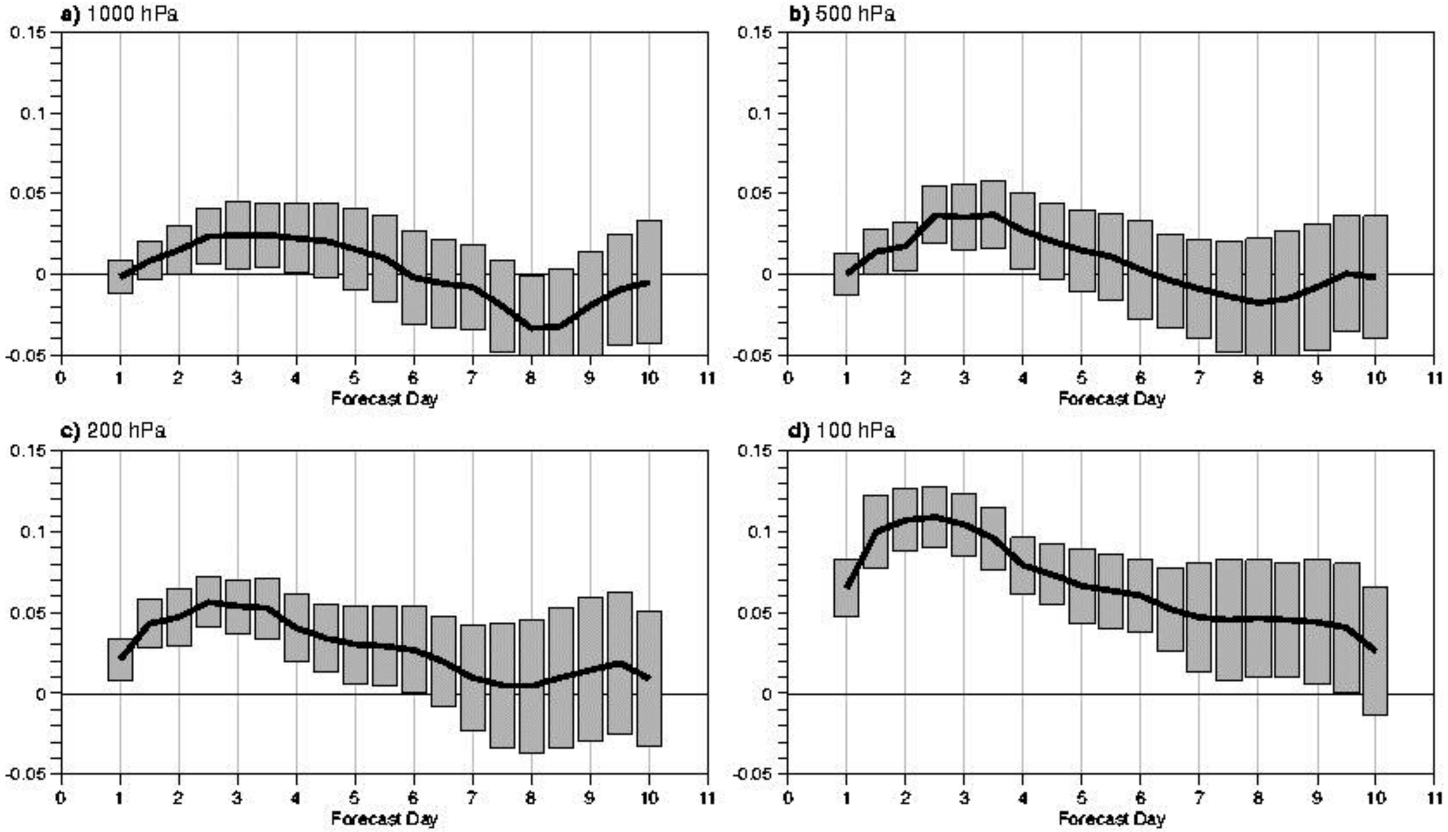
Impact of GPS-RO on ECMWF operational biases against radiosonde measurements



Operational implementation

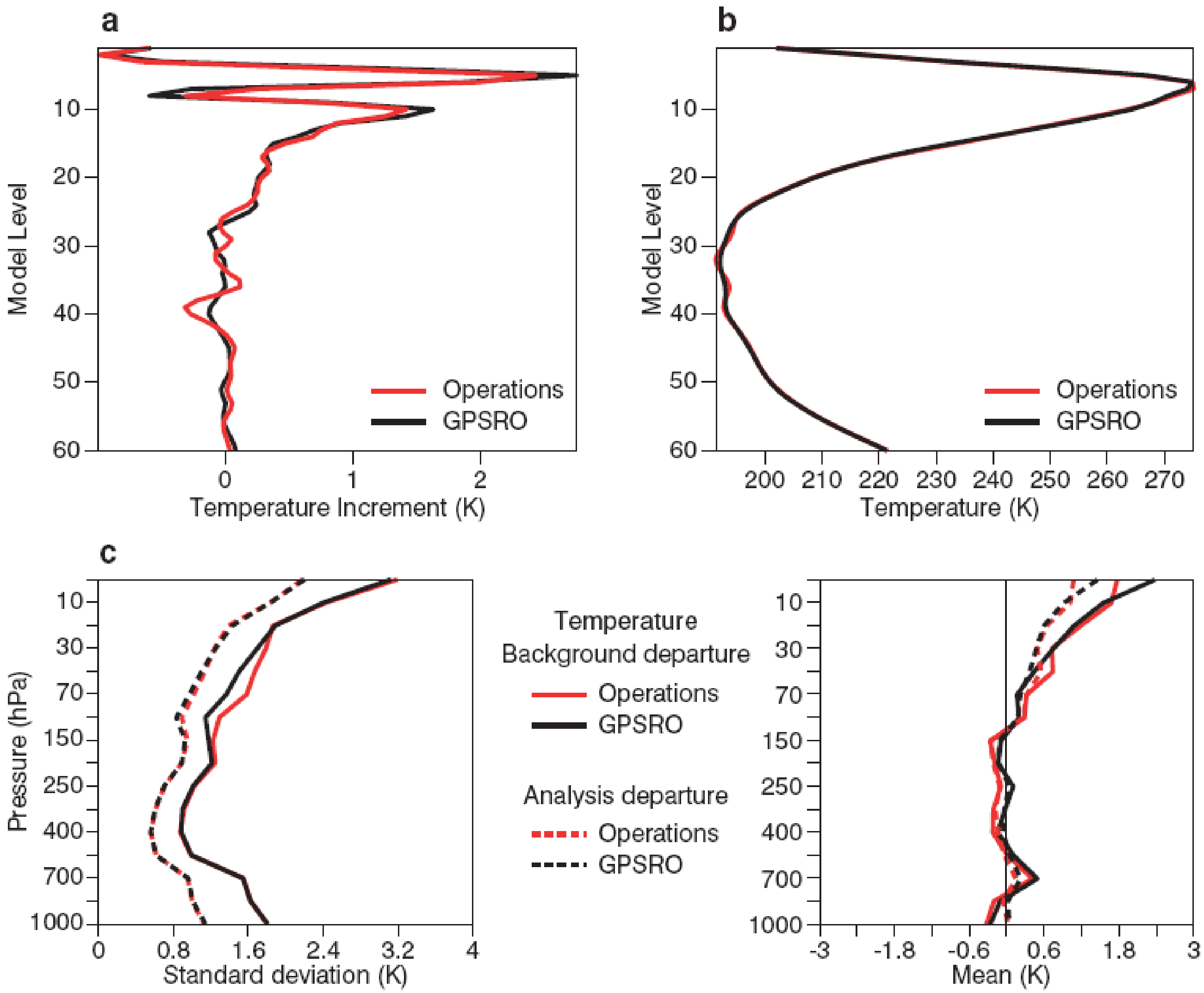
Fractional improvement in the southern hemisphere geopotential height RMS scores

+ve impact



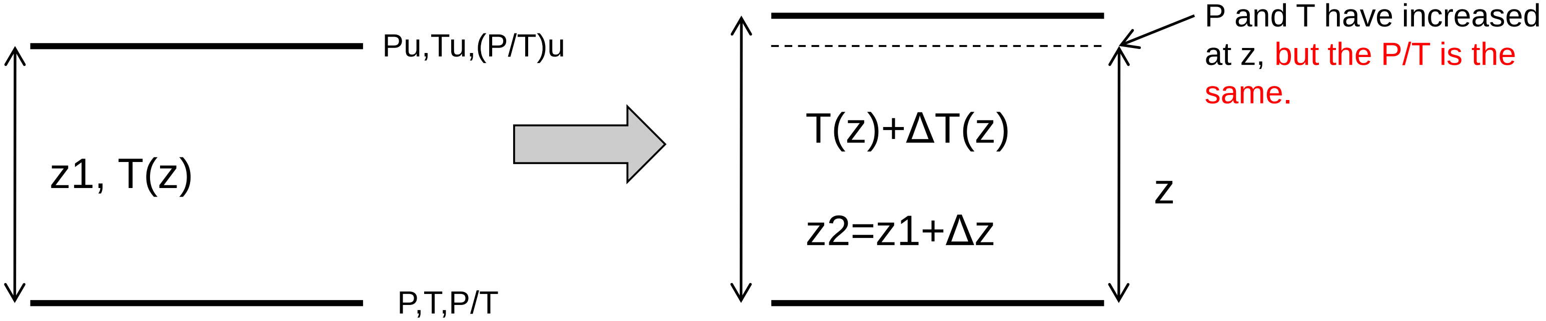
Similar results obtained at the other major NWP centres.

Stratospheric ringing problem over Antarctica reduced by assimilating GPS-RO



BUT 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 z1, with temperature variation T(z) between them. Now add positive perturbation $\Delta T(z) \sim k*\exp(z/H)$, where H is the density scale height



Pu,Tu,(P/T)u

z1, T(z)

P,T,P/T

T(z)+ΔT(z)

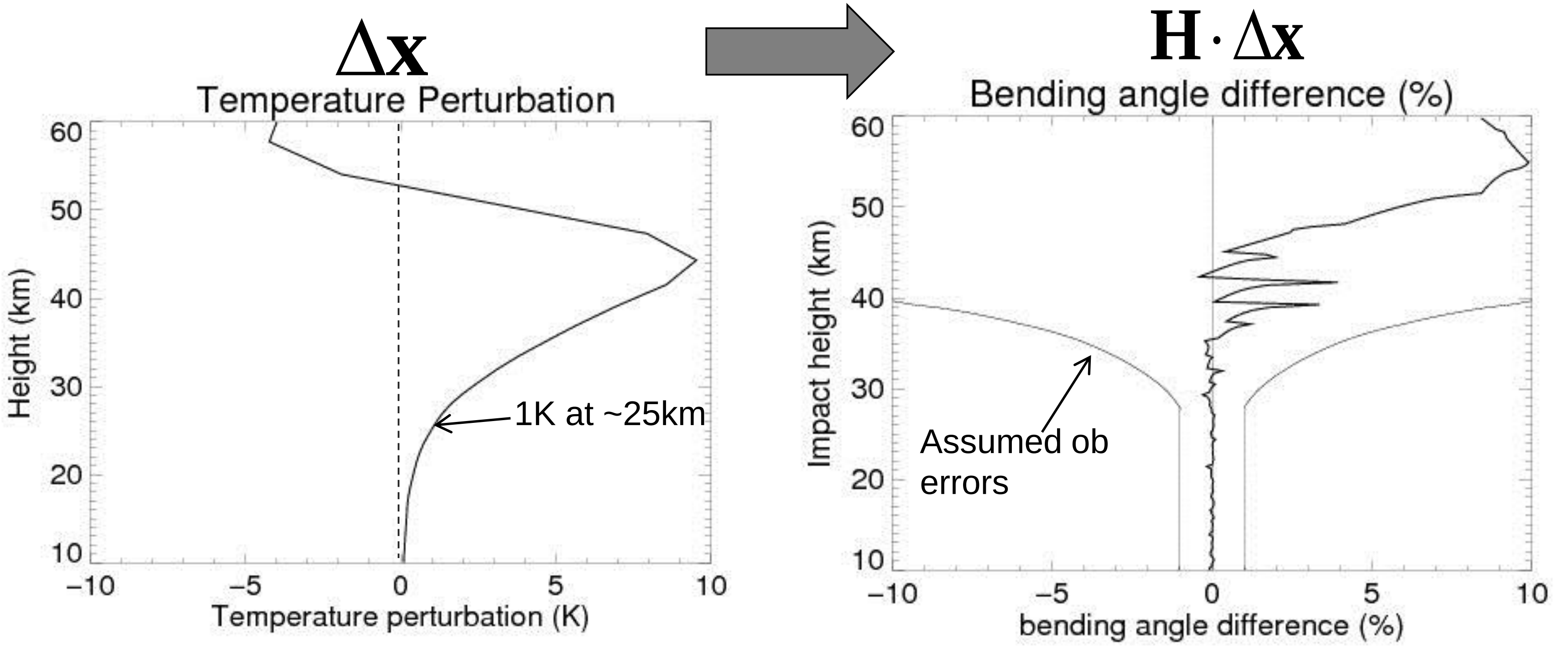
z2=z1+Δz

z

P and T have increased at z, but the P/T is the same.

- The density as a function of height is almost unchanged. **A priori information required to distinguish between these temperature profiles. (Height of a pressure level).**

Null space – how does this temperature difference at the S.Pole propagate through the observation operator

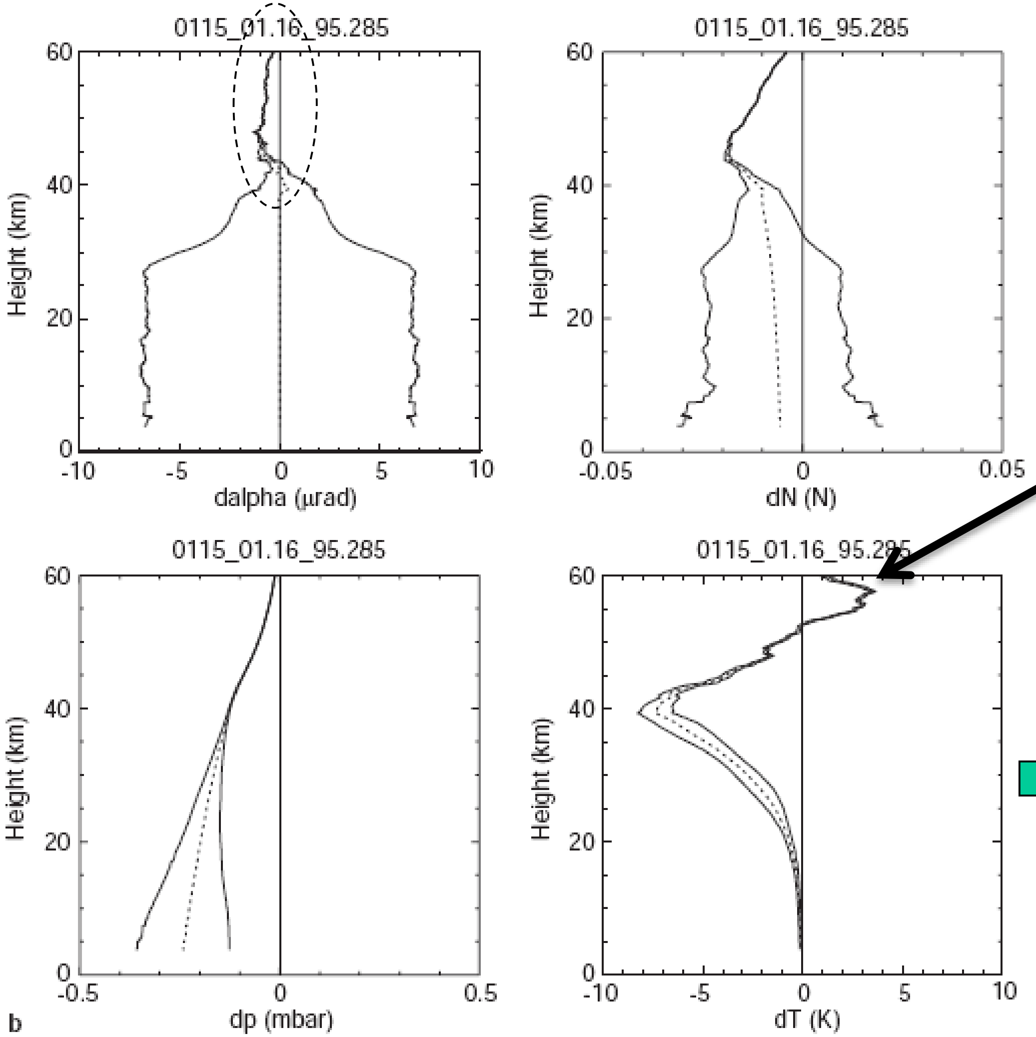


1K at ~25km

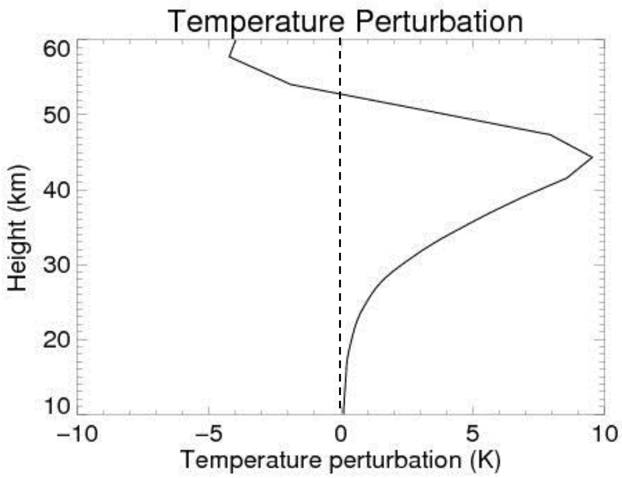
Assumed ob errors

The null space arises because the measurements are sensitive to ~P(z)/T(z). *A priori* information is required to split this into T(z) and P(z).

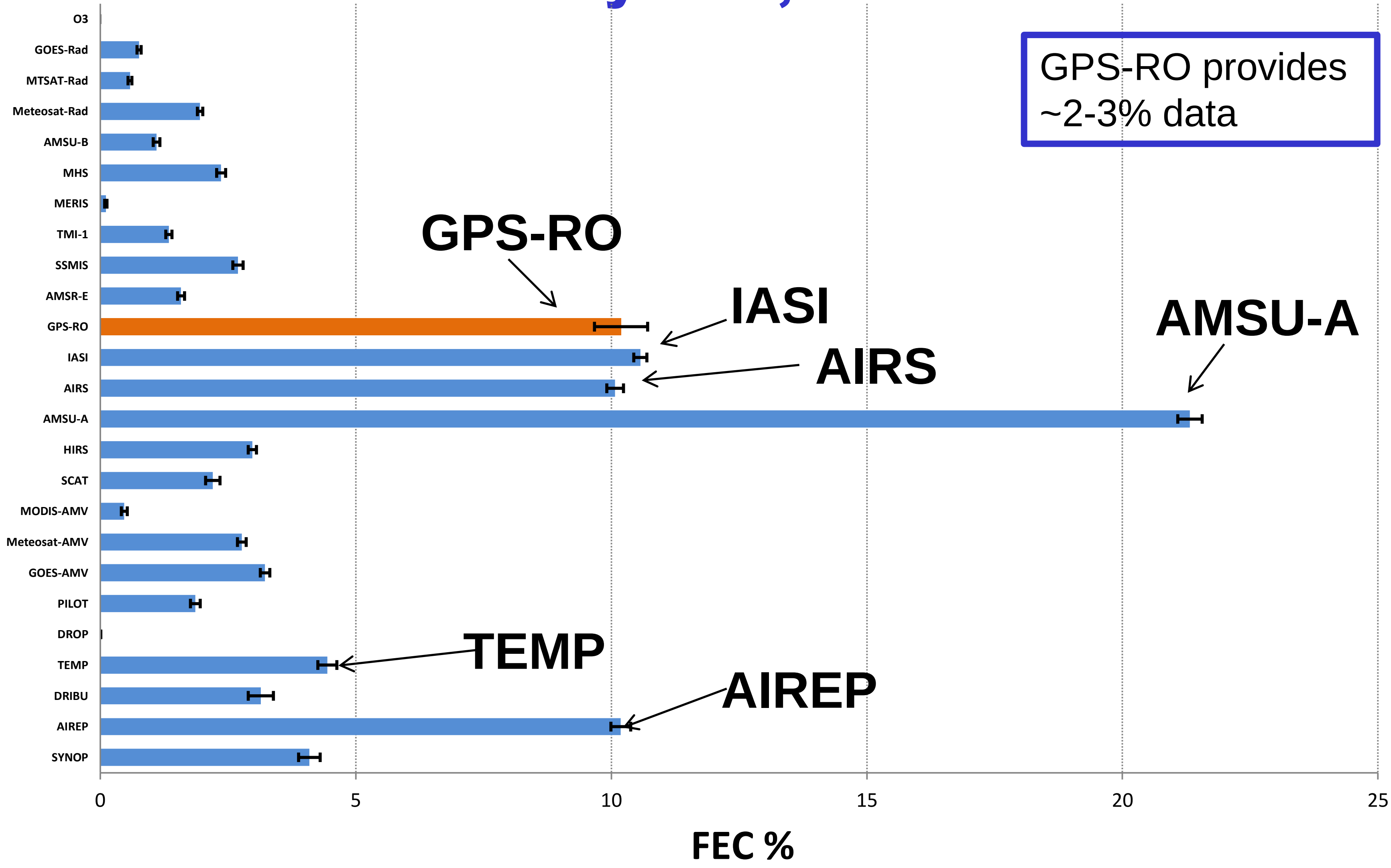
Compare with Steiner et al (Ann.Geophs., 1999,17, 122-138)



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

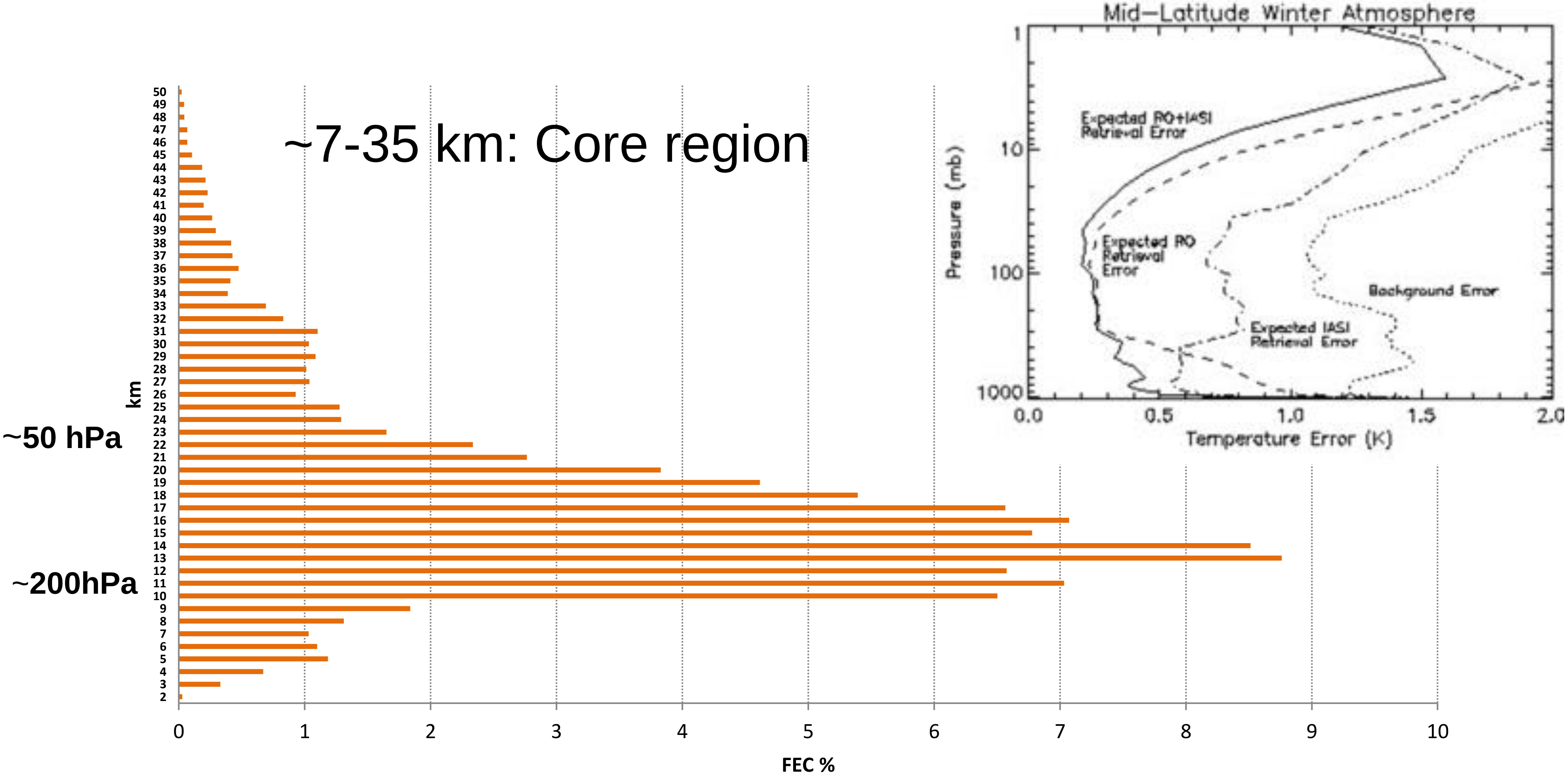


ADJOINT BASED FEC/FSO Contribution (24 h) ECMWF System, June 2011



GPS-RO provides ~2-3% data

Heights where GPS-RO is reducing the 24 hr forecast errors in ECMWF system using adjoint approach



~7-35 km: Core region

~50 hPa

~200hPa

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.

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

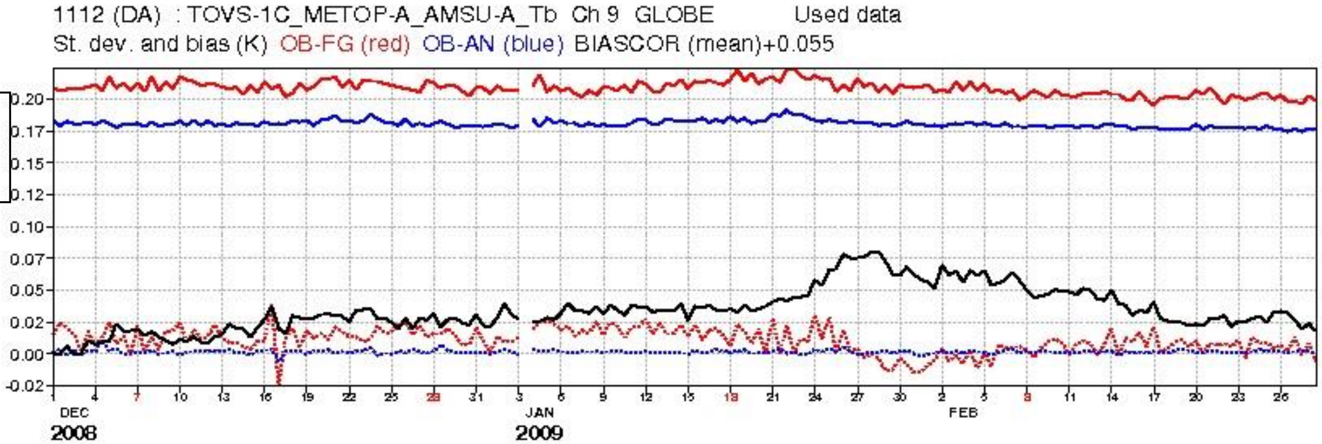
- Demonstrated value in both NWP and reanalysis systems.

- **See also work by Josep Aparicio and Lidia Cucurull.**

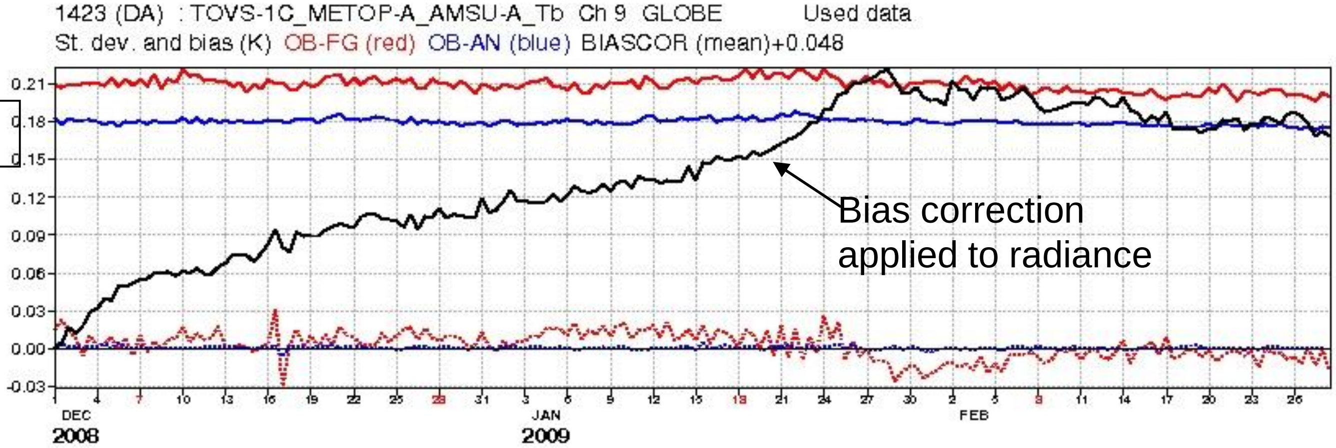
Recent experiment removing GPS-RO from ERA-Interim (Dec. 08, Jan-Feb 09)

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

GPSRO assimilated



No GPSRO

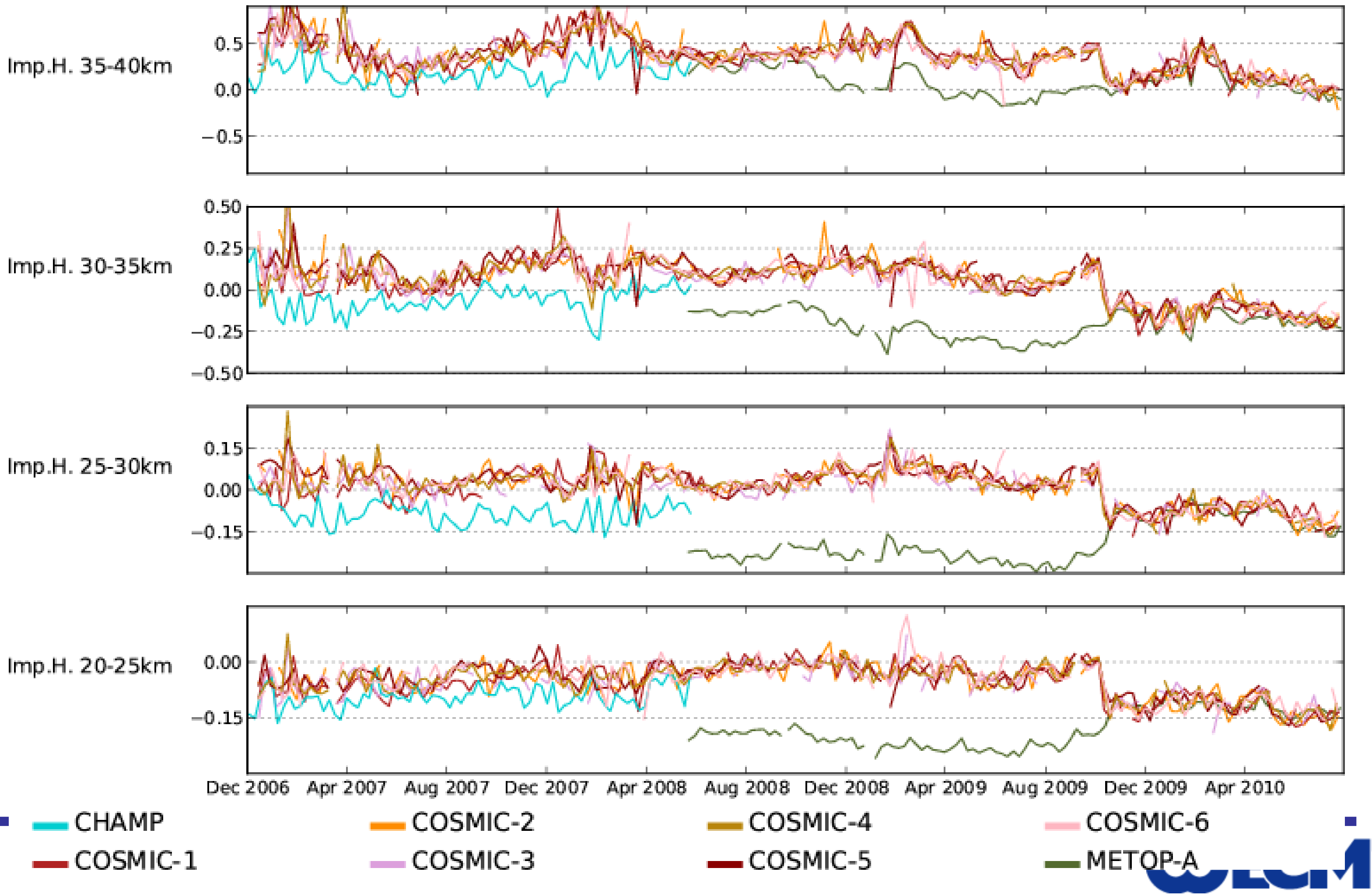


Bias correction applied to radiance

Climate/reanalysis applications

- **RO is likely to become increasingly 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.**

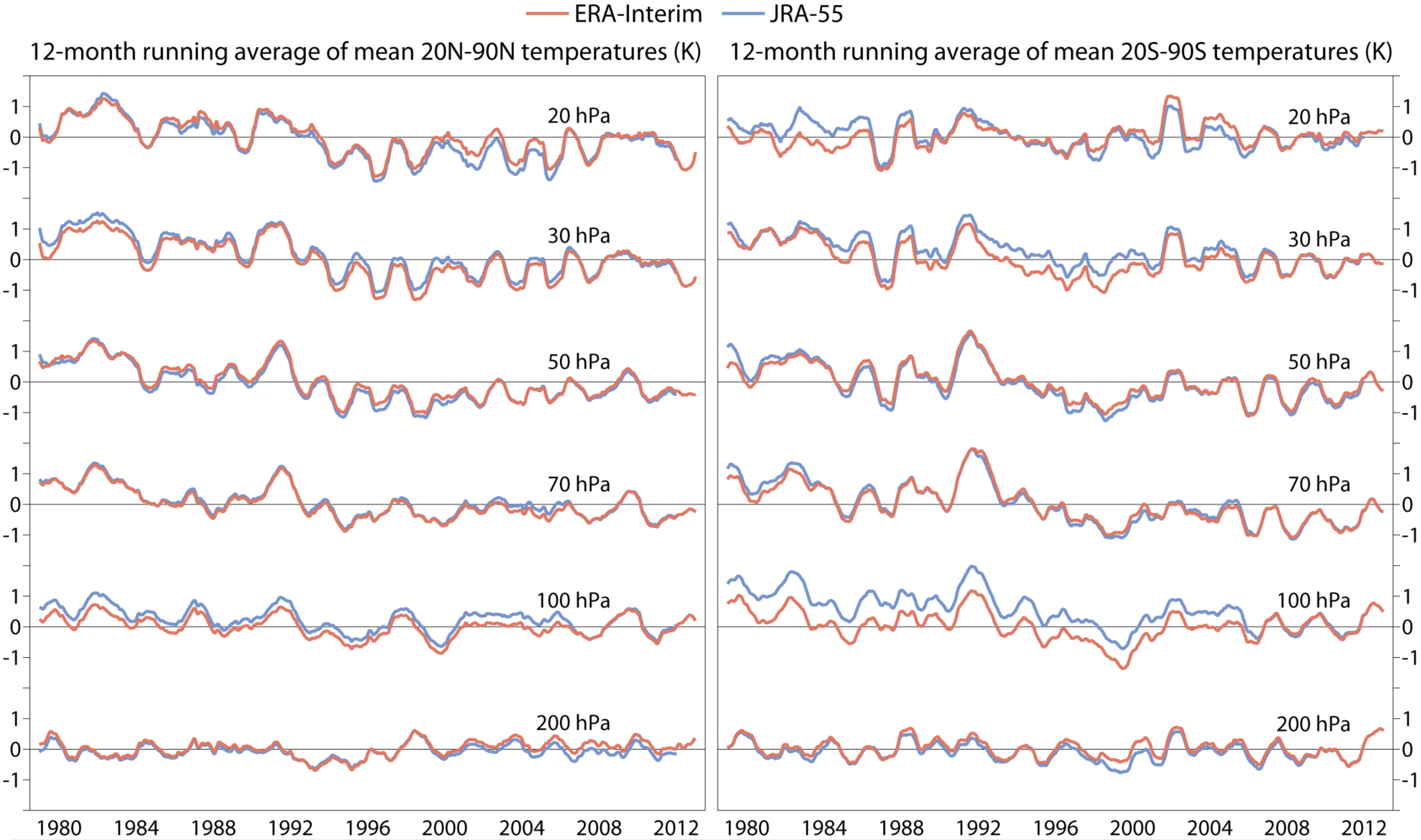
Consistency of GPS-RO bending angles (ERA-Interim Reanalysis, Paul Poli)



ERA-Interim daily Obs minus Background statistics GPSRO B.A. (percent) N.Hem. (20N-90N)

Adrian Simmons

GPS-RO and extratropical-mean temperatures from ERA-Interim and JRA-55



Values are relative to ERA-Interim means for 1981-2010

GPS-RO for model developers

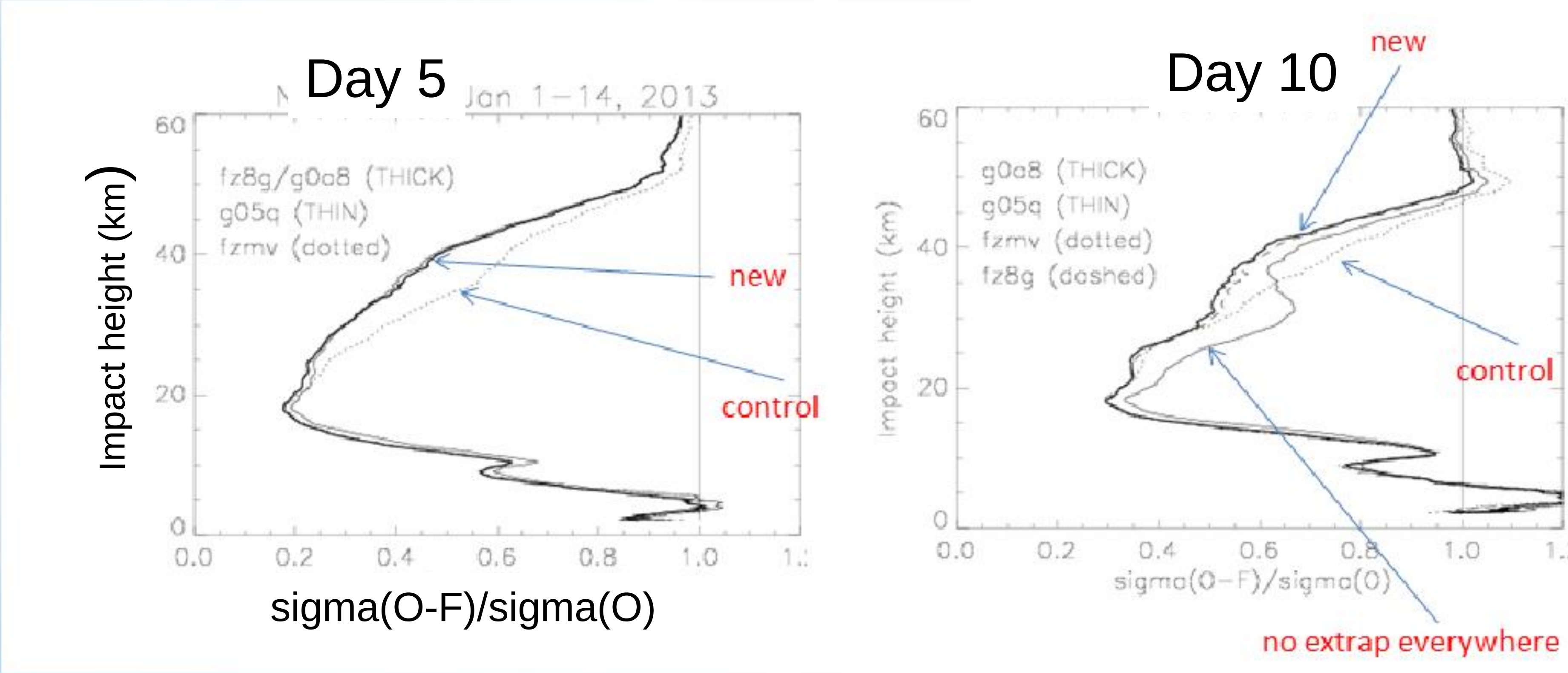
- Some ECMWF forecasts of sudden warming events have been poor (Jan 2013).

- **Michail Diamantakis**: Numerical noise in the wind extrapolation leads to incorrect departure points in the semi-Lagrangian scheme.

- New scheme proposed/developed/tested by **Michail**.

- Simplified 1D bending angle operator (no tangent point drift) to look at the accuracy of the day-5 and day-10 forecasts with the new scheme in bending angle space. Fit to operational GPS-RO data.

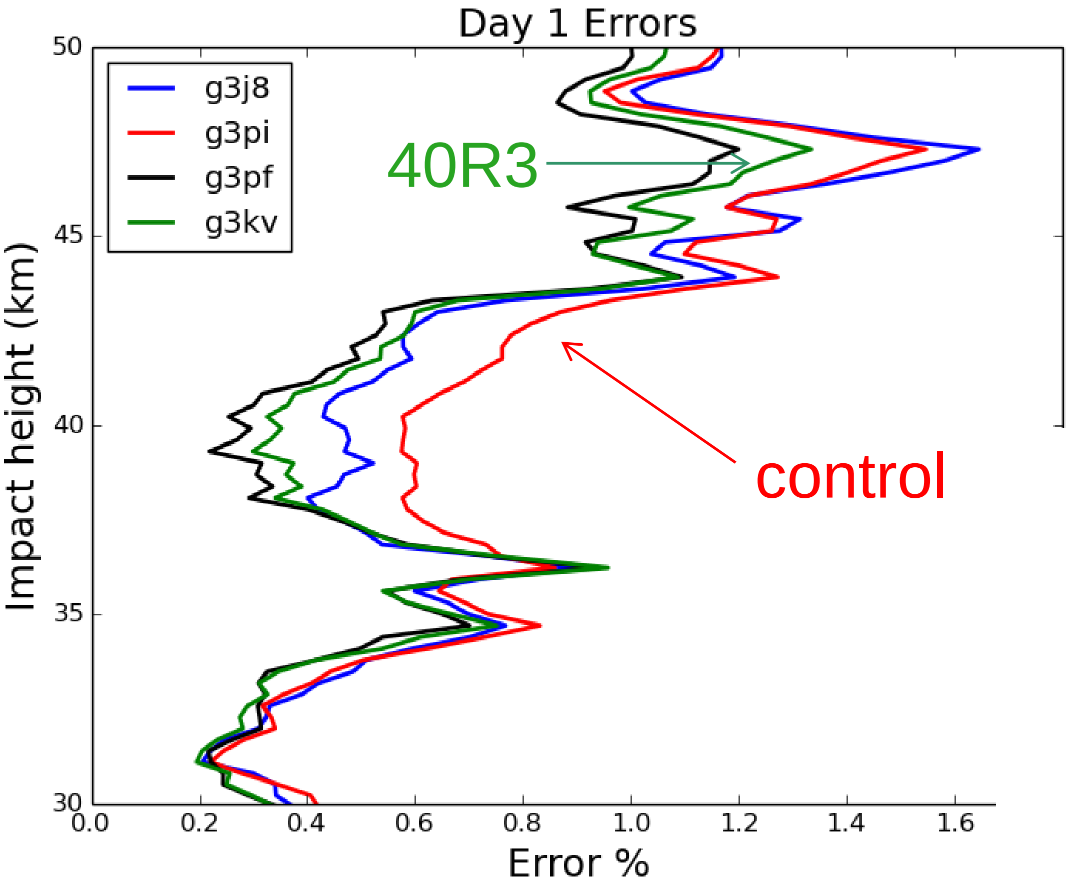
Verification against sat obs: bending angle diagnostics



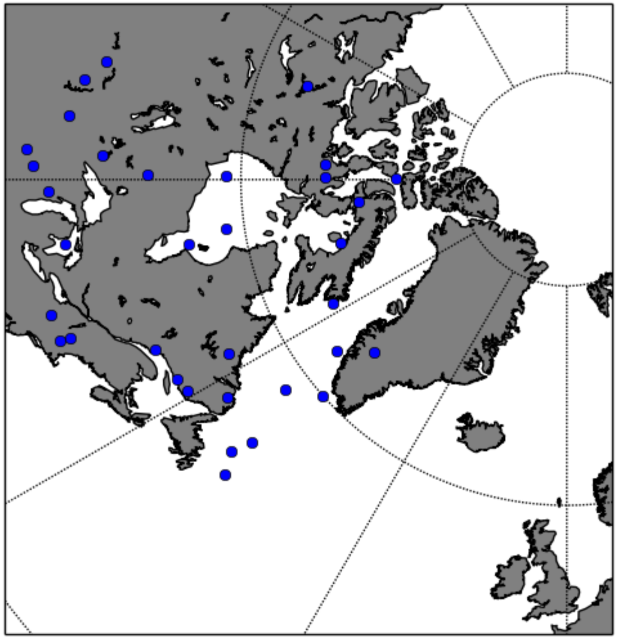
[Standard deviation of GPS-RO bending angle errors (tool developed by Sean Healy)]

- Noticeable improvement at medium-range (day 5, 10)
- Applying non-extrapolatory scheme EVERYWHERE decreases accuracy at medium range ⇒ combined approach the right one

Single 24 hr forecast, Jan 11, 2014



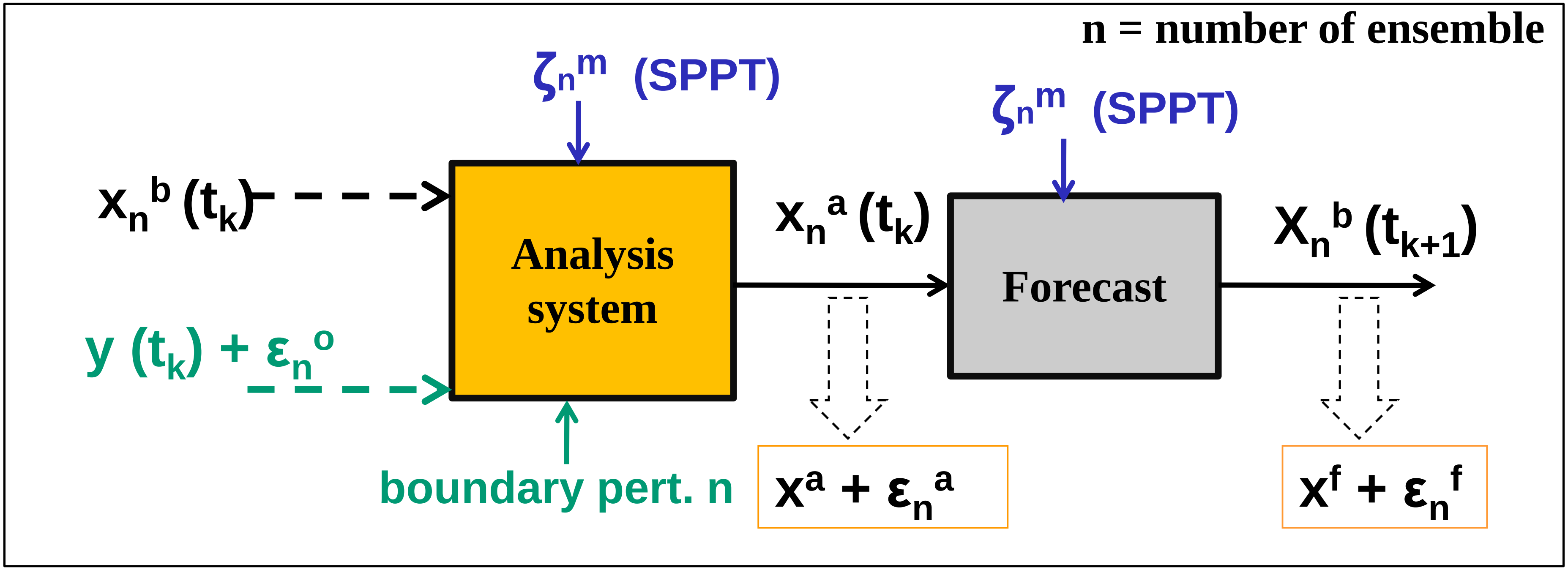
Ob. Locations 35 cases



How many GPS-RO observations do we need?

- Noted GPS-RO contributes ~2-3 % of the data assimilated.
- Studies by *Poli et al (2008)* and *Bauer et al (2014)* indicated that the impact of GPS-RO is not saturated at current ob. numbers.
- "**Ensemble of Data Assimilations**" (EDA) approach for estimating the impact of new data. **EG, Tan et al, QJ, 2007, vol 133, p381, ADM-Aeolus impact**.
- ESA project to estimate how the impact of GPS-RO scales with observation number.
- **We're not doing OSSEs. We only simulate the new data.**

The EDA method



n = number of ensemble

ζ_n^m (SPPT)

ζ_n^m (SPPT)

$x_n^b\,(t_k)$

Analysis system

$y\,(t_k) + \varepsilon_n^o$

boundary pert. n

$x_n^a\,(t_k)$

Forecast

$X_n^b\,(t_{k+1})$

$x^a + \varepsilon_n^a$

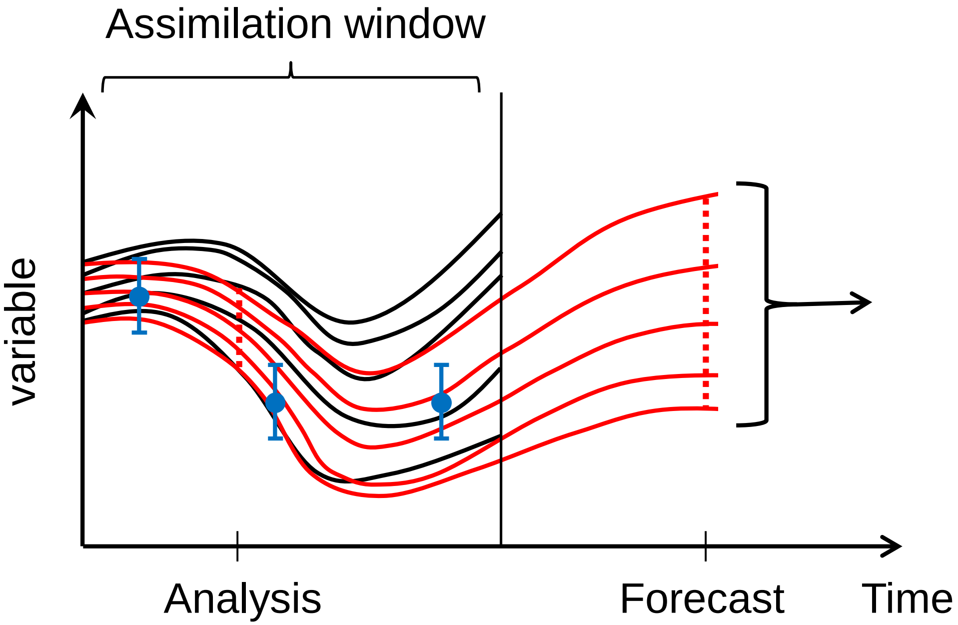
$x^f + \varepsilon_n^f$

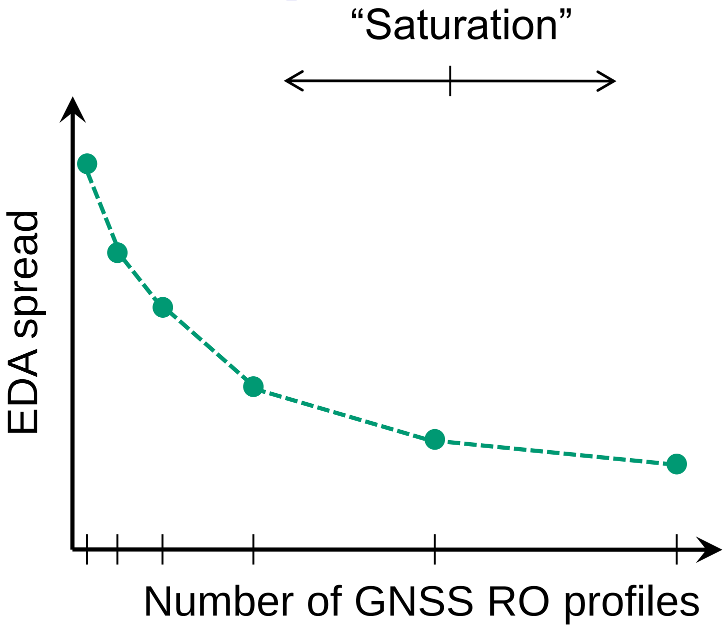
- We cycle 10 4D-Vars in parallel using perturbed observations in each 4D-Var, plus a control experiment with no perturbations.

- The spread of the ensemble about the mean is related to the theoretical estimate of the analysis and short-range forecast *error statistics*.

- Investigate how the ensemble spread changes as we increase the number of simulated GNSS-RO observations.

EDA based observation impact





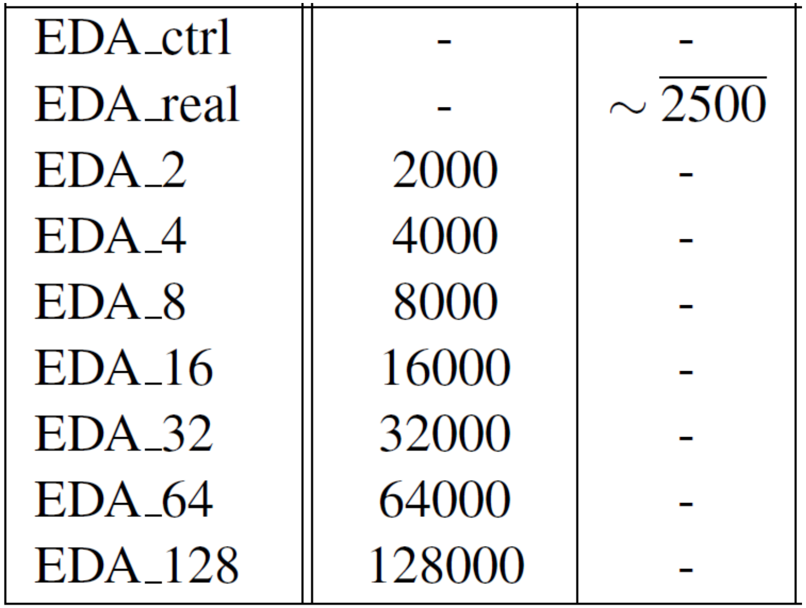
- Aim to investigate ensemble spread as a function of GNSS-RO number.
- Identify, if and when the impact begins to saturate.

Setup of GNSS-RO experiments

- EDA experiments assimilate:

  - all operationally used GOS (apart from GNSS-RO data)

  - plus | simulated | real | GNSS-RO profiles per day

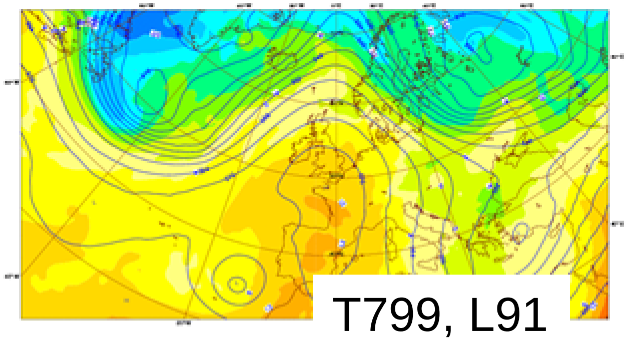


	simulated	real
EDA_ctrl	-	-
EDA_real	-	$\sim \overline{2500}$
EDA_2	2000	-
EDA_4	4000	-
EDA_8	8000	-
EDA_16	16000	-
EDA_32	32000	-
EDA_64	64000	-
EDA_128	128000	-

→ Total of nine EDA experiment that only differ in the number of assimilated GNSS RO data. 6 week period July-August 2008.

Simulation of GNSS-RO data

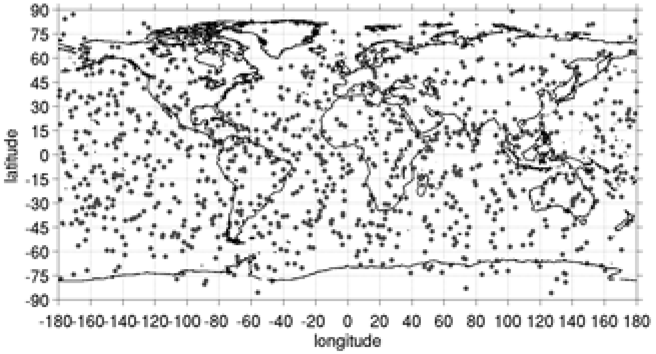
Operational ECMWF analysis
→ proxy for the “truth”



T799, L91

interpolate

randomly distributed
observation time and location



2D
bending angle
operator

We use a 1D operator to assimilate this data.

realistic
observation
errors

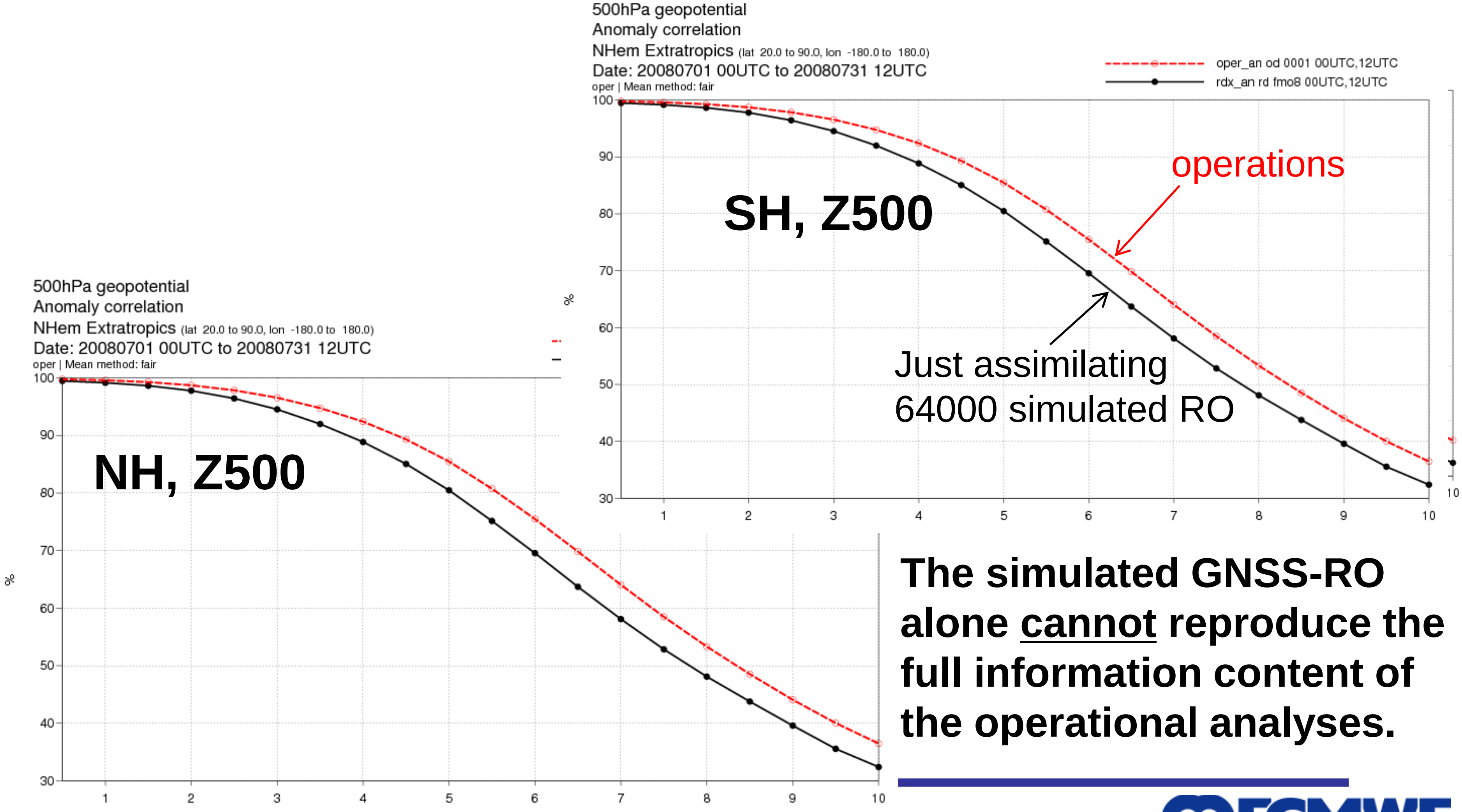
Adjusted to get reasonable (o-b)s

simulated GNSS-RO
bending angle
profiles

On 247 levels and looks like GRAS data

4D-Var test experiments (T511, July 2008)

64000 simulated GNSS-RO vs Full system

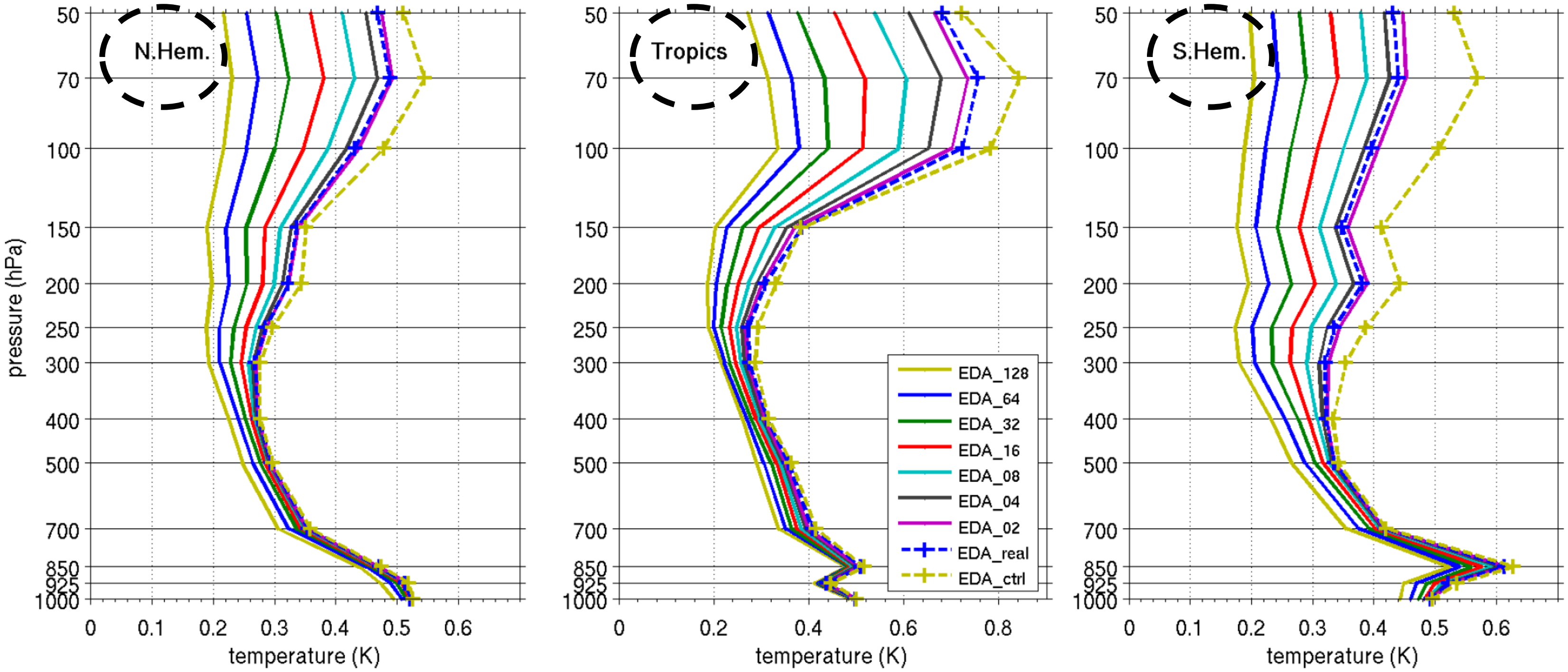


The simulated GNSS-RO alone cannot reproduce the full information content of the operational analyses.

Vertical profiles of EDA spread T(K)

- Temperature uncertainty for the analysis
  → reduced with additional GNSS-RO profiles
- **Very good agreement between EDA_real and EDA_2**

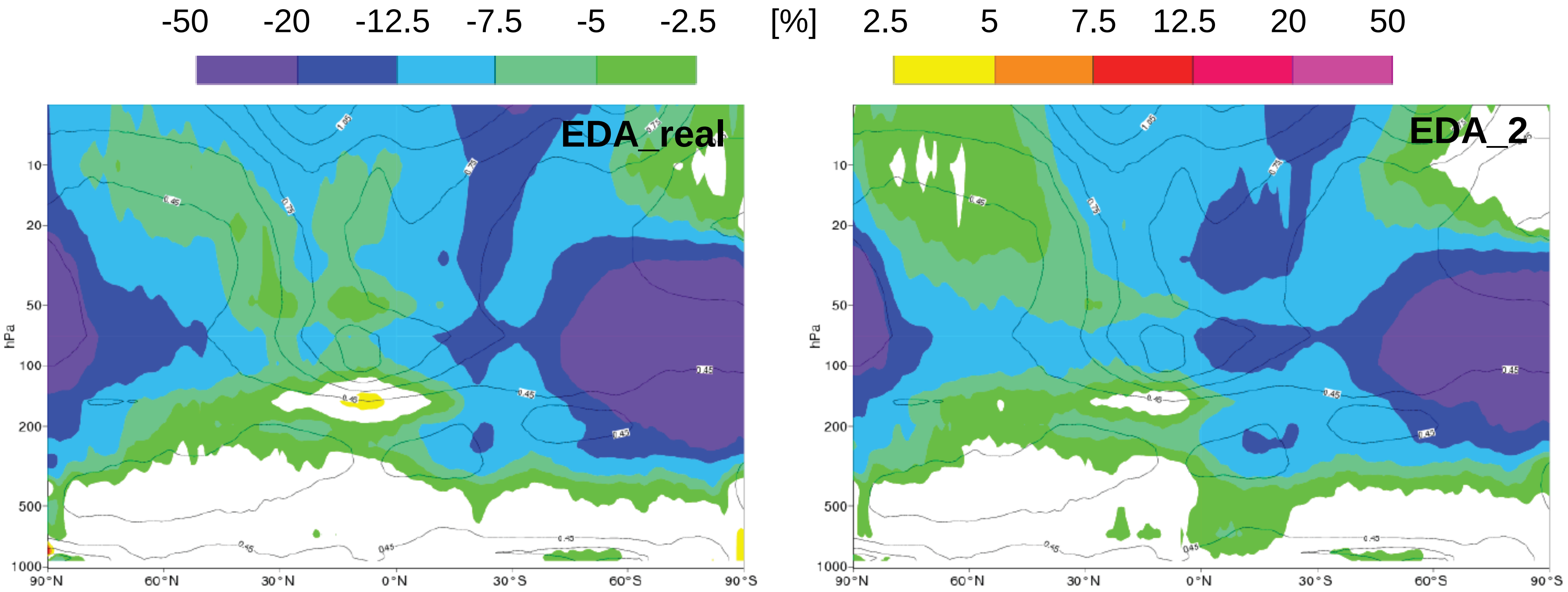
EDA analysis spread for temperature (K)



Cross section of observation impact

$$\frac{\mathrm{EDA\_}n - \mathrm{EDA\_ctrl}}{\mathrm{EDA\_ctrl}}$$

Temperature analysis



- Maximum impact on upper-tropospheric / middle-stratospheric temperatures
- **Very good agreement between real and simulated GNSS RO data in the EDA system.**
- Similar pattern for geopotential height

How we interpret the EDA spread values

- **Information content/error covariance studies** studies in 1D-Var framework for simulated satellite data (e.g. Eyre 1987):

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x} - \mathbf{x}^{\mathrm{b}})^{\mathrm{T}}\mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}^{\mathrm{b}}) + \frac{1}{2}(\mathbf{y}^{\mathrm{o}} - H(\mathbf{x}))^{\mathrm{T}}(\mathbf{E} + \mathbf{F})^{-1}(\mathbf{y}^{\mathrm{o}} - H(\mathbf{x}))$$

$$\mathbf{A} = (\mathbf{B}^{-1} + \mathbf{H}^{\mathrm{T}}\mathbf{R}^{-1}\mathbf{H})^{-1}$$

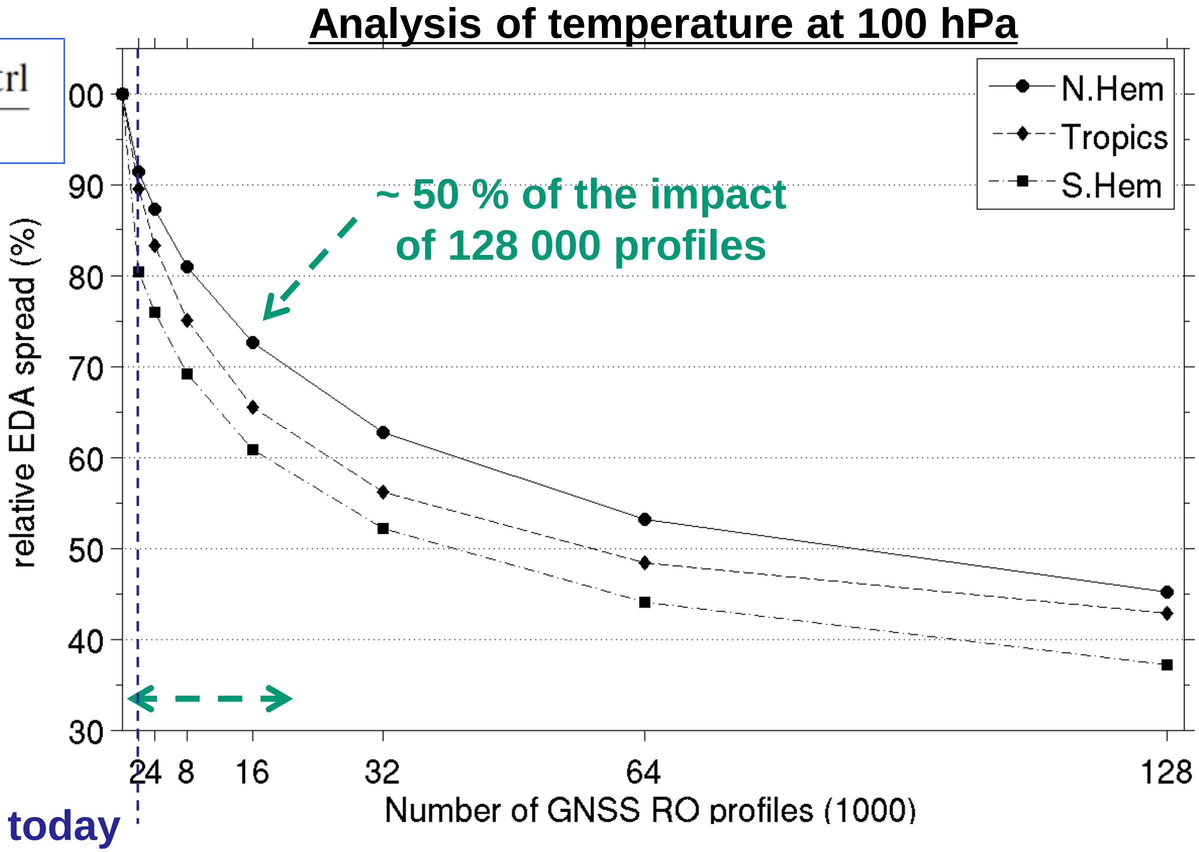
- **We interpret the EDA spread results as a 4D-Var theoretical information content/error covariance study.**

- The spread values are related to the theoretical error statistics, and these are dependent on the assumed obs. error stats. and weighting functions, **<u>not necessarily the real impact of the observations</u>.**

- If the assumed error statistics are unrealistic/incorrect, the spread values will mislead.

Scaling of GNSS RO impact - EDA

$$\frac{\mathrm{EDA\_}n - \mathrm{EDA\_ctrl}}{\mathrm{EDA\_ctrl}}$$



Analysis of temperature at 100 hPa

~ 50 % of the impact of 128 000 profiles

~ 25 million bending angles per day

- **Large improvements up to 16000 profiles per day**
- **Even with 32000 – 128000 profiles still improvements possible**

→ no evidence of saturated impact up to 128000 profiles.

Move towards 2D GPS-RO operators

- The 2D operators take account of the real limb nature of the measurement, and this should reduce the forward model errors defined as

$$H(\mathbf{x}_\mathbf{t}) - \mathbf{y}_\mathbf{t} = \boldsymbol{\varepsilon}_\mathbf{f}$$

Forward model error

Noise free observation

Discrete representation
of true state from model

- Reducing the forward model errors should improve our ability to retrieve information from the observation, but this must be balanced:

Extra Information versus Additional Computing Costs.

2D operator assimilation

1D

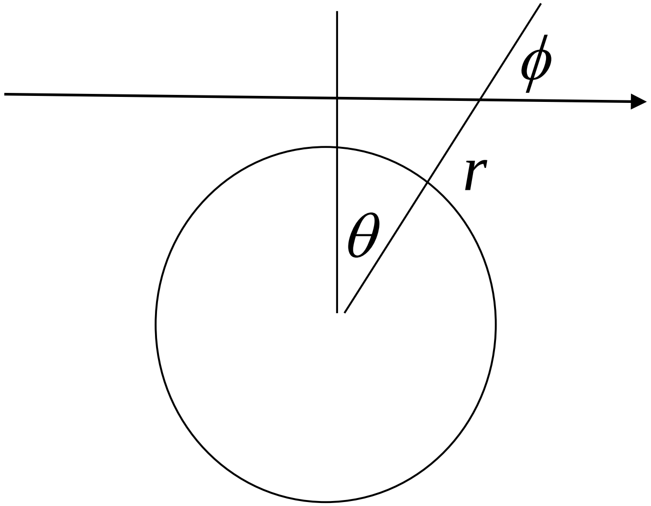
$$\alpha(a) = -2a \int_a^{\infty} \frac{d \ln n / dx}{\sqrt{x^2 - a^2}} dx$$

$$\frac{dr}{ds} = \cos\phi$$

Rodgers
Page 149

$$\frac{d\theta}{ds} = \frac{\sin\phi}{r}$$

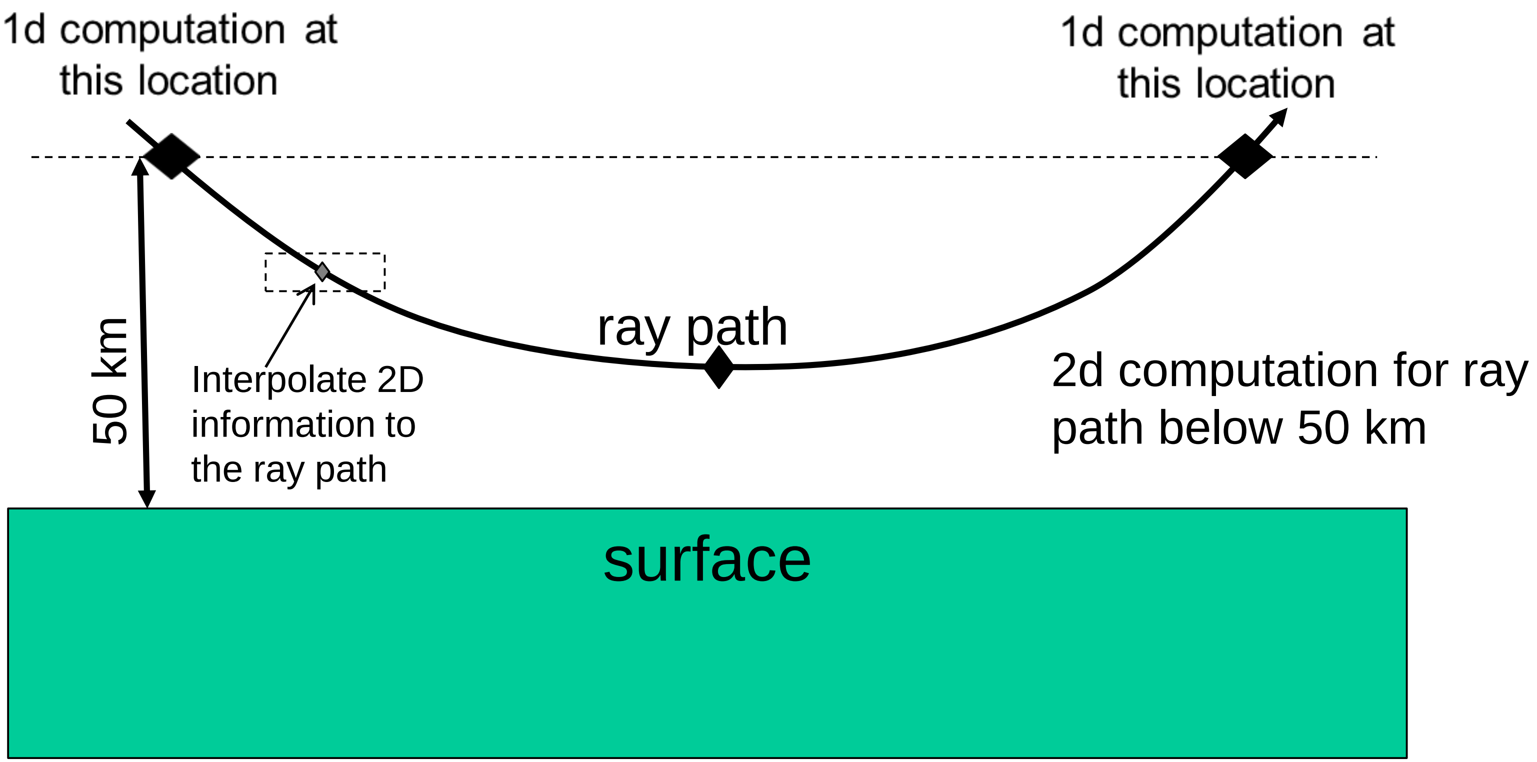
$$\frac{d\phi}{ds} \approx -\sin\phi\left[\frac{1}{r} + \left(\frac{\partial n}{\partial r}\right)_{\theta}\right]$$



Tangent point height derived from impact parameter.

We solve these ray equations for the path **up to 50 km** and then revert to the 1D approach to estimate the bending above **50 km**. *Zou et al suggested similar mixed bending angle/refractivity approach.*

1D/2D hybrid approach



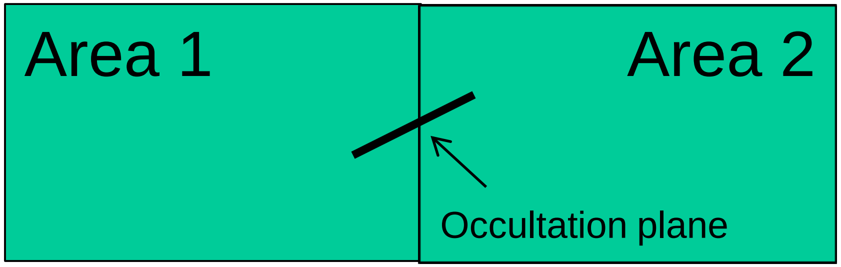
Computational cost

Occultation plane described by 31 profiles in outer loop, but only 7 in inner loop.

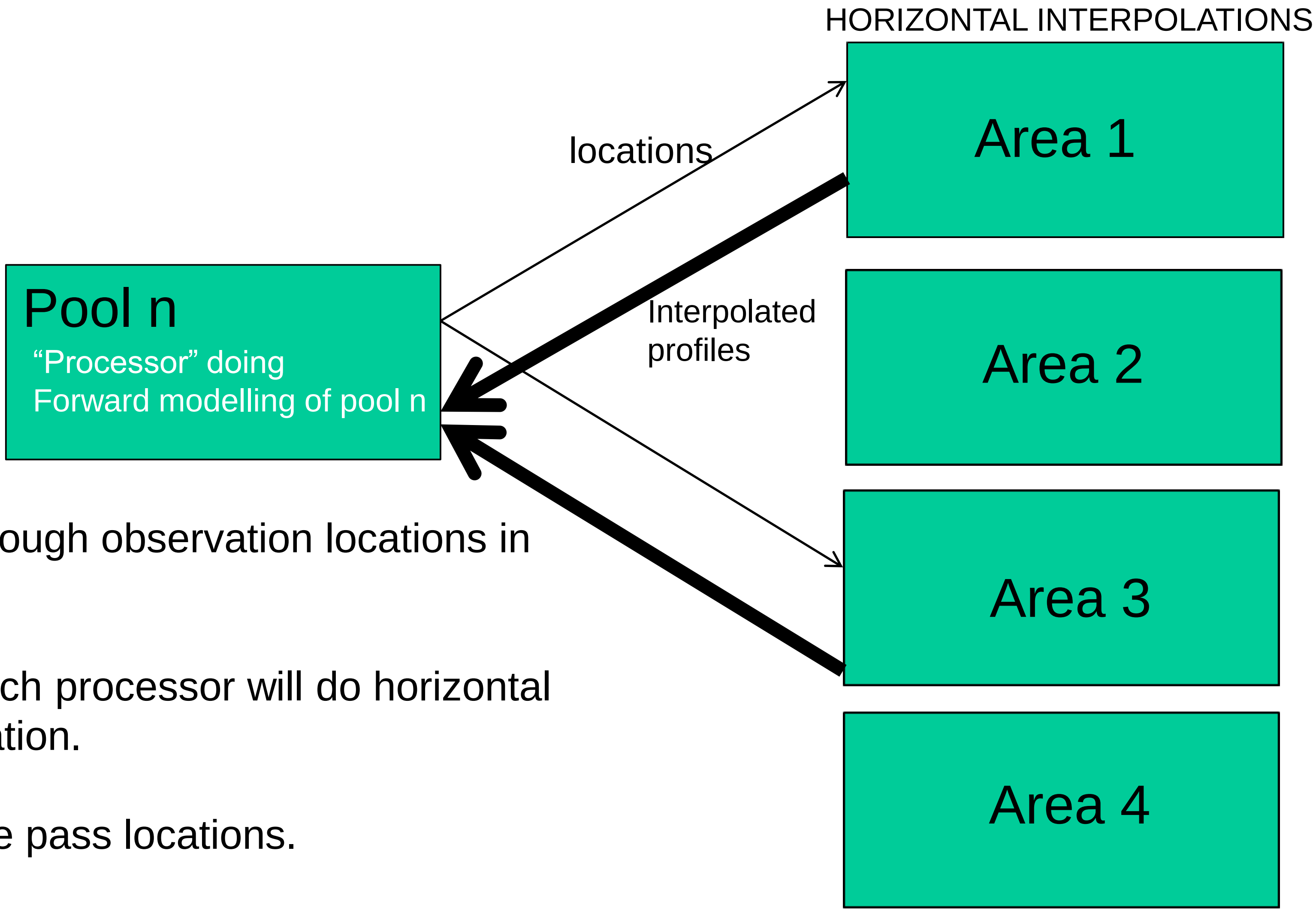
2D operator work

(Mats Hamrud)

- This is how a potential problem with 2d operators is visualised.



- **Lets assume** observations in area 1 are forward modelled using **processor 1** but observations in area 2 use **processor 2**.
- What happens when the occultation plane goes over the boundary?
- **This situation doesn't arise at ECMWF. The basic assumption is wrong.** The horizontal and vertical "interpolations" are performed on different processors.



HORIZONTAL INTERPOLATIONS

locations

Interpolated profiles

Pool n

"Processor" doing
Forward modelling of pool n

Area 1

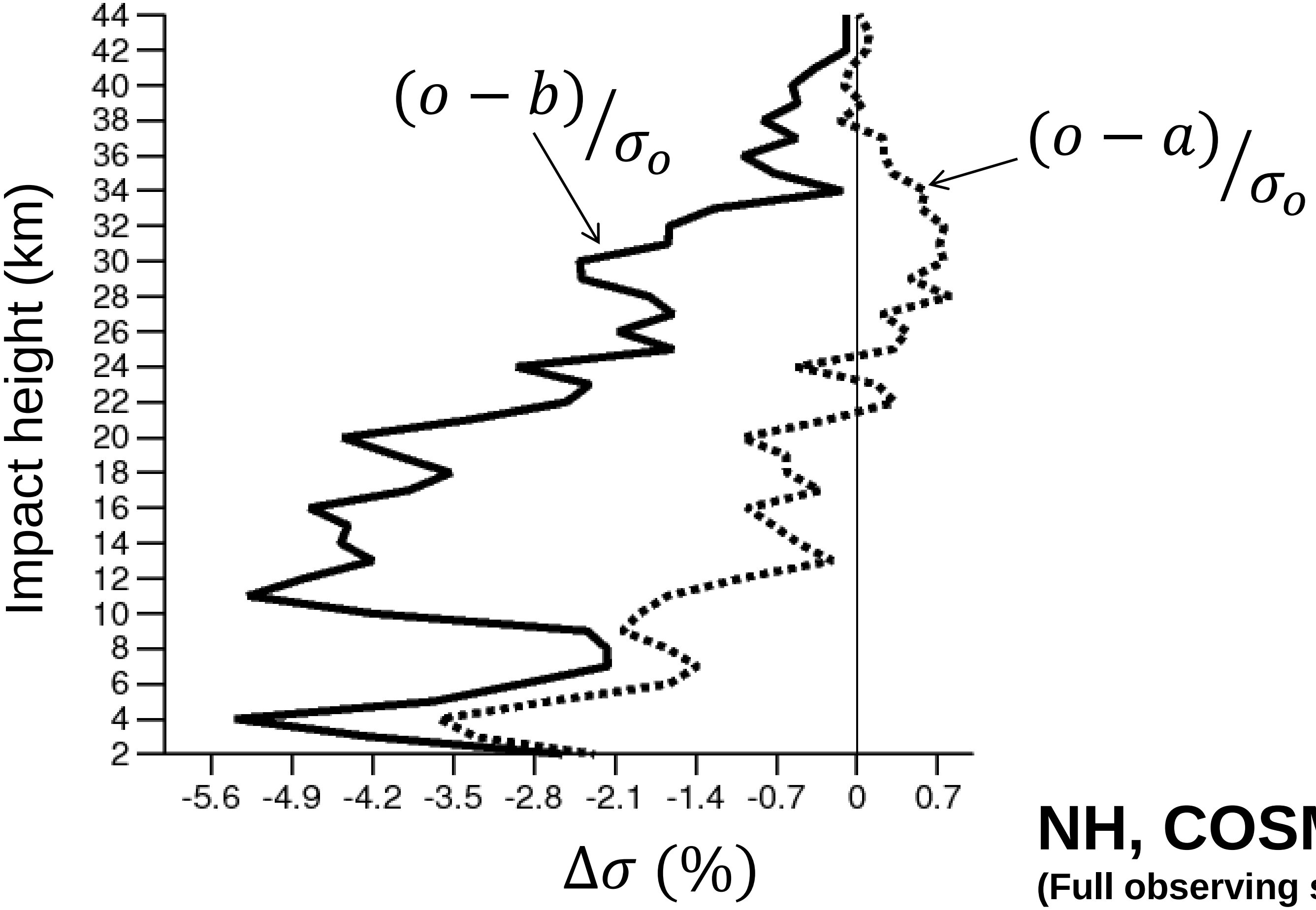
Area 2

Area 3

Area 4

- Loop through observation locations in pool.
- Find which processor will do horizontal interpolation.
- Message pass locations.
- Message pass back interpolated profiles

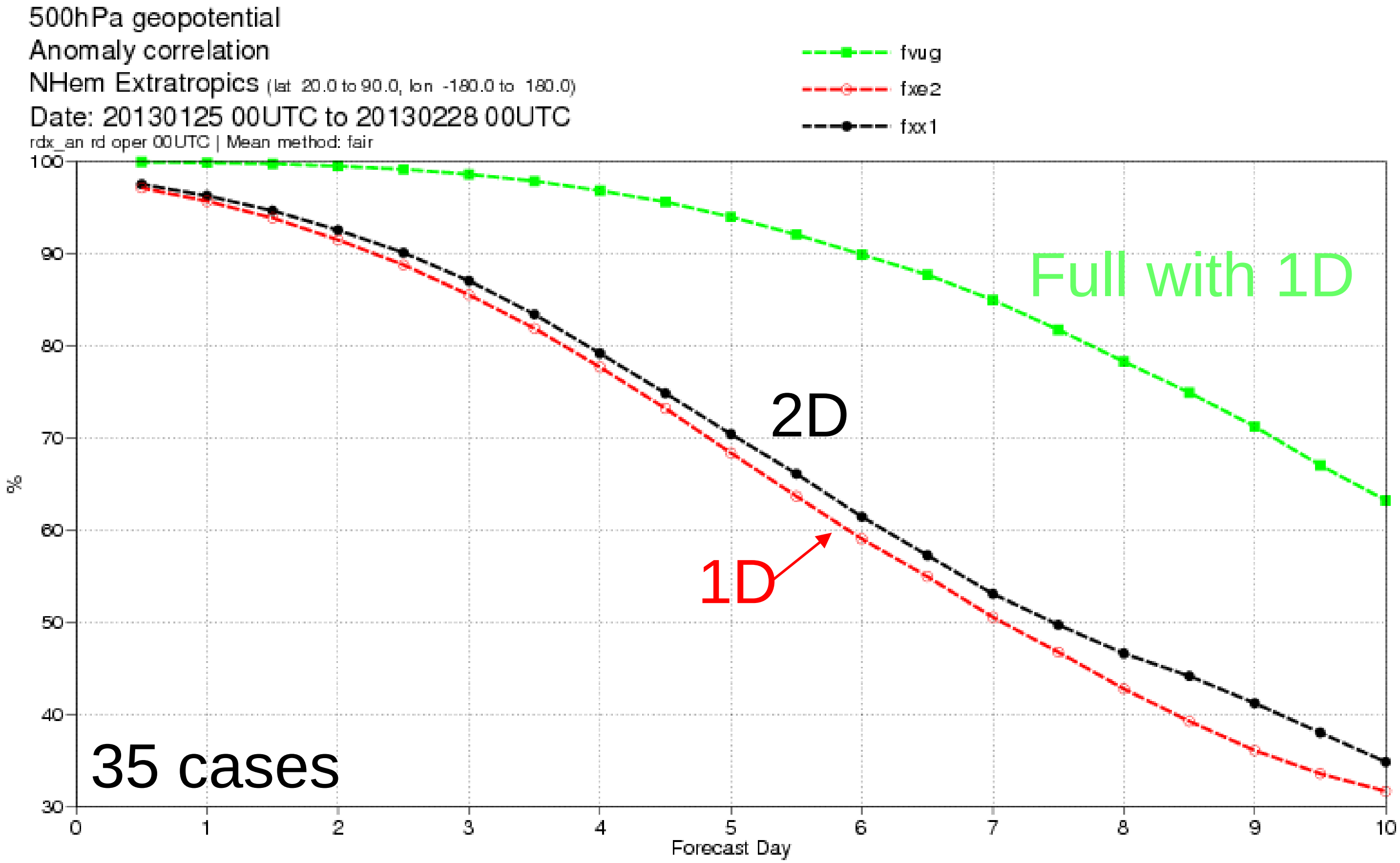
Improvement in GPS-RO (o-b) departure statistics with 2D approach



NH, COSMIC-1

(Full observing system)

GPS-RO ONLY Z500 scores, NH



500hPa geopotential
Anomaly correlation
NHem Extratropics (lat 20.0 to 90.0, lon -180.0 to 180.0)
Date: 20130125 00UTC to 20130228 00UTC
rdx_an rd oper 00UTC | Mean method: fair

Full with 1D

2D

1D

35 cases

Further science improvements with the 2D operator

- Some important physics is missing. The ray tangent height is estimated from a "***constant of motion***" along the path.

$$nr\sin\varphi = a$$

(impact parameter)

- **Its not a constant!** We should integrate along ray-path

$$\frac{d(nr\sin\varphi)}{ds} = \frac{\partial n}{\partial \theta_{\,r}}$$

- Use an "adjusted" impact parameter (*a*→(*a*+Δ*a*)) value will be used in the 2D operator to determine tangent height.

- **In progress. Initial results are neutral. DISAPPOINTING!**

Improving the R Matrix using the “Desrosier” diagnostics (MF, NCEP have looked at this)

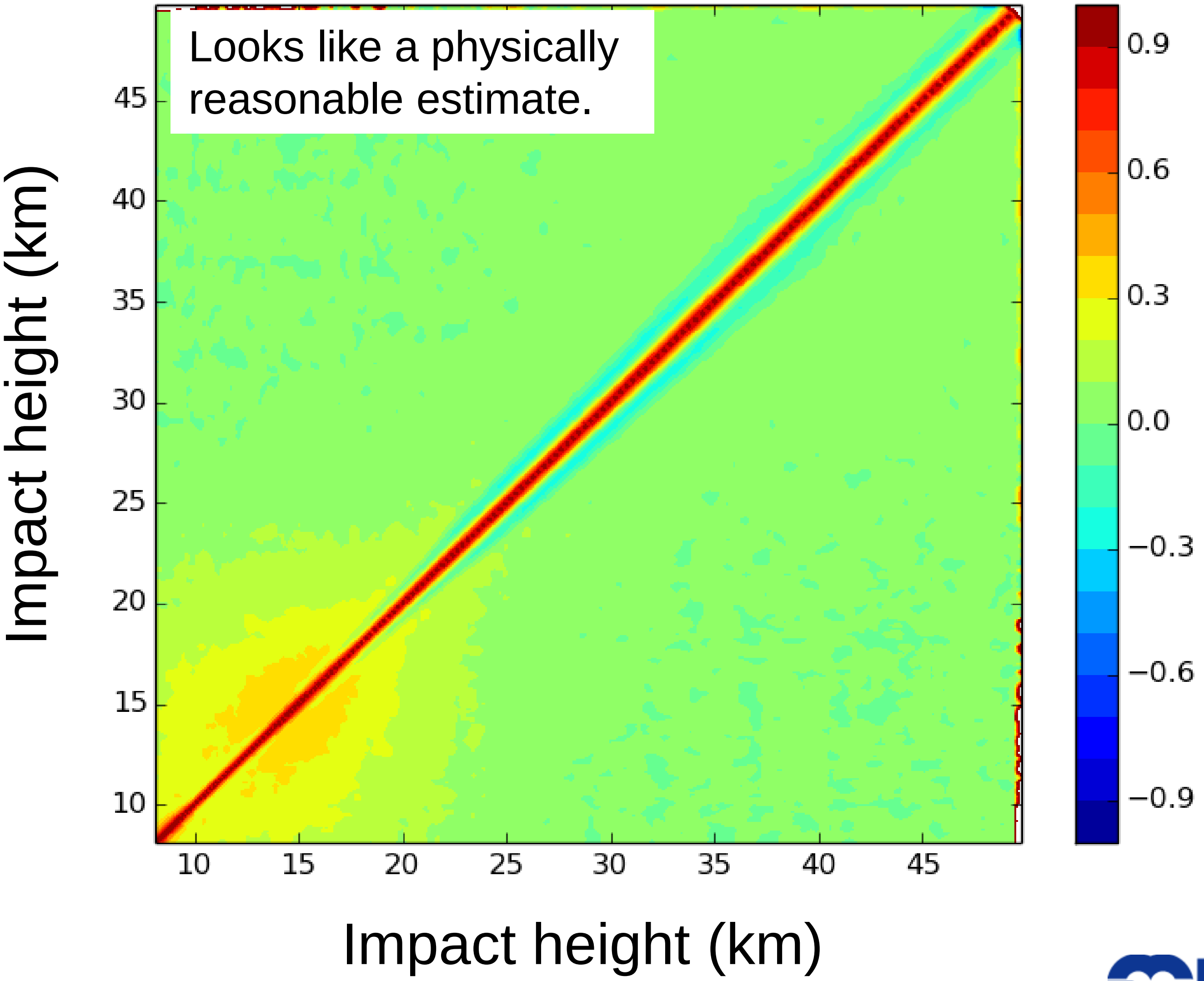
- You can estimate the observation error covariance matrix from

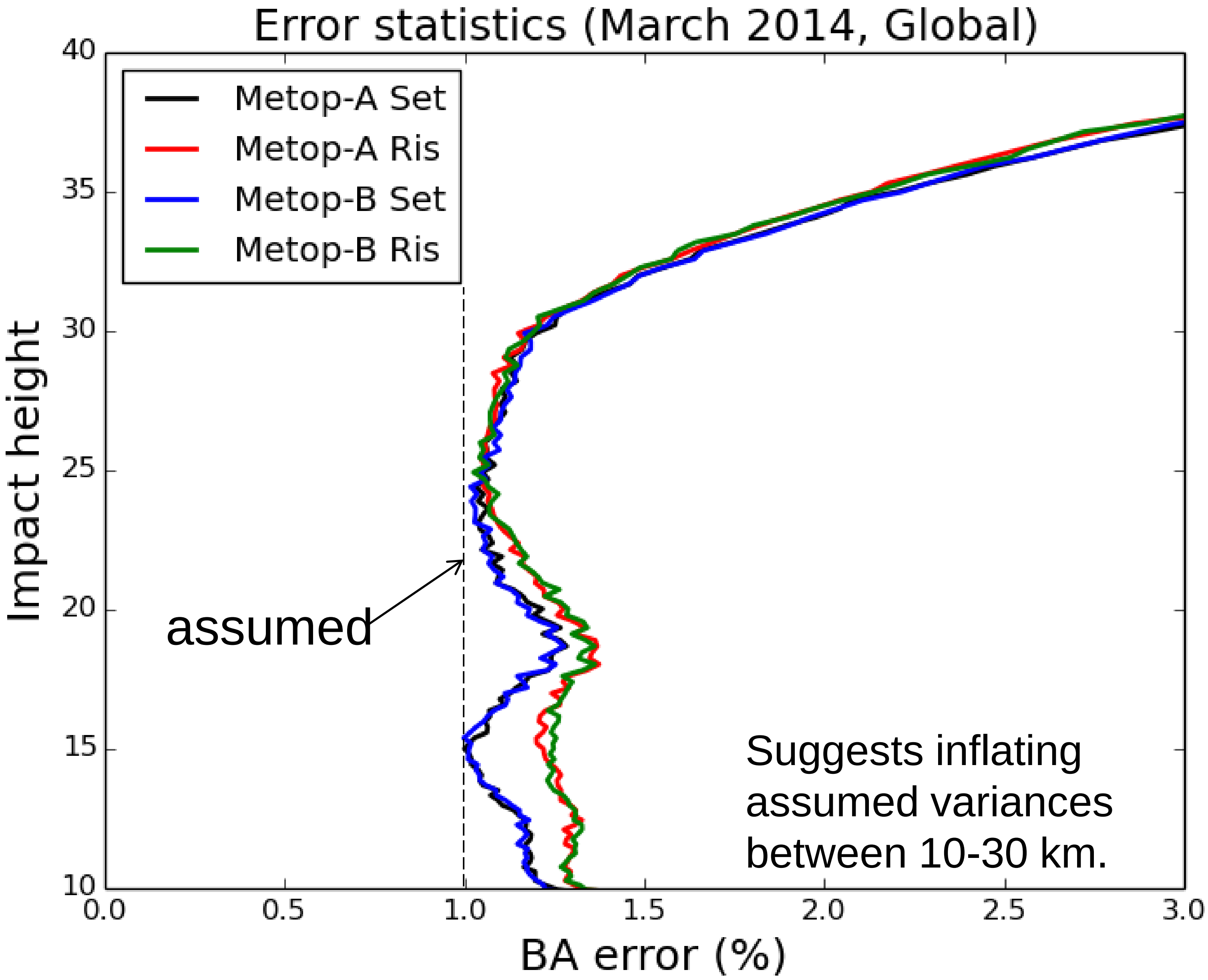
$$\mathbf{R} \approx \overline{\left(\mathbf{y} - H(\mathbf{x}_\mathbf{a})\right)\left(\mathbf{y} - H(\mathbf{x}_\mathbf{b})\right)^{\mathbf{T}}}$$

- **Talk by Niels**. This is used widely now, but strictly it will only produce the correct matrix **if the correct R and B matrices are used to compute the analysis!** It doesn’t guarantee a symmetric estimate.

- Should iterate to account for incorrect matrices.

Metop-A rising correlation matrix (Niels Bormann’s code: See also earlier work by Poli)





assumed

Suggests inflating
assumed variances
between 10-30 km.

Summary

- Reviewed the GPS-RO concept.

- Outlined how we assimilate the data and impact on NWP and reanalysis systems. Impact on the lower/mid stratosphere.

- New work on using GPS-RO for testing model changes that impact the stratospheric temperatures.

- Use of EDA to estimate impact with observation number.

- New/future work
  - Move to a 2D operator in 4D-Var.
  - Improved R matrix.

extra

Some timings with 2D operator for the 4D-Var "inner loop" minimization (TL and AD code.)

"Wall-clock time" (s)	**2D operator**	**1D operator**	**Percentage increase**
Only GPS-RO	275	214	29 %
All observations	548	436	26 %

The increases are "**very significant**", in an operational context and need to be reduced before operational implementation.

Timings on my workstation for a single profile containing 250 bending angles (NO TPD)

	Operator	TL	Adjoint
1D	0.005	0.009	0.017
2D	0.075	0.18	0.51

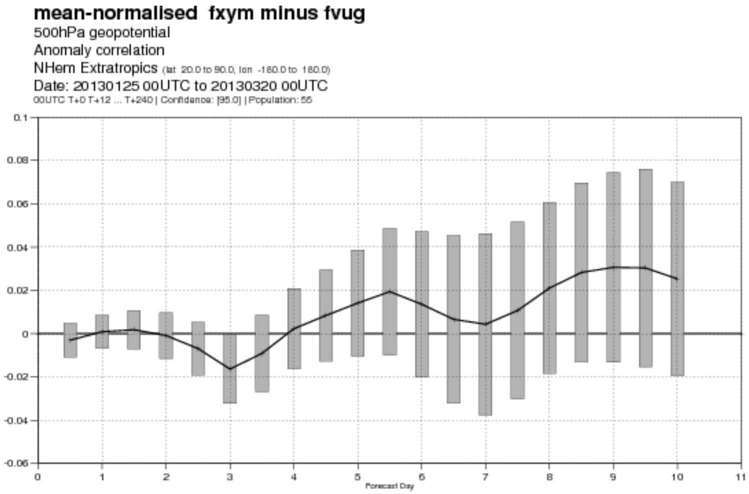
Calculated with the fortran CPU_TIME command.

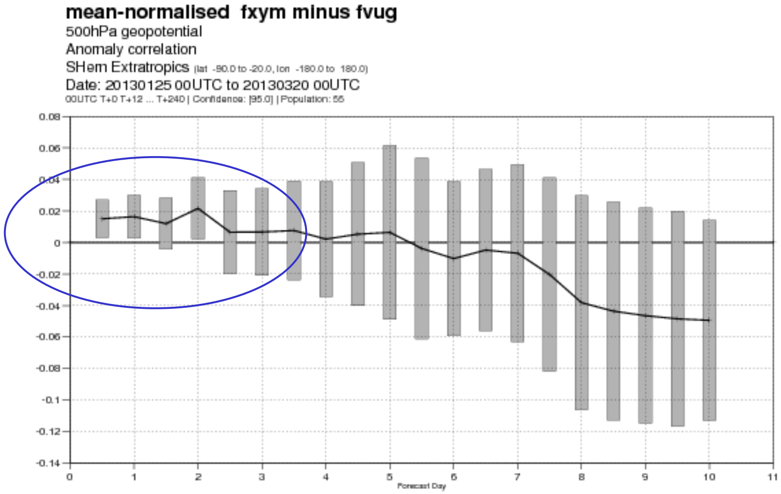
Cost of the bending angle computation, given interpolated model data on height levels.

The bending angle computation **15 times** larger. 2D **adjoint 6 times** more costly than the 2D operator.

2D vs 1D in **full system**, Z500 anomaly correlation

Above 0 = good





Surface pressure information from GPS-RO

- Measuring or retrieving surface pressure information from satellite radiances has been discussed for many years (Smith et al, 1972).

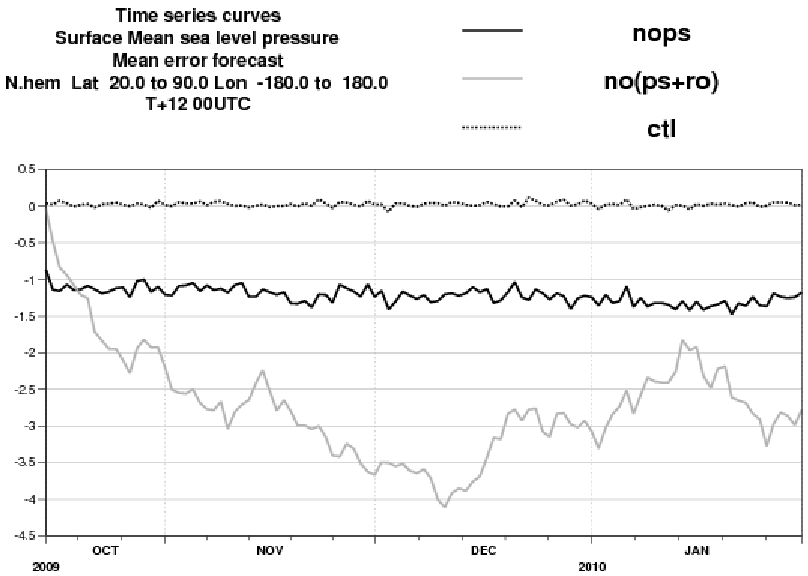
- The GPS-RO measurements have a sensitivity to surface pressure because they are given as a function of height.

- Hydrostatic integration is part of the GPS-RO forward model. If we increase the surface pressure the bending angle values increase.

- **Can GPS-RO constrain the surface pressure analysis when all conventional surface pressure measurements are removed?**

NH 12 hour PMSL forecast scores

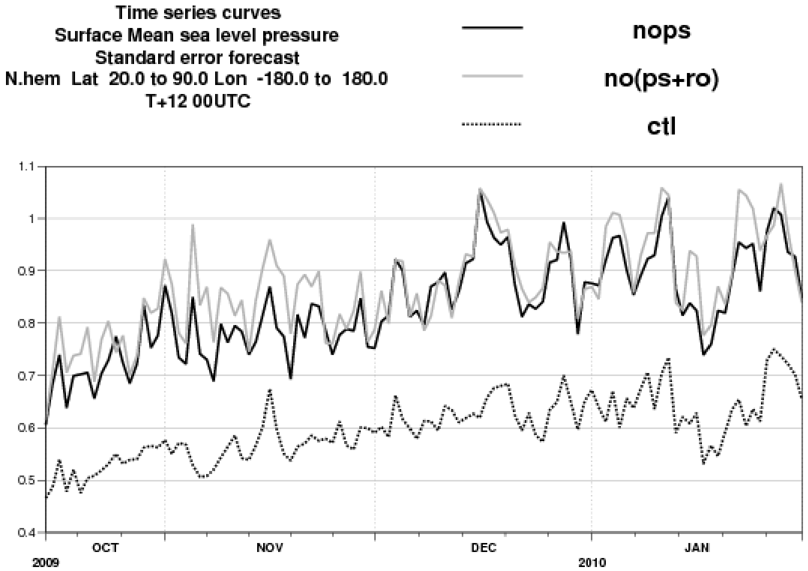
Mean



GPS-RO included.

The GPS-RO measurements manage to stabilise the bias.

Standard deviation



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

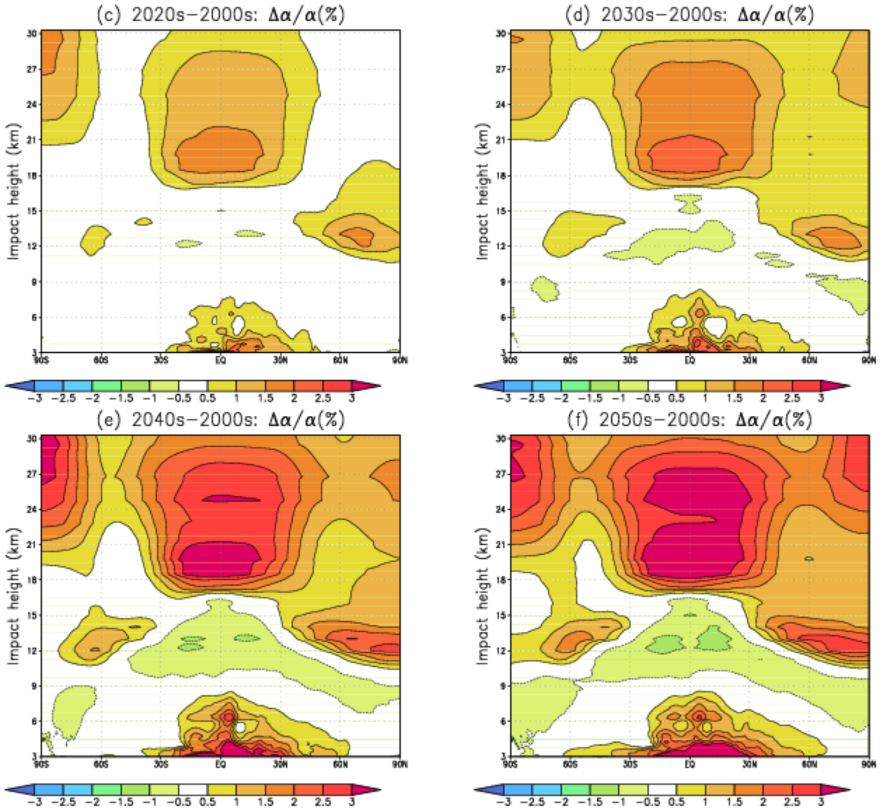
Simulations use:

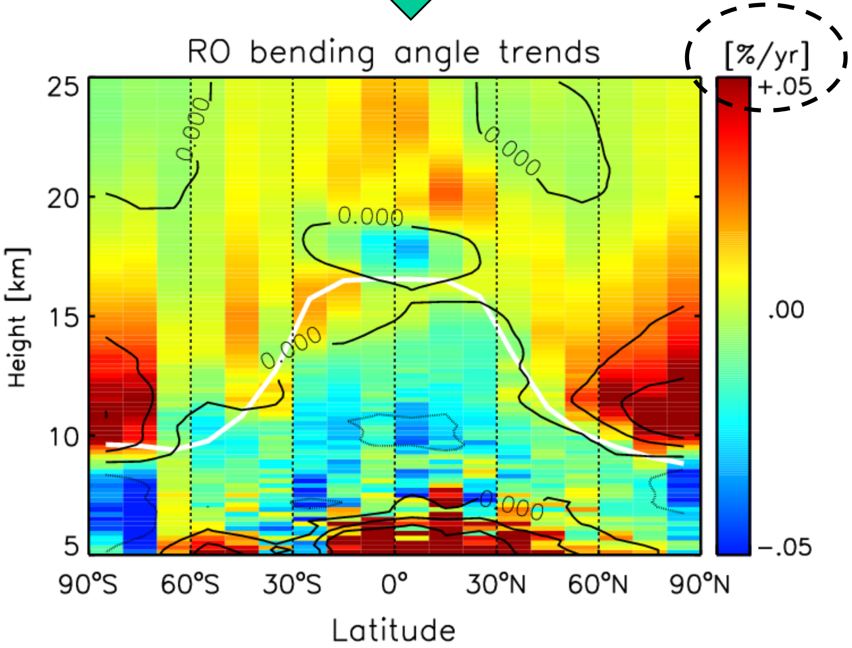
- Met Office Hadley Centre coupled climate model (HadGEM1)
- Climate change scenario (A1B) for 2000 – 2100
- Forward modelling of the GPS-RO bending angles
- Forward modelling of MSU/AMSU brightness temperatures

Provided by Mark Ringer (Hadley Centre)

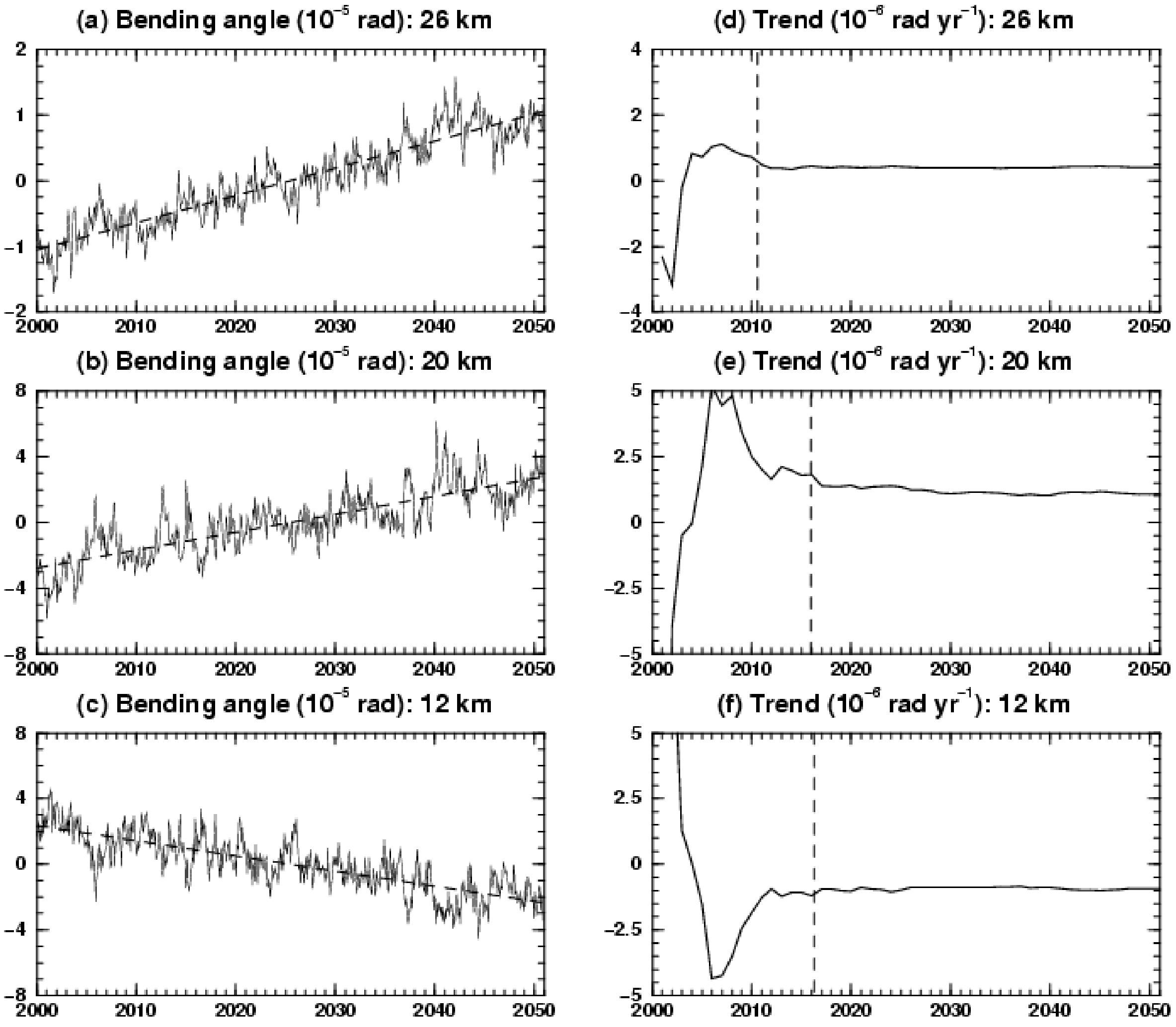
Initial comparison with observations

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





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



(a) Bending angle (10^{-5} rad): 26 km

(d) Trend (10^{-6} rad yr^{-1}): 26 km

(b) Bending angle (10^{-5} rad): 20 km

(e) Trend (10^{-6} rad yr^{-1}): 20 km

(c) Bending angle (10^{-5} rad): 12 km

(f) Trend (10^{-6} rad yr^{-1}): 12 km

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*