
GNSS radio occultation measurements: Current status and future perspectives

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Paul Poli, Carla Cardinali, ...

The EUMETSAT
Network of
Satellite
Application
Facilities



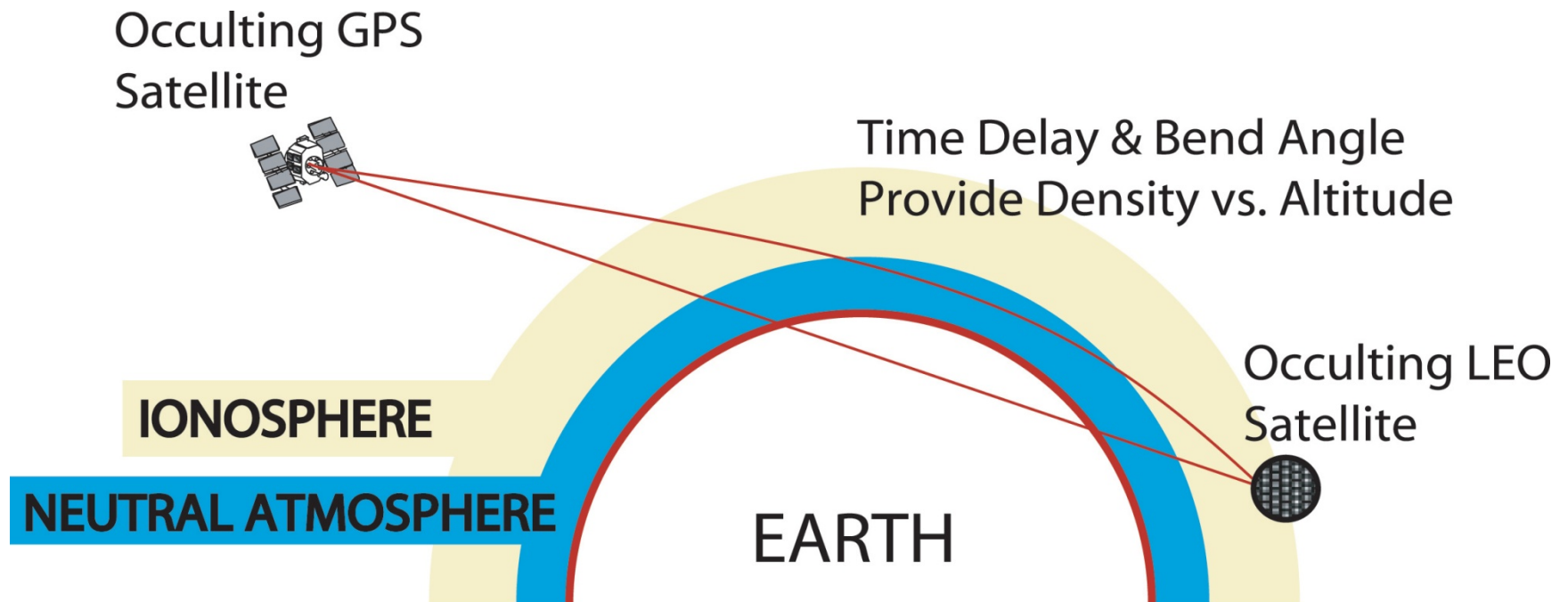
ROM SAF

Radio Occultation Meteorology

Outline

- GNSS radio occultation (GNSS-RO) measurement characteristics.
- Examples of GNSS-RO impact in NWP.
- Surface pressure information content of GNSS-RO.
- Use of an Ensemble of Data Assimilation (EDA) technique to estimate the number of GNSS-RO measurements required for NWP applications. [\(First results from an ongoing ESA study\)](#).
 - *(Science question S6RO)*
- Summary.

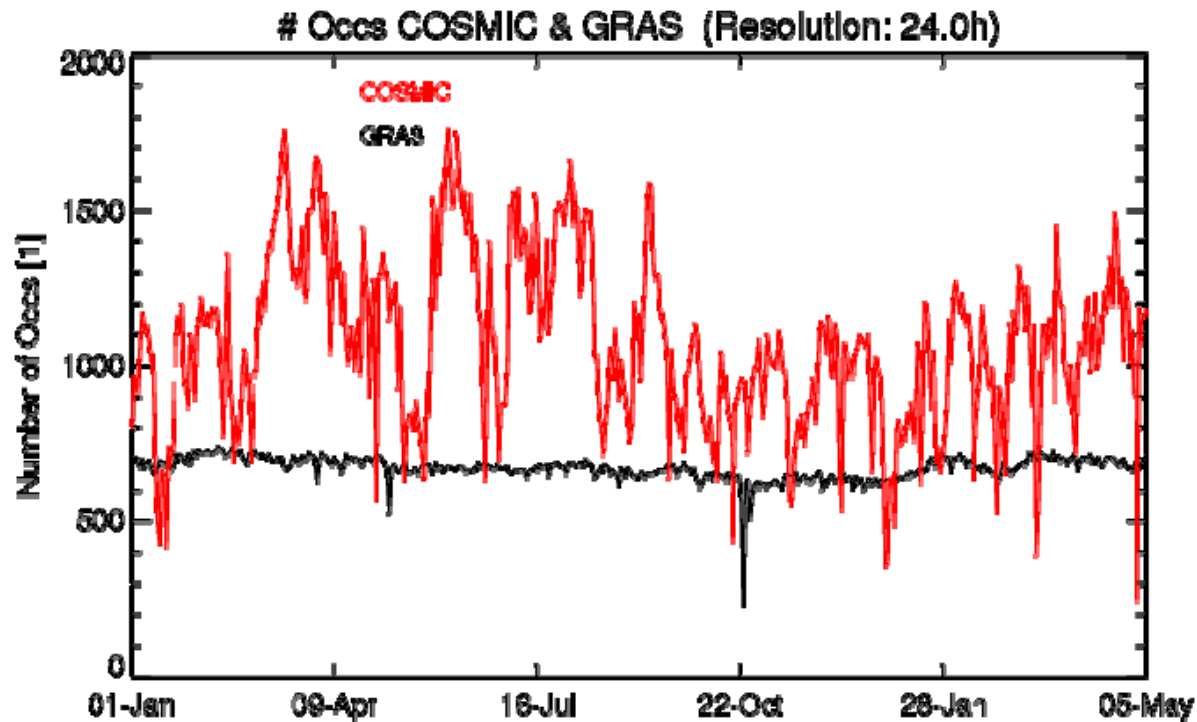
GNSS radio occultation concept



Key measurement characteristics

- Why are GNSS-RO measurements valuable?
 - They complement the information provided by satellite radiances.
- **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.**

GNSS-RO Data Availability



- **GRAS is the only fully operational mission.**
- COSMIC data numbers are falling (COSMIC-2, 6 sats, 2016).
- Supplement with the use of research missions (TerraSAR-X, GRACE-A, C/NOFS).
- **Total ~ 2000-2200 profiles per day.**

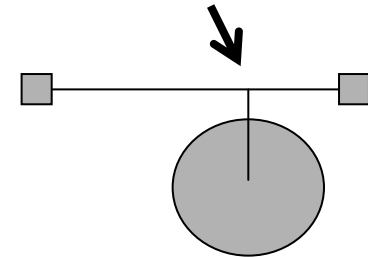
Use of GNSS-RO in NWP

- **All the major Global NWP centres now assimilate GNSS-RO measurements.**
- NWP centres assimilate either:
 - Bending angle profiles (ECMWF, MF, Met Office, DWD, NRL, NCEP)
 - Refractivity (EC, JMA)
- **NWP centres assimilate the measurements without bias correction (except JMA).**
- Essentially treat the information as a 1D profile, not a 2D, limb measurement.
- **NWP centres have generally very found good impact on temperatures between ~7-35 km.**

Assimilation approach at ECMWF

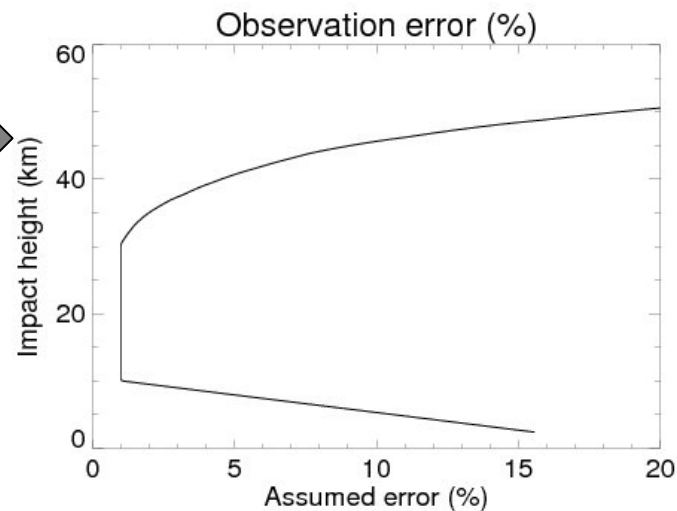
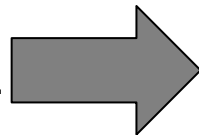
- We assimilate bending angles with a 1D operator. We ignore the 2D nature of the measurement and integrate

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



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

- Observation errors.



Impact at ECMWF

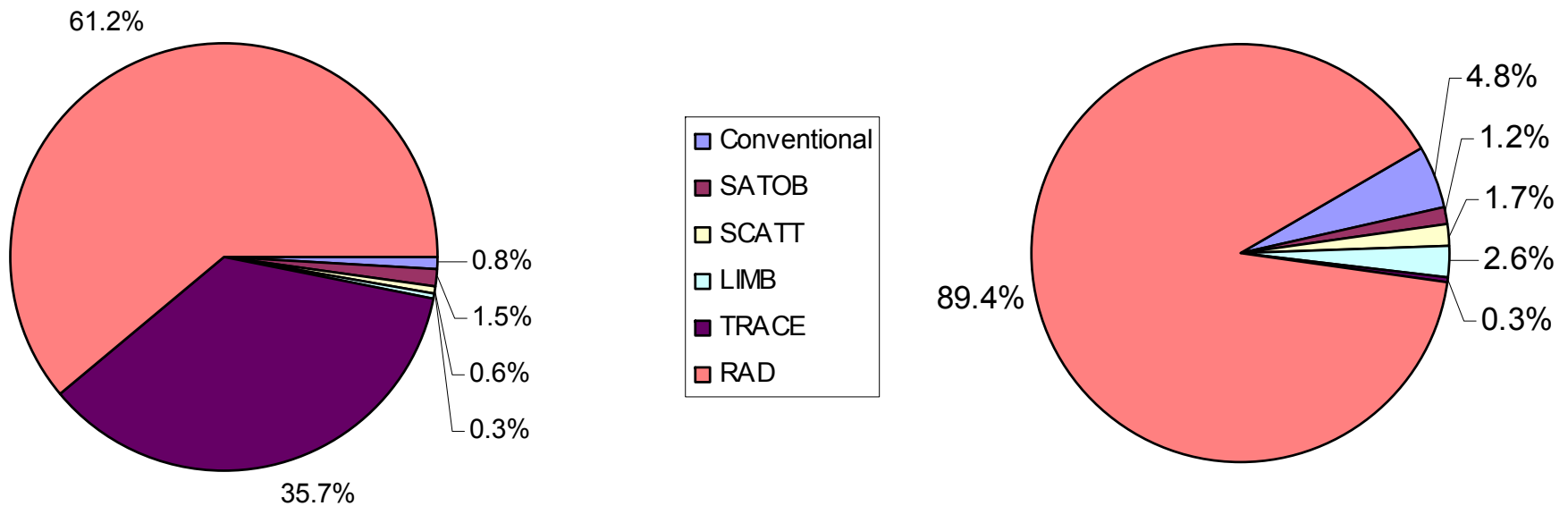
- ECMWF has assimilated GPS-RO bending angles operationally since December 12, 2006.
- Main impact on upper-tropospheric and lower/mid stratospheric temperatures.
 - **GPS-RO measurements are assimilated without bias correction, so they can correct (some) model biases.**
 - **Very good vertical resolution, so they can correct errors in the “null space” of the radiance measurements.**

Data types

Screening

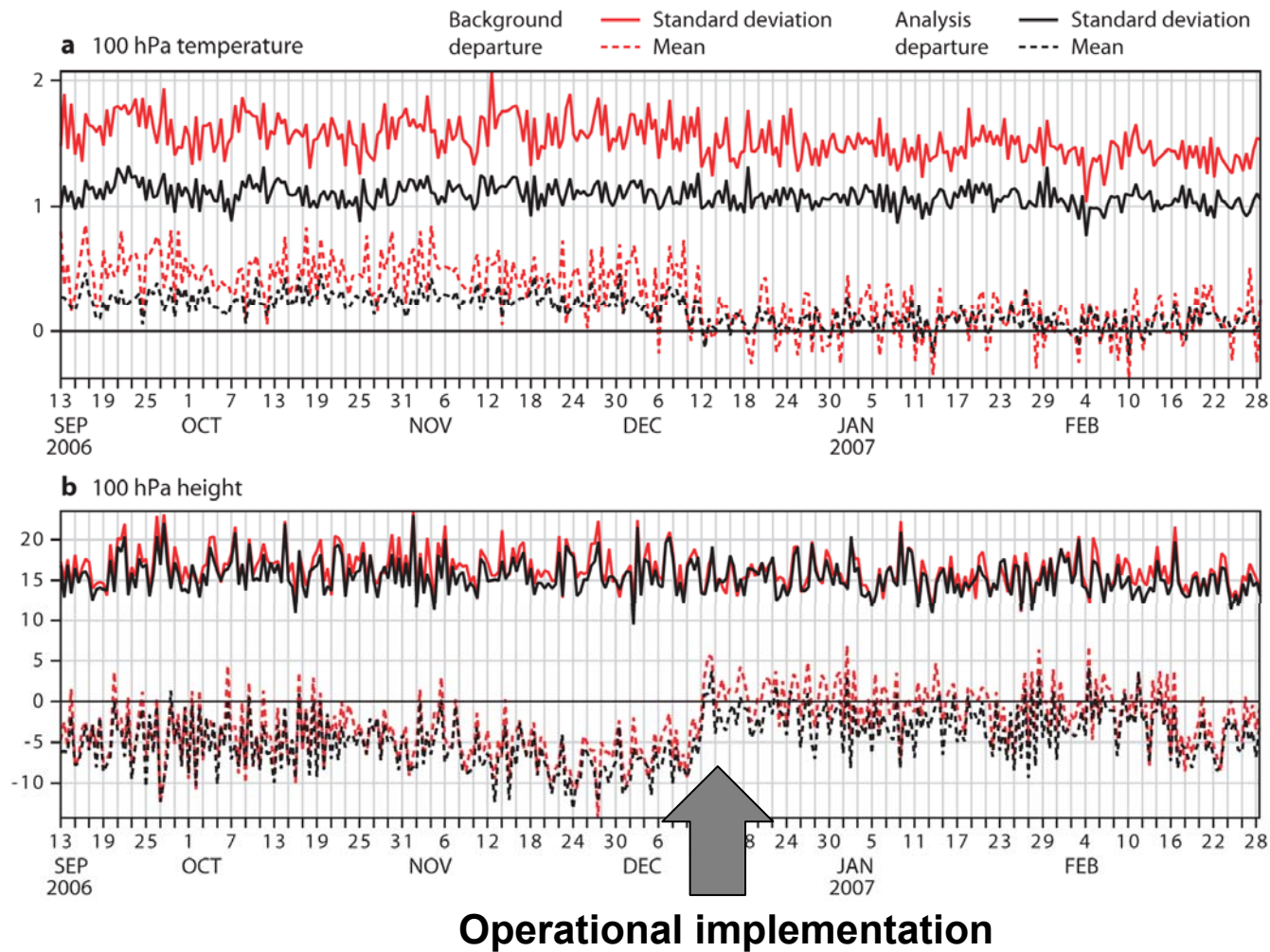


Assimilation

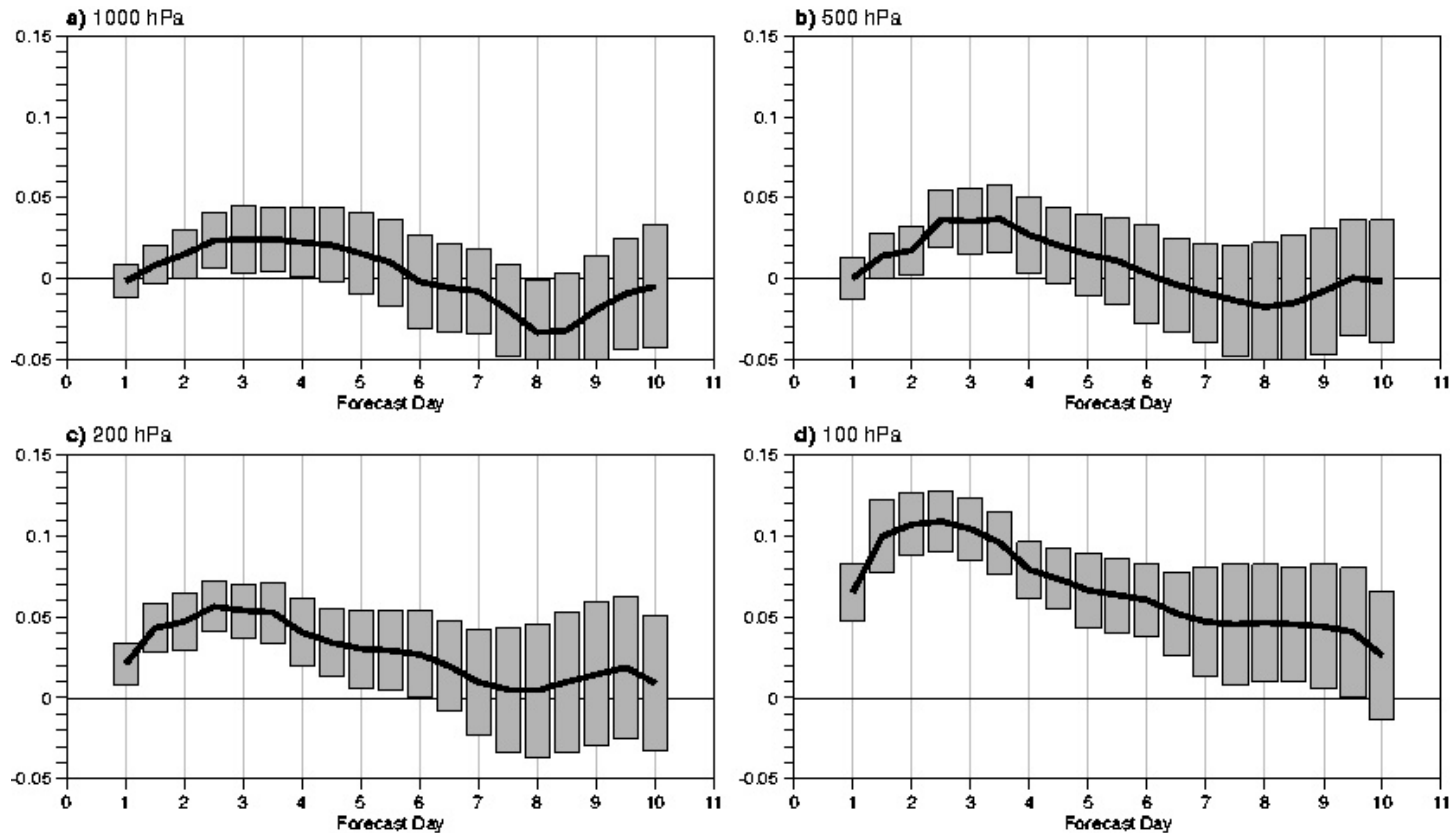


- Satellite data amounts to 99% in screening and 95% in assimilation.
- Radiance data dominates assimilation with 90%.
- **GPS-RO data contributes only ~2-3 % of the assimilated observations - what if it was 20-30%?**

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

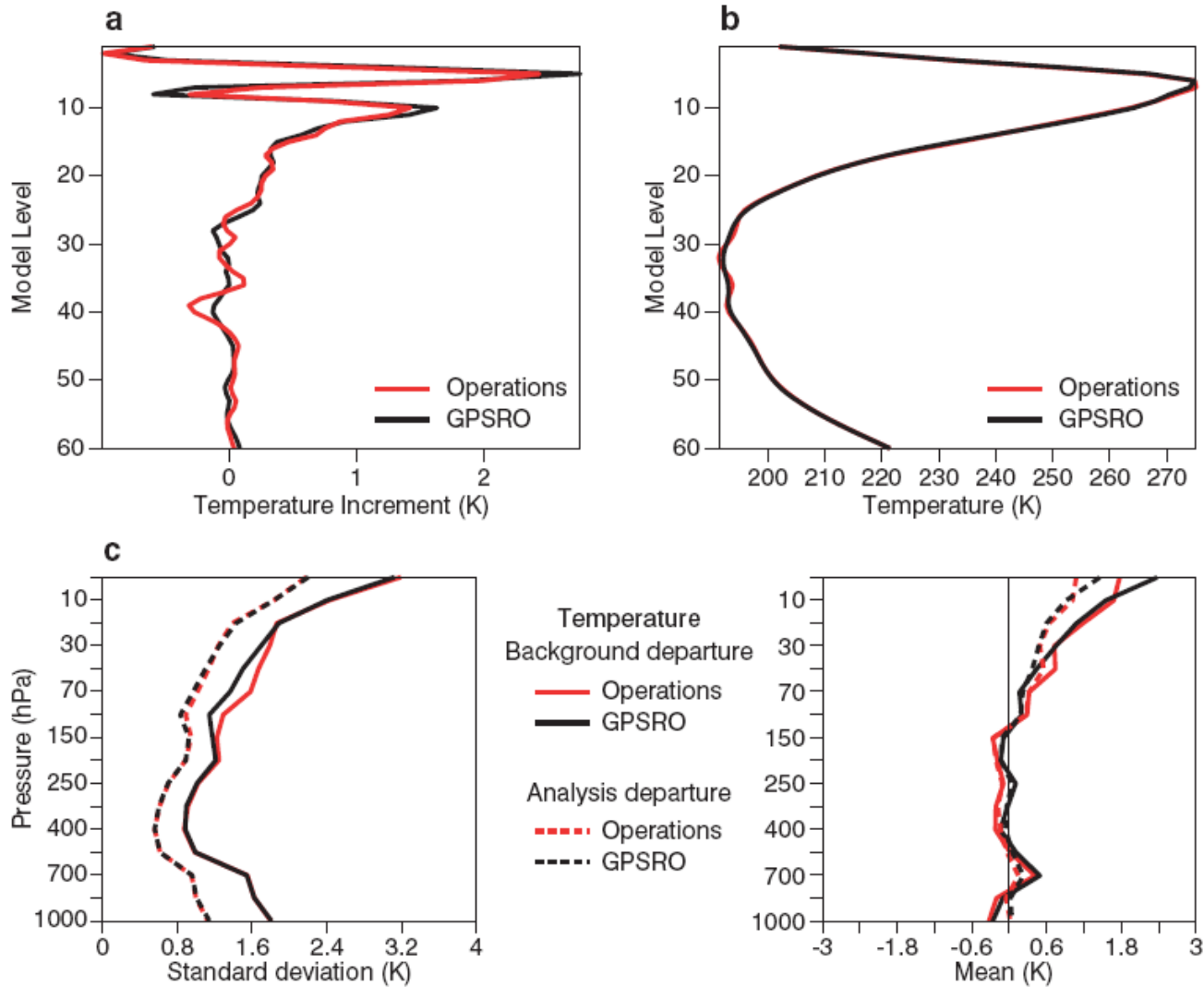


Fractional improvement in the southern hemisphere geopotential height RMS scores



Similar results obtained at the other major NWP centres.

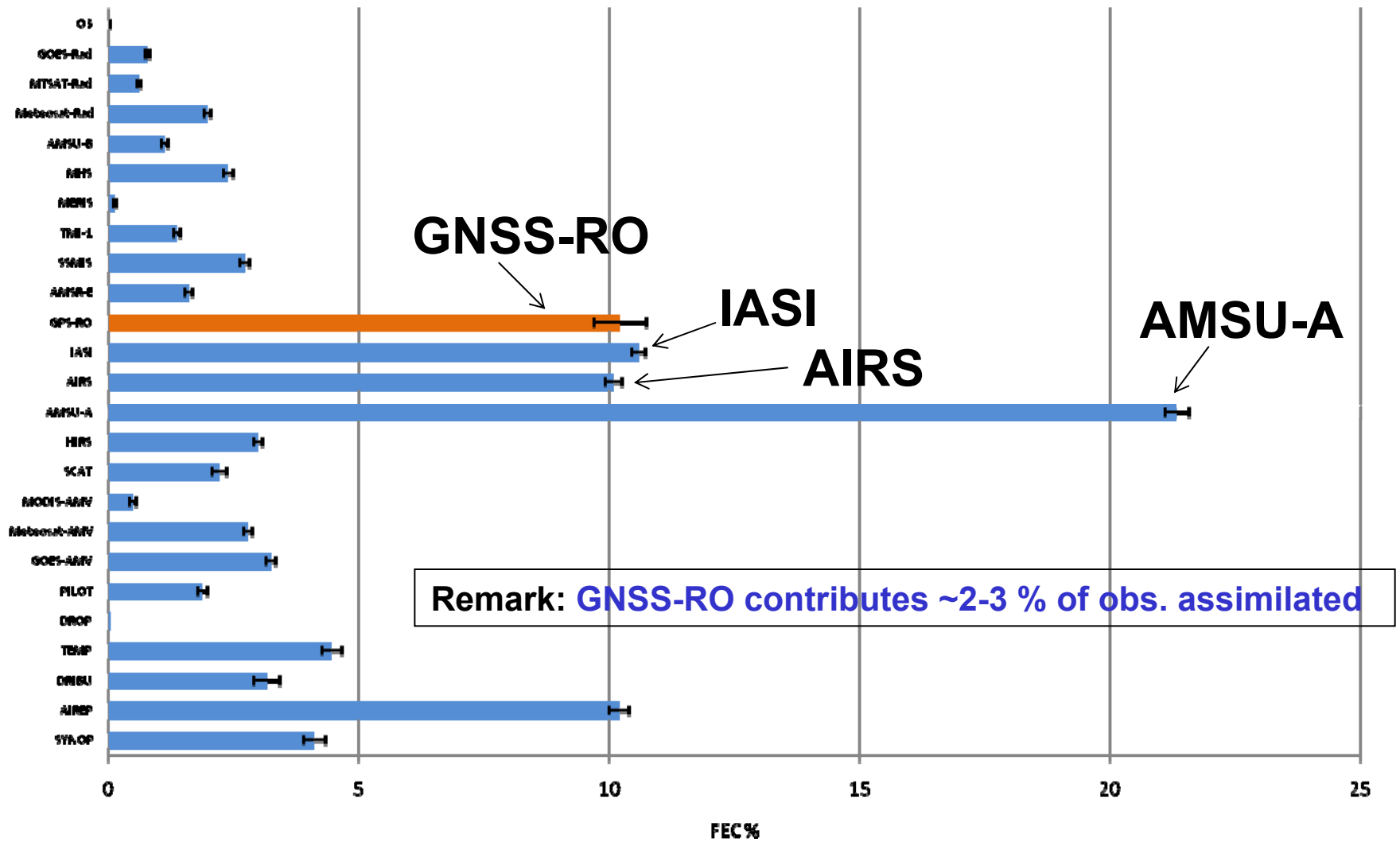
Stratospheric ringing problem over Antarctica solved by assimilating GPS-RO



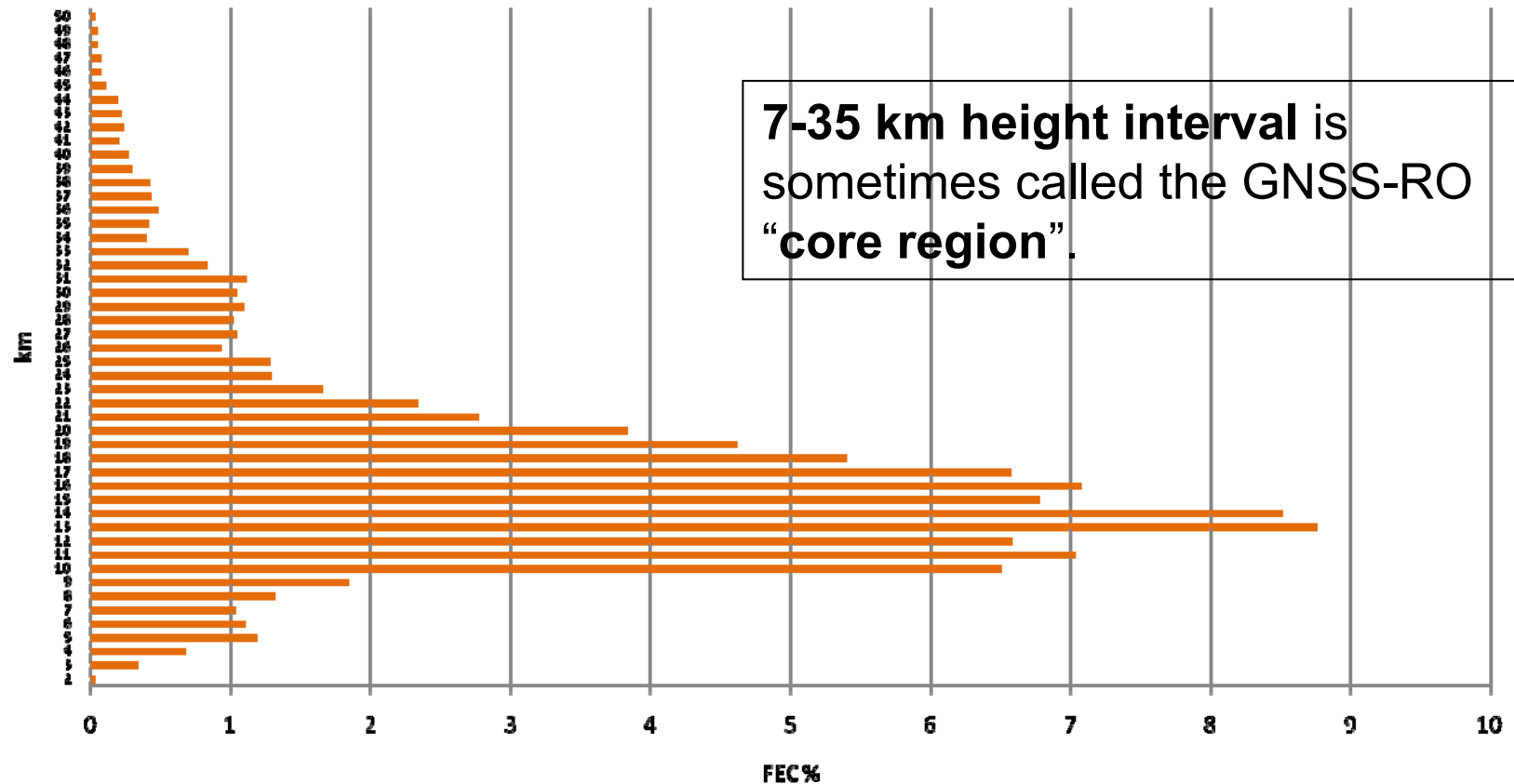
Adjoint-based data assimilation diagnostics (ECMWF work by Carla Cardinali)

- Adjoint techniques are used to estimate how the observing systems (e.g. all AMSU-A) contribute to reducing the 24 hour forecast errors.
- The mathematics can be found in E.G. 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 errors in a **weighted average** of (*surface pressure, tropospheric and stratospheric temperatures and winds*).
- **GNSS-RO scores well because of its impact in the stratosphere.**

FSO: ECMWF System (June 2011)



Heights where GNSS-RO is reducing the 24hr errors



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

GNSS-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 used at ECMWF

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

- Bias corrected radiances are assimilated.

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

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

$$J(\mathbf{x}, \boldsymbol{\beta}) = (\mathbf{x}_b - \mathbf{x})^T \mathbf{B}_x^{-1} (\mathbf{x}_b - \mathbf{x})$$

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

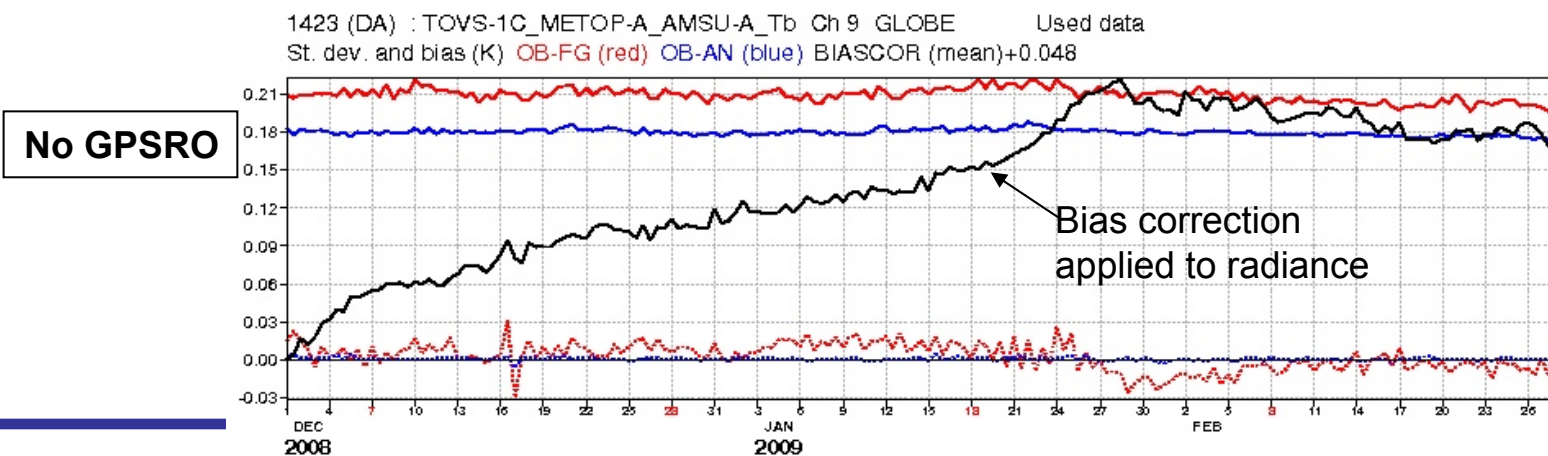
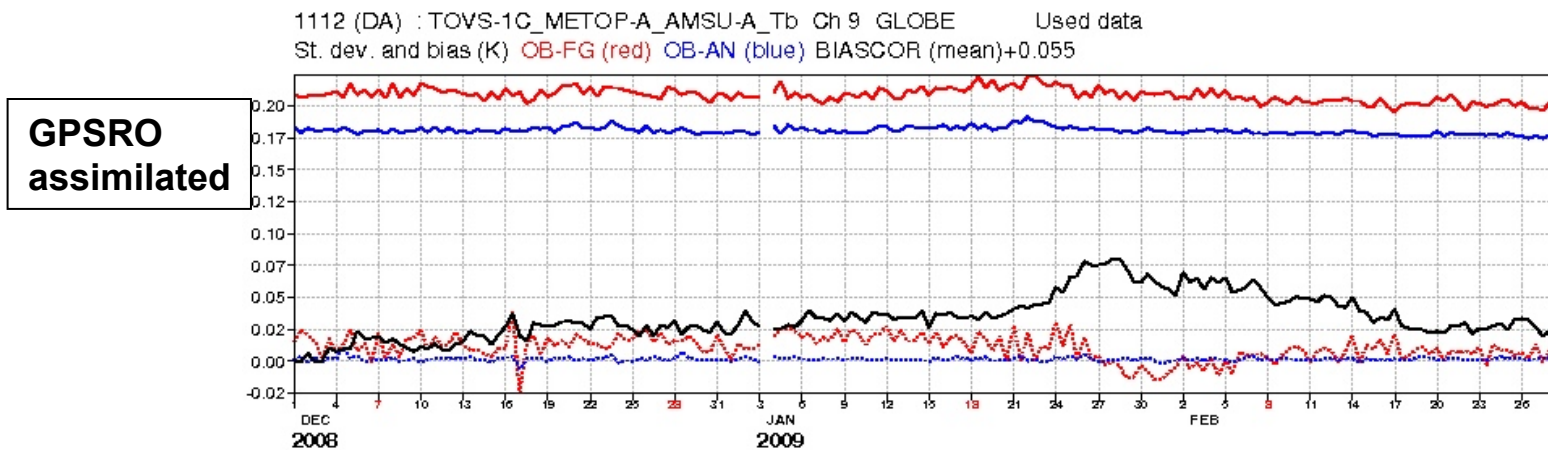
$$(\mathbf{y} - \mathbf{b}(\boldsymbol{\beta}, \mathbf{x}) - H(\mathbf{x}))^T \mathbf{R}^{-1} (\mathbf{y} - \mathbf{b}(\boldsymbol{\beta}, \mathbf{x}) - H(\mathbf{x}))$$

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

- **VarBC** assumes an unbiased model.

Recent experiment removing GNSS-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**.



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

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



CHAMP
COSMIC-1

COSMIC-2
COSMIC-3

COSMIC-4
COSMIC-5

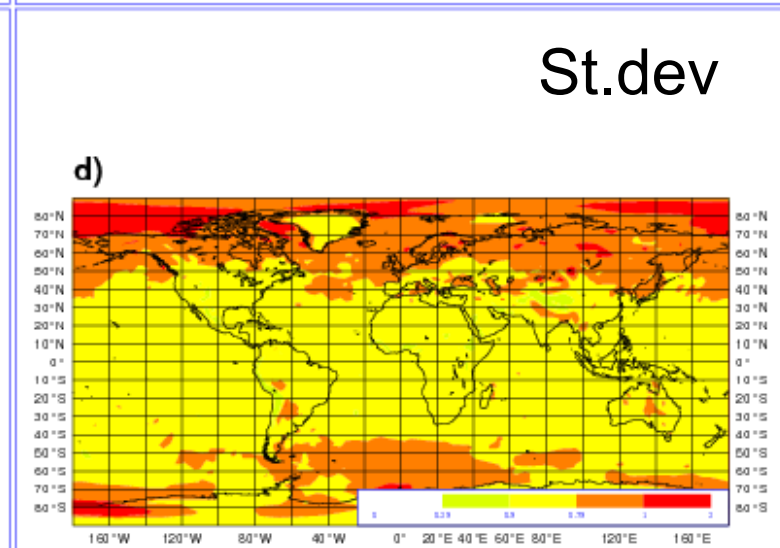
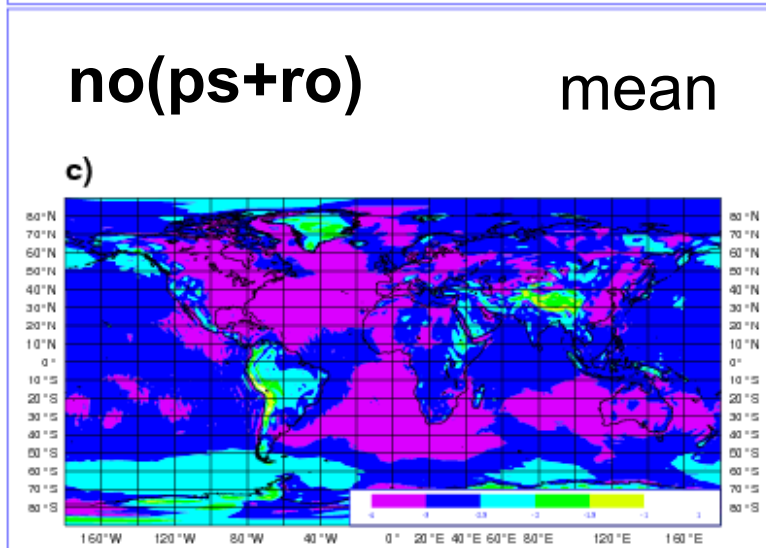
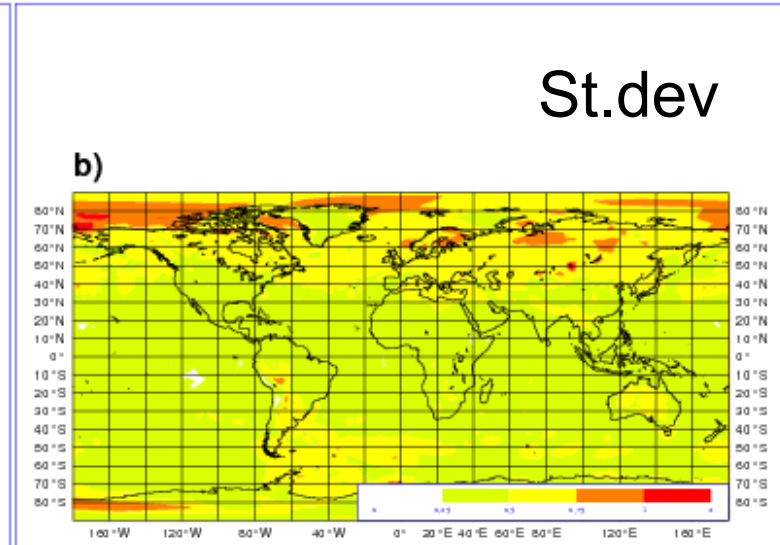
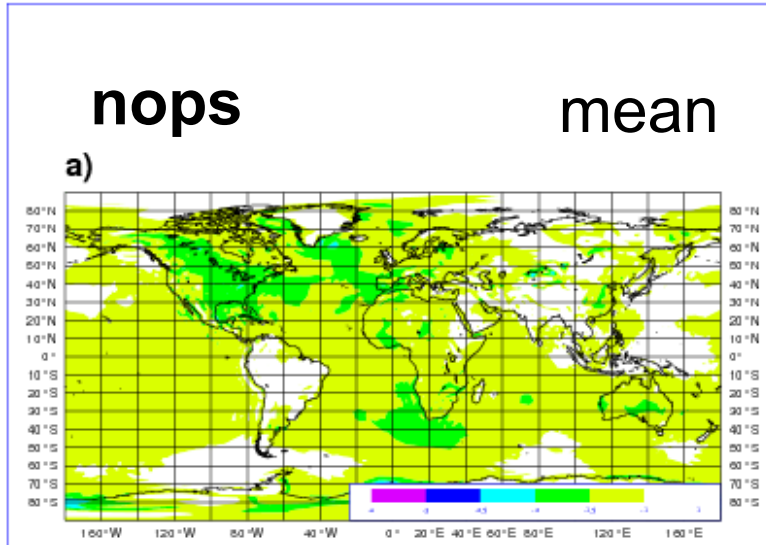
COSMIC-6
METOP-A

Surface pressure information content

- GNSS-RO measurements should provide useful surface pressure information.
 - GNSS-RO measurements assimilated on “height” levels, meaning the hydrostatic integration is part of the ob. operator.
- ECMWF has conducted experiments:
 - Remove all conventional surface pressure observations (**nops**)
 - Remove all conventional surface pressure observations and all GNSS-RO observations. (**no(ps+ro)**)
 - Full observing system (**ctl**)
- Similar to experiments presented at this meeting in (2004).

Mean and standard deviation of surface pressure analysis differences w.r.t. operations

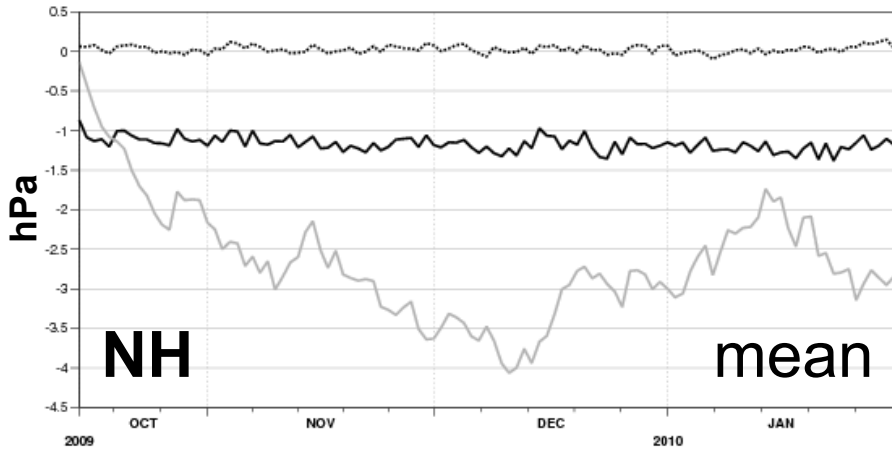
(hPa)



24 hour PMSL Forecast Errors

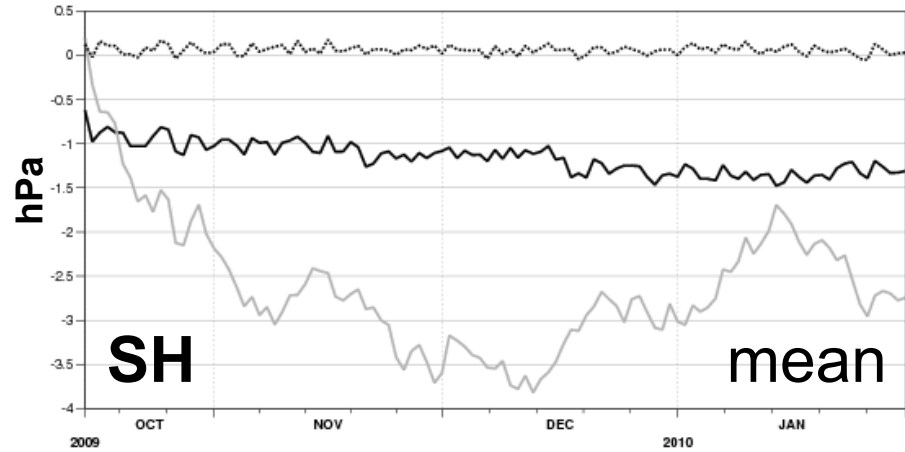
Time series curves
Surface Mean sea level pressure
Mean error forecast
N.hem Lat 20.0 to 90.0 Lon -180.0 to 180.0
T+24 00UTC

— no(ps+ro)
..... ctl



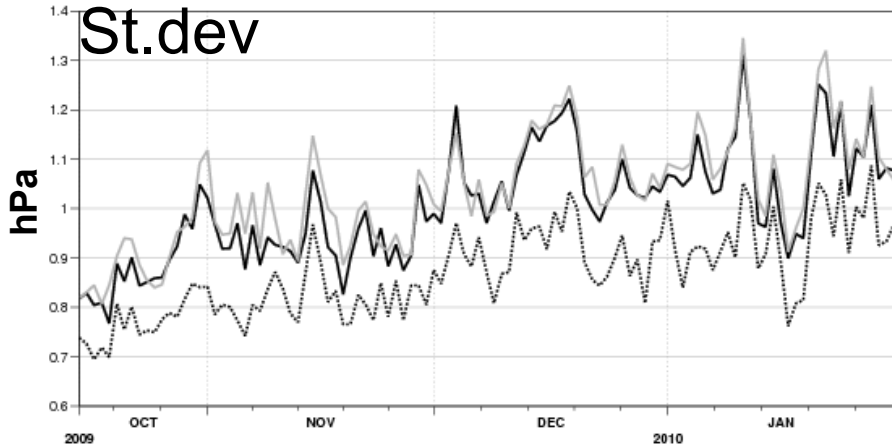
Mean error forecast
S.hem Lat -90.0 to -20.0 Lon -180.0 to 180.0
T+24 00UTC

— nops
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..... ctl



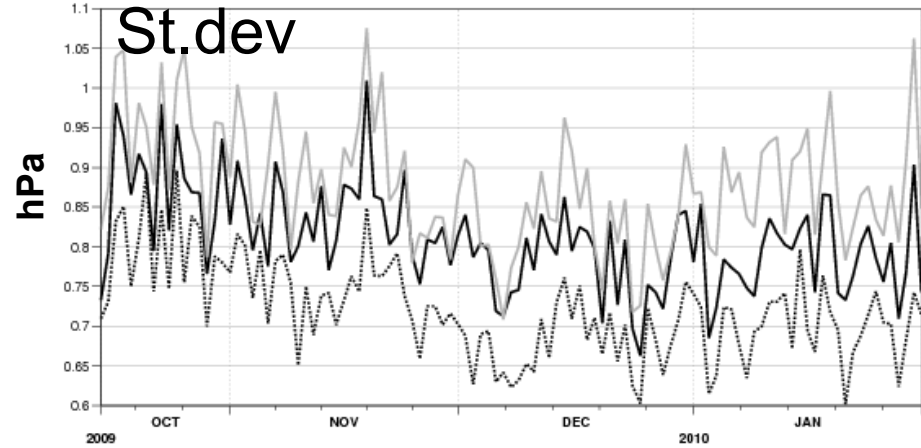
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Time series curves
Surface Mean sea level pressure
Standard error forecast
S.hem Lat -90.0 to -20.0 Lon -180.0 to 180.0
T+24 00UTC

— nops
..... no(ps+ro)
..... ctl



Surface pressure

- The GNSS-RO can constrain the large biases at ~1-1.5 hPa level.
 - This residual bias is related to biases in other variables being aliased into surface pressure increments. *A general problem with remotely sensed surface pressure.*
 - Eg, the biases can be reduced by blacklisting aircraft temperature measurements.
- Large biases that develop in the no(ps+ro) experiment caused by an interaction between VarBC and the assimilation of the conventional upper-air observations.
 - Biases are smaller when VarBC is not evolving.

How many GNSS-RO observations do we need?

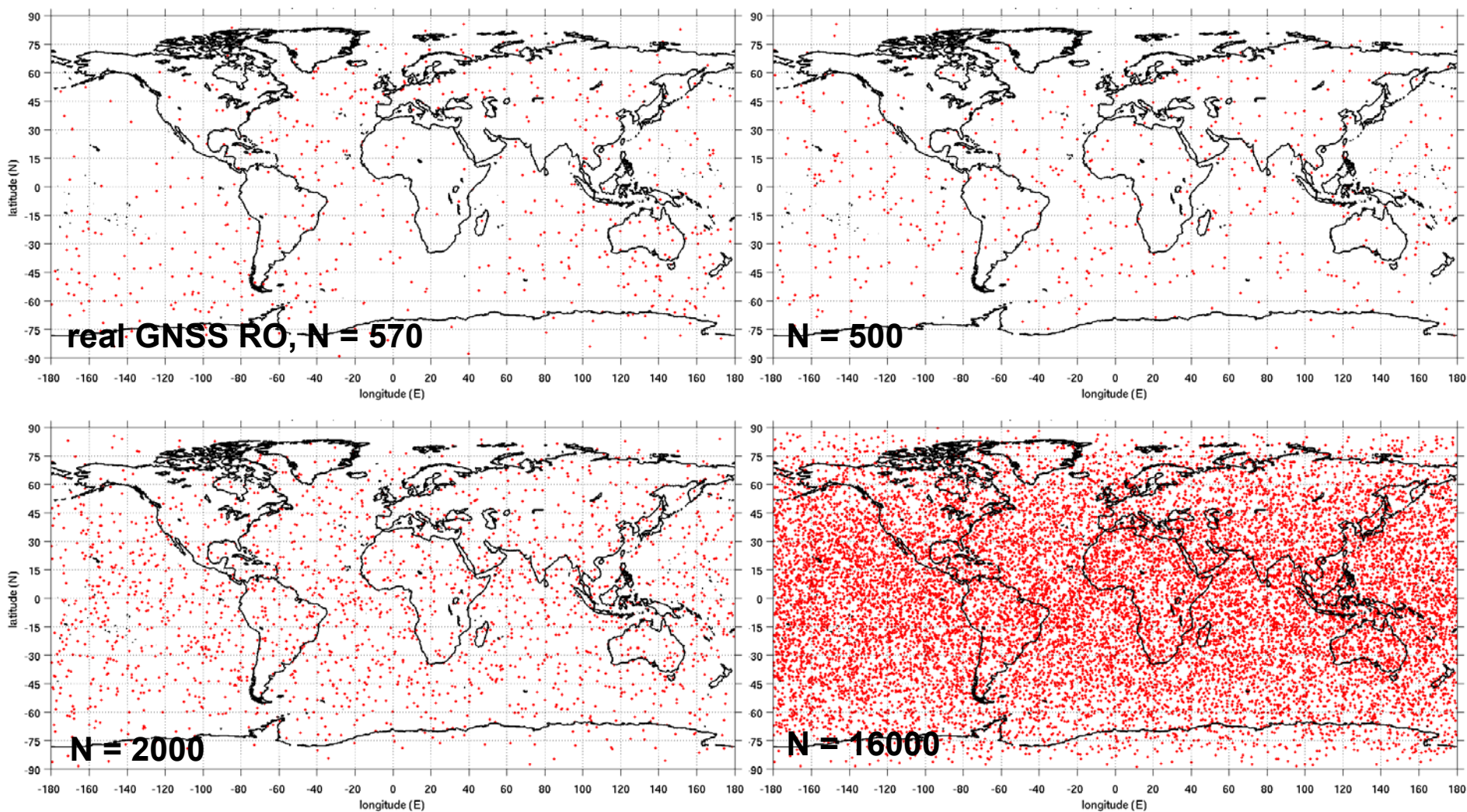
- **No evidence of saturation of impact of GNSS-RO at current levels.** See studies by:
 - Poli et al (2008): GRL, **35**, doi:10.1029/2008GL035873
 - Radnoti et al (2010) : ECMWF tech memo. 638.
- But how many do we need before saturation? **Ongoing ESA funded study at ECMWF (Florian Harnisch).**
- Use Ensemble of Data Assimilation (EDA) Techniques to estimate the impact (or information content) of 2000, 4000, 8000, 16000, 32000, 64000 GNSS-RO profiles per day.
- Approach based on work by Tan et al (QJ, 2007 **133**, 381-390).

EDA observation number study details

- 3 Month period July – September, 2008.
- GNSS-RO measurements simulated from ECMWF operational analyses. CY33R1, T799.
- Measurements assumed to be randomly distributed in time and space across the globe.
- Measurements **simulated** with a 2D observation operator.
- Realistic errors have been added and (o-b) statistics are consistent with real data.
- Studies use CY37R3, the current operational cycle at ECMWF .

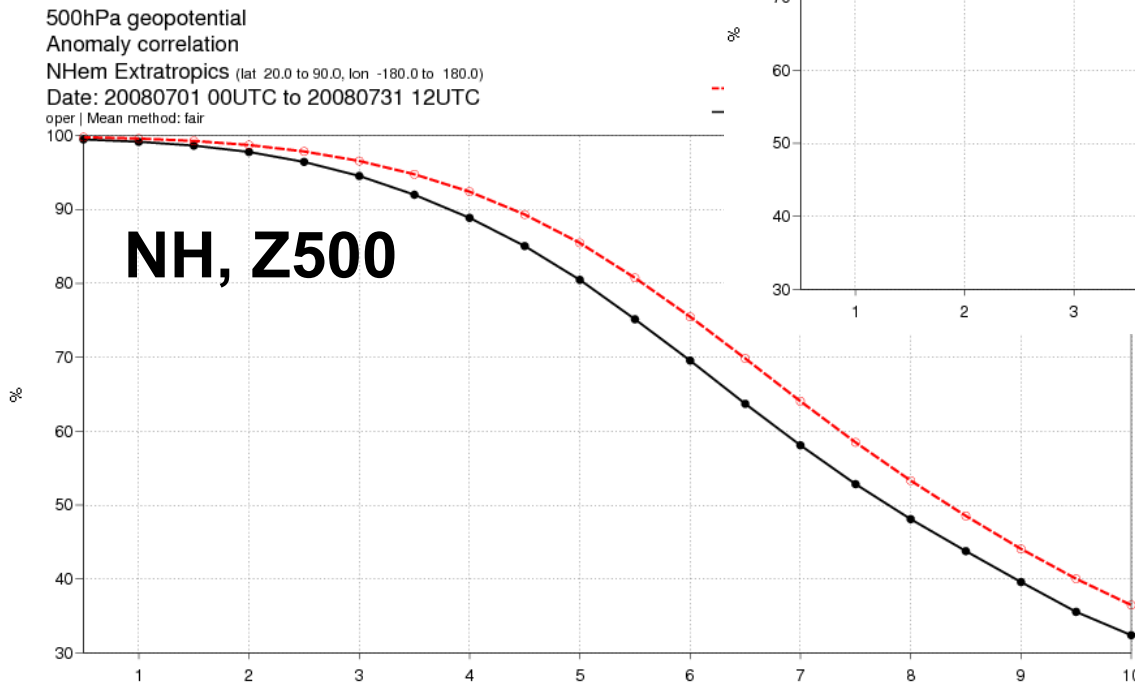
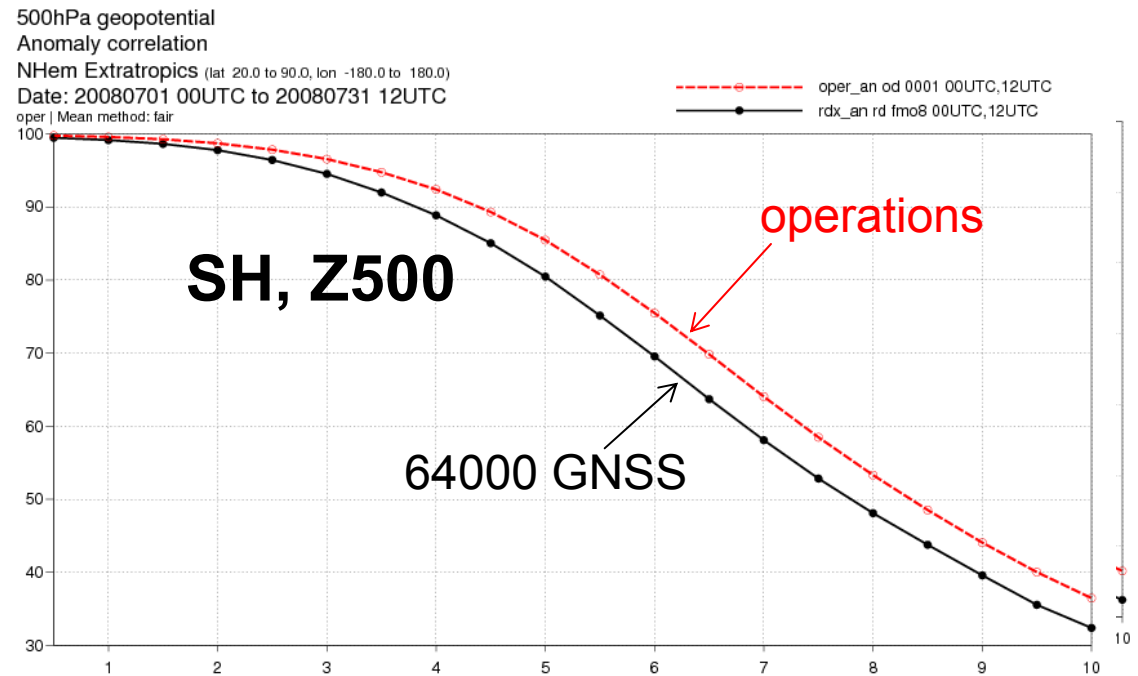
Simulation of GNSS RO observations

Typical 6-hourly observation coverage



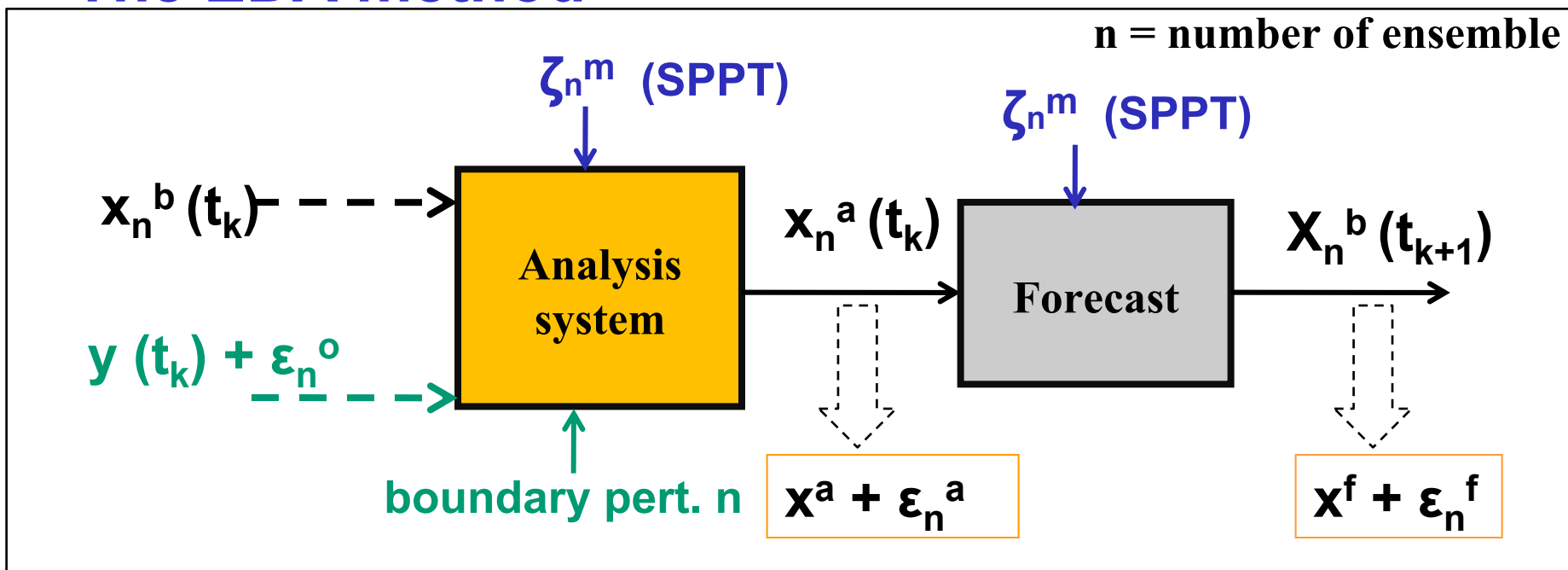
4D-Var experiments (T511, July 2008)

64000 simulated GNSS-RO vs Full system



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

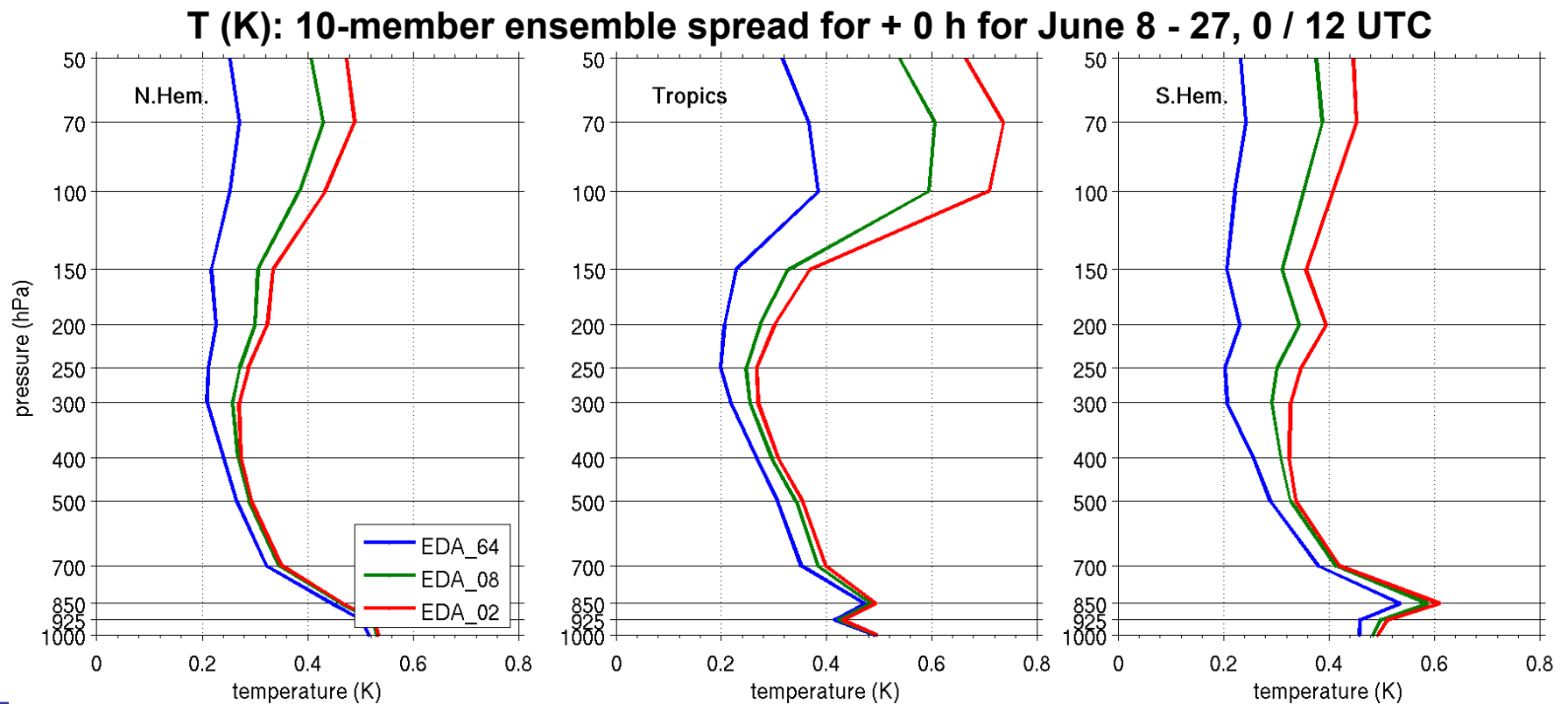
The EDA method



- We cycle 10 4D-Vars in parallel using perturbed observations in each 4D-Var.
- 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.

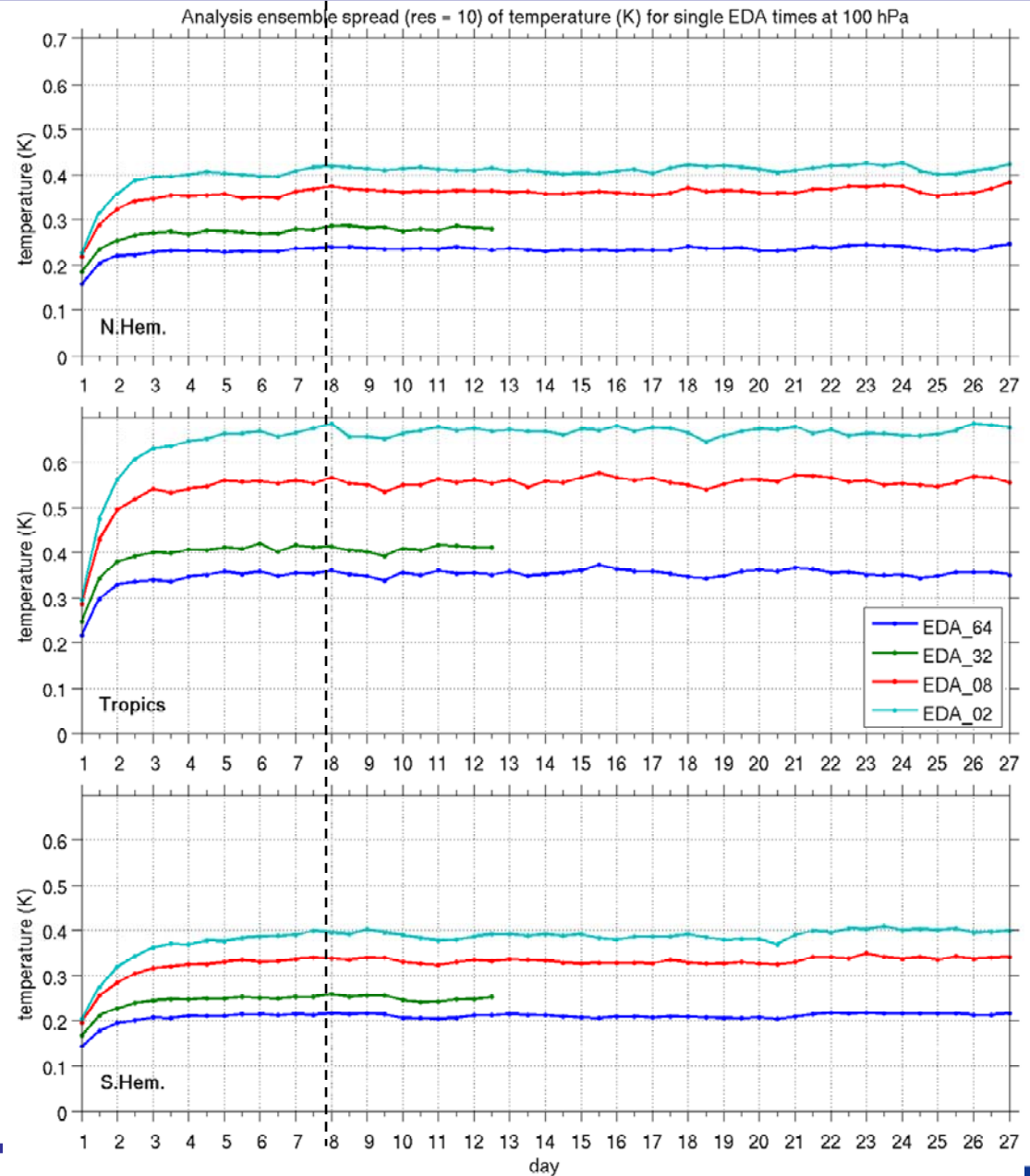
First results

- Reduction of ensemble spread of **temperature analysis** with more GNSS-RO profiles
- **No evidence of saturation with 8000 simulated observations.**



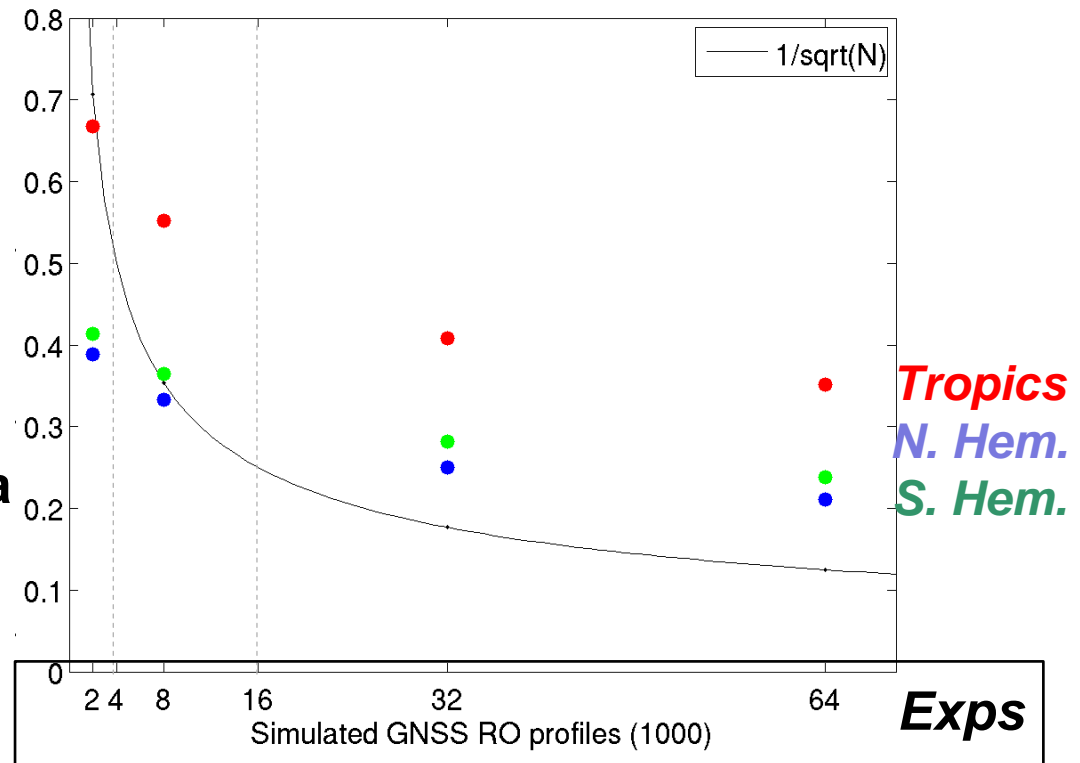
First results

- No initial background perturbation
- Short-term ensemble forecasts provide the next background
- Cycling produces background perturbations
- Less than 7 days to reach stable state
- Only minor fluctuations



First results

4-day period of
Analysis Ensemble Spread
of **Temperature (K) at 100 hPa**



- Spread is still reduced with 64000 GNSS RO profiles
- Spread reductions much smaller than $1/\sqrt{N}$
- Indications for saturation of spread reduction
- Different behaviour for other levels and parameters

Summary

- Outlined main characteristics of GNSS-RO.
- Surface pressure from GNSS-RO.
 - GNSS-RO can constrain large surface pressure biases, but the results are sensitive biases in other parameters.
- **Continuity of GNSS-RO observation numbers is the major concern.** GNSS-RO observation number study:
 - Presented early ESA study results which suggest that 8000 obs. per day are not saturated.
 - Suggest “**WMO Vision for GOS in 2025**” be revisited. ***IROWG NWP sub-group recommendation.***

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)

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



CHAMP
COSMIC-1

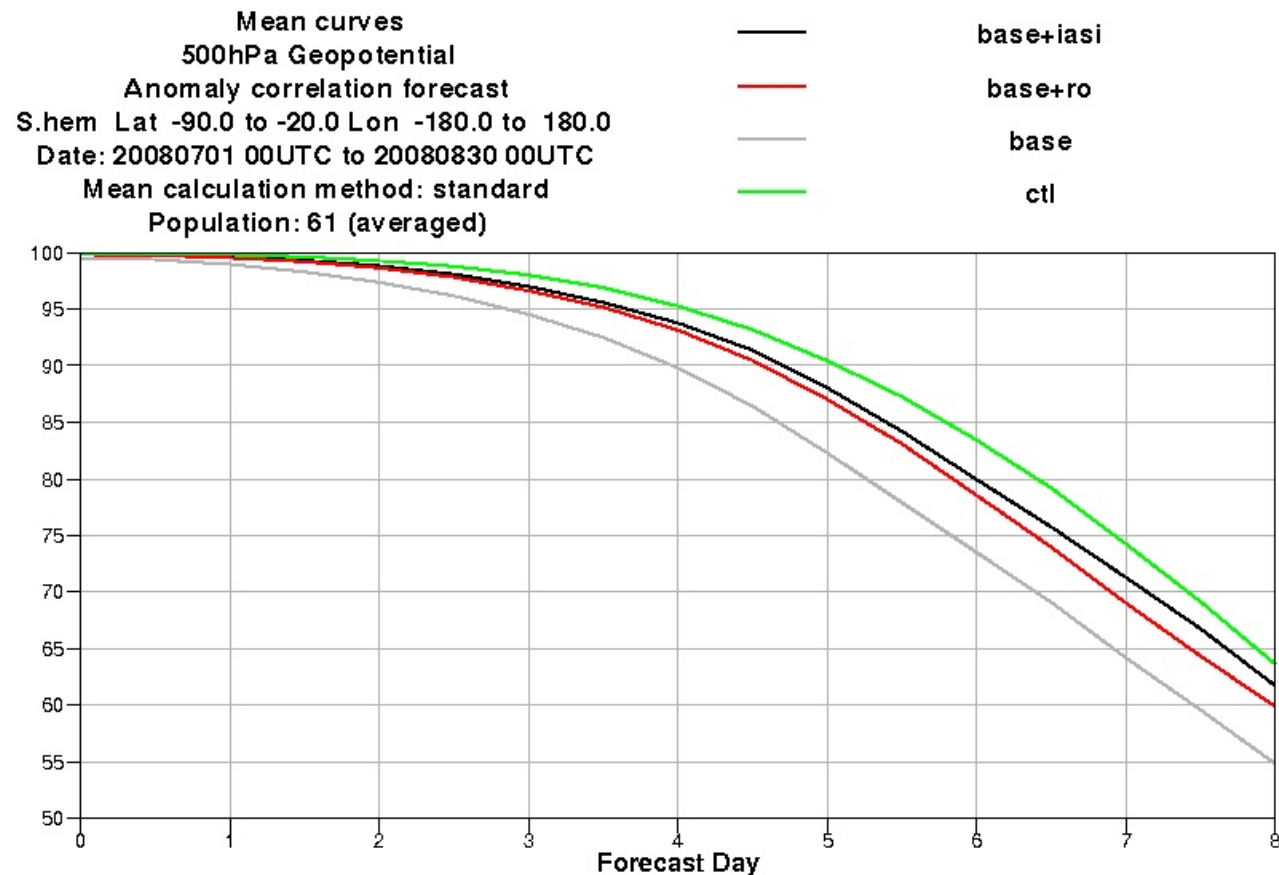
COSMIC-2
COSMIC-3

COSMIC-4
COSMIC-5

COSMIC-6
METOP-A

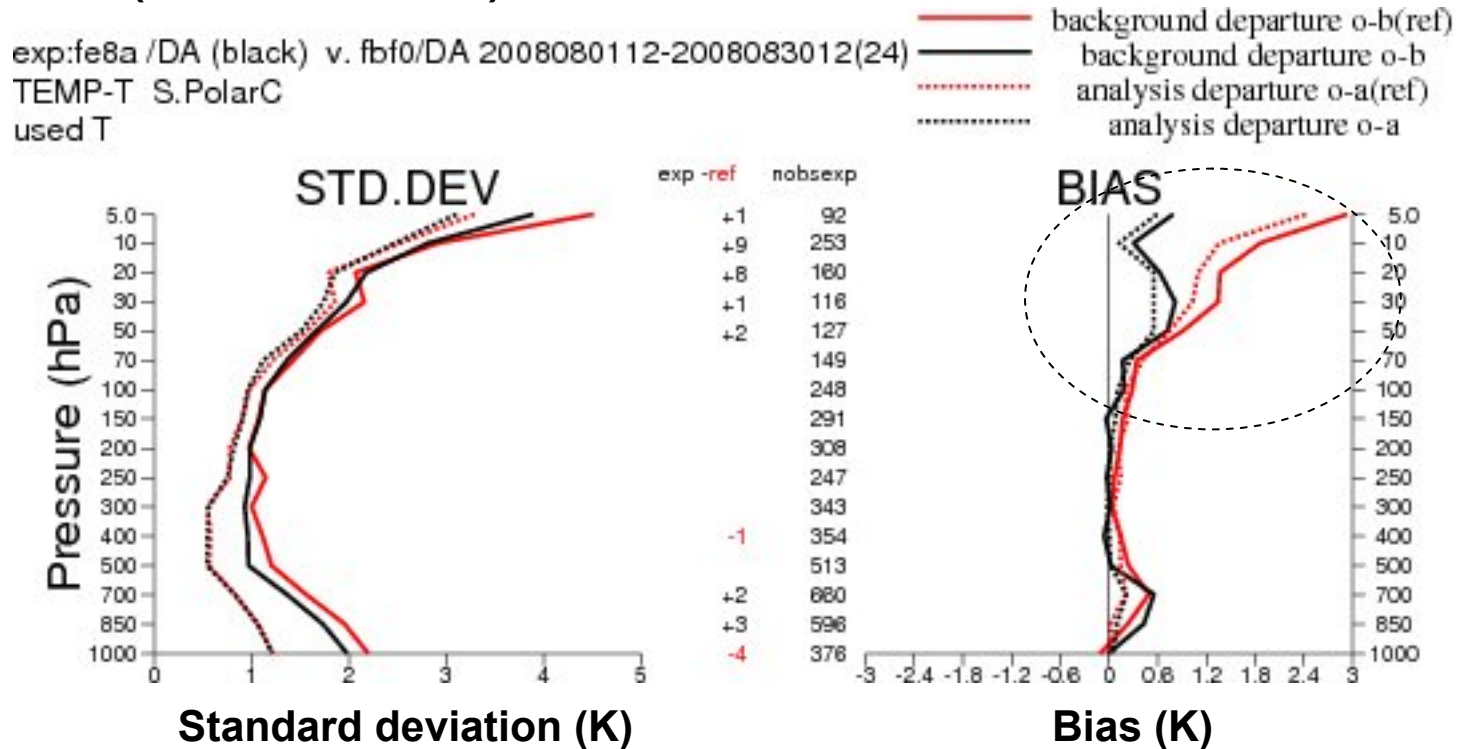


Comparison with IASI, relative to a poor baseline system.



How many GPSRO receivers would we need to equal the impact of IASI?

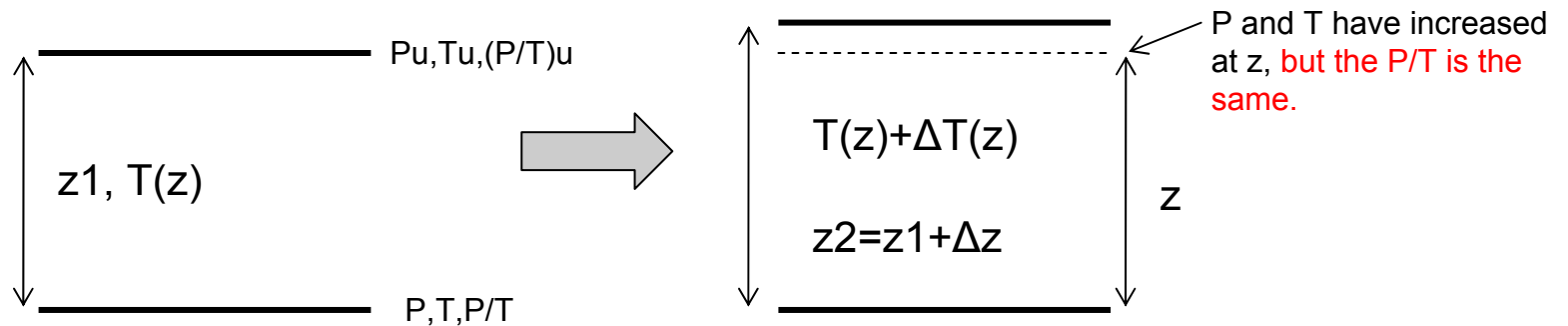
(IASI + RO) vs RO fit to radiosonde T



(IASI + RO) is producing much better stratospheric biases than just GPSRO generally, but most obvious at the S.Pole. Why is GPSRO not doing a better job? **The GPSRO measurement has a “null space”.**

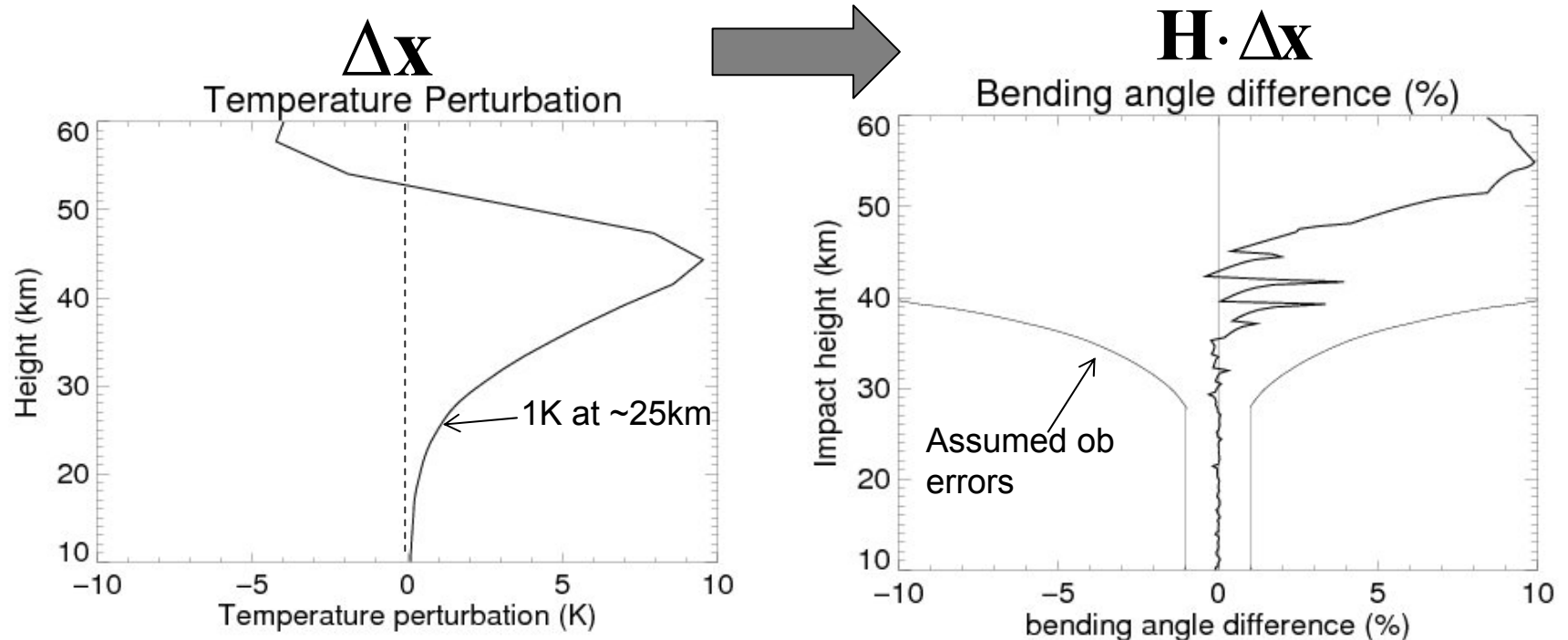
GPS RO “null space”

- The measurement is related to density ($\sim P/T$) on height levels and this ambiguity means that the effect of some temperature perturbations can't be measured. Assume two levels separated by z_1 , with temperature variation $T(z)$ between them. Now add positive perturbation $\Delta T(z) \sim k \cdot \exp(z/H)$, where H is the density scale height



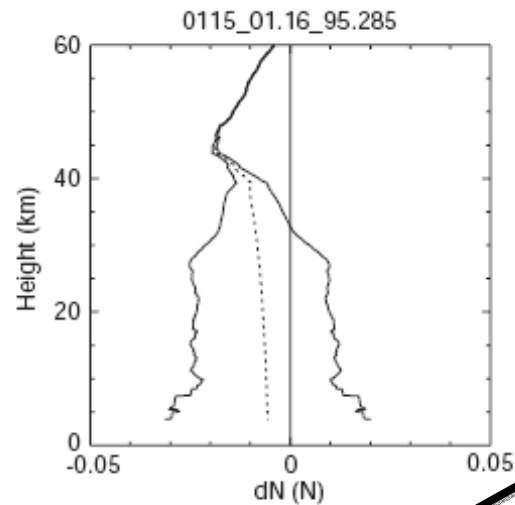
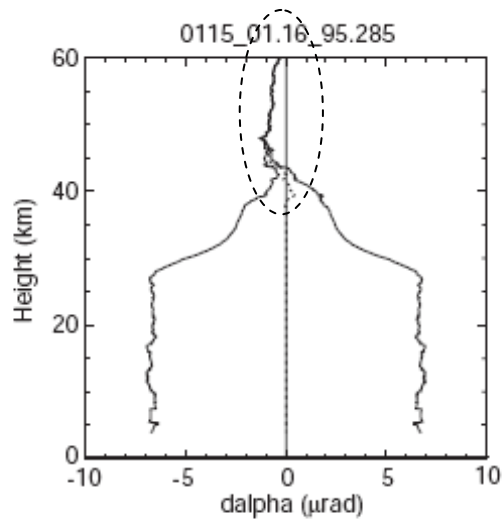
- The density as a function of height is almost unchanged. **A priori information required to distinguish between these temperature profiles.**

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

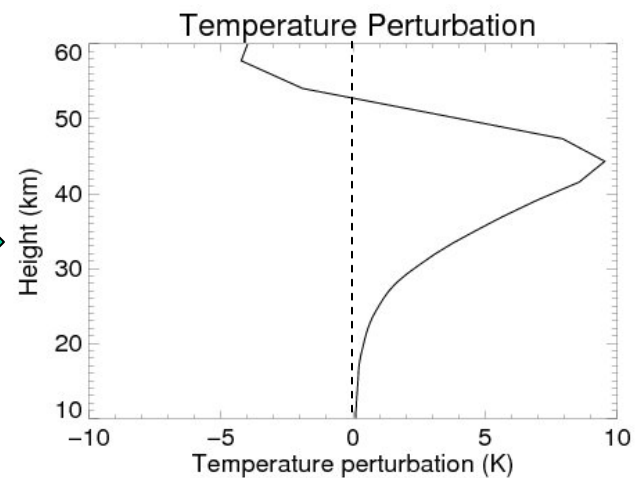
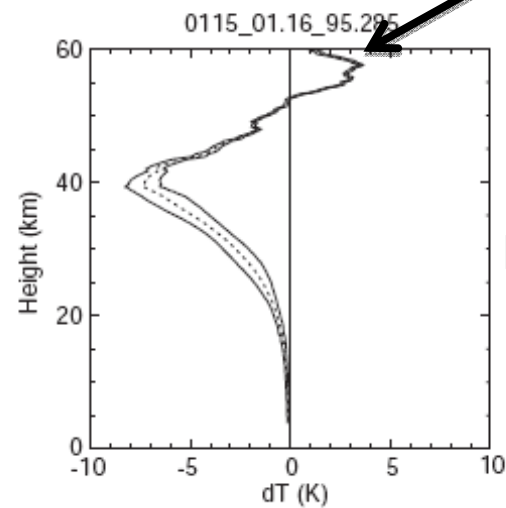
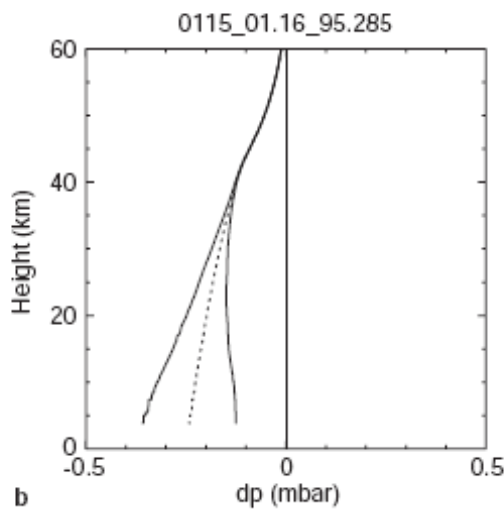


The null space arises because the measurements are sensitive to density as function of height ($\sim P(z)/T(z)$). *A priori* information is required to split this into $T(z)$ and $P(z)$. We can define a temperature perturbation $\Delta T(z) \sim k \cdot \exp(z/H)$ which is in the GPSRO null space. Therefore,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

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



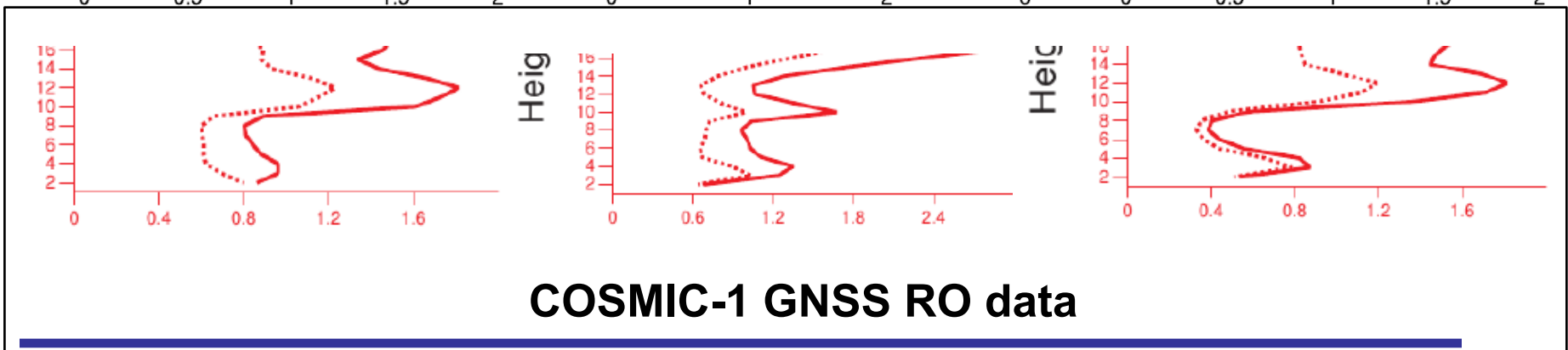
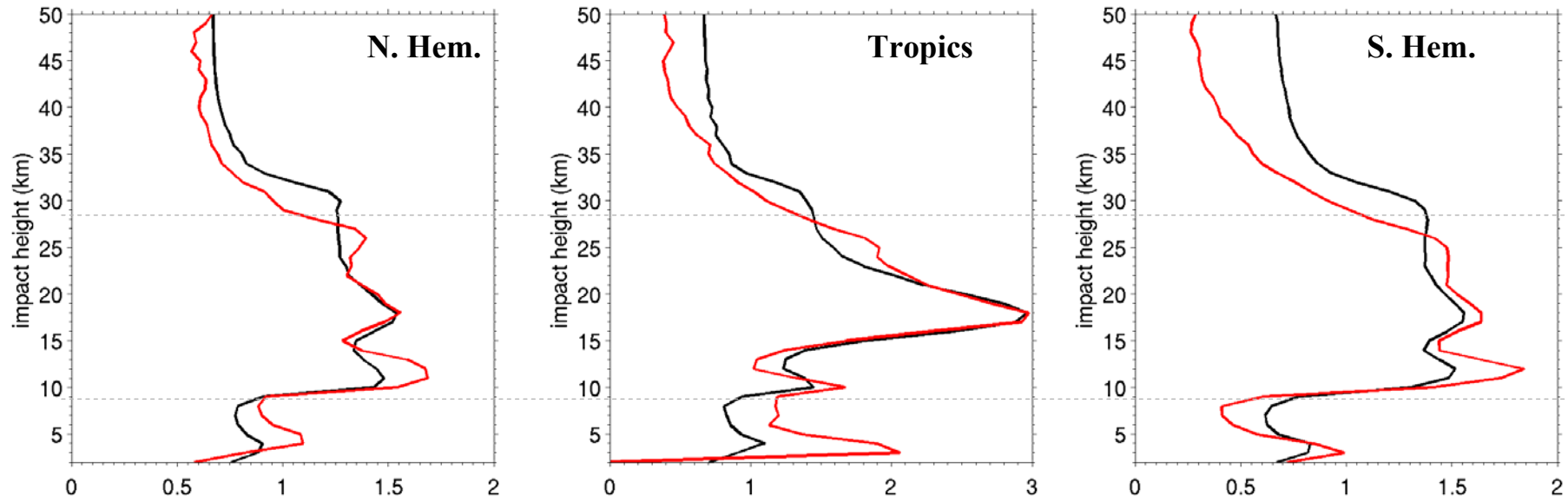
Temperature retrieval error caused by a 5 % bias in the background bending angle used in the statistical optimization



4D-Var test experiment for July 2008

simulated 64000 GNSS RO
normalized background fit

operational used GRAS GNSS RO
normalized background fit



Comparison GNSS_64 and GNSS_16

- RMS fit of GNSS_64 and **GNSS_16** to radiosonde observations
- improved fit with 64000 GNSS RO profiles

