First forecast impact experiments with CHAMP radio occultation (RO) measurements at ECMWF

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Acknowledgements

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Outline

1) GRAS-SAF 1D bending angle observation operator.
2) Assumed observation/forward model errors.
3) A summary of 4D-Var forecast impact experiments using CHAMP data from 1st August – 29th September, 2003.
4) Estimate of the *Degrees of Freedom for Signal* (*DFS*) of RO in 4D-Var.
5) Initial results with 2D operators - “single profile” tests.
6) Conclusions and future plans.

1D bending angle operator

Assuming spherical symmetry the bending angle can be written as:

$$\alpha(a) = -2a \int_a^\infty \frac{d \ln n / dx}{(x^2 - a^2)^{1/2}} dx$$

$$(x = nr) \longleftarrow \textit{Convenient variable}$$

We evaluate this integral using the NWP profile information at the location of the "**occultation point**" defined by UCAR as location where the excess phase exceeds 500m for the first time.

I'm using the **GRAS-SAF** bending angle code developed by myself and Christian Marquardt (To be used in validation of GRAS data at EUMETSAT).

1D bending angle operator: main steps

- Calculate the geopotential height of model levels (*Note NWP surface pressure used here*) .
- Calculate refractivity, N, on (full) model levels.
- Convert to geometric heights (and radius) using a transform given by List (*Smithsonian Met Tables*).
- Calculate the refractive index-radius product, $x=nr$, on full levels.
- Evaluate the integral assuming N varies exponentially between the model levels with x.

1D bending angle operator

We **assume** the refractivity varies exponentially between the model levels

$$\frac{d\ln(1+10^{-6}N)}{dx} \approx 10^{-6}\, dN/dx$$

$$= -10^{-6} k_l N_l \exp(-k_l(x-x_l))$$

$$k_l = \ln\left(N_l/N_u\right)/(x_u - x_l)$$

and approximate $\sqrt{x^2-a^2} \approx \sqrt{2a(x-a)}$ to obtain

(Error less than 0.1% ~1/(8ka))

$$\Delta\alpha(a) = 10^{-6}\sqrt{2a}\,k_l N_l \exp(x_l - a)\int_{x_l}^{x_u} \frac{\exp(-k_l(x-a))}{\sqrt{x-a}}\,dx$$

Aside: Note the connection between the bending angle integral and the modified Bessel function. Useful for testing!

$$K_0(ka)\times\exp(ka) = \int_{x=a}^{\infty} \frac{\exp(-k(x-a))}{\sqrt{x^2-a^2}}\,dx$$

1D Bending angle operator

Hence, the bending can be written analytically

$$\Delta\alpha(a) = 10^{-6}\sqrt{2\pi k_l a}N_l \exp(k_l(x_l - a)) \times$$
$$\left[erf(\sqrt{k_l(x_u - a)}) - erf(\sqrt{k_l(x_l - a)}) \right]$$

where *"erf"* is the Gaussian error function. Total bending angle given by summing up contributions of this form. Bending above the model top is handled quite easily in this approach.

$$\Delta\alpha_{ext}(a) = 10^{-6}\sqrt{2\pi k_l a}N_l \exp(k_l(x_l - a)) \times$$
$$\left[1 - erf(\sqrt{k_l(x_l - a)}) \right]$$

The forward model is not computationally expensive!

Assumed observation/forward model errors

The derived bending angles are interpolated to 200 fixed impact heights (*h*=a-Roc) between the surface and 40km. Separation is ~100m near surface, 300m near 40km.

The percentage error in bending angle falls linearly from 10% at *h*=0 to 1% at *h*=10km.

Above 10km we use MAX(1%, 6μrad).

<u>**NO vertical correlations included**</u>.

Map these to refractivity space with an Abel transform, will give refractivity errors comparable to Kuo et al. (2004).

Assimilation Experiments

Performed with the ECMWF 4D-Var system at T319 resolution (~62.5 km horizontal grid). Ran my own control at this resolution. All other available data, including AIRS, assimilated (**~2.7 million** per 12 hours).

CHAMP data from 1st August – 29th September 2003. **Experiment 1** used bending angle data processed by UCAR with **Full Spectral Inversion** (FSI) "raw" bending angle data. Typically **12,500** bending angles assimilated per 12 hours (cf 2.7 million other obs!).

"Raw" means no statistical optimization of the bending angles.

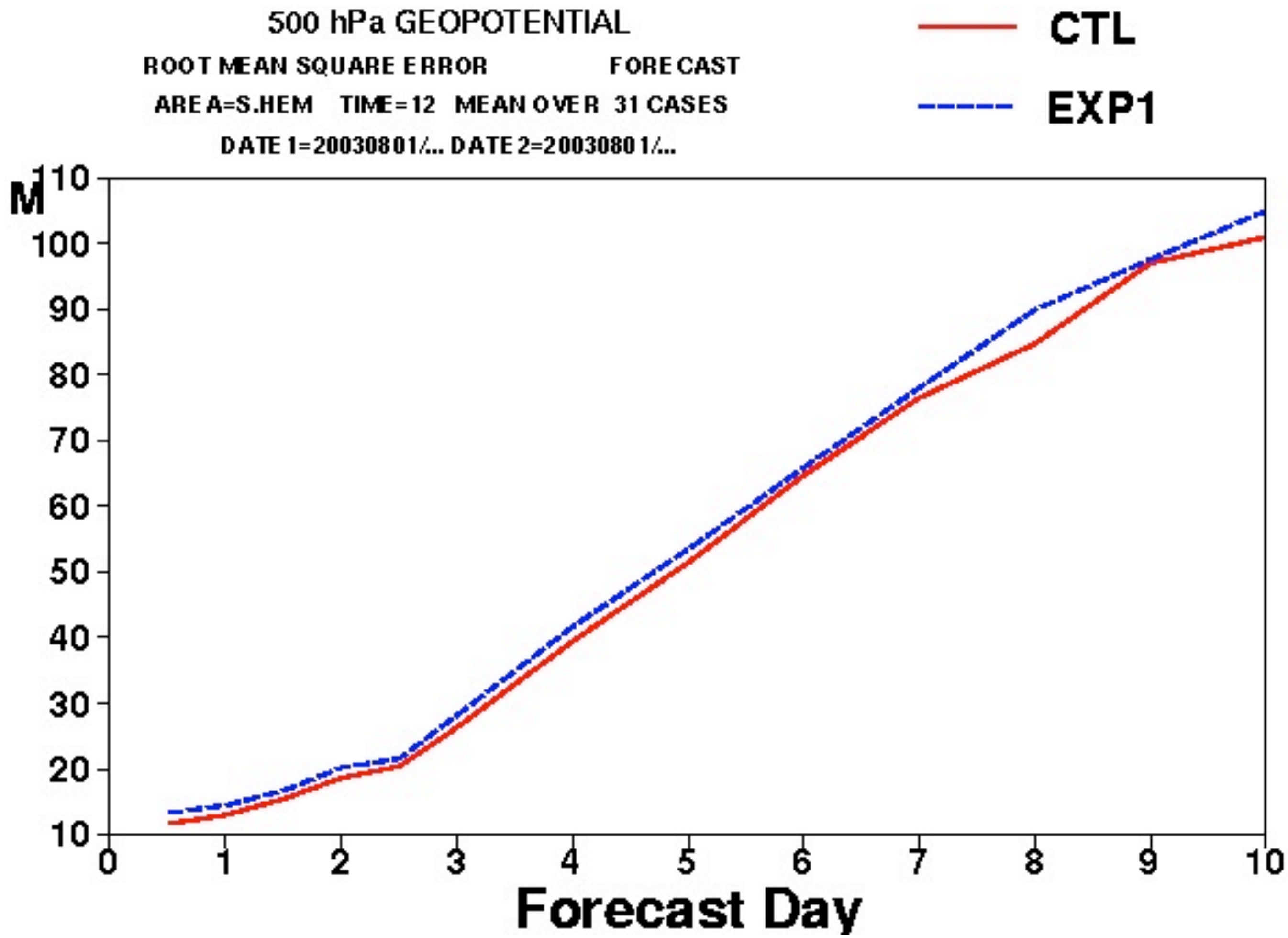
Assimilation Experiments (2)

Blacklisted all bending angles with impact heights (h=a-ROC) less than 5km. *Known biases in the bending angles*.

Experiment 1: 1st Aug – 31st Aug, 2003

Good improvement in the stratosphere (details later in talk) but **a clear degradation of the southern hemisphere 500hPa heights against observations and analyses**, which we will deal with first.

RMS error in 500hPa Z in SH



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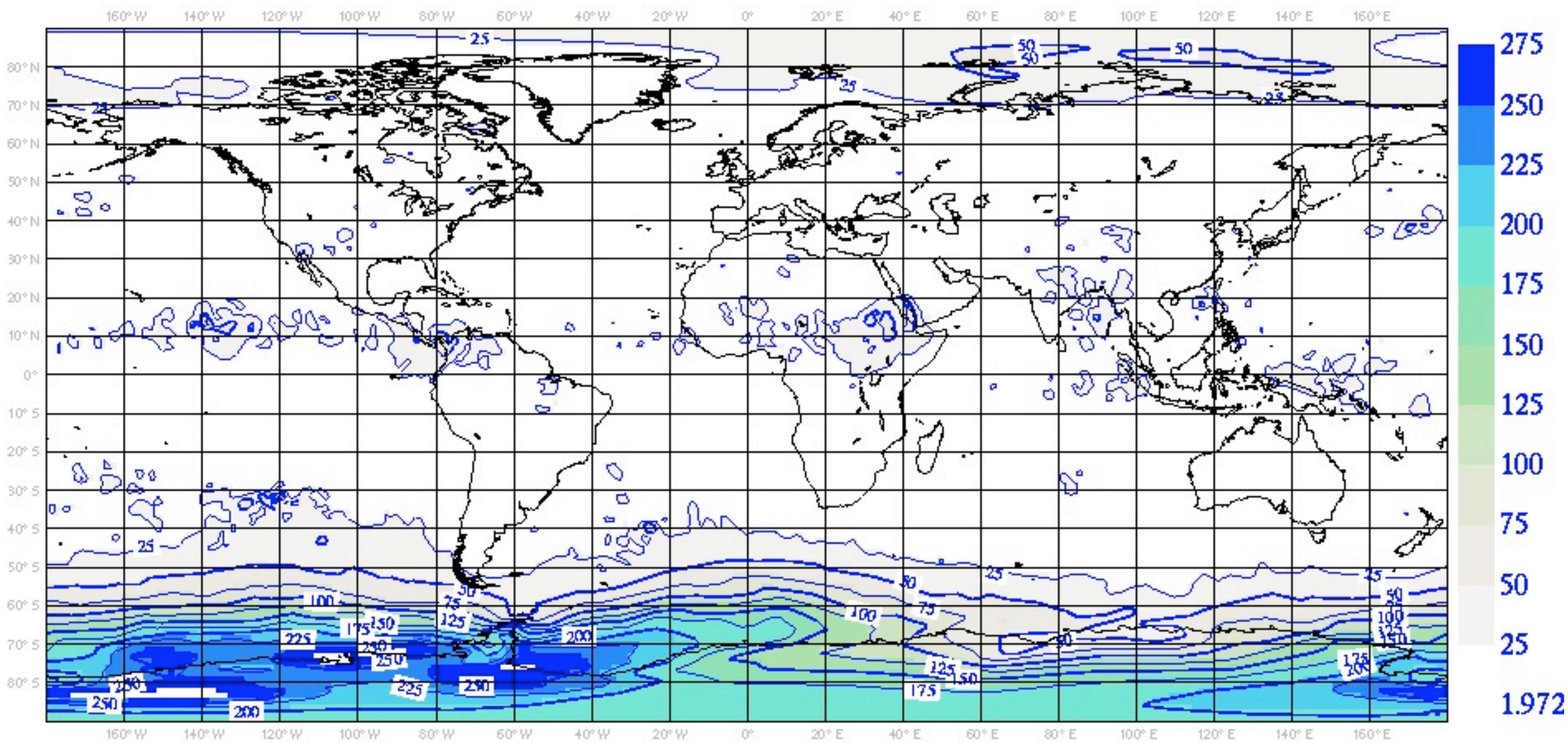
RMS of control-experiment surface pressure analysis differences (Pa)



The SH 500Z problem – Ps increments

The largest errors were over Antarctica and appear to be a result of large surface pressure increments.

By assuming uncorrelated errors, we are probably overestimating the surface pressure information.

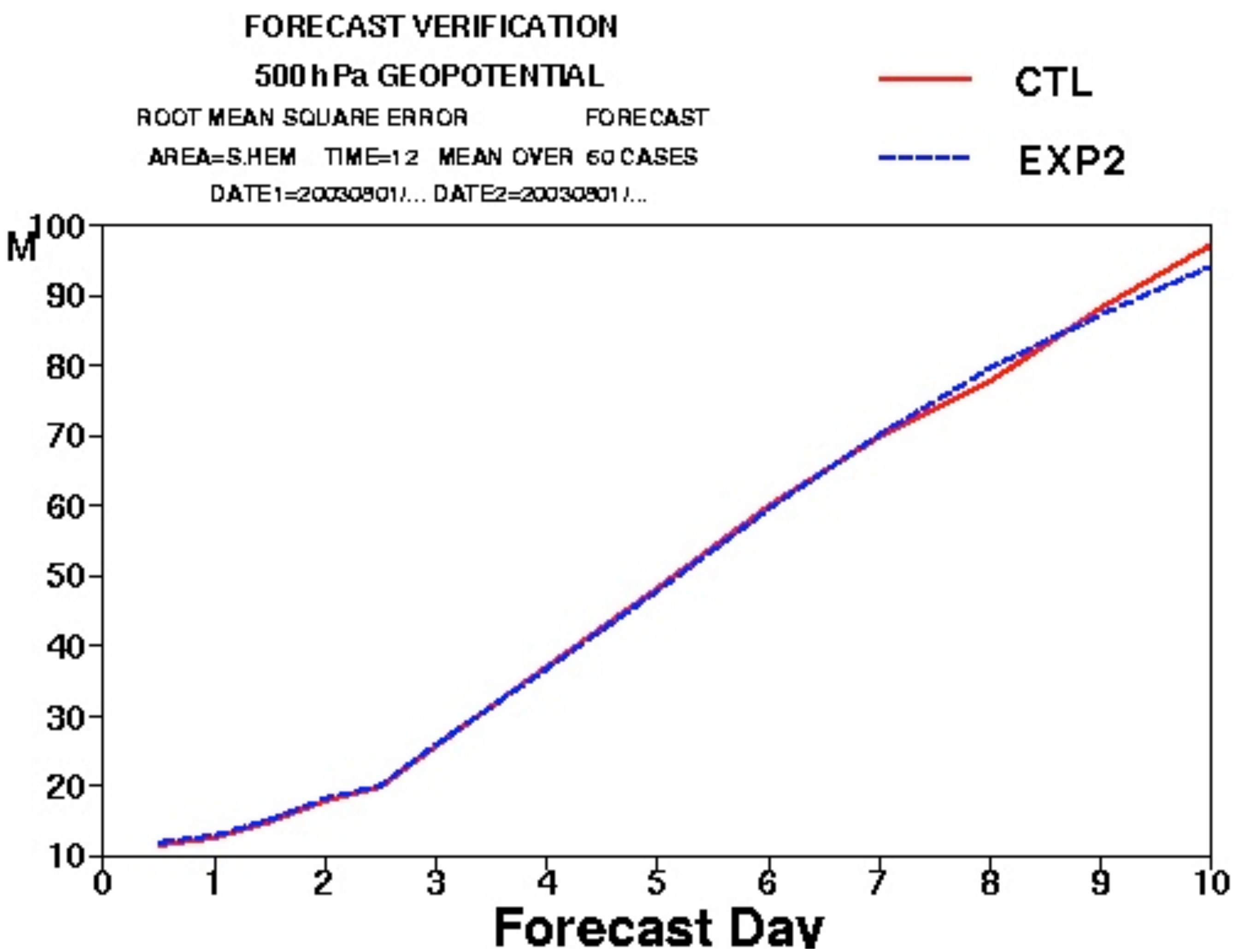
On the other hand, blacklisting impact heights for h <5km usually limits the surface pressure information – except over high orography!

Antarctica: high orography combined with a relatively high RO observation density, few other surface pressure obs.

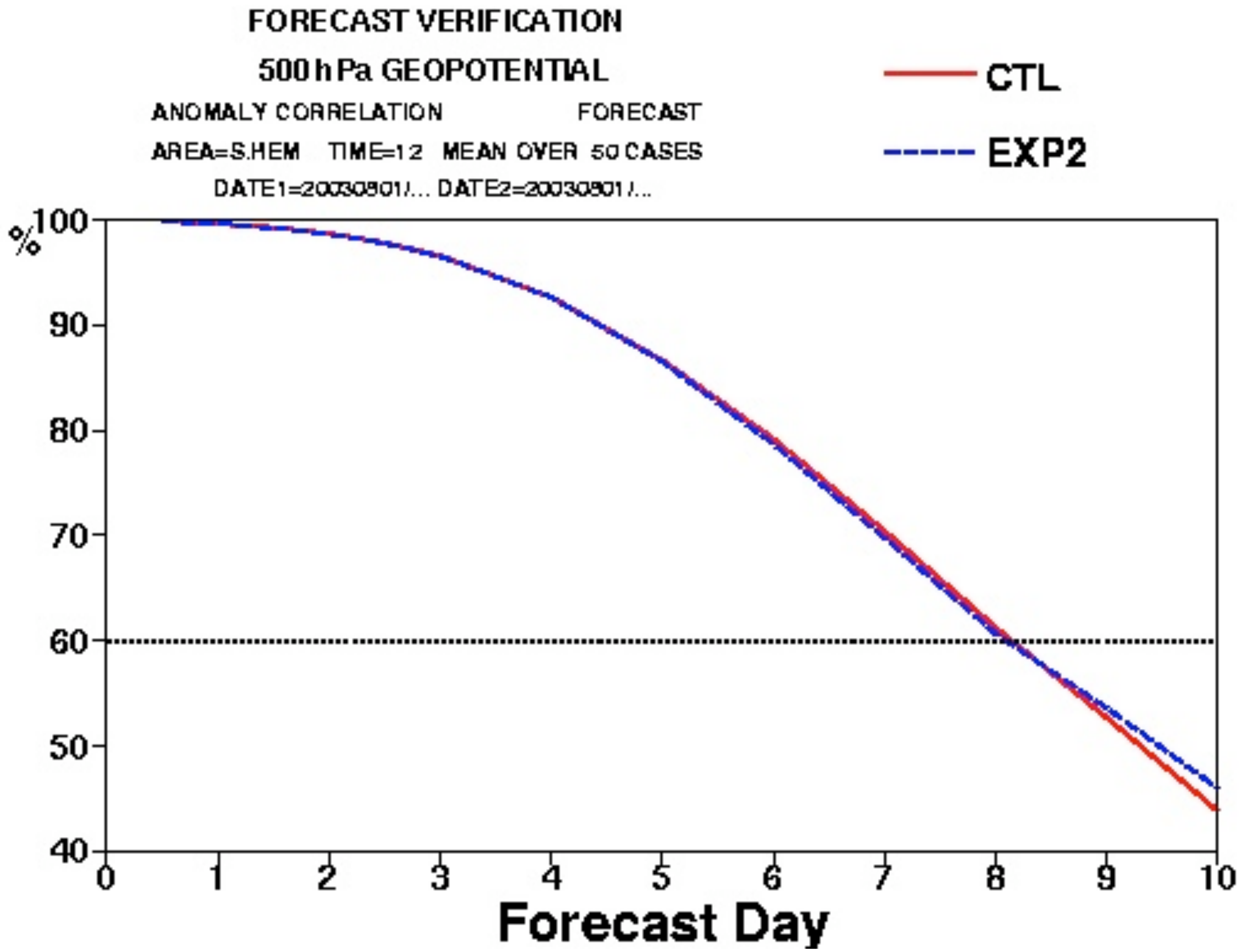
Experiment 2: 1st Aug. 29th Sept. 2003.

Modified the tangent-linear and adjoint routines to stop the hydrostatic surface pressure increments for GPS observations.

This was found to reduce the 500hPa height problems.

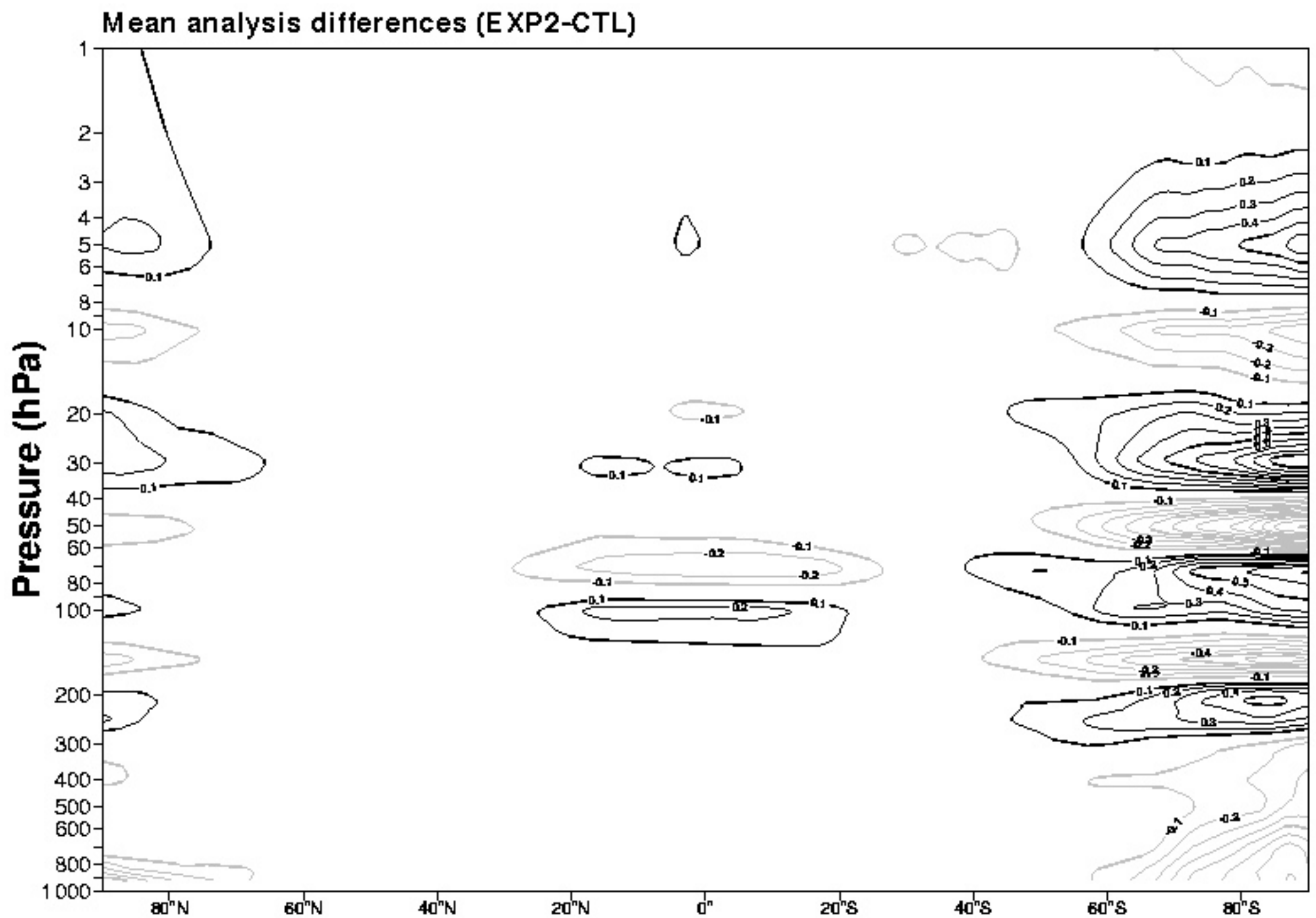


FORECAST VERIFICATION
500 hPa GEOPOTENTIAL
ROOT MEAN SQUARE ERROR FORECAST
AREA=S.HEM TIME=12 MEAN OVER 60 CASES
DATE1=20030801/... DATE2=20030801/...
CTL
EXP2
M
100
90
80
70
60
50
40
30
20
10
0 1 2 3 4 5 6 7 8 9 10
Forecast Day

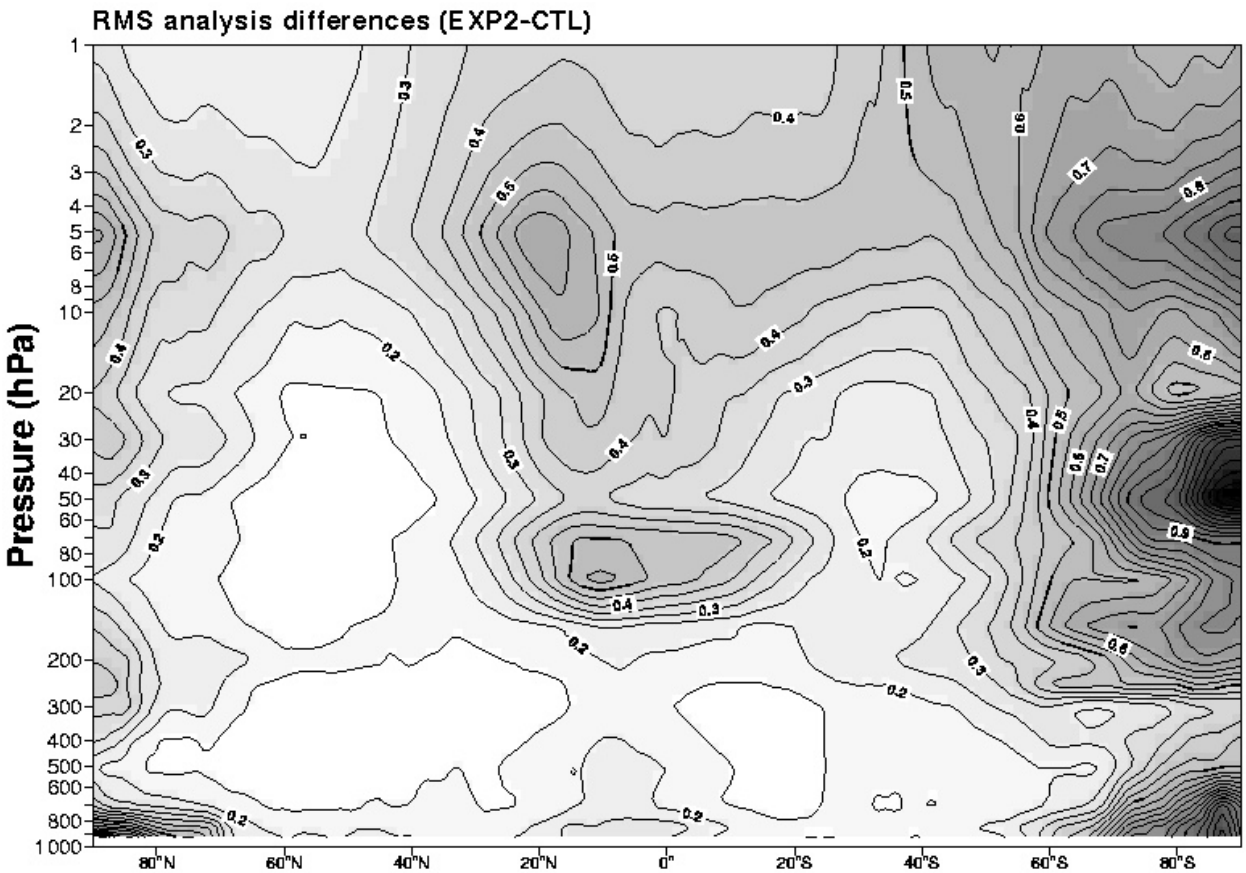


Neutral results with this measure.

Zonally averaged mean temperature analysis differences

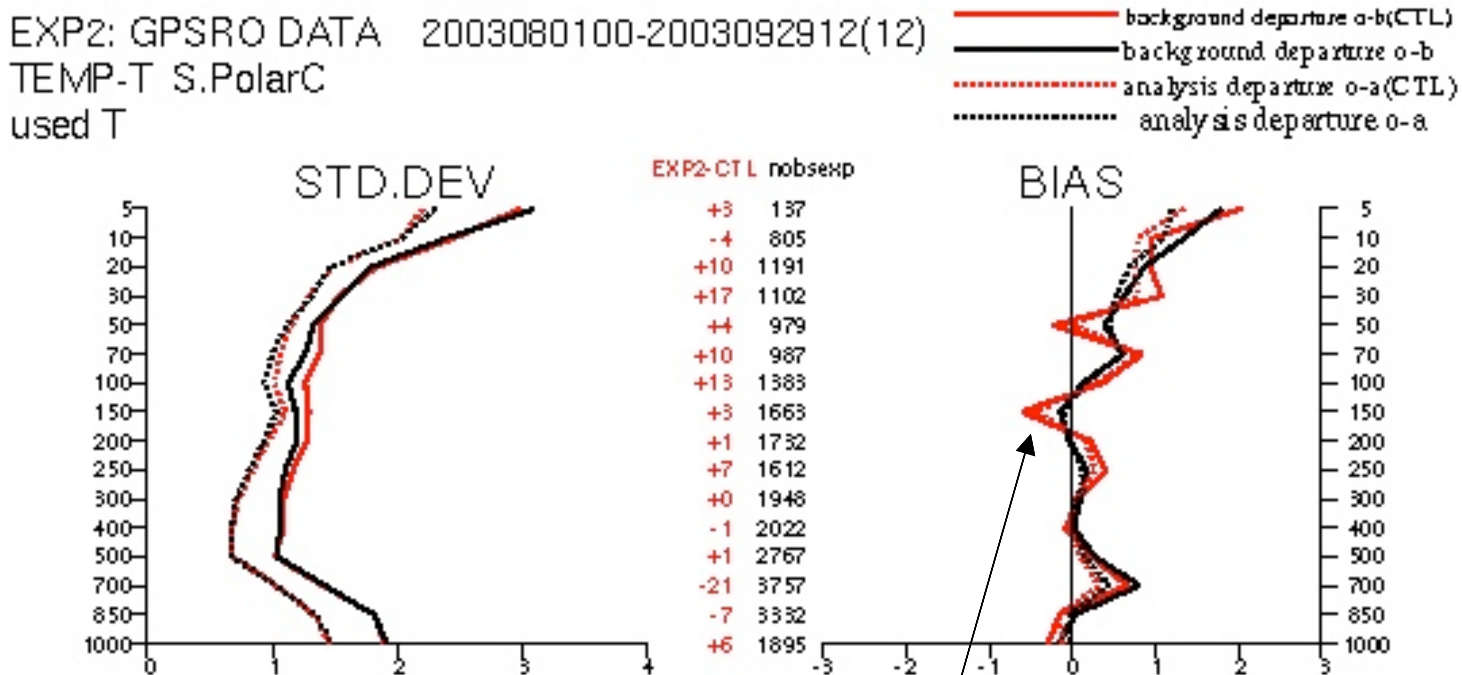


Zonally averaged RMS analysis differences



Significant differences in analyses despite low number of GPS RO observations!

Radiosonde comparisons for Antarctica 12h forecasts



Red lines: control

Black: experiment

Structure in the mean fit caused by inconsistencies in the AIRS and AMSU bias corrections schemes (G. Kelly, ECMWF Pers. Comm)

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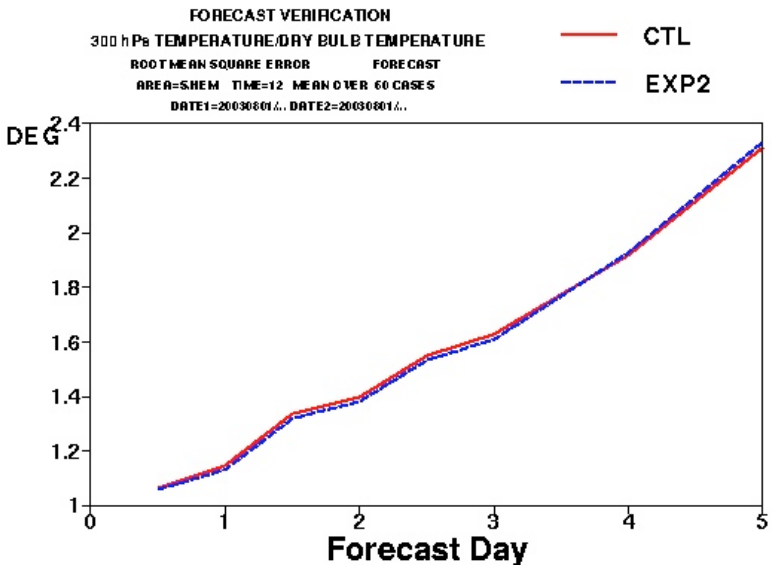
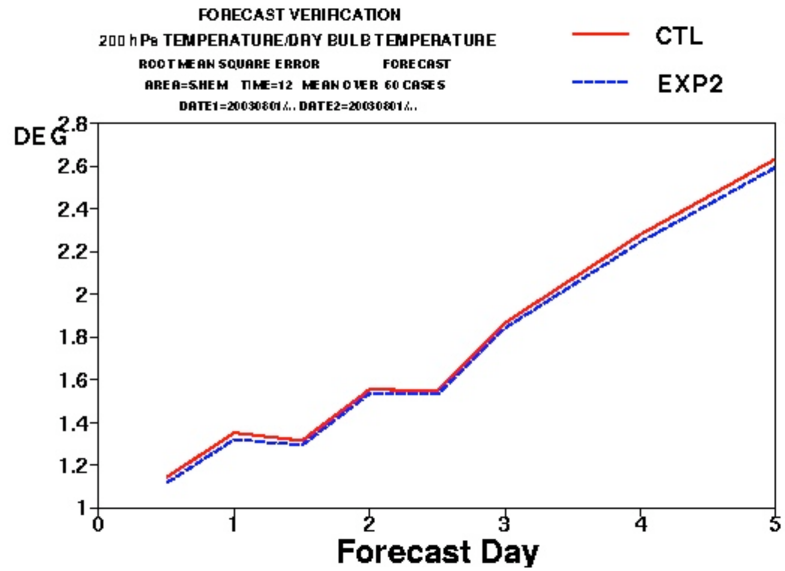
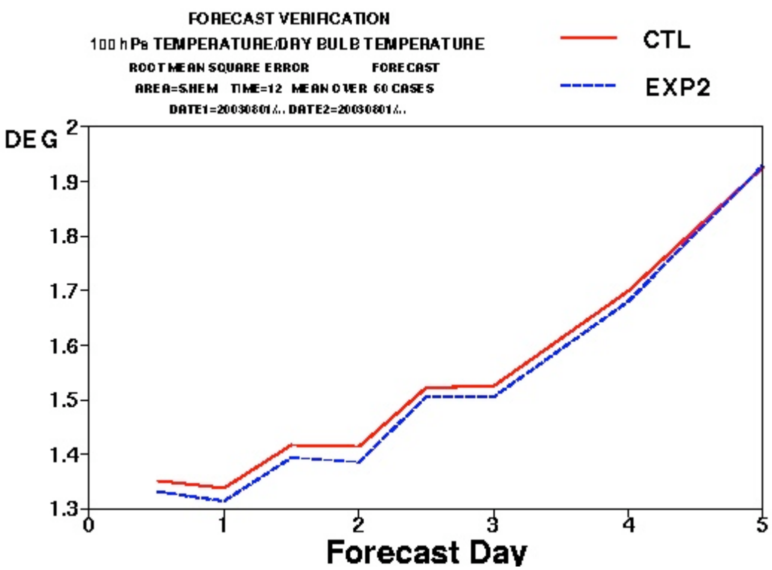
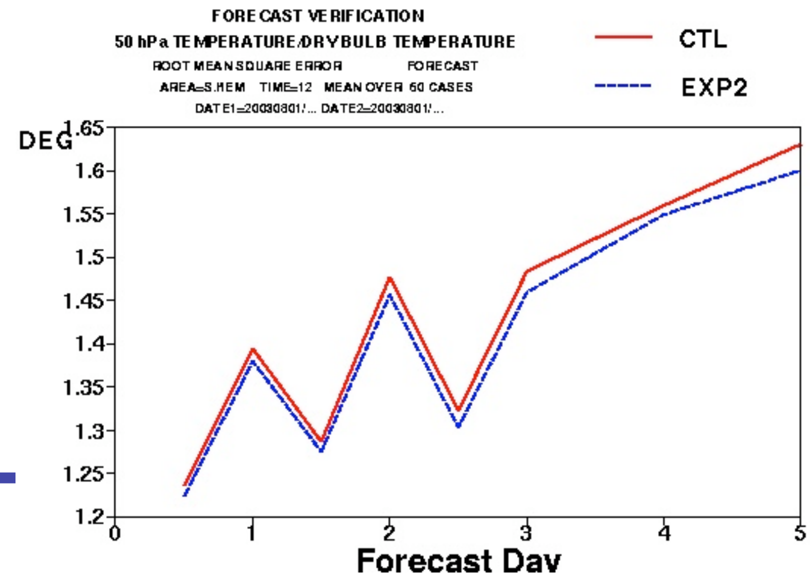
Verification against radiosondes (SH)

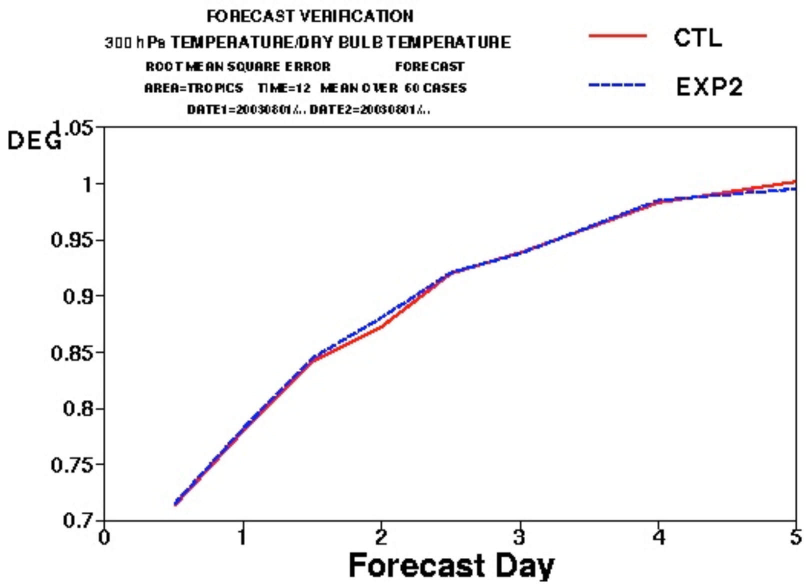


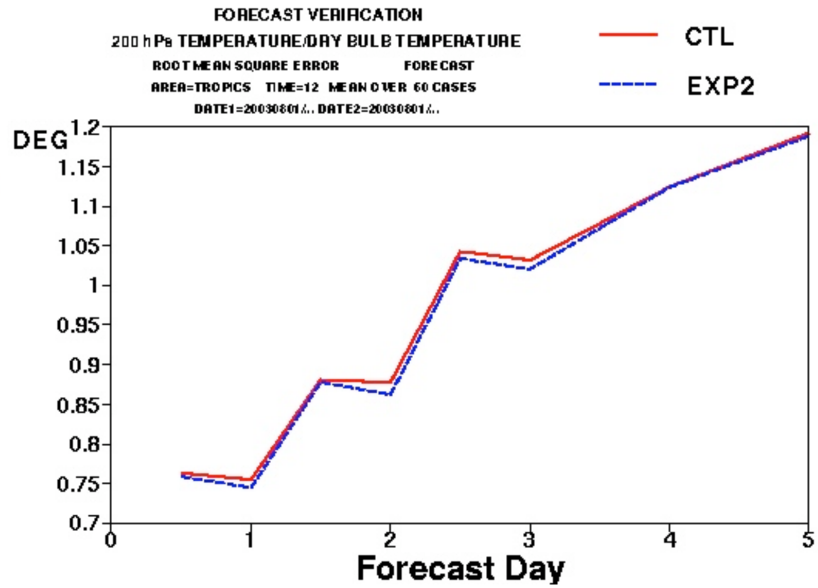


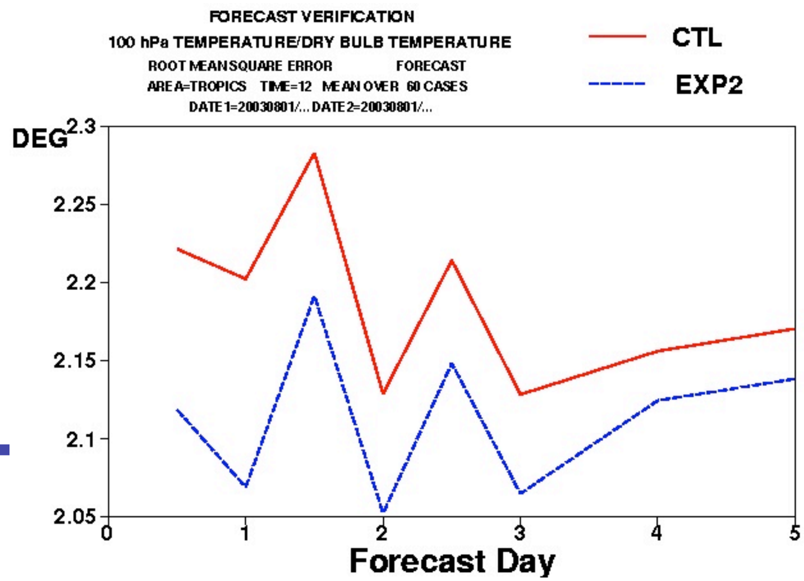


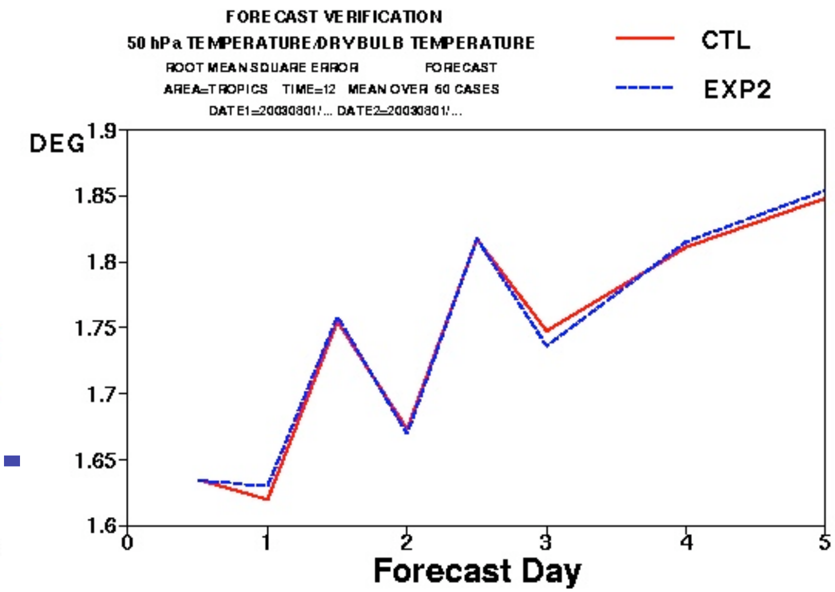


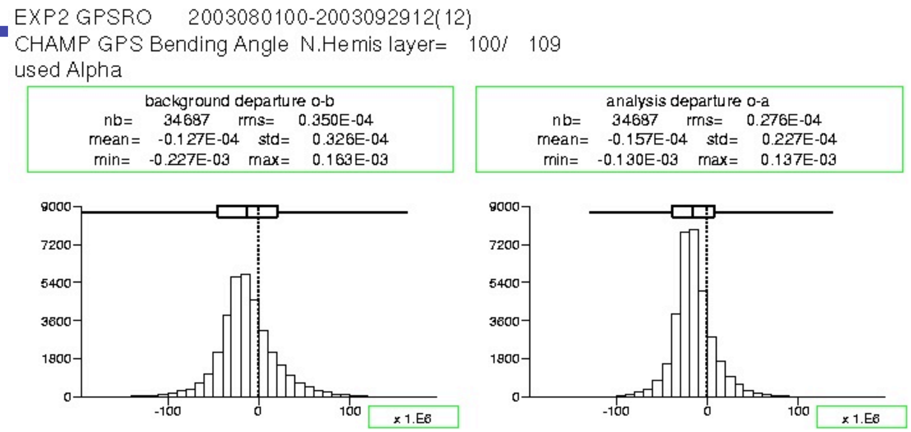
Verification against radiosondes(Tr)

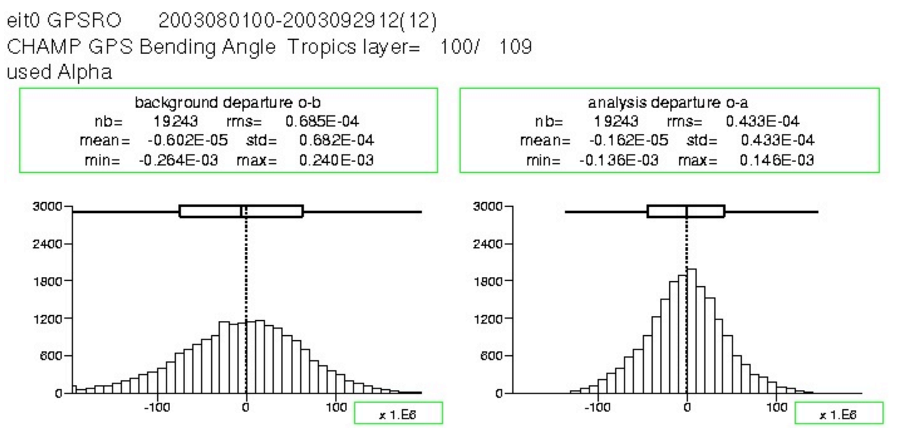


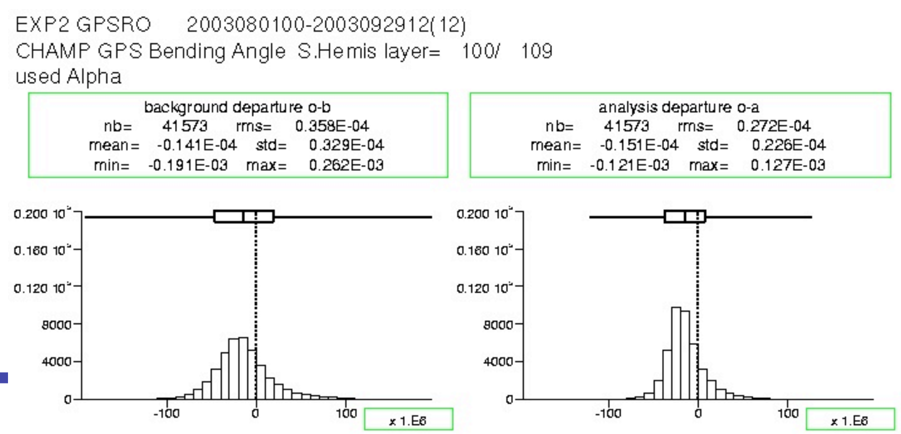












Impact heights between 17.5km – 20km.

REPRESENTATION ERROR

Significantly broader distributions in the tropics -gravity waves? Trying to introduce structure that the model doesn't represent.

Degrees of Freedom for signal (*DFS*)

The DFS is an information content measure that is used widely in satellite meteorology, e.g., in channel selection. It can be written as,

Ie, the Trace of the "Averaging-Kernel"

$$DFS = \mathbf{Tr}(\mathbf{I} - \mathbf{A}\mathbf{B}^{-1})$$

Solution error covariance

Background error covariance

Recently, there has been increasing interest in calculating the *DFS* of the 4D-Var system as a means of comparing the contribution of different ob-types, but its quite complicated because of the size of the matrices (Fisher, 2003).

DFS(2)

But we have found (Rodgers, 2000) an alternative approach because

$$
\begin{aligned}
DFS &= \mathbf{Tr}(\mathbf{I} - \mathbf{AB}^{-1}) \\
&= \overline{(\mathbf{x}_b - \mathbf{x}_a)^{\mathrm{T}} \mathbf{B}^{-1} (\mathbf{x}_b - \mathbf{x}_a)}
\end{aligned}
$$

Hence, we can estimate the *DFS* from the time series “Jb” cost value at the analysis.

Further, we can estimate the DFS of the RO observations by looking at the differences of the Jb in the control and experiments.

DFS(3)

The DFS of the control is

$$DFS_{CTL} = 66110 \pm 321$$

The DFS of the GPS experiment is

$$DFS_{EXP2} = 68811 \pm 324$$

Hence, the DFS associated with the GPS measurements

$$DFS_{GPS} = DFS_{EXP2} - DFS_{CTL}$$

$$= 2700 \pm 64$$

We have increased the total number of observations by ~0.5% but Increased the DFS by ~4%.

Hence, the DFS per RO profile is **~34** (2700/80) and
The DFS per bending angle is **~0.216** (2700/12500).

Put these numbers in context, Fisher (2003) estimates the DFS of 40 AMSUA radiances from 5 profiles as in a 2 degree by 2 degree box as

$$DFS_{AMSUA\_40} = 2.6162$$

The DFS of AIRS is

$$DFS_{AIRS} = 6970 \pm 140$$

This is ~10% of the total (typically, 1 million radiances).

Current work

We are currently testing a 2D observation operator in the 4D-Var system. This has required substantial re-coding of the 4D-Var to enable the use of 2D operators (Mats Hamrud). The 2D operator solves the bending angle integral, but uses the radial gradient for the rays position within the 2D plane.

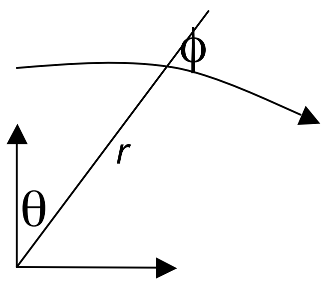
Now depends on θ!

$$\Delta\alpha = -a\int_{x_l}^{x_u} \frac{d\ln n / dx}{(x^2 - a^2)^{1/2}}\,dx$$

$$\Delta\theta = |\Delta\alpha| + |\Delta\phi|$$

$$\Delta a = \left(\frac{\partial n}{\partial\theta}\right)_r \Delta s$$

Δs, the change in path-length, can be written in terms of $\Delta\theta$.



All the rays start from the same “occultation point” – as defined in the UCAR file. A plane 2D plane is constructed using the azimuthal angle defined in the UCAR file. The 2D plane contains 31 profiles separated by 40km. Central profile = occultation point.

1) calculate the bending from the tangent point along the path towards the LEO
2) Calculate the bending from the tangent point along the path towards the GPS.
3) Add these bending angles together to get the total bending.

The height of the tangent point (starting point of the 2D ray path) is estimated from the “derived impact parameter” – i.e., the value given in the data file. It is derived assuming spherical symmetry!

Single ob

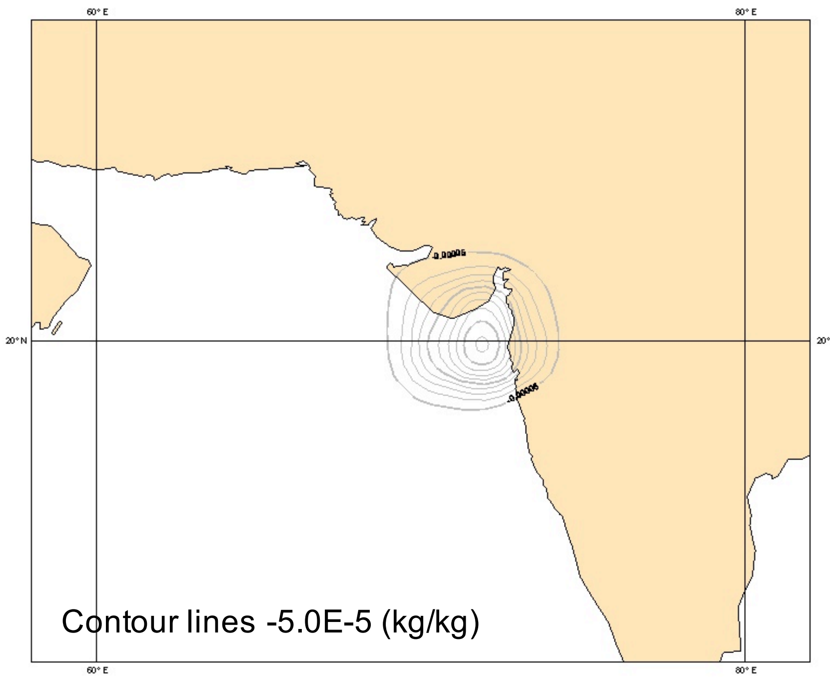
We have only just started testing the 2D operator within the 4D-Var system. We have tried just assimilating 1 RO profile and comparing the increments obtained with the 1D and 2D operators.

The occultation point is at 19.8N, 76.1E, with an azimuthal angle of –161.0 (relative to North), date 20040601.

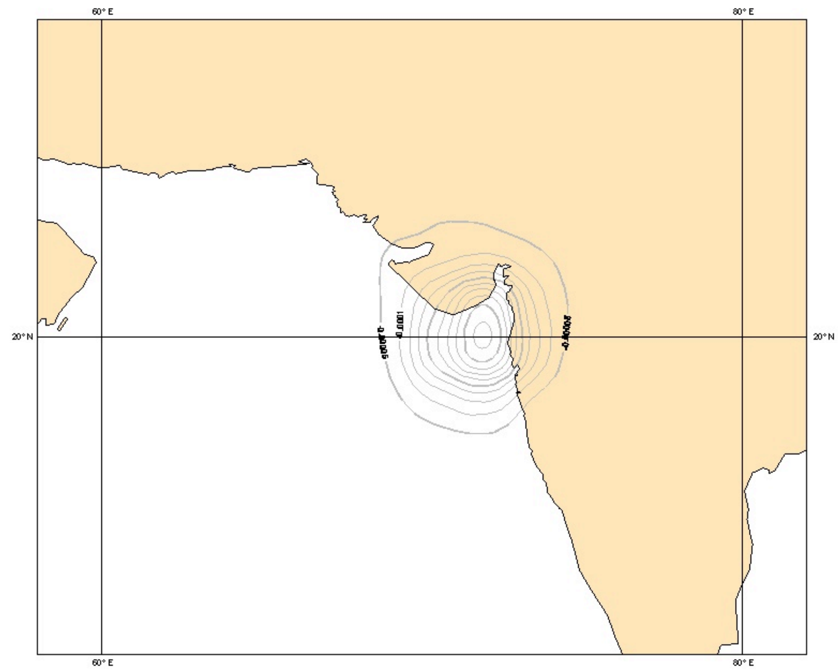
This profile was just picked at random for testing – its not special.

Specific humidity increments at ~763hPa

1D Operator



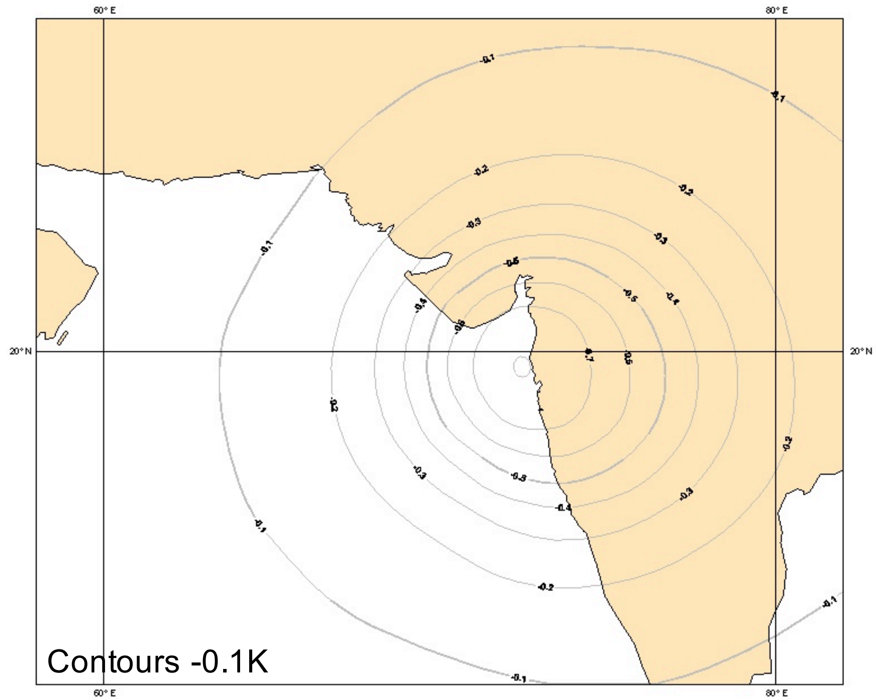
2D Operator



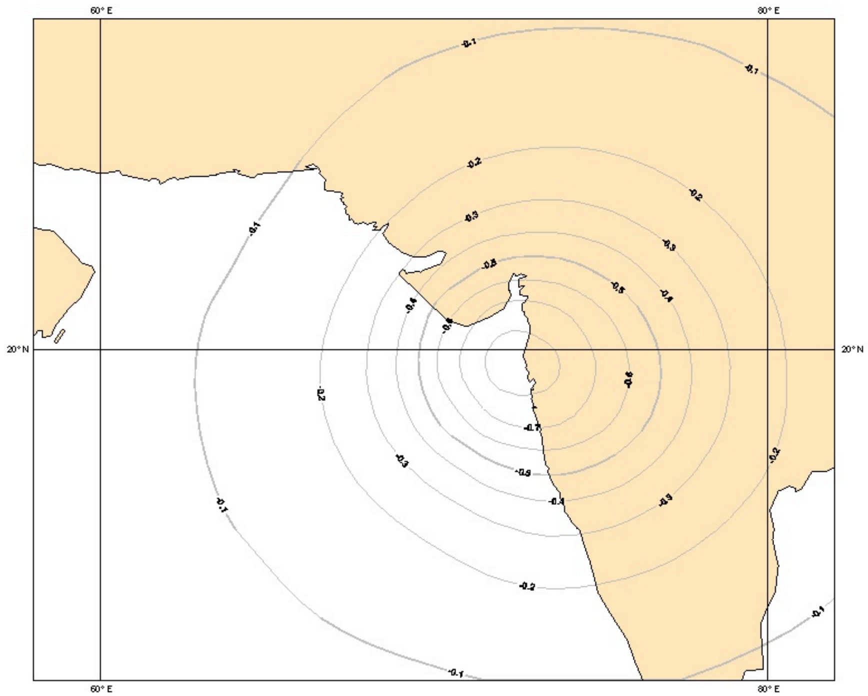
Slightly broader increments with the 2D operator – in this case.

Temperature increments at ~177hPa

1D Operator



2D Operator



Notice how broad the increments are in both cases – the width is primarily governed by the **B** matrix.

Summary

- Implemented a GRAS-SAF 1d bending angle observation operator in the ECMWF 4D-Var system.
- In the first forecast impact experiments we had problems with the surface pressure increments. They were switched off.
- We have found that relatively few CHAMP observations lead to quite significant temperature analysis differences in the stratosphere.
- The CHAMP measurements improve the forecast fit to radiosondes in the SH (300-50 hPa) and 100 hPa in the tropics.
- Large DFS information content value associated with GPS observations.

Summary (2)

- The results strongly refute the argument "*we don't need radio occultation because we have millions of satellite radiances that will do the job".*

- I think we've now shown that RO provides something new to the assimilation system. RO measurements clearly provide information that is complementary to existing observation types.

- Not requiring bias correction is a great strength of GPSRO.

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Current/Future work

- More testing of the 2D-operator in the 4D-Var system.
- Perform forecast impact experiments to investigate the improvements introduced with the 2D approach.