Assimilation of GPS radio occultation measurements at the Met Office

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Talk outline

1. Met Office assimilation system / observation operator
2. Status of RO in operations
3. Recent impact studies
4. Future developments

Met Office system: brief summary

- NWP model is the Unified forecast model (UM):
  - Non-hydrostatic equations
  - Height as the vertical co-ordinate.
  - Charney-Philips grid-staggering in the vertical.
  - Terrain-following near the surface.
- Variational data assimilation system (VAR):
  - Incremental 4D-Var.
    - Uses perturbation forecast (PF) model to map background error info to the time of the observations
    - PF has simplified linearised physics, rather than direct tangent linear/adjoint of non-linear UM.

RO assimilation method within VAR:

- Given state vector $\mathbf{x_1}$ on the 1st iteration:
  - Forward model *N* using **non-linear operator:** $\mathbf{y_1} = H(\mathbf{x_1})$
  - Calculate local gradient i.e. jacobian, sometimes called **K** matrix: $\dfrac{\partial \mathbf{y_1}}{\partial \mathbf{x_1}} = \dfrac{\partial H(\mathbf{x_1})}{\partial \mathbf{x_1}} = \mathbf{K}$
- Store $\mathbf{x_1}$,$\mathbf{y_1}$ and the **K** matrix.
- On subsequent iterations given incremented state vector $\mathbf{x_n}$:
  - apply the **tangent-linear** approximation to estimate $\mathbf{y}(\mathbf{x_n})$:

$$\mathbf{y_n} = \mathbf{y_1} + \mathbf{K}\left(\mathbf{x_n} - \mathbf{x_1}\right)$$

- Use $\mathbf{y_n}$ and $\mathbf{K^T}$ matrix to calculate on nth iteration:
  - Observation cost function (J_{obs}):

$$(J_{obs})_n = \frac{1}{2}(\mathbf{y}_n - \mathbf{y}_{obs})^{\mathbf{T}}\mathbf{R}^{\mathbf{-1}}(\mathbf{y}_n - \mathbf{y}_{obs})$$

  - Gradient of J_{obs} wrt **x**:

$$\frac{\partial (J_{obs})_n}{\partial \mathbf{x}_n} = \left(\frac{\partial \mathbf{y}_1}{\partial \mathbf{x}_1}\right)^{\mathbf{T}} \mathbf{R}^{\mathbf{-1}}(\mathbf{y}_n - \mathbf{y}_{obs}) = \mathbf{K}^{\mathbf{T}}\mathbf{R}^{\mathbf{-1}}(\mathbf{y}_n - \mathbf{y}_{obs})$$

- Total GPSRO J_{obs} and gradient information used with contributions from other observation data in the minimisation problem to produce an updated **x**.

1D Refractivity operator summary

1. Interpolate model column data to occ time and location: to give **x**

GPSRO **x** is pressure (P) on ρ levels & relative humidity (RH) on θ levels

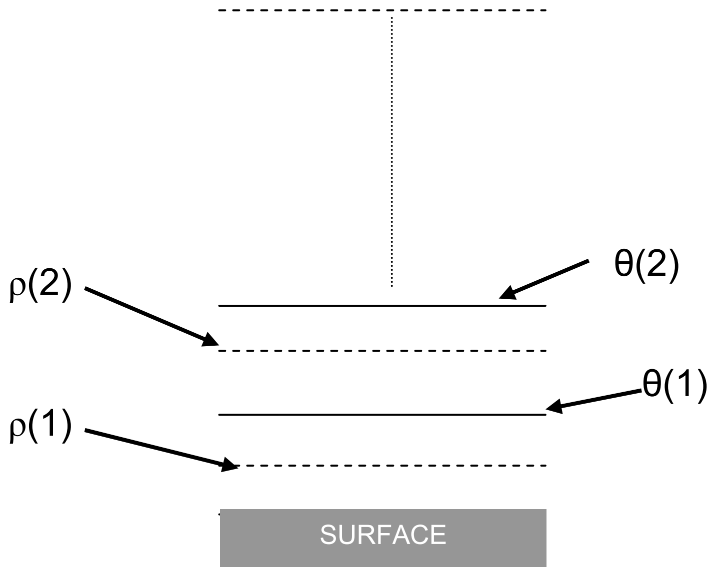
2. Interpolate Exner from ρ to θ levels to get P on θ levels

3. Calculate layer mean *virtual* temperature on θ levels

4. Calculate layer mean temperature on θ levels, using RH

5. *N* calculated on θ levels using Smith-Weintraub formula

6. N interpolated to obs heights



1D refractivity operator strengths/weaknesses

- Strengths:
  - Simple and quick.
  - No extrapolation above model top, as required for *BA*.
- Weaknesses:
  - A priori data introduced high up (>~25 km) from climatology in *N* data.
  - **R** matrix more complicated for *N* than *BA*?
- Future updates:
  - Use q instead of RH.
  - Adjust code for *BA* assimilation.
  - Met Office system not yet capable of incorporating 2D operators.

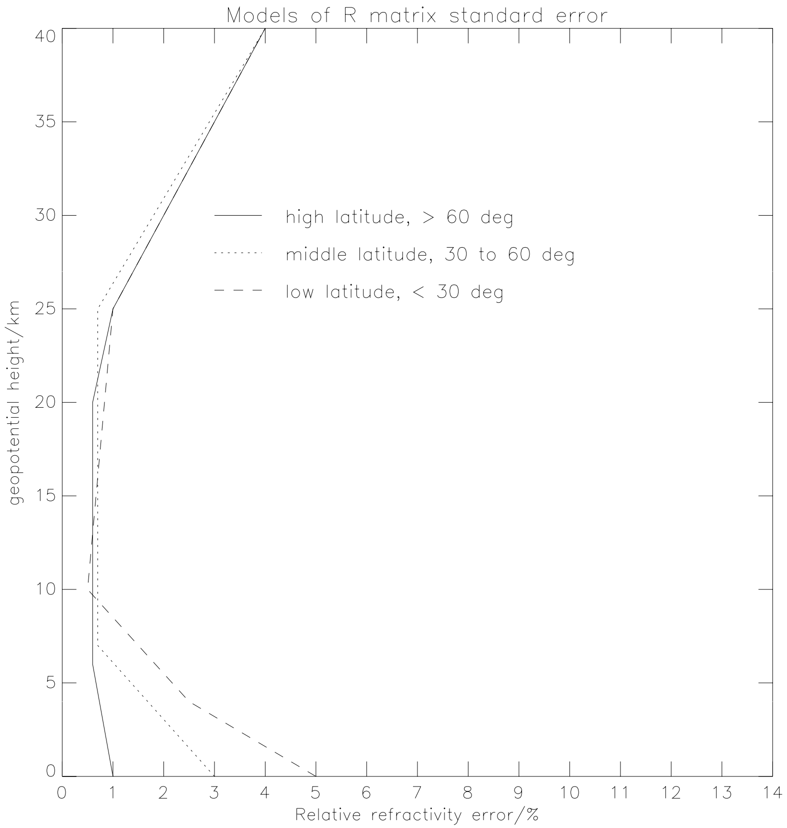
GPSRO used in global model

Met Office

- UM:
  - Ran at N320L50 i.e. ~40 km mid lat horizontal resolution, 50 vertical levels, top ~ 0.1 hPa (~63 km).
  - Forecasts out to 6 days.
- VAR:
  - 6 hour assimilation window.
  - First iteration non-linear using N320 3, 6, 9 hour forecast background information.
  - Subsequent tangent-linear iterations use increments to model columns.
  - Non-linear iteration is ran on every 10^{th} iteration.
  - Other significant data types assimilated: Sonde, IASI, AIRS, ATOVS, Aircraft, Satwind, Scatwind, Surface, SSMI, SSMIS

Global model: GPSRO specific

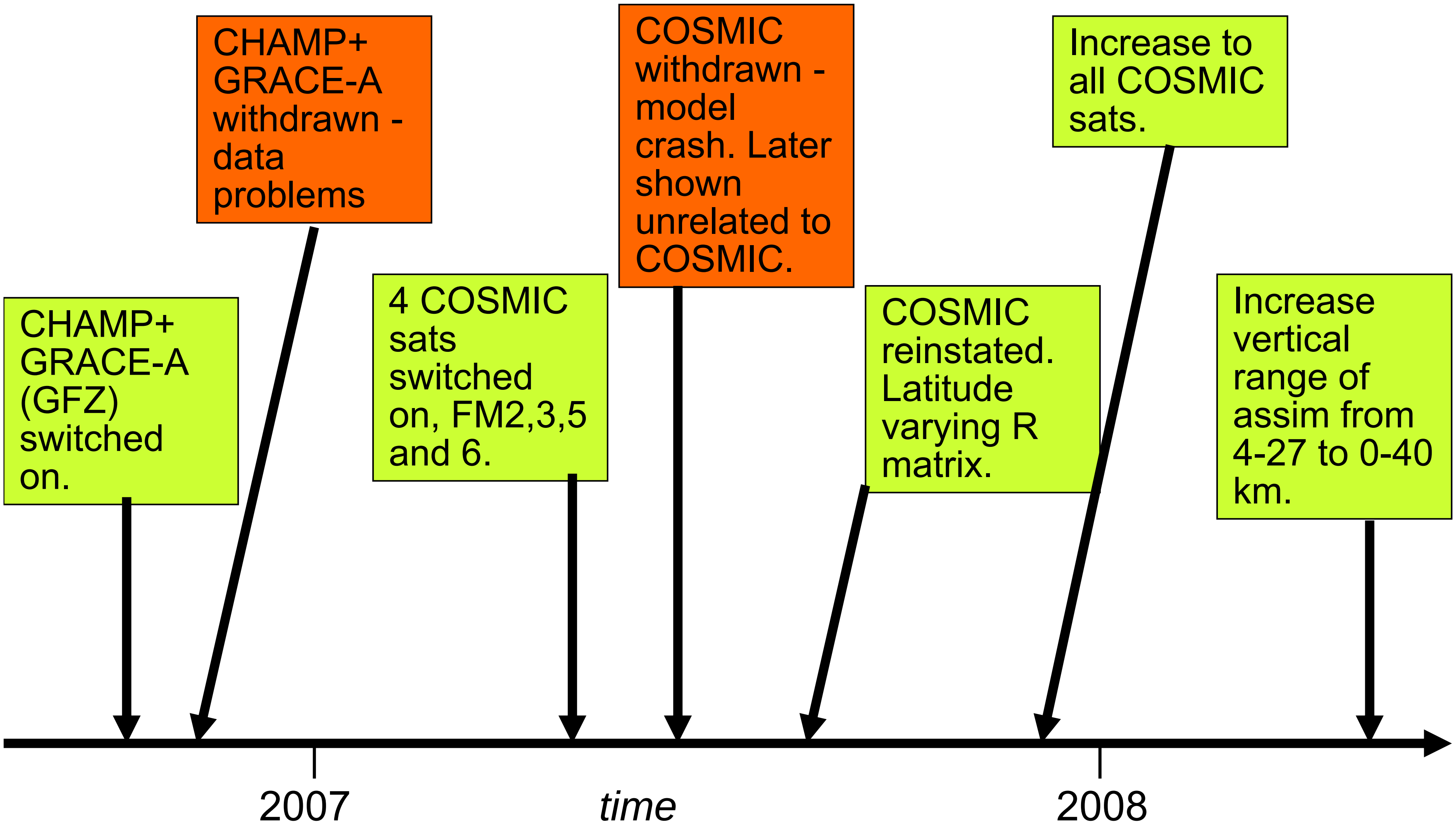
- Use **R** matrix for low, middle and high latitudes.
  - Based on *(O-B)/B* std dev using COSMIC.



$$R_{ij} = \sigma_i \sigma_j \exp\left(\frac{-\left| z_i - z_j \right|}{H} \right)$$

  - Assume an exponentially decaying vertical correlation model with a scale length of 3.3 km.
- QC of *N* data based on output of a 1D-Var.

Global model operational status

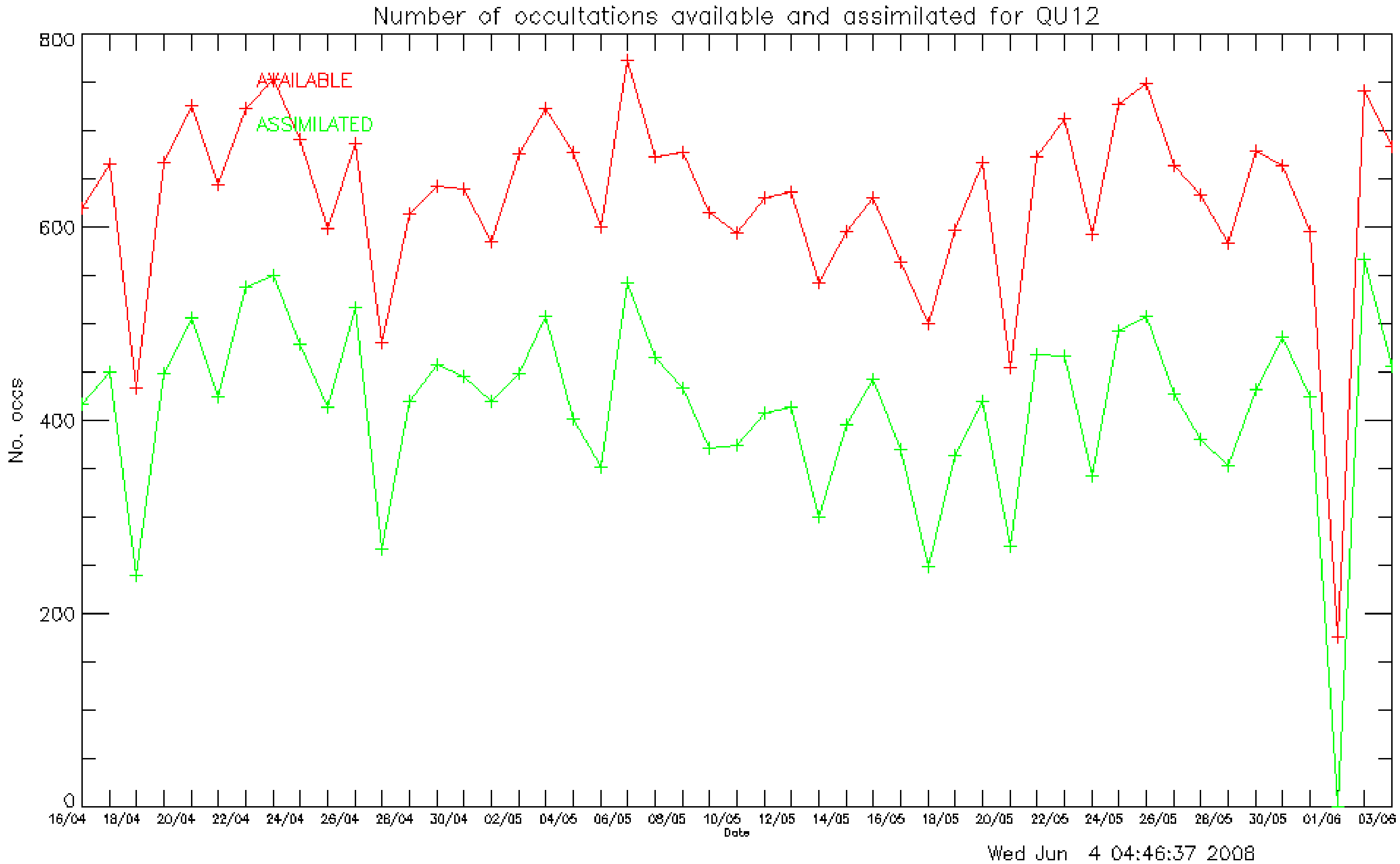


Number of *N* profiles assimilated in global model

Update run to produce better background for next run

•Assimilated = COSMIC data

•Available = COSMIC + GRAS+GRACE-A+CHAMP

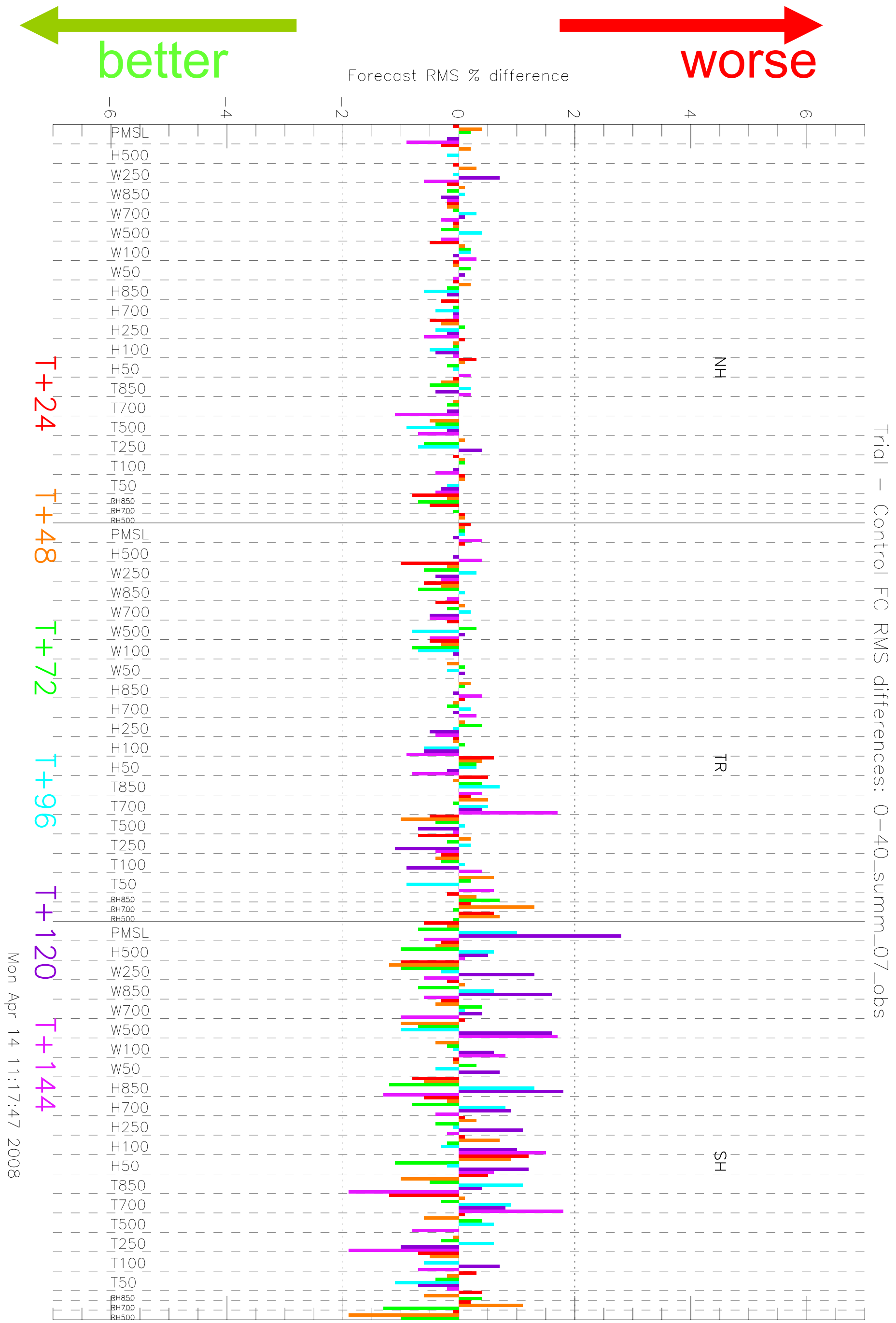


Impact studies: increasing vertical range

- Increasing the vertical range of assimilation from 4-27 km to 0-40 km gave a small benefit to:
  - Tropospheric relative humidity in extratropics.
  - Winds - highly valued by customers.
  - Stratosphere model bias.
- Routine verification against sondes and analyses is only up to 50 hPa (~21 km).

Met Office

Forecast RMS % diff. against **obs** (mainly radiosondes)

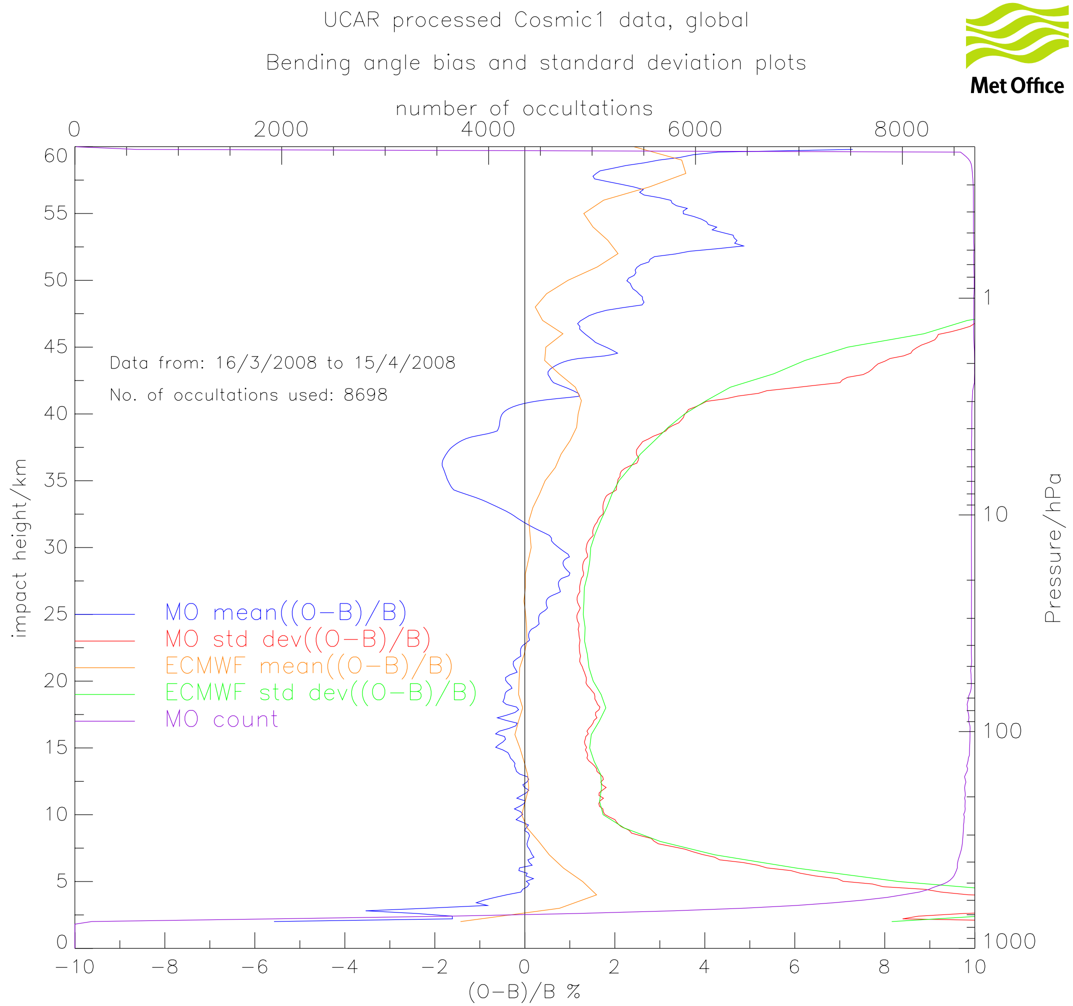


Control= 4-27 km

Exp=0-40 km
Jun 2007

Stratosphere global model bias compared to COSMIC

- *BA (O-B)/B* stats show a distinct 'S' shape bias at > 50 hPa (~22km, around model level 35).
- ECMWF stats shown for comparison: has its own biases

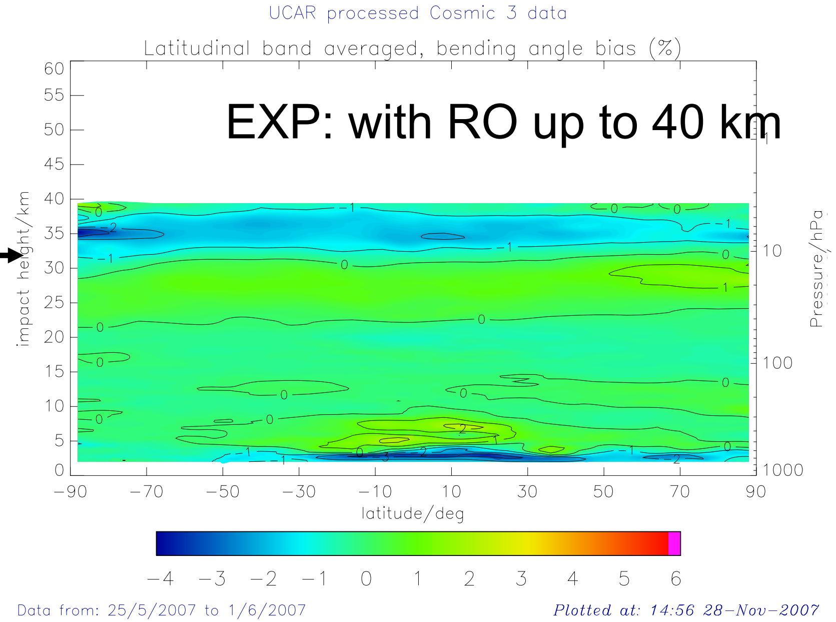


See latest GRAS SAF monitoring: http://monitoring.grassaf.org

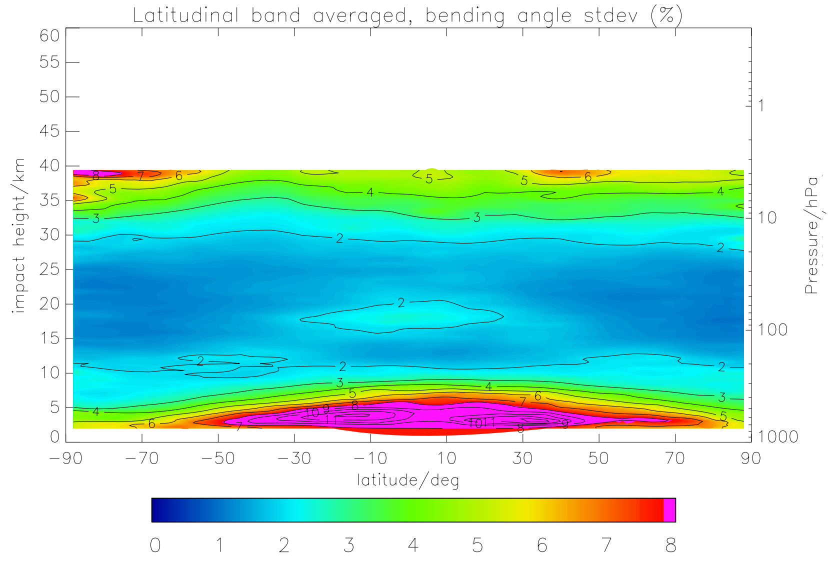
Impact on bias of RO up to 40 km

- Stratospheric bias reduced by *N* assimilation up to 40 km.
- Plot uses BA before statistical optimisation.

Mean
(O-B)/B



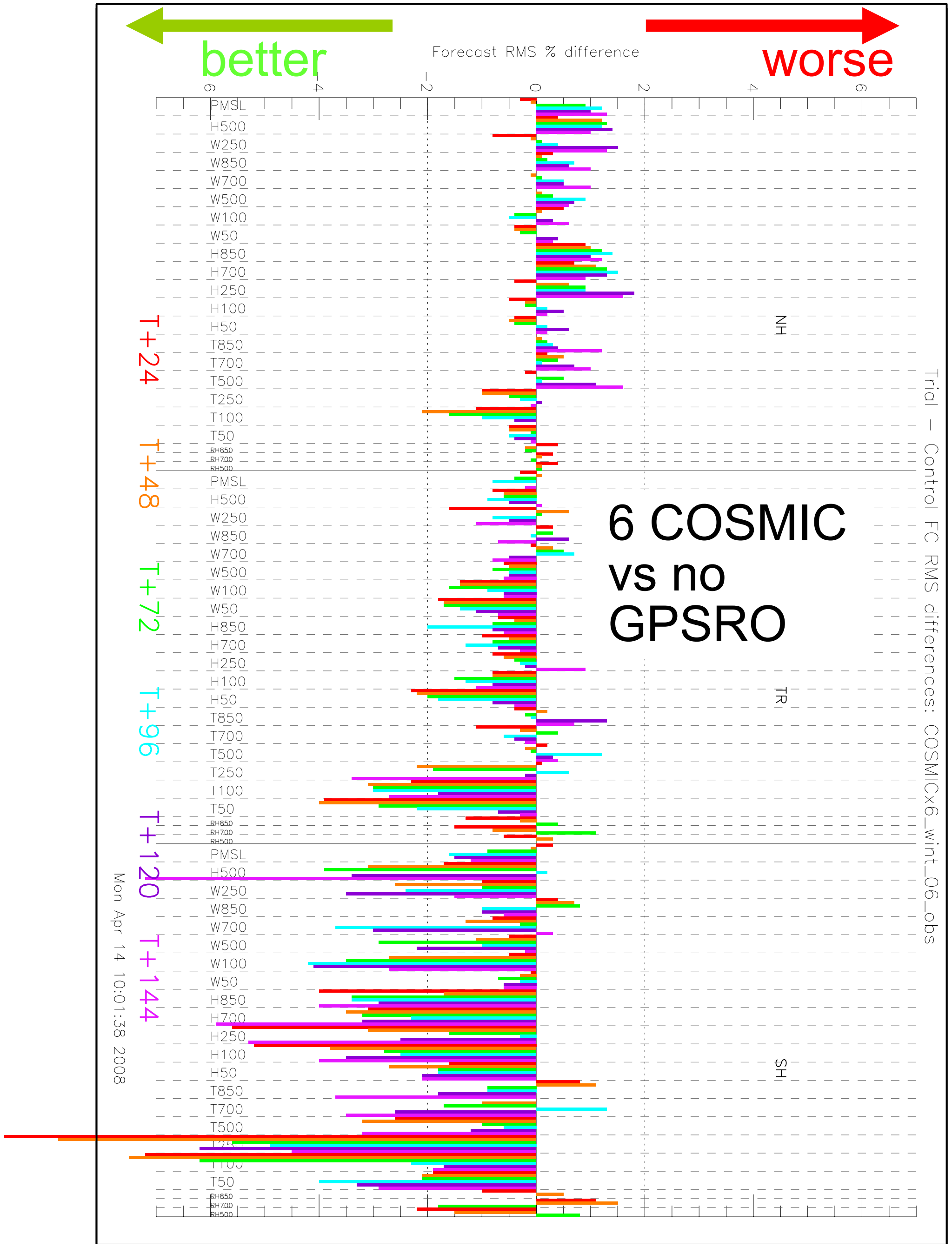
St. Dev.
(O-B)/B



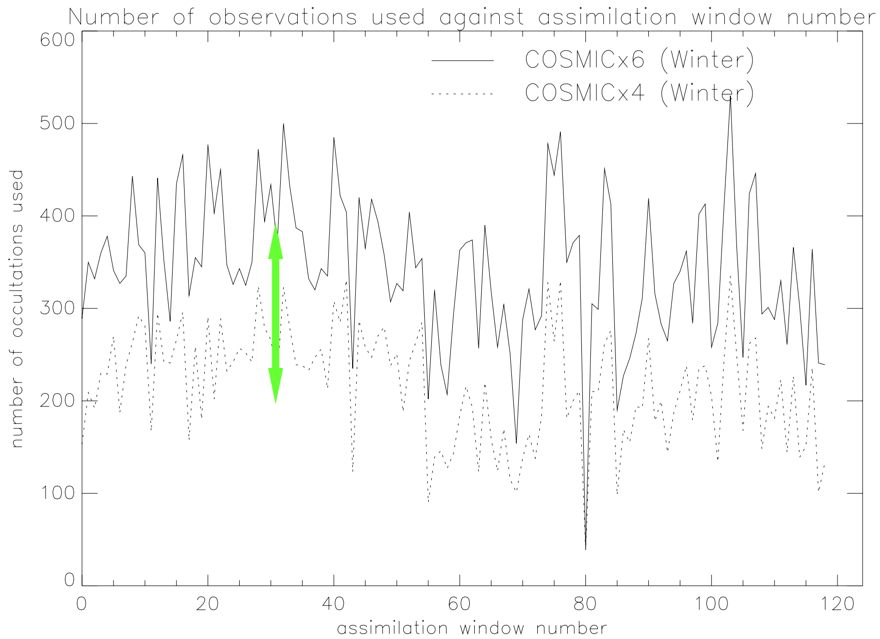
Impact of using more RO data

- More data seen to increase magnitude of the impact:
  - Dec 2006, going from 4 to all 6 COSMIC sats.
  - Jun 2006, going from 4 COSMIC to (6 COSMIC +CHAMP+GRACE-A).
  - Jan 2008, GRACE-A and CHAMP (GFZ) on top of COSMIC. Small improvements in geopotential height.
- Would be interesting to run experiment using incrementally more data - how saturated with RO are we?

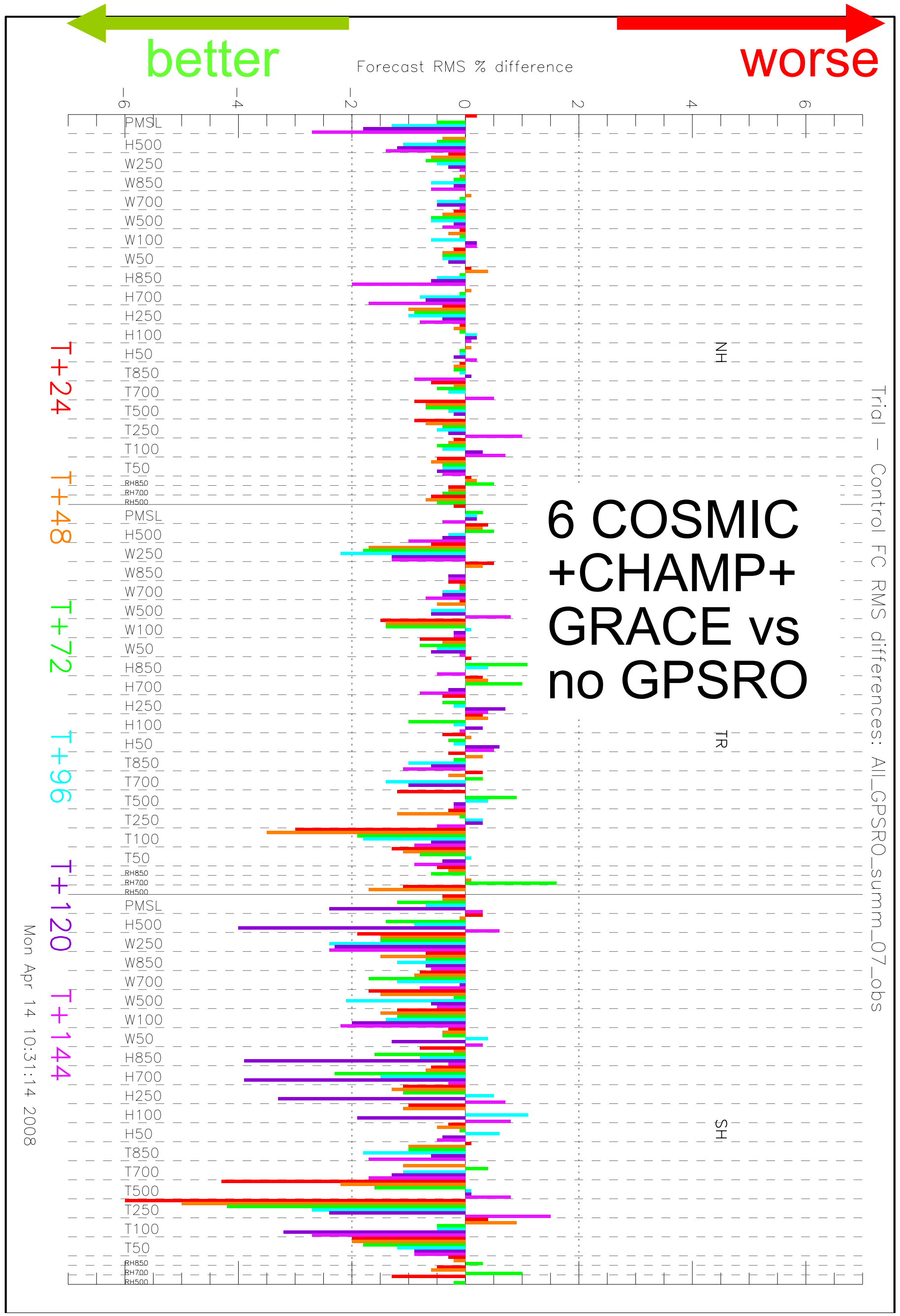
Forecast RMS % diff. against **obs**, Dec 2006 trials



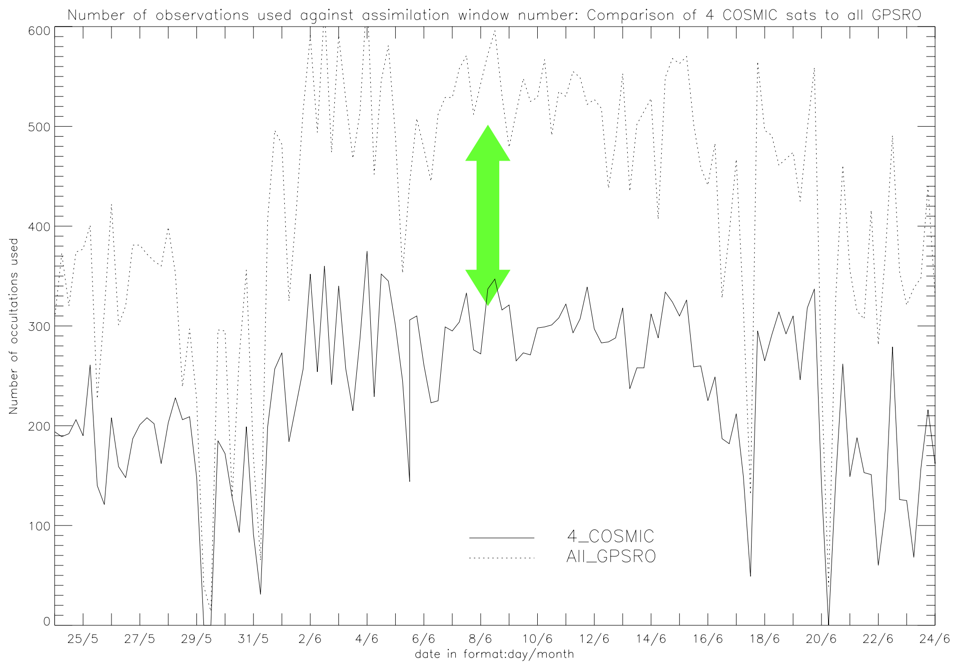
Increase in no. of occultations:



Forecast RMS % diff. against **obs**, Jun 2007 trials



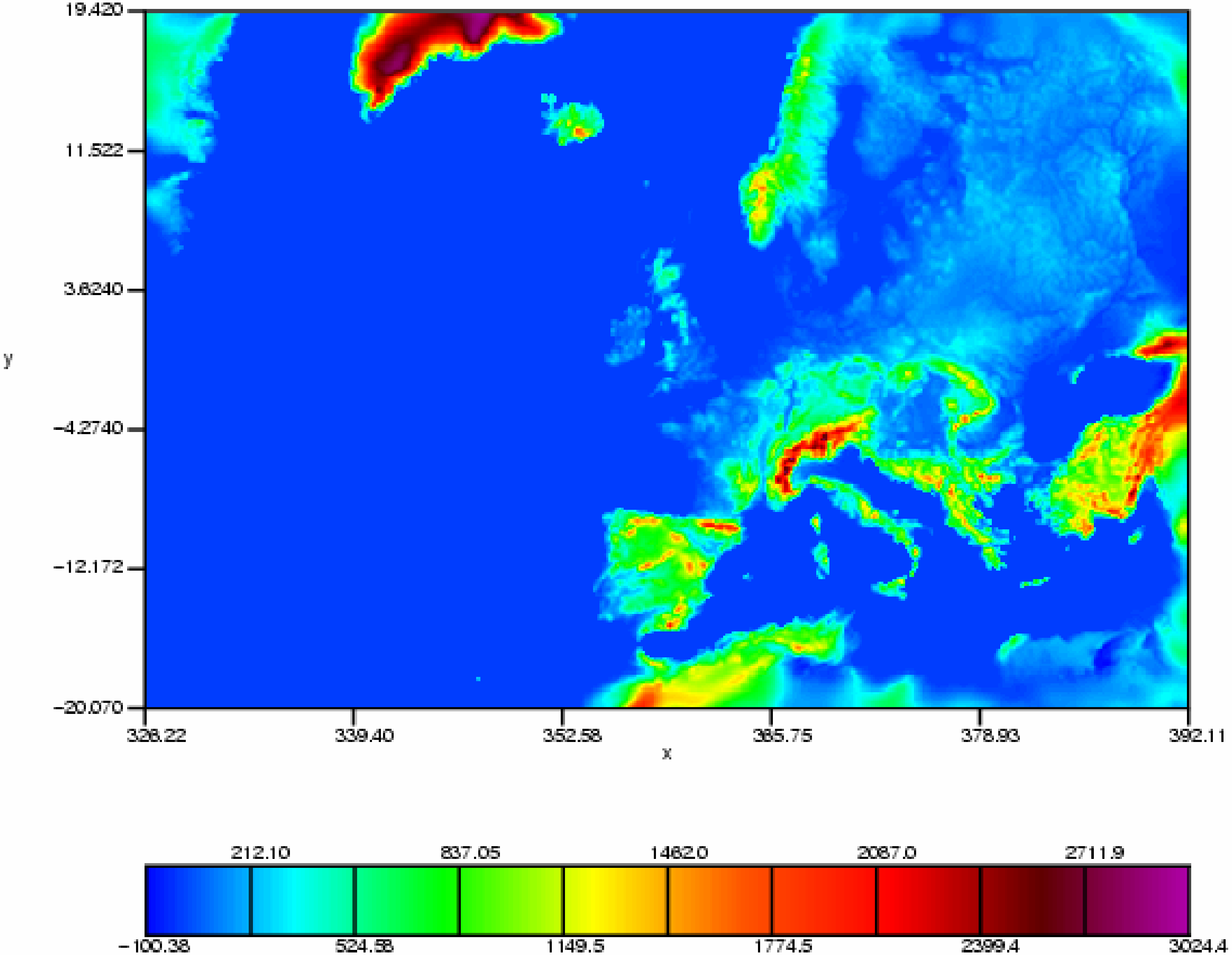
Increase in no. of occultations:



GPSRO in limited-area models

- Ob types implemented into the global model then go into limited-area models with relatively little testing.
- Concerns higher horizontal resolution - problems using 1D *N* operator.
- Ran test of *N* assimilation using 1D operator.

NAE (North Atlantic and European) area



NAE test setup

Met Office

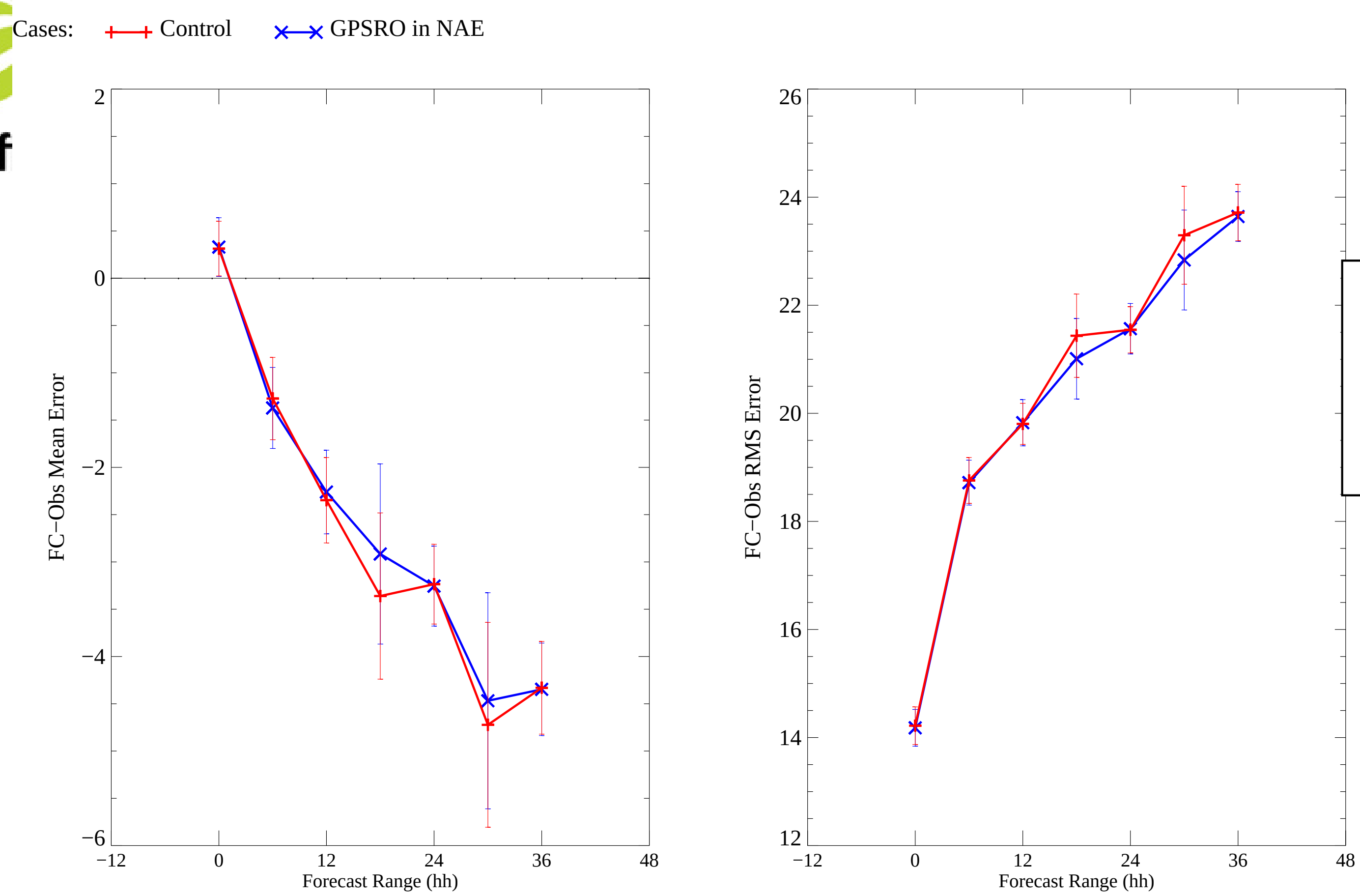
- 24 km resolution (half operational res. to reduce time).
- 38 vertical levels, ~40 km model top. 4D-Var.
- Typically around 20-30 occs assimilated per cycle. All COSMIC +CHAMP+GRACE-A, using 0-40 km vertical range.
- 20 day period of testing from 24/04/08 to 26/05/08 (with some gaps)

NAE test results

Met Office

- Verified using limited area **NWP index**. A Met Office score system based on comparisons to observed fields useful in limited-area model forecasting:
  - Surface visibility, 6 hr precipitation accumulation, total cloud amount, cloud based height (3/8 Cover), surface temp. and surface wind.
- Saw a small overall improvement. Particularly in surface visibility.
- NAE area NWP index increased by +0.13 %, i.e. slightly positive. UK area NWP index +1.23%, although significance in question over limited area and short period.

Some GPSRO in NAE verification



700 hPa RH (%) vs sondes. NAE area.

68% error bars calculated using $S/(n-1)^{1/2}$

Mean error

RMS error

CONTROL

GPSRO

Future updates/plans

- **operational changes**, planned for July 2008.
  - **Global model:** use of MetOp GRAS (10-30 km vertical range), CHAMP+GRACE-A (GFZ) on top of COSMIC.
  - **NAE model:** use of COSMIC, CHAMP and GRACE-A (0-40 km):
- **Further tuning** of system:
  - Obs errors and correlations.
  - Vertical ranges.
- **Experiment** with BA assimilation

Any questions?