The assimilation of GPS Radio Occultation measurements at the Met Office

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ABSTRACT

In the past few years GPS radio occultation (GPSRO) measurements have been made available to the Met Office with the quality and timeliness suitable for use in operational numerical weather prediction. Since July 2006 we have been provided with data from the FORMOSAT-3/COSMIC constellation of six satellites, which substantially increased the quantity available for operational assimilation. Measurements from the GRAS, CHAMP and GRACE-A radio occultation instruments have also become available for operational use. In this paper we describe the current method for assimilating GPSRO at the Met Office and summarise the overall impact of GPSRO as determined from forecast impact experiments, as well as refinements to the observation plus forward model errors and the vertical range for assimilation. The resulting forecasts are verified against their own analyses and in situ observations. FORMOSAT-3/COSMIC refractivity measurements are shown to give an appreciable positive impact which has led to the data being used operationally at the Met Office.

1 Introduction

GPS radio occultation (GPSRO) measurements provide information suitable for use in meteorology with a high vertical resolution, high absolute accuracy and low noise. The high absolute accuracy stems from the fact that GPSRO is fundamentally a time measurement using atomic clocks and is calibrated precisely by measurements made outside the atmosphere. It is therefore a very stable measurement with time and between different RO instruments. See Kursinski et al. (1997) and Melbourne et al. (1994) for detailed descriptions of the technique. Forecast impact experiments have previously shown that GPSRO measurements can provide positive impact on global numerical weather prediction (NWP) models with the use of relatively few occultations, especially in the upper troposphere and lower stratosphere, for example see Healy et al. (2005) and Healy and Thépaut (2006) for the impact of CHAMP data. Many NWP centres now operationally assimilate GPSRO (mostly FORMOSAT-3/COSMIC data): e.g. Met Office, ECMWF, NCEP, Météo-France and Environment Canada. Given that GPSRO has been proven as a useful measurement we now focus on maximising its impact, in particular the tuning of the assimilation system and making use of all available data sources.

This paper describes the assimilation of GPSRO at the Met Office and discusses operational changes that have been implemented to improve the impact. We mainly focus on experiments using data from the FORMOSAT-3/COSMIC constellation (which are referred to as COSMIC from now on). It is structured as follows. Section 2 describes the history and present status of GPSRO in operations at the Met Office. Section 3 describes how the observations are assimilated at the Met Office. Results of the impact of GPSRO data on the global NWP model are discussed in Section 4. The conclusions are presented in Sections 5.

2 A review of the operational use of GPSRO at the Met Office

Over the past few years GPSRO measurement data have become available in sufficient quantity, timeliness and quality to be used in operational NWP at the Met Office and at other NWP centres. CHAMP data provided by GFZ (German Research Centre for Geosciences) became available in near real-time (NRT) on 22 February 2006 and GRACE-A on 28 May 2006. After showing positive results in forecast impact experiments assimilating refractivity (Buontempo et al., 2008), CHAMP and GRACE-A data were made operational in the global model on 26 September 2006. As far as we are aware the Met Office was the first NWP centre to assimilate GPSRO operationally. Unfortunately, the GFZ data was later (17 November 2006) withdrawn from operations due to quality issues at that time. It should be stressed that following this short period of poor quality NRT data, the quality of GFZ data has been very good. The Met Office processing of GPSRO data was later modified to use a stricter quality control scheme to mitigate any future re-occurrences.

Data from the COSMIC constellation of six satellites, processed by UCAR (University Corporation for Atmospheric Research), became available on 28 July 2006 and soon after experiments were begun to test its impact and suitability for operational use. Experiments of the August 2006 period gave disappointing results and this may have been due to a combination of factors: the satellites then being poorly spread, the observation errors were far from optimal and there may have been bugs in the early processing, consequently this delayed the operational use of COSMIC. Experiments ran for November/December 2006 showed a positive impact (as shown later in this report); hence the data began to be used operationally in the global model at the next available opportunity, which was 15 May 2007. Unfortunately COSMIC was withdrawn from operations due to global model crashes on 11 June 2007; these crashes were later shown to be unrelated to COSMIC and it was reinstated at the next opportunity which was 14 August 2007. Since then COSMIC has remained operational and it is a very consistent and valuable data source.

We initially assimilated the four most well spread COSMIC satellites as a cautious response to the satellites then being in similar orbits, since horizontal error correlations are not currently accounted for nor do we horizontally thin the data. Also, a global model problem (as already mentioned) led to concerns over using too much observational data in the stratosphere over Antarctica, which postponed an earlier increase to assimilate all six. The use of all available COSMIC became operational on 27 November 2007.

Initially the vertical range of assimilation was 4-27 km to avoid assimilating refractivity biases seen in the monitoring (http://monitoring.grassaf.org). For example there are negative biases lower than 5 km in areas of high water vapour (Ao et al., 2003), representivity errors inherent in the 1D operator (Healy, 2001) when the atmosphere is non-spherically symmetric and upper stratospheric biases between processing centres (von Engeln, 2006) due to the differing processing methods (mostly due to the bending angle statistical optimisation methods used). However, experiments testing the vertical range 0-40 km showed small positive impact, so this vertical range became operational in April 2008.

As with all observation data used in operational NWP, the timeliness is critical, especially with a 6 hour assimilation window. In July 2008 $\sim$90% of the COSMIC data arrived in the Met Office observations database within 3 hours. GFZ processed data showed slightly better statistics and 100% of GRAS data arrived within 3 hours. We operationally use on average $\sim$300 COSMIC occultations in the main global runs (every 6 hours) due to the constraints of a model cut-off time; $\sim$500 are used in the update global runs which are used to produce the background (first guess) for the next main global run. The use of GRAS, CHAMP and GRACE-A takes the operational update run usage up to $\sim$700 occultations per cycle. After seeing positive impact in recent testing, we started using this data operationally on 22 July 2008.

3 The Met Office assimilation method

3.1 The observations

The processed GPSRO observations most commonly assimilated by NWP centres are the ionosphere-corrected bending angle as a function of impact parameter or the atmosphere's refractivity as a function of geometric height. Meteorological information is provided by the direct assimilation of either observation type since refractivity can be forward modelled from temperature, total pressure and water vapour pressure model information and hence bending angles are forward modelled from refractivity (Eyre, 1994). There are advantages and disadvantages to both methods; currently at the Met Office we assimilate GPSRO with a 1D refractivity observation operator.

When assimilating bending angle the bending above the model top needs to be estimated, thus introducing an error in the forward modelling, whereas when assimilating refractivity the bending angle observation noise high-up (typically higher than 40 km) has to be removed by statistical optimisation with climatological bending angle information, thus introducing non-local errors via the Abel transform. If the model top is sufficiently high, say above ∼60 km, then the bending angle forward modelling error will be relatively small and bending angle should be the best quantity to assimilate, but this is yet to be shown in practice. For refractivity the effect of the extra processing makes the definition of observation errors more complicated than for bending angle, in that the vertical correlation of errors becomes larger and more complicated than for the original bending angles. However the forward modelling to bending angle makes the forward model errors more complicated. Recent experiments at the Met Office have indicated however that that refractivity assimilation is fairly insensitive to changes in the vertical error correlations.

The main reason the refractivity operator was chosen is that when the code was written the global model top was only around 40 km, compared to now being over 60 km. Also, the operator is a quick and simple method and it was proven to give positive impact in early trials using CHAMP data. Deciding whether to change to a 1D bending angle operator given the now higher model top is an issue that will be investigated in the near future. The Met Office assimilation system is currently not easily compatible with the more accurate ray-tracing forward models that take account of the limb-geometry of the observation, e.g. see Healy et al. (2007).

3.2 Details of Met Office GPSRO assimilation

The NWP model used at the Met Office is known as the Unified forecast model (UM, see Davies et al. (2004)); it employs non-hydrostatic equations, uses geopotential height as the vertical co-ordinate with Charney-Phillips grid-staggering and the model levels are terrain-following near the surface. The steps involved in forward modelling from UM forecast fields to vertical profiles of refractivity are:

1. Interpolate the UM background to the occultation time (linear interpolation using the 3, 6 and 9 hour forecasts) and to the occultation location i.e. nominal latitude and longitude given (bilinear interpolation using the nearest 4 grid points). This is a standard procedure for all observation types.
2. The required UM fields are the pressure on ρ geopotential height levels and the relative humidity on θ geopotential height levels. The θ levels are staggered relative to the ρ levels, see figure 1. The aim is to calculate model refractivity on the θ levels.
3. θ level pressure is obtained by the linear interpolation of ρ level Exner pressure to the θ levels.
4. θ level layer mean virtual temperature is then calculated using the Exner pressure on the θ levels and the geopotential heights and Exner pressure values on the surrounding ρ levels.
5. Layer mean temperature on θ levels then calculated by incorporating the relative humidity information with the layer mean virtual temperature.

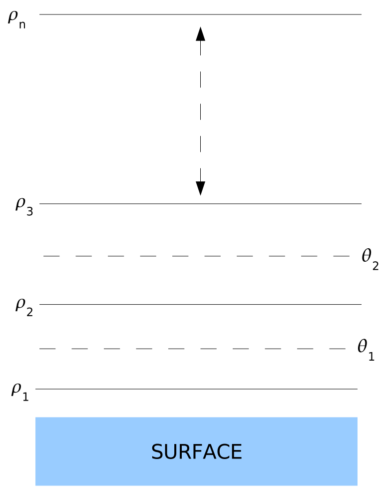


Figure 1: Schematic of unified model vertical level structure

6. Refractivity is then calculated on θ levels, using the commonly used empirical formula (Smith and Weintraub, 1953), given pressure, temperature and water vapour pressure.
7. The model refractivity is then interpolated onto observation refractivity geopotential height (a conversion from geometric to geopotential height is done) using a log-linear method.

A more detailed description of the forward operator can be found in Rennie (2008). The forward model is incorporated into the Met Office variational data assimilation system (VAR). Briefly, some details on the current VAR system:

1. It uses incremental 4D-Var (Rawlins et al., 2006).
2. It uses a perturbation forecast (PF) model to map background error information to the time of the observations. The PF has simplified linearised physics, rather than using the non-linear UM and its direct tangent linear and adjoint, and it is generally run at a lower horizontal resolution than the UM.

The steps involved in the assimilation of GPSRO within VAR are:

1. Given the state vector $\mathbf{x_1}$ on the 1^{st} iteration, forward model to refractivity $\mathbf{y_1}$ using the non-linear operator, H:

$$\mathbf{y_1} = H(\mathbf{x_1}) \tag{1}$$

and calculate local gradient i.e. Jacobian, sometimes called **K** matrix:

$$\frac{\partial \mathbf{y_1}}{\partial \mathbf{x_1}} = \frac{\partial H(\mathbf{x_1})}{\partial \mathbf{x_1}} = \mathbf{K} \tag{2}$$

2. Store $\mathbf{x_1}$, $\mathbf{y_1}$ and the **K** matrix.

3. On subsequent iterations given an incremented state vector $\mathbf{x_n}$: apply the tangent-linear approximation to estimate $\mathbf{y}(\mathbf{x_n})$:

$$\mathbf{y_n} = \mathbf{y_1} + \mathbf{K}(\mathbf{x_n} - \mathbf{x_1}) \tag{3}$$

4. Given the forward model error plus observation error covariance matrix **R** and the observed refractivity profile $\mathbf{y_{obs}}$, use $\mathbf{y_n}$ and $\mathbf{K^T}$ to calculate on the nth iteration the observation cost function:

$$(J_{obs})_n = \frac{1}{2}(\mathbf{y_n} - \mathbf{y_{obs}})^{\mathbf{T}}\mathbf{R^{-1}}(\mathbf{y_n} - \mathbf{y_{obs}}) \tag{4}$$

   and gradient of J_{obs} with respect to **x**:

$$\frac{\partial (J_{obs})_n}{\partial \mathbf{x_n}} = (\frac{\partial \mathbf{y_1}}{\partial \mathbf{x_1}})^{\mathbf{T}}\mathbf{R^{-1}}(\mathbf{y_n} - \mathbf{y_{obs}}) = \mathbf{K^T}\mathbf{R^{-1}}(\mathbf{y_n} - \mathbf{y_{obs}}) \tag{5}$$

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

4 Impact of GPSRO

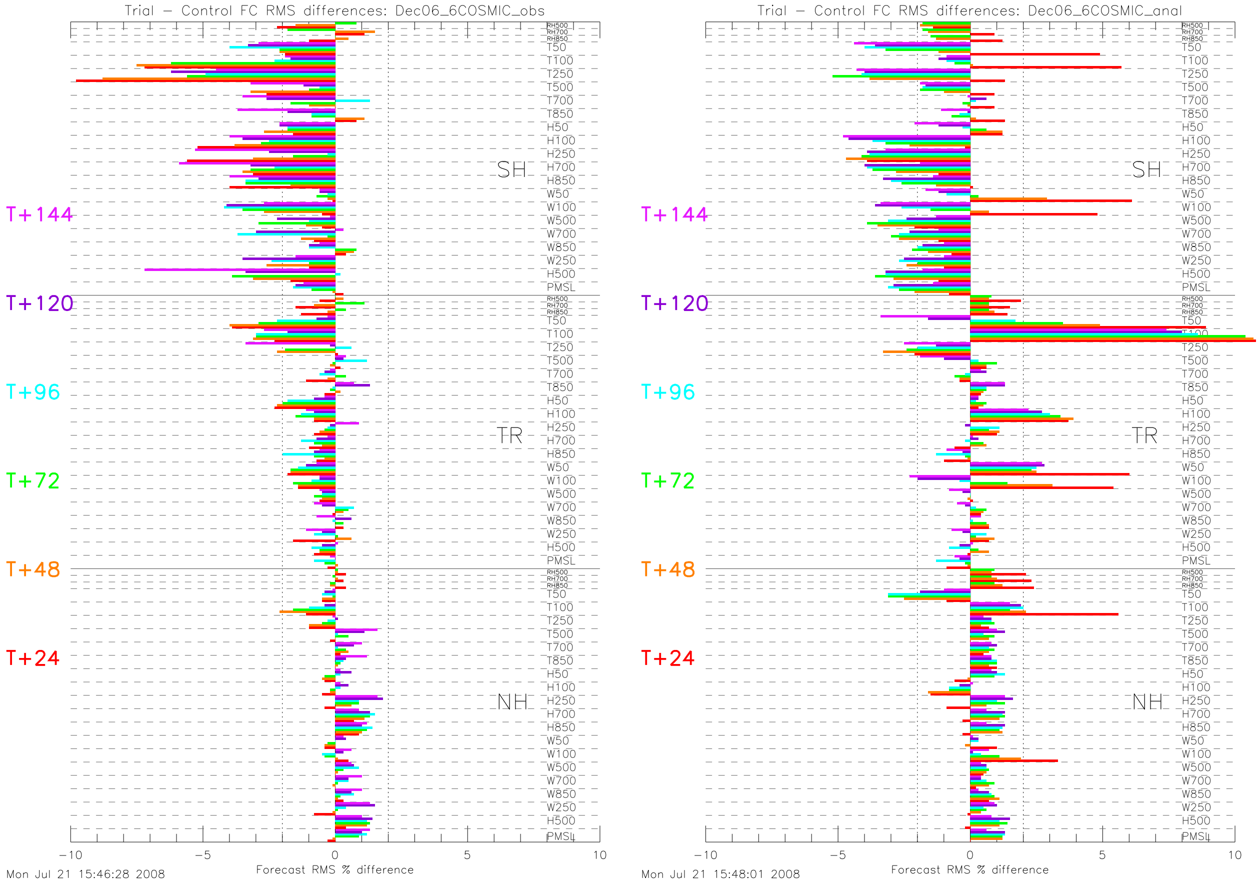
Various experiments have been run over the past couple of years to investigate the impact of GPSRO on global NWP model forecasts. This section summarises the observed impact; more detail on the experiments can be found in Rennie (2008).

4.1 Results from November/December 2006 experiments

Figure 2 shows the impact of assimilating all available COSMIC refractivity during a month's trial starting late November 2006. Note the format for figure 2 will be used for all verification results. The figure is based on the RMS (root mean square) differences between NWP model forecasts and the data we want to verify against (observations or analyses) at the validity time of the forecast. The RMS fit is calculated for the trial and the control. In a trial we make a change on top of the control e.g. add GPSRO assimilation. The figure shows the percentage difference in RMS fit between the trial and control. Negative values are where the trial forecasts fit the verification data better than those of the control.

The statistics are shown for many fields and forecast ranges e.g. the letters to the right of each plot refer to the forecast field being verified; H = geopotential height, W = wind speed, T = temperature, RH = relative humidity. The numbers following the field letters refer to the pressure level in hPa. The different colours indicate the forecast ranges being verified e.g. T+24 (shown in red) corresponds to a 24 hour forecast. The plot is also split into SH (southern hemisphere), TR (tropics) and NH (northern hemisphere).

Regarding figure 2, the trial used roughly 300-400 occultations per update cycle for this period. COSMIC refractivity was assimilated in the vertical range 4-27 km with a fixed **R** matrix for the globe, see figure 3, labelled 'Steiner + increased low', where 'Steiner' is based on suggestions from Steiner and Kirchengast (2005). The 'increased low' which significantly increased the values below 10 km was a first attempt to down-weight the data, given the very strong influence it was producing in early experiments. The verification in figure 2(a)



(a) verification against observations (b) verification against analyses

Figure 2: Verification of November/December 2006 experiment: 6 COSMIC vs no GPSRO (see text for explanation)

is made against observations, which are nearly all radiosonde observations, apart from surface observations of PMSL (pressure at mean sea level). Figure 2(b) shows an equivalent plot to figure 2(a) but with the verification against the trial and control's own analyses at the corresponding forecast validity times.

One can see large improvements in the SH for both observations and analyses for temperature and geopotential height from 850 to 50 hPa. The improvements in 250 and 100 hPa temperatures and geopotential heights are particularly large, up to $\sim$10 % improvement in RMS error against observations. This pressure range corresponds to around 10 to 15 km i.e. the upper troposphere, lower stratosphere, where GPSRO has the largest information content. Note also that wind speed is improved as an indirect response to GPSRO assimilation. The same fields are improved in the tropics, but to a smaller magnitude, as seen against observations.

A feature that stands out is the degradation seen in the NH for some of the fields, especially at longer forecast time ranges. An explanation was found for this; a modified **R** matrix that included variation with latitude with smaller errors low down and $\sim$10% larger errors high up (see figure 3) rectified some of the long forecast range degradation in the NH. The off-diagonal covariances of **R** were given by a simple exponential drop-off model with a scale height of 3.3 km for all cases.

Also note from figure 2(b) the sharp degradation seen against analyses in the tropics in 50 and 100 hPa temperature, whereas the same fields improved against observations. More detailed verification showed that the RMS error improvement against radiosondes is mainly due to the mean error improving, which implies that the degradation against analyses is more to do with the trial analyses being pulled further from the model climatology than the control analyses. Using the new **R** matrix mitigated a lot of the degradation against analyses at the expense of some impact against radiosonde temperatures and geopotential heights at 50 and 100 hPa. The

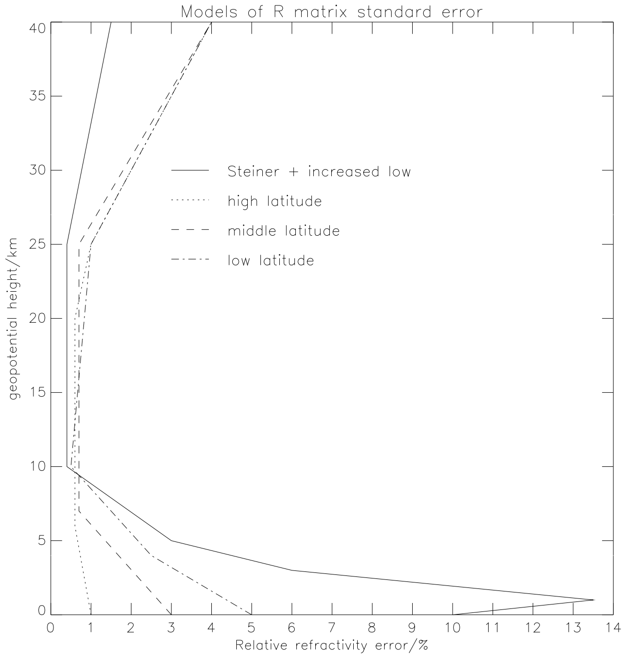


Figure 3: Different models of the observation plus forward model refractivity relative error. The sold line is the original global errors, the other lines are the three latitude specific error profiles based on $(O-B)/B$ standard deviation plots for COSMIC data in 2007.

new **R** matrices led to the GPSRO cost function in VAR decreasing by 10%, showing that the increase in errors above 10 km was the most important change. This was deemed to be a more reasonable value given that, with the global **R** matrix, the GPSRO cost function was larger than ATOVS (Advanced TIROS Operational Vertical Sounder) and the temperature observations from radiosondes.

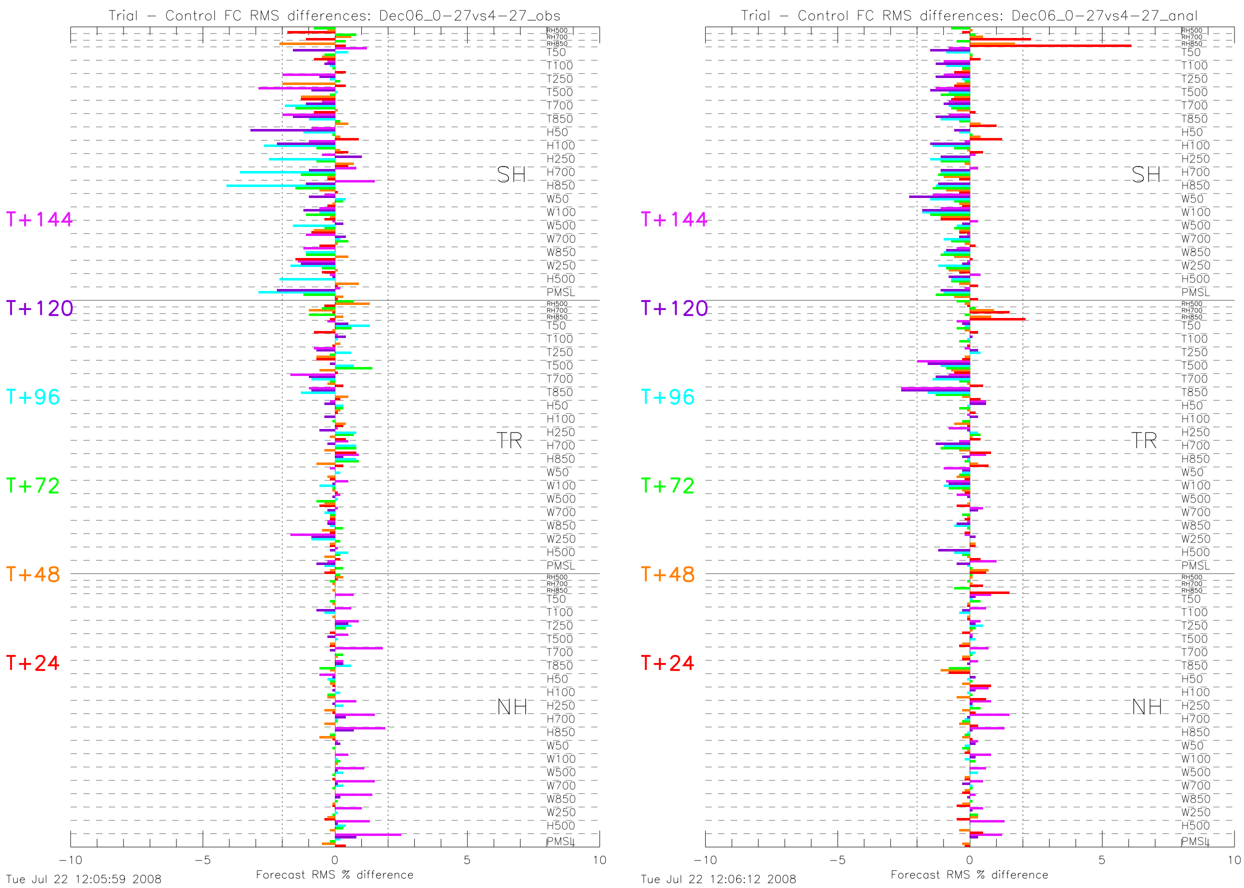
Changing the vertical range for COSMIC assimilation to 0-27 km gave modest positive impact as can be seen in figure 4. Note this was using the latitudinally varying **R** matix. Again, most of the improvements are in the SH. Any benefit to low level relative humidity is hard to judge from this; the results are mixed against observations and negative against analyses.

4.2 Results from May/June 2007 experiments

The impact of assimilating all available GPSRO data (COSMIC, CHAMP and GRACE-A) in May/June 2007 with a 0-40 km vertical range and the latitude varying **R** matrix can be seen in figure 5. The trial used roughly 400-500 occultations per update cycle for this period.

The impact against observations are consistently positive though not as impressive as the November/December 2006 result for the SH; the largest impact is again in the SH. As in the November/December 2006 result there is degradation of tropical temperature analyses at 100 and 50 hPa, presumably for the same reasons as in November/December 2006. One significant difference is that the degradation of the NH with respect to observations as seen in November/December 2006 has gone, to be replaced by a small positive impact.

Experiments extending the upper range to 40 km showed no significant impact by the standard verification method in either season, mainly because it only extends up to 50 hPa ($\sim$20km) and the **R** matrix gives GPSRO increasingly less weight above 25 km. Comparing the observation-background statistics with and without GPSRO up to 40 km showed GPSRO was improving the stratospheric model biases, see figure 6. Note figure 6 is in bending angle space (using a 1D operator) to demonstrate that refractivity assimilation up to 40 km



(a) verification against observations (b) verification against analyses

Figure 4: Verification of November/December 2006 experiment: 0-27 km vertical range vs 4-27 km vertical range

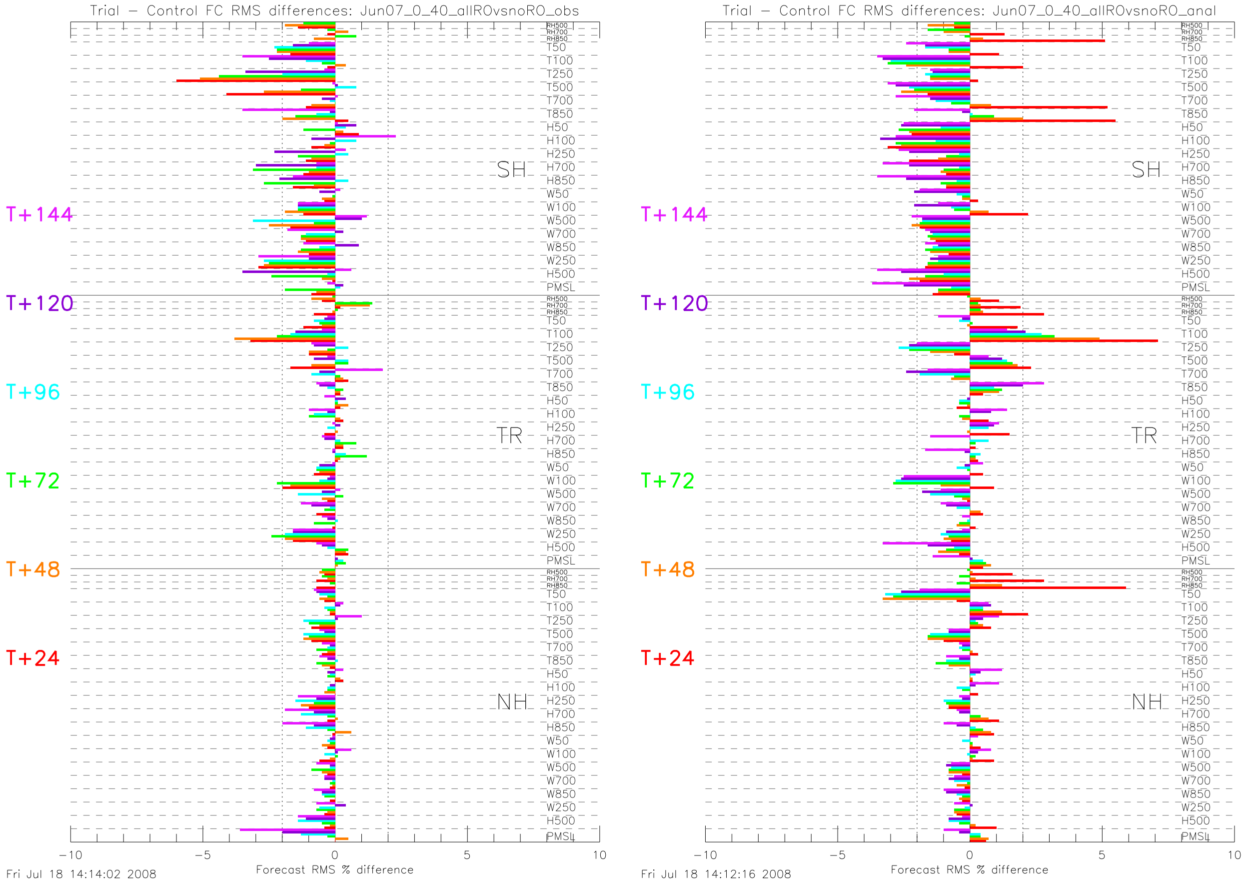
does not adversely affect model biases through the introduction of a priori climatological information. These stratospheric biases are unique to the Met Office global model as seen by comparisons to ECMWF statistics in bending angle space (see http://monitoring.grassaf.org).

Although biases were improved in the May/June 2007 experiments, this bias is still clearly visible in operational monitoring. Recent evidence suggests that other observation types, in particular radiance measurements, are dominating over GPSRO above ∼30 km and the analyses are in fact pulling away from the GPSRO information, which perhaps suggests the high level errors are too pessimistic and also the static bias correction scheme for radiance measurements at the Met Office is reinforcing the model bias and the shear volume of radiance data is swamping the relatively unbiased (at ∼30 km) GPSRO observations.

IASI (Infrared Atmospheric Sounding Interferometer) data was tested (Hilton and Atkinson, 2008) with the same control for this period and the verification is shown in figure 7; this helps to put the GPSRO results into perspective. IASI appear to have stronger impact in some fields than GPSRO, however IASI's impact against observations is mixed whereas GPSRO's is consistently positive. It should be noted that studies have shown that IASI and GPSRO can provide complementary information for NWP (Collard and Healy, 2003).

5 Conclusions

We have shown that the current Met Office operational assimilation system for GPSRO gives a generally strong positive impact when assimilating COSMIC data (and CHAMP, GRACE-A in May/June 2007). The 100 and 200 hPa temperature and geopotential height model fields are improved the most, in particular in the SH where



(a) verification against observations

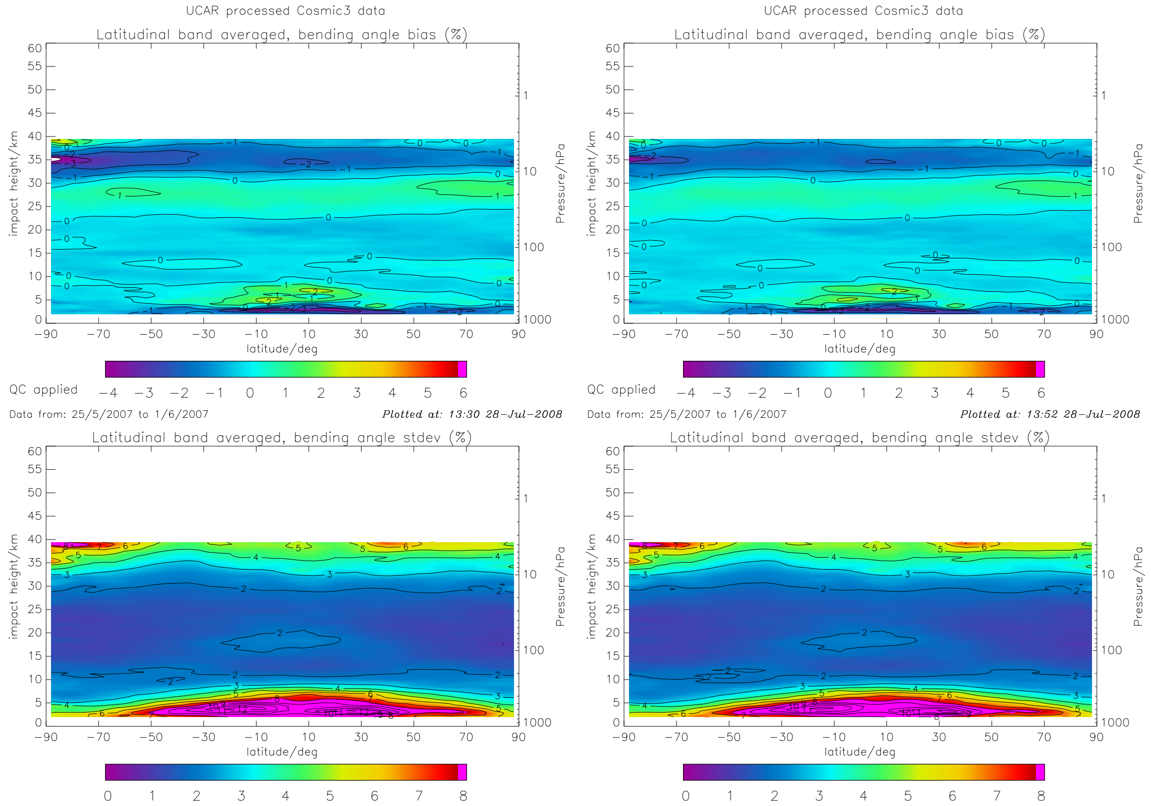
(b) verification against analyses

Figure 5: Verification of May/June 2007 experiment: 0-40km vertical range with all GPSRO vs no GPSRO

there is a lack of conventional observational data. It was seen that GPSRO is providing an impact that is comparable to that of IASI, which is pleasing considering the greater volume of data that IASI is providing.

The best results were obtained using a latitudinally varying **R** matrix based on the standard deviation of COSMIC $O-B$ statistics. Increasing the vertical range of GPSRO assimilation was shown, in two seasons, to provide a small positive impact according to the standard methods of verification. Examination of the bending angle $O-B$ statistics demonstrated a reduction in the stratospheric global model bias on assimilating refractivity up to 40 km.

Given GPSRO's positive effect on NWP we are currently assimilating all available GPSRO refractivity data in operations i.e COSMIC, CHAMP, GRACE-A and GRAS.



(a) No GPSRO assimilated (b) All GPSRO assimilated

Figure 6: Zonally averaged bending angle $(O-B)/B$ statistics, using FM3 observation data and 6 hour forecasts as background, for the first six days of May/June 2007 experiment

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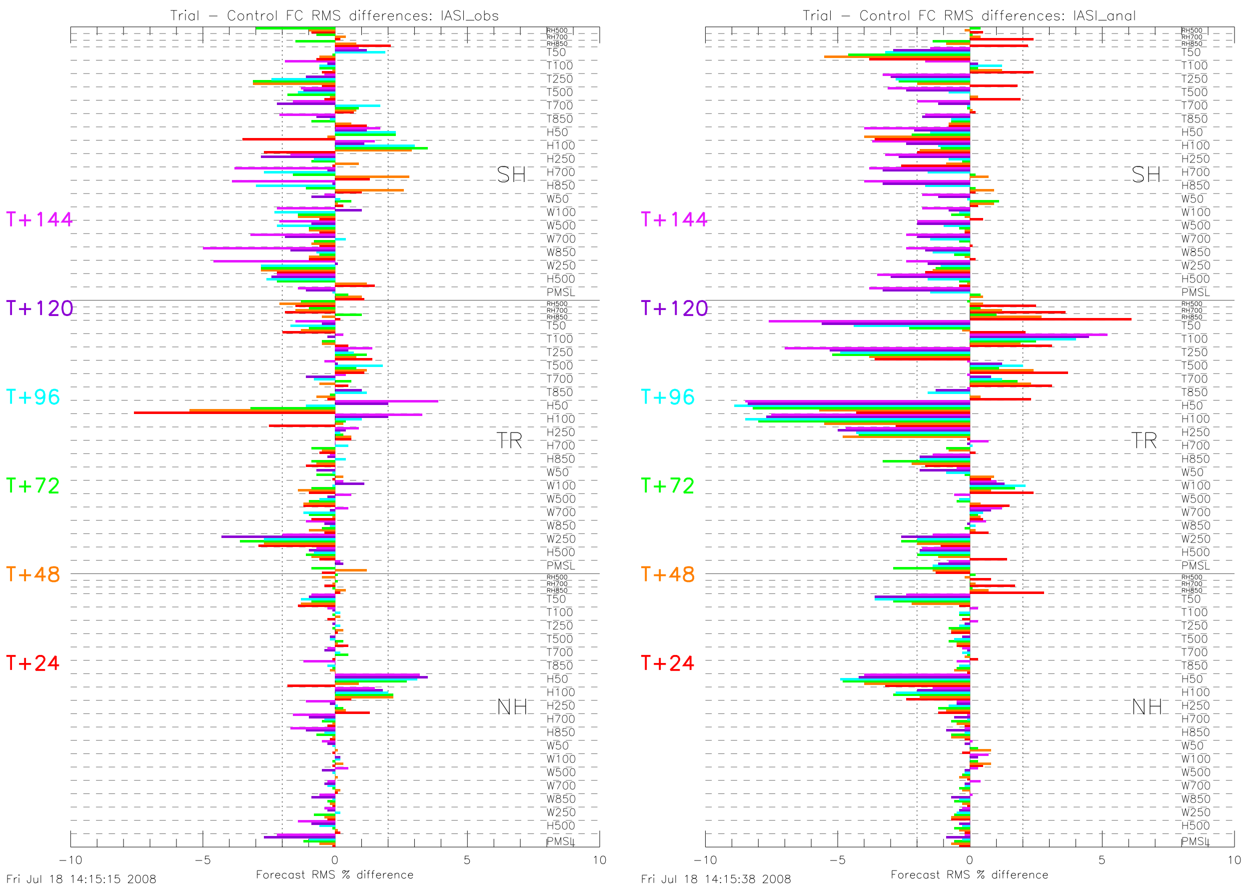
References

Ao, C., Meehan, T., Hajj, G., Manucci, A., and Beyerle, G., Lower troposphere refractivity bias in GPS occultation retrievals, *J. Geophys. Res.*, *108*, doi:10.1029/2002JD003 216, 2003.

Buontempo, C., Jupp, A., and Rennie, M., Operational NWP assimilation of GPS radio occultation data, *Atmos. Sci. Lett.*, available online, DOI: 10.1002/asl.173, 2008.

Collard, A. and Healy, S., The combined impact of future space-based atmospheric sounding instruments on numerical weather prediction analysis fields: A simulation study, *Q. J. R. Meteorol. Soc.*, *129*, 2741–2760, 2003.



(a) verification against observations

(b) verification against analyses

Figure 7: Verification of May/June 2007 experiment: IASI vs no IASI

Davies, T., Cullen, M. J. P., Malcolm, A. J., Mawson, M. H., Staniforth, A., White, A. A., and Wood, N., A new dynamical core for the Met Office's global and regional modelling of the atmosphere, *Q. J. R. Meteorol. Soc.*, *131*, 1759–1782, 2004.

Eyre, J., Assimilation of radio occultation measurements into a numerical weather prediction system, ECMWF Technical Memorandum No. 199, 1994.

Healy, S., Radio occultation bending angle and impact parameter errors caused by horizontal refractive index gradients in the troposphere: A simulation study, *J. Geophys. Res.*, *106*, 11 875–11 889, 2001.

Healy, S. and Thépaut, J.-N., Assimilation experiments with CHAMP GPS radio occultation measurements, *Q. J. R. Meteorol. Soc.*, *132*, 605–623, 2006.

Healy, S., Jupp, A., and Marquardt, C., Forecast impact experiment with GPS radio occultation measurements, *Geophys. Res. Lett.*, *33*, doi: 10.1029/2004GL020 806, 2005.

Healy, S., Eyre, J. R., Hamrud, M., and Thépaut, J.-N., Assimilating GPS radio occultation measurements with two-dimensional bending angle observation operators, *Q. J. R. Meteorol. Soc.*, *133*, 1213–1227, 2007.

Hilton, F. and Atkinson, N., Assimilation of IASI at the Met Office and assessment of its impact through observing system experiments, in *16th International TOVS Study Conference, Angra dos Reis, Brazil, 7-13 May, 2008*, Seminar proceedings, 2008.

Kursinski, E., Hajj, G., Schofield, J., Linfield, R., and Hardy, K., Observing earth's atmosphere with radio occultation measurements using the Global Positioning System, *J. Geophys. Res.*, *102*, 23.429–23.465, 1997.

Melbourne, W., Davis, E., Duncan, C., Hajj, G., Hardy, K., Kursinski, E., Meehan, T., and Young, L., The application of spaceborne GPS to atmospheric limb sounding and global change monitoring, Publication 94–18, Jet Propulsion Laboratory, Pasadena, Calif., 1994.

Rawlins, F., Ballard, S., Bovis, K., Clayton, A., Li, D., Inverarity, G., Lorenc, A., and Payne, T., The Met Office global four-dimensional variational data assimilation scheme, *Q. J. R. Meteorol. Soc.*, *133*, 347–362, 2006.

Rennie, M., The assimilation of GPS radio occultation data into the Met Office global model, Met R&D Technical Report 510, Met Office, UK, 2008.

Smith, E. and Weintraub, S., The constants in the equation for atmospheric refractivity index at radio frequencies, in *Proc. IRE*, vol. 41, pp. 1035–1037, 1953.

Steiner, A. and Kirchengast, G., Error analysis for GNSS radio occultation data based on ensembles of profiles from end-to-end simulations, *J. Geophys. Res.*, *110*, DOI: 10.1029/2004JD005 251, 2005.

von Engeln, A., A first test of climate monitoring with radio occultation instruments: Comparing two processing centers, *Geophys. Res. Lett.*, *33*, doi:10.1029/2006GL027 767, 2006.