Assimilation of GPS radio occultation measurements at ECMWF

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1 Introduction

GPS radio occultation (GPSRO) measurements are an important new component of the global observing system, and it is now becoming clear that they are producing a positive forecast impact at the operational numerical weather prediction (NWP) centres (See papers by Cucurull, Poli, Rennie and Aparicio in this volume.) The measurements are useful because they provide complementary information to that provided by satellite radiance measurements. The GPSRO measurements have good vertical resolution, an all-weather capability and they can be assimilated without bias correction.

This paper describes how the GPSRO measurements are assimilated operationally at ECMWF and outlines recent research activities. In section 2, we describe the GPSRO assimilation options and then explain the reasoning behind ECMWF's approach of using a one-dimensional bending angle operator. In section 3 it is demonstrated how the GPSRO measurements act as "anchor points" for the bias correction of AMSU-A radiances in a variational bias correction scheme. The first forecast impact experiments with the GRAS instrument on MetOP-A are presented in section 4. In section 5, we discuss the development of two-dimensional observation operators and the impact of including observation error covariance models. A summary is given in section 6.

2 Assimilation options and approach adopted at ECMWF

The assimilation options for GPSRO measurements were first considered by Eyre (1994), who recommended either bending angle or refractive index (refractivity [1]) assimilation. Bending angle and refractivity assimilation code is available as part of the Radio Occultation Processing Package (ROPP). This package can be downloaded from http://garf.grassaf.org/.

Most operational centres assimilate either bending angle or refractivity profiles using one-dimensional observation operators. One dimensional operators assume local spherical symmetry through the application of Bouguer's formula (Born and Wolf, 1984), which states that the impact parameter, a, is a constant along the ray-path when the refractive index is a function of just the radial coordinate, r. The impact parameter, a, is defined at any point on the ray-path as

$$a = nr\sin\phi \tag{1}$$

where n is the refractive index, r is the radius and ϕ is the angle between the ray vector and the local radius vector. When the spherical symmetry assumption is valid it can be shown that the bending angle and refractive-index profiles are related through an Abel transform pair (e.g. Kursinski *et al.* 1997). The bending angle, α, as a function of impact parameter, a, can be written in terms of the refractive index,n,

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

[1] Refractivity, N, is defined as $N = 10^{-6}(n-1)$, where n is the refractive index.

where $x = nr$. Conversely, the refractive index, can be written in terms of the bending angle profile

$$n(x) = \exp\left[\frac{1}{\pi}\int_x^\infty \frac{\alpha(a)}{(a^2 - x^2)^{1/2}} da\right] \tag{3}$$

Note that the upper limit of both integrals is ∞ and this implies that some *a-priori* information will be introduced when they are evaluated.

In principle, the assimilation of either bending angle or refractivity profiles with one-dimensional operators should be be equivalent because the profiles are related through an invertible transform. However, this is not the case because *a-priori* information is introduced as a result of the upper limits in both integrals. In fact, it can be argued that the assimilation choice really depends on the vertical range over which the data is intended to be used, and the height of the uppermost NWP model level. For models with a model top of $\sim$ 30 km or less the assimilation of refractivity profiles is a good approach. However, assimilating refractivity above 30 km can be problematic because the "observed" refractivity values above this height are increasingly influenced by information derived from climatology models such as MSIS90. This is introduced at the "statistical optimization" processing step (e.g., Hocke 1997) which is intended to smooth and extrapolate $\alpha(a)$ by combining it with a simulated profile from a climatology. Clearly this will complicate the refractivity errors and vertical correlations.

The assimilation of bending angle profiles potentially increases the vertical range over which useful temperature information can be derived. Although the use of bending angles requires an estimate of the bending associated with the ray-path above the model top, this is not a major problem if the model top is $\sim$ 20 km above the tangent height of the uppermost bending angle that is being assimilated. For example, the top of the ECMWF model is now 0.01 hPa, which corresponds to a height of $\sim$ 80 km. The magnitude of the bending above the model top can be estimated for a refractivity profile which decays exponentially, using an analytical expression based on the Gaussian error function (Healy and Thépaut, 2006)

$$\Delta\alpha = 10^{-6}\sqrt{2\pi a k} N \exp(k(x-a)) \left[1 - \mathrm{erf}(\sqrt{k(x-a)})\right] \tag{4}$$

where N is the refractivity, k is the inverse of the refractivity scale-height and x is the nr product. These values should all be evaluated at the model top. Assuming $N \sim 4 \times 10^{-3}$ and $k = 1.8 \times 10^{-4}$, the bending above the model top for a ray with a tangent height of $\sim$ 60 km is less than 0.1 microradians, which is around an order of magnitude less than the assumed error level. Therefore, ECMWF assimilates bending angle profiles with the ROPP one-dimensional bending angle operator, described in Healy and Thépaut (2006).

3 GPSRO impact on variational bias correction (VARBC)

Accurate bias correction is crucial for the successful assimilation satellite radiance measurements. ECMWF has recently implemented an adaptive, variational bias correction (VARBC) scheme (Dee, 2005) for both operational forecasts and ERA Interim Reanalyses. In the VARBC approach, the bias correction parameters are estimated as part of the 4D-Var minimization. The bias coefficients estimated at a given cycle are then used as the *a-priori* estimate for the next assimilation cycle, so the bias correction coefficients continually evolve in time. Automating the bias correction in this way has been very successful, and in fact VARBC was instrumental in the early operational assimilation of IASI radiances at ECMWF (Andrew Collard, pers. comm.). However, it is important to note that VARBC assumes that the NWP model itself is unbiased, and this requires that some measurements are assimilated without bias correction. Such measurements provide "anchor points" for the VARBC, that stop a gradual drift towards the model climatology. GPSRO measurements are assimilated without bias correction, so they should provide anchor points for the VARBC. The potential importance of GPSRO measurements to the bias correction of satellite radiance measurements was noted by Working Group 3 at the ECMWF/EUMETSAT NWP-SAF Workshop on Bias estimation and correction in data assimilation.

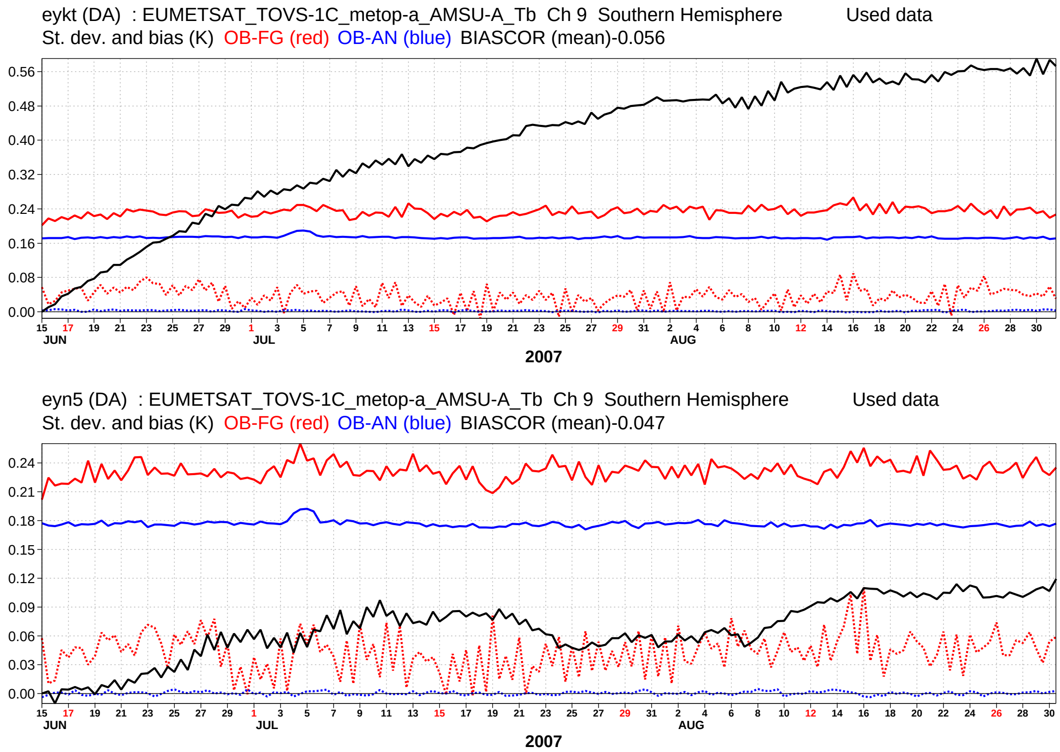

Figure 1: The evolution of the mean and standard deviation of the (o-b) and (o-a) radiance departures and the applied bias correction for AMSU-A, channel-9 in the southern hemisphere. The upper panel shows the results for CTL experiment and the lower panel for the COSMIC experiment. The solid red and blue lines shows the standard deviations of the (o-b) and (o-a), respectively. The dotted red and blue lines show the (o-b) and (o-a) mean departures after bias correction, respectively. The black line shows the applied bias correction. Note that the vertical axes differ in the upper and lower panels.

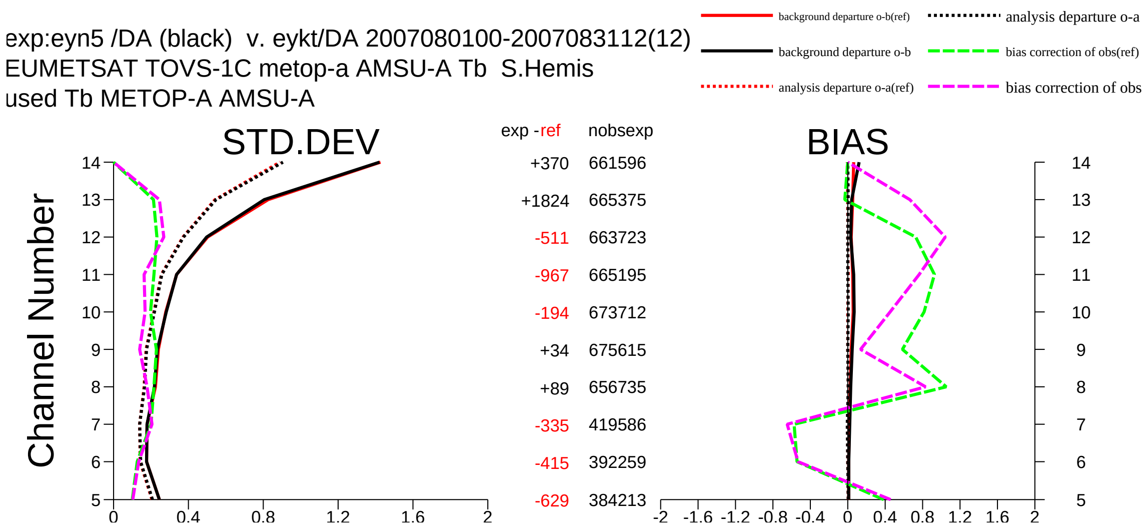

Figure 2: The mean and standard deviation of the (o-b) (solid lines) and (o-a) (dotted lines) departures for all AMSU-A channels for August 1-31, 2007. The pink and green dashed lines are the bias corrections applied to the channels in the COSMIC and CTL experiments, respectively.

The impact of GPSRO measurements on the temporal evolution of bias correction parameters estimated in VARBC has been investigated by running forecast impact experiments with a simplified NWP system. The CONTROL (CTL) experiment assimilates all the conventional observations used operationally at ECMWF and radiances from the AMSU-A and MHS instruments on MetOP-A. The COSMIC experiment is identical to the CTL experiment except that COSMIC bending angle profiles are also assimilated. The experiments cover the period from June 15 to August 31, 2007.

Figure 1 shows the temporal evolution of the bias correction applied to the MetOP-A, AMSU-A channel 9 radiances in the southern hemisphere in the CTL and COSMIC experiments. The channel 9 weighting function peaks near 100 hPa, where the GPSRO information content is greatest, and it is clear that the COSMIC measurements have a major impact on the temporal evolution of the applied bias correction. Figure 2 shows the mean and standard deviations of the radiance departures and the bias correction applied the the radiances for both the CTL and COSMIC experiments. These statistics are for the final month of the experiment, August 1-31, 2007. The bias correction applied to channels 8, 9, 10 and 11 is larger in the CTL experiment (green line) than in the COSMIC experiment (pink line). Furthermore, the short-range forecasts from COSMIC experiment are in better agreement with observations. Figure 3 shows the background and analysis departures for radiosonde temperatures and the noise normalised background departures for COSMIC-4 bending angles, in the southern hemisphere for the final month of the experiment. In the CTL experiment, a larger bias is subtracted from the channel 9 radiances, but this is not consistent with the radiosonde observations and it introduces a negative temperature bias at 100 hPa. It also produces a large positive bias in the bending angle departures near 18 km. This is because essentially bending angles are inversely proportional to temperature. These results indicate that the radiosondes in the southern hemisphere are not sufficient to anchor the channel 9 bias correction, and that the COSMIC bending angles are performing an important role. Note that the magnitude of the bias correction applied to channels 12 and 13 is larger in the COSMIC experiment than in the CTL (Figure 2), which appears counter to the argument given above. However, the evolution of the bias correction for different channels is correlated because of the overlapping weighting functions, so constraining channels 8, 9, 10 and 11 will have some impact on channels 12 and 13. In fact, although the bias applied is larger for channels 12 and 13 in the COSMIC experiment, this appears to produce a mean state which is more consistent with the ECMWF operational model during this period.

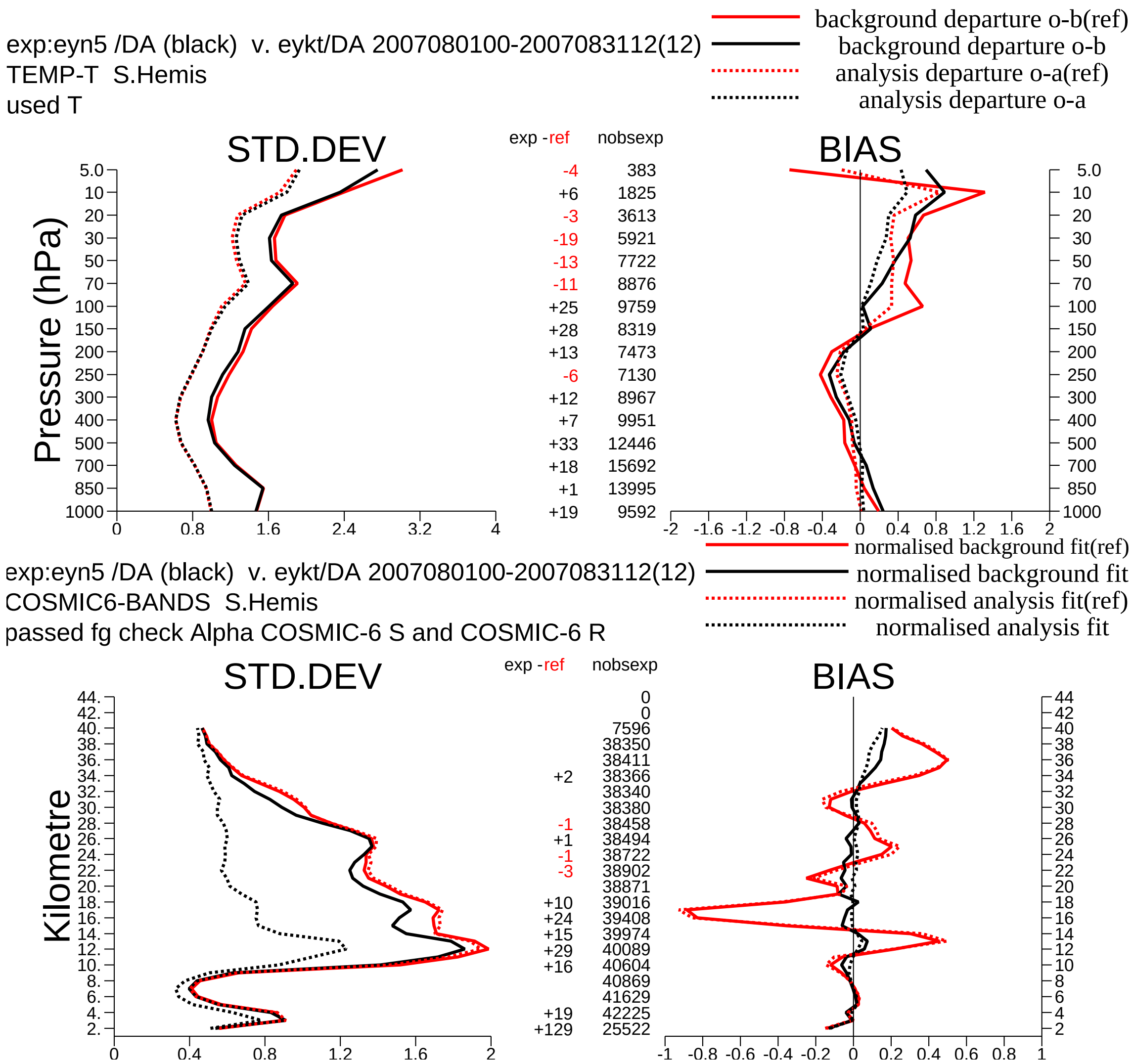

Figure 3: The upper panel shows mean and standard deviation of the short-range forecast fit to radiosonde temperature measurements in the southern hemisphere, for the COSMIC (black line) and CTL (red lines) experiments. The solid lines are the (o-b) departures and the dotted lines are the (o-a) departures. The lower panel shows the corresponding results for COSMIC-4 measurements.

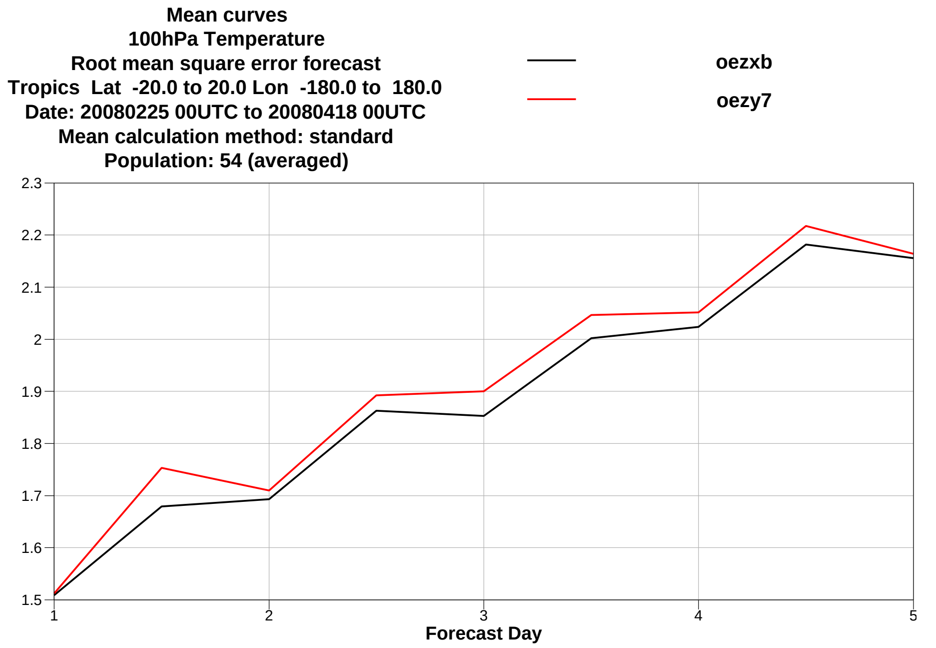

Figure 4: The RMS fit to radiosonde temperature measurements at 100 hPa in the tropics with forecast-range, assimilating GRAS (black line) and not assimilating GRAS (red line).

4 First results with GRAS

The GRAS instrument on MetOP-A was declared pre-operational on February 21, 2008 and operational on April 17, 2008. ECMWF began monitoring GRAS bending angle departures in operations on February 25, 2008 as part of the GRAS SAF near-real-time monitoring activities (see http://www.grassaf.org/). The first assimilation experiments with GRAS at ECMWF covered the period February 25 to April 18, 2008. GRAS provides around 650 profiles per day. The measurements are currently processed with a phased-lock-loop and the retrieval is based on the geometrical optics approximation. These processing techniques are known to introduce biases in the troposphere and this limits how close to the surface we can assimilate the measurements. We have adopted a conservative strategy, blacklisting bending angles with impact heights less than 8 km in the northern and southern hemisphere and below 10 km in the tropics.

During the assimilation experiment we found that around 1% of the bending angles contained gross errors, including negative bending angles as low as 10 km. However, these can be removed easily with a standard "first-guess departure check" quality control (QC) procedure. The statistics of the departures that pass this QC are comparable to COSMIC measurements. The forecast impact of GRAS is neutral in the troposphere, but this is not surprising given the blacklisting. GRAS has a small positive impact in the stratosphere. For example, Figure 4 shows the forecast fit to radiosonde temperatures at 100 hPa in the tropics. The improvement at days 1.5 and 3 is statistically significant at the 95% level. The results with GRAS are not as impressive as when COSMIC measurements were first introduced into operations at ECMWF in December 2006. However, there are typically 2000 COSMIC measurements per day and they corrected some long-standing, relatively large stratospheric temperatures biases. Hence, the GRAS measurements are trying to improve upon much better stratospheric temperature analyses and forecasts, so the impact is smaller. This has been confirmed in recent experiments where GRAS has been assimilated in the absence of COSMIC measurements. Although the impact of GRAS is relatively small, it was decided to start assimilating the data operationally at ECMWF on May 20, 2008.

One interesting result that has become apparent in extended operational monitoring of the GPSRO satellites is that the GRAS and COSMIC measurements appear to have slightly different bias characteristics in the upper-

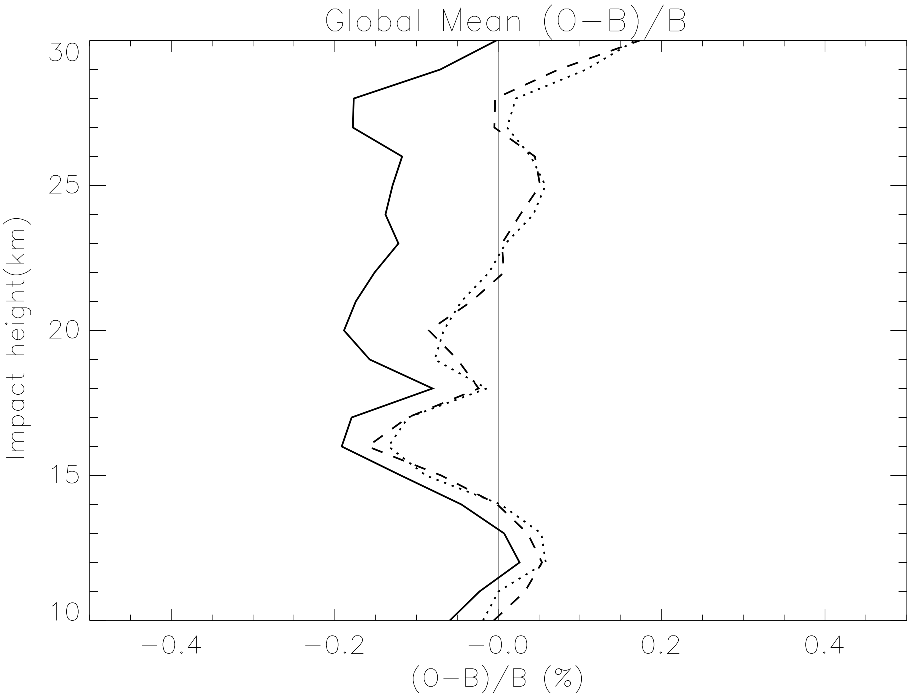

Figure 5: A comparison of the globally averaged, mean (o-b)/b departures for GRAS (solid), COSMIC-4 (dashes) and COSMIC-6 (dotted), for the period September 23 to October 20, 2008.

troposphere and lower-stratosphere. Figure 5 shows the globally averaged bias in the first guess bending angle departures for GRAS, COSMIC-4 and COSMIC-6, for impact heights between 10 to 30 km, covering the period September 23 to October 20, 2008. In general, the GRAS departures are $\sim$ 0.1% to 0.2% smaller than the COSMIC departures from all six COSMIC satellites. The six COSMIC satellites are all very consistent with each other. However, it is interesting to note that the GRAS departures appear to be consistent with CHAMP and GRACE-A measurements, which are currently monitored at ECMWF but not actively assimilated. These small differences in the bias characteristics do not present a problem for NWP, and they can probably be attributed to differences in the orbit determination and processing software, which result in “structural uncertainty” in the bending angles. However, these differences may be important in climate monitoring and reanalysis activities, and probably require further investigation in this context.

5 Recent Work

5.1 A two-dimensional bending angle operator

Two-dimensional (2D) observation operators make use of *a priori* knowledge of the horizontal gradients in the atmosphere provided by an NWP forecast when simulating the observation. They do not overcome the inherently low horizontal resolution of the GPSRO measurements, which contain very little information on the small-scale horizontal atmospheric structure (Sokolovskiy *et al.* 2005). However, they should reduce possibility of degrading a good NWP forecast as a result of misinterpreting the information content of the observations, particularly in areas of strong horizontal gradients (Eyre 1994). In addition, the 2D operators should reduce the size of the bending angle innovations as a consequence of reducing the forward model error.

The GRAS SAF will release a 2D bending angle operator as part of an ROPP upgrade during 2009. This software will be available to the international community for download at http://garf.grassaf.org/. The ROPP

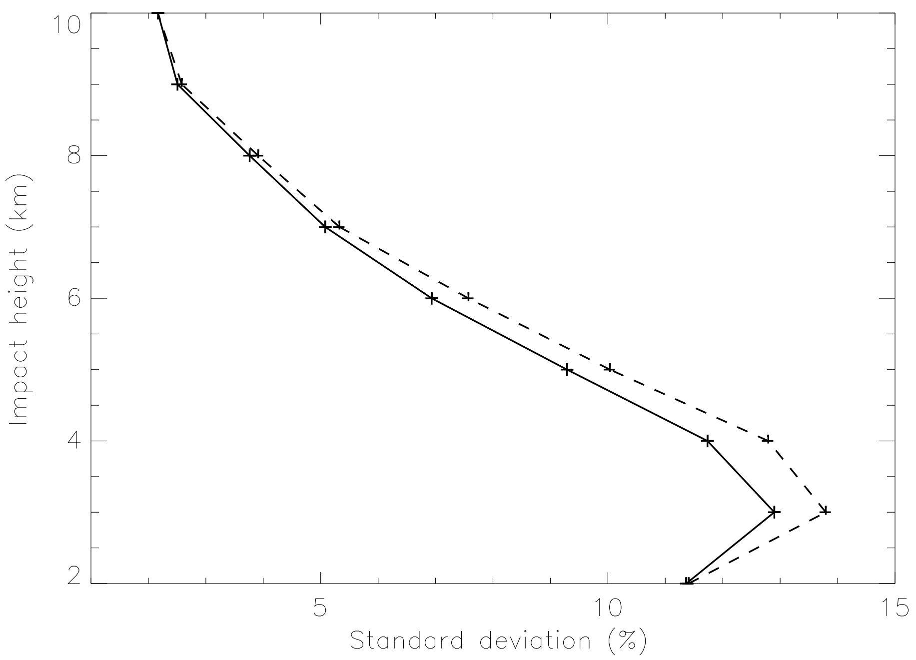

Figure 6: The standard deviation of the (o-b)/b departures, zonally averaged between 30 North to 60 North, for the 2D (solid line) and 1D (dashed line) observation operators.

2D operator is based on the approach outlined in section 3.2 of Healy *et al.* (2007), but with some additional computational efficiency savings. In the new code, a full 2D calculation is only performed below a user prescribed impact height, which is currently set at 10 km. The bending above this height is estimated with a 1D calculation. The motivation for this new approach is that it a complex, 2D calculation is only required in the troposphere where the horizontal refractive-index gradients are large, as a result of gradients in the humidity. Furthermore, a number of studies have demonstrated that 1D operators are perfectly adequate in the stratosphere. However, note that the code is flexible with a variable 2D/1D transition height, so the user can perform a fully 2D calculation for the entire ray-path if required.

The ROPP 2D operator has been tested in the ECMWF assimilation system in a 28 day experiment for the period July 1 to July 28, 2007. Figure 6 shows the standard deviation of the zonally averaged first guess bending angle departures ((o-b)/b) between 30 degrees North and 60 degrees North, for the 2D operator (solid line) and the 1D operator used in operations (dashed line). The 2D operator reduces the standard deviation by $\sim$ 8%, which is very encouraging. Further work is required to determine the forecast impact of the 2D operator relative to the 1D operator in extended experiments.

5.2 Correlated observation errors

We have investigated the forecast impact of vertically correlated bending angle errors. The main problem with introducing correlations is that the combined observation and forward model error correlation matrix is still poorly understood. In the stratosphere the correlations are probably dominated by errors introduced in the preprocessing of the bending angles. Bending angles are derived from the time derivative of phase delay measurements. The finite difference approximation of this derivative – which is usually combined with smoothing of the phase delays – can introduce quite broad negative correlations (e.g., Syndergaard 1999, Poli *et al.* 2008). However, it should be noted that the differentiation is performed on 50 Hz phase data, which will have an equivalent vertical sampling of a few 10's of metres. The bending angles assimilated operationally typically have a vertical separation of $\sim$ 200 m or more because of vertical thinning. In principle, if the phase delays were

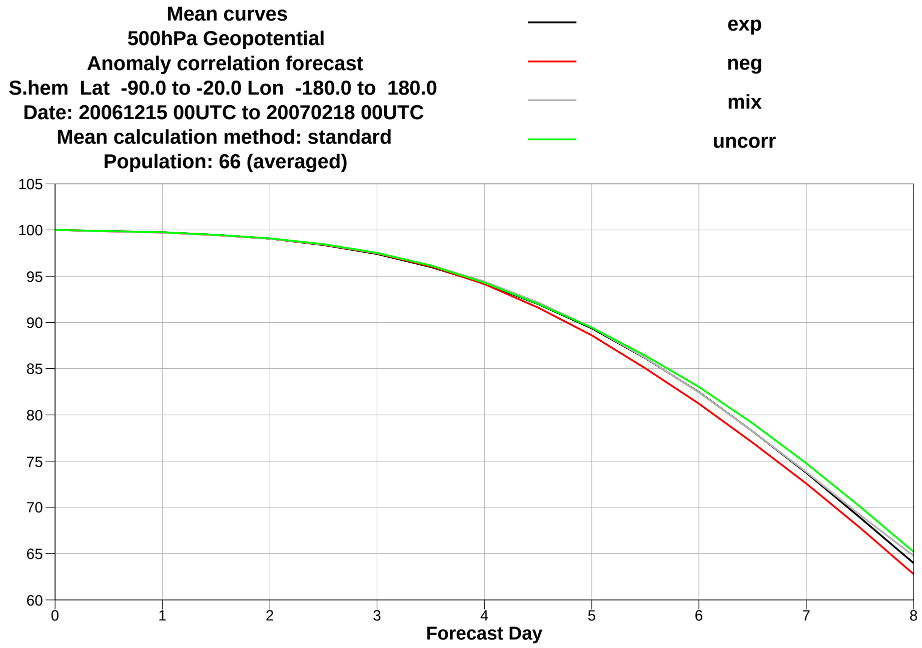

Figure 7: The anomaly correlation in the southern hemisphere for the vertically correlated observation error experiments.

smoothed over a vertical range of less than 200 m, then the negative bending angle error correlations could be minimized, but this would probably increase the noise level (See paper by Poli, this volume). In the troposphere the correlations are probably dominated by correlated forward model errors. One of the largest errors in the 1D operator is the use of the impact parameter provided with the observation to derive the tangent point height. This approximation will introduce positively correlated errors in regions of strong horizontal gradients.

As a result of the considerations outlined above, we have investigated three correlation models. The first model assumes that the correlations decay exponentially with impact parameter separation and is of the form $c(i,j) = \exp(-|a_i - a_j|/H)$, where $H = 1000$m over the entire vertical interval. The second model attempts to parameterise the negative correlations. The off-diagonal terms are $c(i,i+1) = 0.5, c(i,i+2) = 0.2, c(i,i+3) = c(i,i+4) = c(i,i+5) = -0.3, c(i,i+6) = -0.1$ and $c(i,j) = 0.0$ for $j > 6$ over the entire vertical interval. The third model assumes an exponential decay using $H = 500$m for impact heights less than 10 km, with the negative correlation model used above this height. These models are referred to as “exp”, “neg” and “mix”, respectively. They have been compared with an uncorrelated model (“uncorr”) for the period December 15, 2006 to February 18, 2007. So far, the results with the correlated error covariance matrices have been disappointing and it has been difficult to produce a forecast impact as good as the uncorrelated experiment. For example, the 500 hPa height anomaly correlation for the southern hemisphere in show in Figure 7. The negative correlation model produces the poorest scores and tends to result in the largest temperature increments in the troposphere.

These results suggest that simplified correlations matrices – based on some quite ad-hoc assumptions – are probably not accurate enough to investigate the role of vertical error correlations thoroughly. Further work is required to understand the combined observation/forward model error correlation matrix. One possible method for estimating the forward model error component could be based on the statistics of 1D-2D bending angle operator differences and this will be investigated in the future.

6 Summary

ECMWF currently assimilates GPSRO bending angles with a 1D observation operator, which is part of the ROPP software package. The assimilation of bending angles is preferable because it circumvents some potential problems associated with the "statistical optimization" processing step, which introduces climatology into refractivity values above 30 km. However, if the NWP model top is low ($\sim$10 hPa) then the use of refractivity profiles is a reasonable option.

One of the strengths of GPSRO measurements is that they can be assimilated without bias correction. This means that they provide anchor points for the VARBC scheme used to correct radiance measurements. We have demonstrated how the assimilation of COSMIC measurements modifies the temporal evolution of mid-stratospheric AMSU-A channels in a simplified NWP system. Furthermore, the assimilation of the COSMIC measurements significantly improves the fit to radiosonde observations. These experiments clearly demonstrate the value of GPSRO measurements to the bias correction of radiance measurements and illustrate the complementary nature of the GPSRO measurements.

The first results with GRAS are encouraging and ECMWF has used the data operationally since May 20, 2008. GRAS cannot yet be assimilated down to the surface because of current limitations in the processing of the data, but these will be overcome during 2009. We have found that about 1% of the data contains gross errors, but this can be removed with relatively simple QC. The GRAS impact on stratospheric temperatures is not as large as when COSMIC became operational, but this is because GRAS is being assimilated on top of COSMIC measurements, meaning that the GRAS measurements are now trying to improve upon a much better stratospheric analysis.

An efficient 2D bending angle operator has been developed and tested within the ECMWF assimilation system. This operator reduces the magnitude of the innovations by $\sim$ 8% in the northern hemisphere mid-latitudes, when compared with a 1D operator. Experiments with vertically correlated errors have not been very successful to date, but this is probably because the combined forward model/observation error correlation matrix is not well understood. The statistics of 1D-2D simulated bending angle differences may provide some insight into forward model error correlations in the lower troposphere, and this will be investigated in the future.

Acknowledgements

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