Potential for radio occultation to identify and correct other satellite observation biases

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ABSTRACT

The GPS radio occultation (GPSRO) measurement technique is described and it is demonstrated that these measurements can be assimilated without bias correction. Four-dimensional variational (4D-Var) assimilation forecast impact experiments have been conducted with CHAMP GPSRO bending angle profiles from 1st June – 31st July, 2004. The CHAMP bending angles have been assimilated using a one-dimensional bending angle observation operator. It is shown that these measurements reduce the well known "stratospheric ringing" problem over Antarctica. More generally, assimilating the CHAMP measurements improves analysis and forecast fit to radiosonde temperature measurements in the southern hemisphere on the 300, 200, 100 and 50 hPa levels, over the day-1 to day-5 forecast range. The implications of these results for the bias correction of other satellite measurements is discussed.

1 Introduction

The importance of measurements that can be assimilated without bias correction is widely recognised within the operational numerical weather prediction (NWP) community. These data help to distinguish between model and observation biases and they provide "anchor points" to prevent model drift in adaptive bias correction schemes (Dee 2006). In principle, GPS radio occultation (GPSRO) measurements can be assimilated without bias correction, and from 2006 the GRAS instrument on METOP (Loiselet *et al.* 2000) and the constellation of six satellites, COSMIC (Anthes *et al.* 2000) will provide measurements in near-real-time. The measurements are globally distributed, have an all-weather capability and good vertical resolution. The GPS/MET (Kursinski *et al.* 1996; Rocken *et al.* 1997) and CHAMP (Wickert *et al.* 2001) GPSRO "proof-of-principle" experiments have demonstrated that the measurement technique provides temperature information with a sub-Kelvin accuracy between heights of $\sim$ 7 km to 25 km. It has been shown that the GPSRO information content is complementary to that of satellite radiance measurements (Collard and Healy, 2003). Furthermore, recent forecast impact experiments, where the CHAMP measurements have been assimilated without bias correction (Healy *et al.* 2005; Healy and Thépaut 2006), have demonstrated that a relatively small number of observations can partially correct known model errors and biases in the lower-stratosphere.

The aim of this study is to provide a realistic assessment of the information content of GPSRO measurements and to highlight the possible applications to the bias correction problem. In section 2 the pre-processing from the raw measurements to the assimilated quantities is discussed, in order to demonstrate that the GPSRO measurements are less prone to calibration errors than other satellite measurements. The bending angle observation operator used in this study is described in section 3, and it is shown that the forward model is unlikely to be a signifi cant source of bias. In section 4, we outline four dimensional variational (4D-Var) forecast impact experiments with CHAMP GPSRO measurements, which demonstrate that relatively few GPSRO observations can produce large differences in the mean analysis state in the stratosphere, partially correcting a known assimilation problem. The conclusions are given in section 5.

2 The GPSRO measurement technique

A number of authors have presented detailed descriptions of the basic physics and processing of the GPSRO measurements (Melbourne *et al.* 1994; Kursinski *et al.* 1997; Hajj *et al.* 2002) and only a brief outline is given here. Fundamentally, the GPSRO technique is based on measuring the time required for a radio signal to propagate from a GPS satellite to a receiver on board a low earth orbiting (LEO) satellite. The atmosphere and ionosphere modify the speed of the signal because the refractive index along the path is not unity, and the ray-path between the satellites is curved as a result of gradients in the refractive index. These effects combine to produce an excess phase delay, relative to that expected for a straight line path in a vacuum.

The GPS satellite transmits signals at L1=1575.42 MHz and L2=1227.60 MHz and the motion of the LEO means that vertical profiles of the phase delays at the L1 and L2 frequencies can be determined. The L1 and L2 phase delays are "calibrated" to account for special and general relativistic effects and to remove clock errors (Hajj *et al.* 2002). The time series of calibrated phase delays are then differentiated with respect to time to provide Doppler shifts. Note that the Doppler shift values are not sensitive to fixed biases in the phase measurements as a result of the differentiation. The Doppler shift is related to the bending along the ray-path, which is characterised by the bending angle α_i, where the subscript is $i = 1$ or $i = 2$, for the L1 and L2 signals, respectively. Deriving α_i from the Doppler shift is an ill-posed problem. It is made well-posed by assuming that the variable known as the impact parameter, a, has the same value at the GPS and LEO satellites. This enables α_i and a to be derived simultaneously, given accurate estimates of position and velocity of the satellites.

At this stage the bending angle contains contributions from both the neutral atmosphere and the ionosphere. Fortunately the ionosphere is dispersive and the ionospheric bending can be removed – or corrected – to first order by taking a linear combination of the L1 and L2 values (Vorob'ev and Krasil'nikova, 1994). However, residual ionospheric noise limits the information content of corrected bending angles above ~ 35 – 40 km. There is also some question as to whether the ionospheric correction has error characteristics that vary during the solar cycle. This may be important in climate applications.

When the refractive index field is spherically symmetric, a is constant along the ray-path and the profile of refractive index, n, as a function of height can be derived from the profile of corrected bending angles as a function of impact parameter, $\alpha(a)$, using an Abel transform,

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

where $x = nr$ and r is the radius. Note that the upper limit of this integral is ∞ and therefore the evaluation of eq.1 usually requires the introduction of some a-priori information in order to extrapolate $\alpha(a)$. The three main processing centres, GFZ Potsdam, UCAR and JPL apply different extrapolation methods and this leads to differences of $\sim 0.5\%$ in the derived refractivity ($N = 10^6(n-1)$) profiles above 30 km, as illustrated in recent comparison studies (Jens Wickert, pers. comm. 2005).

The refractivity, N, can be written as

$$N = 10^6(n-1) = \frac{c_1 P}{T} + \frac{c_2 P_w}{T^2} \tag{2}$$

where P is the total pressure, P_w is the water-vapour pressure and T is the temperature; $c_1 = 77.6\mathrm{K/hPa}$ and $c_2 = 3.73 \times 10^5 \mathrm{K^2/hPa}$ are empirically derived constants (Bean and Dutton, 1968). In the stratosphere and upper-troposphere $P_w \sim 0$, so the refractivity, N, is linearly proportional to the density. This means that a profile of N can be vertically integrated to provide pressure as a function of height, using the hydrostatic relationship. A temperature profile can then be derived using the ideal gas law. However, note that some a-priori information is required to initialise the hydrostatic integration (See Kursinski *et al.* 1997).

In the lower-troposphere additional a priori is required to derive temperature and humidity information from the refractivity profile. Information content studies suggest that the measurements primarily contain water vapour information in the lower-troposphere, but it has yet to be demonstrated that it is of sufficient quality to be useful in operational NWP. For example, it is well known that the GPSRO refractivity profiles in the tropical lower-troposphere are biased low when compared with ECMWF analyses (Rocken *et al.* 1997; Ao *et al.* 2003). However, this is an area of ongoing research and it is hoped that more sophisticated processing methods will improve the data quality in the lower-troposphere.

3 Forward modelling

Although the GPSRO forward problem is less familiar to the meteorological community than the radiative transfer problem that arises in satellite radiance assimilation, it is in fact much simpler and is based on straightforward physics – Snells law of refraction. At ECMWF we have assimilated ionospheric corrected bending angles using a one-dimensional operator[1]. This approach is computationally efficient and it is preferable to the assimilation of refractivity because the observation errors are simpler.

The observation operator evaluates the "bending angle integral" (e.g, Kursinski *et al.* 1997) given the observed impact parameter a

$$\alpha(a) = -2a \int_a^{\infty} \frac{\frac{d \ln n}{dx}}{(x^2 - a^2)^{1/2}} dx \qquad (3)$$

where α is the total ionospheric-corrected bending angle, n is the refractive index derived from the model and $x = nr$, where r is the radius value of a point on the ray-path. The solution of this integral is described in detail by Healy and Thépaut (2006). Briefly, the geopotential heights of the model levels are calculated using standard routines (Simmons and Burridge, 1981). They are then converted to geometric heights (List 1984) and subsequently radius values. The refractivity on the model levels is estimated with eq.2. The accuracy of eq.2 has been discussed by Kursinski *et al.* (1997). Comparisons with a three term expression given by Bevis *et al.* (1992) suggest that the largest errors are of order 0.15% for saturated air in the lower-troposphere, but more generally the errors are less than 0.1%. Therefore, uncertainty in the refractivity parameters is unlikely to be a significant source of forward model bias. The upper limit of eq3 means that we must estimate the ray bending above the model top, but the magnitude of this is small compared to the assumed observation errors and therefore it is not a major source of bias.

4 Assimilation experiments with CHAMP

Forecast impact experiments have been conducted with CHAMP measurements for the period 1st June, 2004 to 31st July, 2004. The CHAMP bending angles are assimilated without bias correction. The experiments use cycle 29R1 of the 4D-Var assimilation system (Rabier *et al.* 2000; Klinker *et al.* 2000), run in the early-delivery mode (Haseler, 2004). The forecast model has 60 levels in the vertical, the horizontal resolution is T511 and the 4D-Var increments are at T159. The CHAMP GPSRO measurements have been processed by UCAR (Kuo *et al.* 2004), but have been interpolated and thinned onto 180 fixed "impact heights" between the surface and 40 km. The impact height, h, is defined as $h = a - R_c$, where R_c is the radius of curvature for the

[1]Two-dimensional bending angle operators have also been investigated, but these will not be described further in this study.

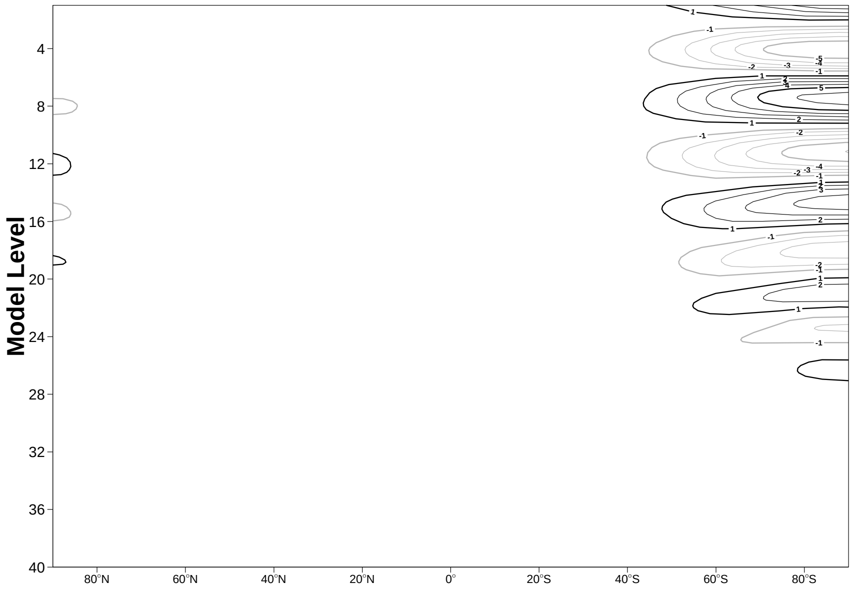

Figure 1: The zonally averaged, mean temperature analysis differences (GPSRO - CTL) on model levels 1 to 40, averaged from 1st June – 31st July, 2004.

observation. The combined observation/forward model bending angle errors are assumed to be uncorrelated in the vertical. The standard deviation of the combined errors is assumed to vary with h. The percentage error is assumed to be 10% of the observed value at $h = 0$, falling linearly with h to 1% at $h = 10$ km. Above 10 km, the error is assumed to be 1% of the observed value until this reaches a lower limit of 6×10^{-6} radians. A 4D-Var diagnostic which is based on the GPSRO contribution to the observation cost function value at the analysis state, normalised by the number of bending angles that have been assimilated, suggests that the error model is reasonable.

The control experiment (CTL) assimilates the set of satellite and conventional measurements that are used operationally. The number of pieces of data that are assimilated during a 12 hour assimilation window is typically $\sim$ 2.7 million for the control experiment. The GPSRO experiment is identical to the control except that the CHAMP measurements are also assimilated. Typically $\sim$ 12500 bending angles are assimilated during a 12 hour assimilation window. Despite the relatively low number of bending angles, they produce a clear difference in the mean analysis state over Antarctica, as illustrated in Figures 1 and 2. The mean temperature differences in the stratosphere are up to 5K and from Figure 2 it is clear that the GPSRO measurements are producing a much smoother mean analysis state than in the control experiment. Furthermore, the GPSRO measurements improve the fit to radiosondes in this region, as illustrated in Figure 3 which shows the forecast and analysis fit to radiosonde temperature measurements over Antarctica. Both the mean and standard deviations are improved and in the lower-stratosphere and fewer radiosonde measurements are rejected in the GPSRO assimilation experiment. The sharp structure in the mean fit of the control experiment is an example of ECMWF's "stratospheric ringing" problem (Tony McNally, pers. comm. 2005). This arises because the radiance measurements introduce large temperature increments at the upper model level near the winter pole to correct a model bias. The vertical correlation structure in the background error covariance matrix then spreads this information down the profile, superimposing an oscillatory perturbation on the stratospheric temperatures. The perturbation appears to be in the null-space of satellite radiance measurements because of their limited vertical resolution, meaning that it does not degrade the fit to the radiance measurements even though

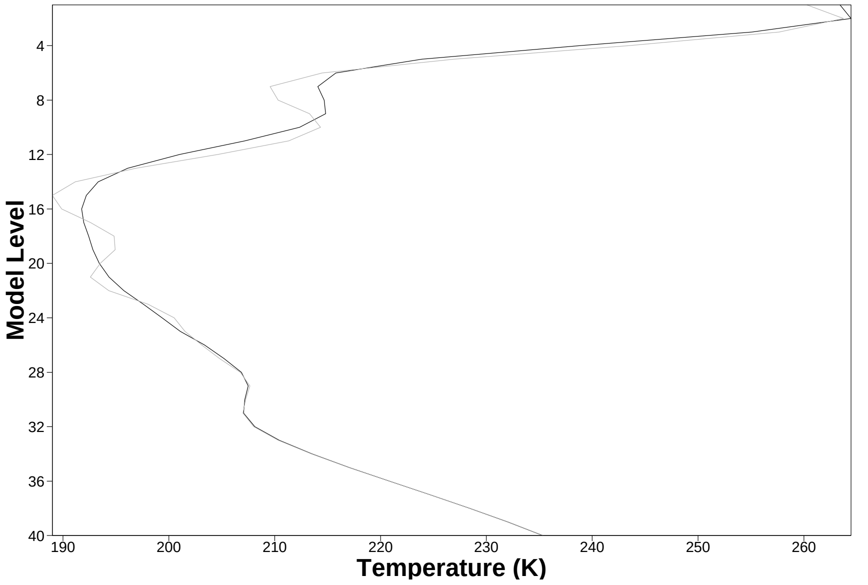

Figure 2: The mean temperature analyses over Antarctica on model levels for the CTL (grey) and GPSRO (black) experiments, averaged from 1st June – 31st July, 2004.

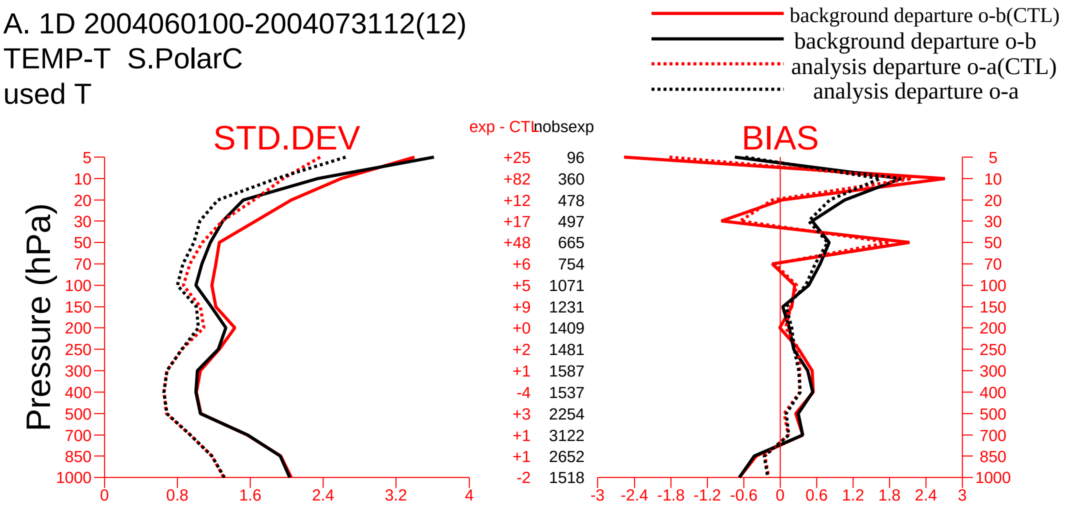

Figure 3: The standard deviation and bias of the 12h forecast and analysis fit to radiosondes (radiosonde - NWP) in Antarctica for the CTL (red) and the GPSRO (black) experiments. The central column gives the number of comparisons on the pressure levels.

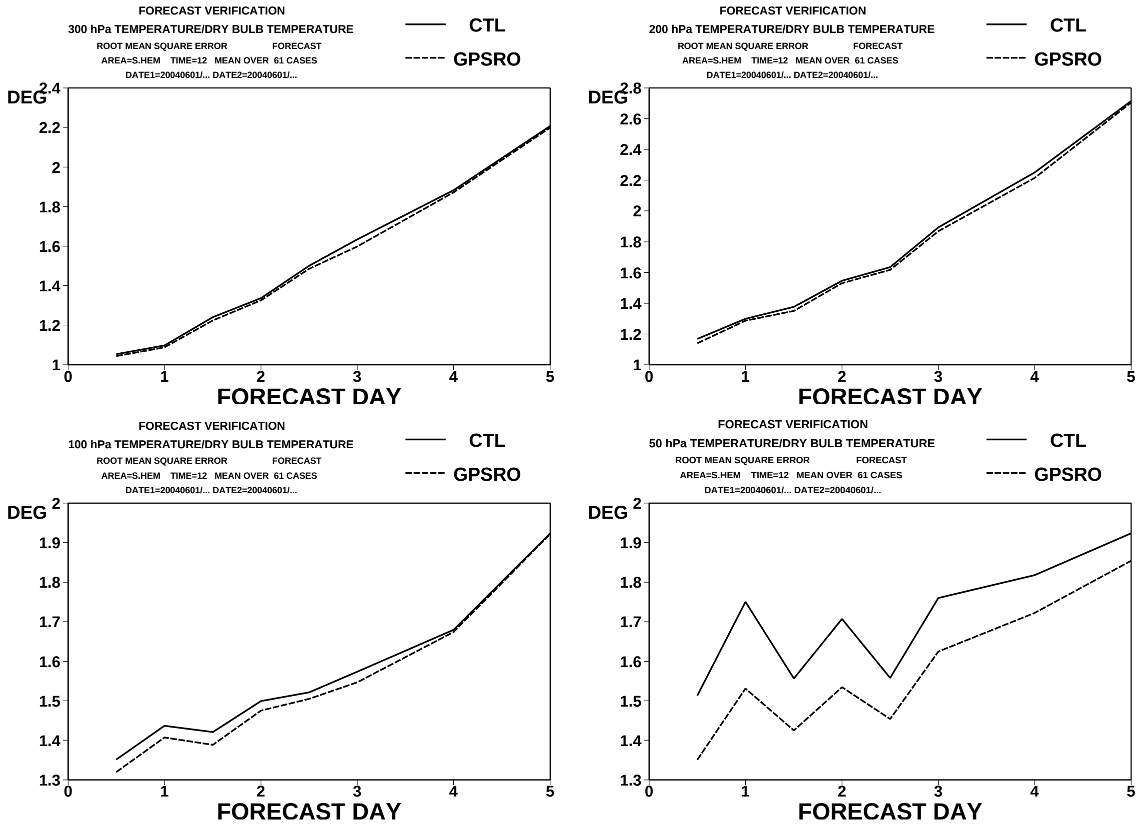

Figure 4: The RMS fit to radiosonde temperatures at 300, 200, 100 and 50 hPa in the southern hemisphere for the CTL (solid) and GPSRO (dashed) experiments.

it is physically unrealistic. However, the GPSRO measurements are able to identify and partially correct this error because the vertical resolution is much better (Collard and Healy, 2003). This is a clear example of how satellite radiance and GPSRO measurements complement each other. The GPSRO measurements alone cannot correct the model error at the upper model level near 65 km because their information content falls rapidly above $\sim$ 40 km, but they can introduce additional constraints in the lower-stratosphere that reduce the stratospheric ringing problem.

Assimilating the GPSRO measurements improves the RMS fit to radiosonde temperature measurements in the upper-troposphere and lower-stratosphere of the southern hemisphere over the day-1 to day-5 forecast-range, as illustrated in Fig.4 for the 300, 200, 100 and 50 hPa pressure levels. The improvements are statistically significant (Healy and Thépaut, 2006). More generally, the lower-stratospheric results are neutral against radiosondes in the northern hemisphere and there is some improvement at 100 hPa in the tropics, although there is also a degradation at 50 hPa.

5 Conclusions

These results clearly show that a relatively small number of CHAMP GPSRO measurements can have a significant forecast impact in lower-stratosphere of the southern hemisphere, particularly in Antarctica where there is a known assimilation problem. This illustrates the value of observations with good vertical resolution, that can be assimilated without bias correction. However, note that there were no significant differences in the AIRS and AMSU-A bias statistics in the control and GPSRO experiments presented here. The quantity of data from one GPSRO instrument, CHAMP, is probably not sufficient to compete with other satellite measurements to constrain the thickness of broad layers in the atmosphere. From 2006 the GRAS instrument on METOP and the COSMIC constellation will increase the number of GPSRO measurements by almost an order of magnitude, and it may then be possible to see a direct affect on the radiance statistics. This will be investigated in future work.

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