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Radio Occultation Meteorology

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Single Frequency Radio Occultation Retrievals: Impact on Numerical Weather Prediction

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ROM SAF

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Abstract

The impact of single frequency processing of GPS radio occultation (GPS-RO) measurements on numerical weather prediction has been investigated. Metop-B GRAS measurements have been degraded by adding 6 microradian and 12 microradian random Gaussian noise. The additional noise is most significant in the stratosphere, because to first order bending angle values fall exponentially with height. The degraded data have been assimilated in a system where all other GPS-RO measurements are restricted to a latitude band between 40 North and 40 South. The impact of noisy data has been compared with experiments where the weight of the Metop-B GRAS measurements in the stratosphere has been increased by reducing the assumed standard deviation of the observation errors to 1.5 microradians.

The main forecast impact is on temperature biases in the stratosphere. The results show that the increase in noise levels will have a noticeable impact on the mean temperature analysis, particularly in polar regions and above 5 hPa. The bias corrections applied to satellite radiances are also affected. For example, the bias corrections applied to channel 13 of Metop-B AMSU-A differ by $\sim$ 0.15 K. Increasing the noise levels degrades the mean of the short-range forecast departures with respect to radiosonde temperature measurements above 200 hPa. The root-mean-square (RMS) temperature errors are degraded by $\sim 1\%$ at 30 hPa for the day-1 to day-5 forecast range because of the additional noise. However, there is no degradation in RMS at 100 hPa. The introduction of vertically correlated errors does not affect the main results.

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1 Chapter

1.1 Introduction

The possible termination of the GPS L2/P(Y) code in 2020 would have significant implications for the dual frequency processing of GPS radio occultation (GPS-RO) measurements made with the Metop GRAS instruments. Marquardt *et al.* (2013) (MARQ13, hereafter) have recently discussed this issue in some detail, and have examined the possible application of single frequency processing techniques (De La Torre Juarez *et al.* 2004; Larsen *et al.* 2005) to retrieve the neutral bending angle profiles, α, as a function of impact parameter, a. They have estimated that the standard deviation of the bending angle errors in stratosphere is likely to increase to between $\sim$ 6 microradians and 12 microradians, depending on the level of smoothing implemented in the new single frequency processing chain. This increase in noise is most significant in the stratosphere, because to first order bending angles fall exponentially with height, with the exponential decay given by the density scale height. The increased noise values can be compared with the current operational requirements for the GRAS instrument which is 1 microradian, and the more conservative noise value currently assumed when assimilating the measurements into NWP systems, which is now 3 microradians at ECMWF. It is useful to note that ECMWF assimilates GRAS measurements up to 50 km currently. The climatological mean bending angle with a tangent height at 50 km is $\sim$ 16 microradians. Therefore, if the standard deviation of noise increases up to 12 microradians it will represent $\sim$ 75 $\%$ of the climatological average bending angle value. It seems unlikely that ECMWF will still assimilate the data up to 50 km if this is the case.

It is clear that the loss of the L2/P(Y) code will lead to a significant reduction in the accuracy of the Metop GRAS bending angle profiles assimilated into NWP systems in the stratosphere. Therefore, this study is an attempt to assess how the increased noise on the GRAS bending angle profiles will affect the impact of the measurements in NWP. However, it is important to recognise that as the global observing system (GOS) has improved, and NWP systems have generally become more robust, the reliance on any single instrument – or even any single observation type – has diminished. It has become increasingly hard to demonstrate large, statistically significant positive forecast impacts with new observations. To some extent, most individual changes are now “small” and incremental, but their accumulation forms the basis of the gradual evolution and improvement in global NWP skill (See English *et al.* (2013) for a detailed discussion).

Despite relatively low observation numbers, the GPS-RO measurements are now considered useful in NWP because they complement the information provided by satellite radiances. This is primarily because the GPS-RO have good vertical resolution, and they can the assimilated without bias correction to the NWP model. The latter is important because it means that the GPS-RO are “anchor measurements” in the variational bias correction scheme (Dee 2005). These characteristics are also important for climate reanalyses (Poli *et al.* 2010). MARQ13 have noted that the increased noise will probably impact the ability of the GPS-RO measurements to anchor the bias corrections applied to the radiances. This has now been tested and quantified in the ECMWF system.

In this study we have added random noise to real Metop-B GRAS measurements, prior to the assimilation of the data, in order to estimate the impact of the single frequency processing. We have tried to simulate the impact in a worst case GPS-RO scenario. In addition to all other data types used operationally, only degraded data from one GRAS instrument is available globally, with other non GRAS GPS-RO measurements are only available in the latitude band between 40 North and 40 South ($\pm 40^{\circ}$). This restriction of the non GRAS data is because it is possible that only the first six COSMIC-2 satellites will be funded, and they will only provide measurements in the $\pm 40^{\circ}$ latitude band. We cannot fully reproduce the impact of a degraded GRAS instrument on top of the tropical COSMIC-2 measurements, but the configuration we have investigated is as close as we can get with the existing real data. The noise added to the Metop-B GRAS measurements is 6 microradians and 12 microradians, consistent with the estimates provided in MARQ13. The impact of vertical error correlations caused by additional smoothing in the single frequency processing has also been considered.

Therefore, the aim of the study is to quantify the forecast impact of the degraded GPS-RO data in a specific scenario where 1) GPS codes have been changed, 2) Metop GRAS measurements subsequently have degraded quality, and 3) COSMIC-2 programme has not been fully funded. The results provided here may help inform any decisions regarding to the modification of the GRAS receiver on Metop-C.

A brief review of the single frequency processing is given in section 1.2, and then the assimilation experiments will be described in section 1.3. The main results are presented in section 1.4. The discussion and conclusions are in section 1.5.

1.2 Single Frequency Processing

Single frequency processing of GPS-RO observations is described in more detail by De La Torre Juarez *et al.* (2004), Larsen *et al.* (2005) and MARQ13. Briefly, the approach is based on the fact that the ionosphere has an equal but opposite effect on the phase and group velocity of the L1 signal. Decomposing the phase (ϕ_{l1}) and pseudorange (ρ_{l1}) measurements into a neutral atmospheric delay term, η_n, and an ionospheric contribution gives

$$\phi_{l1} = \eta_n - \frac{40.3}{f_{l1}^2}\int_s n_e ds \tag{1.1}$$

$$\rho_{l1} = \eta_n + \frac{40.3}{f_{l1}^2}\int_s n_e ds \tag{1.2}$$

where n_e is the electron density and s is the ray path. Subtracting the pseudorange from the phase delay isolates the ionospheric contribution to the delay

$$\phi_{l1} - \rho_{l1} = -2\frac{40.3}{f_{l1}^2}\int_s n_e ds \tag{1.3}$$

These differences will be noisy, so some form of filtering or smoothing of the time-series is required which will be denoted by an overbar (MARQ13). A synthetic L2 time series can be modelled – or reconstructed – using the L1 measurements with

$$\phi_{l2} = \phi_{l1} - \frac{1}{2}\left(1 - \frac{f_{l1}^2}{f_{l2}^2}\right)\overline{(\phi_{l1} - \rho_{l1})} \qquad (1.4)$$

and this can subsequently be used in the standard dual frequency processing, with the ionospheric correction being carried at the bending angle level (Vorob'ev and Krasil'nikova, 1994). Alternatively, an ionospheric corrected phase value, ϕ_c, can be estimated directly with

$$\phi_c = \phi_{l1} - \frac{1}{2}\overline{(\phi_{l1} - \rho_{l1})} \qquad (1.5)$$

In GPS-RO, the ionospheric correction of bending angles is usually considered superior to the correction at the phase level, because the ray paths of the L1 and L2 signals differ (Vorob'ev and Krasil'nikova, 1994). However, this argument does not apply to the reconstructed data because the phase and pseudorange paths are the same, so it is not obvious if the reconstruction of the L2 phase values is strictly necessary.

MARQ13 note that the accuracy of the pseudorange measurements is far lower than the phase measurements, and therefore the pseudorange errors dominate the errors in $\overline{(\phi_{l1} - \rho_{l1})}$. In addition, the pseudorange is measured at just 1 Hz, and this will produce broad error correlations in both the reconstructed ϕ_{L2} and the corrected ϕ_c values.

The accuracy of the single frequency retrievals will be determined to some extent by the smoothing that can be applied to the $\overline{(\phi_{l1} - \rho_{l1})}$ differences. de le Torre Juarez *et al.* (2004) filter the $\overline{(\phi_{l1} - \rho_{l1})}$ differences up to 30 s because they argue that the underlying function is relatively smooth, and it can be approximated with a low order polynomial. MARQ13 estimate that the standard deviation of the bending angle errors produced with the single frequency approach will range between 6 microradians and 12 microradians, depending on the level of smoothing. These estimates are used in the assimilation experiments outlined in section 1.3.

1.3 Assimilation Experiments

The experiments are performed for the period from April 1, 2013 to June 15, 2013. They are IFS cycle CY38R2 using incremental 4D-Var, with a 12 hour assimilation window, at T511 horizontal resolution and 137 levels in the vertical.

The control experiment (CONT) uses all observations that were assimilated operationally for this period, plus measurements from Metop-B IASI and ASCAT. The GPS-RO measurements are assimilated with the global error model currently used operationally at ECMWF. The standard deviations of the combined observation/forward model errors are assumed to vary with impact height, which is defined as (h = impact parameter minus radius of curvature). The percentage error is assumed to be 20$\%$ 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 3$\times 10^{-6}$ radians. The errors are assumed to be uncorrelated in the vertical. The 3 microradian lower limit is typically applied above $\sim$ 30 km because of the exponential decay with height of the observed bending angles. The shape of the assumed error statistics profile reflects the information content of the measure.

The percentage errors are smallest in the 10 - 30 km height interval, sometimes called the “core region”. Above 30 km, the percentage errors increase because of instrument noise and residual ionospheric errors. Below 10 km, the assumed errors increase because of horizontal gradient errors and limitations in the forward modelling. The GPS-RO assimilation uses a one-dimensional bending angle observation operator.

The baseline experiment (BASE) is identical to CONT, except that all GPS-RO measurements are “blacklisted”, meaning that they are not actively assimilated. The BAND experiment is the baseline configuration (BASE), plus all non-GRAS GPS-RO measurements in the latitude band between 40 North and 40 South. The 12_MIC experiment is the BAND configuration, plus degraded Metop-B GRAS measurements globally. The Metop-B GRAS measurements are degraded by adding random noise with a standard deviation of 12 microradians to measured values stored in the operational BUFR files. The random noise added is not vertically correlated in the 12_MIC experiment. The assumed error statistics used in the assimilation of the data are modified so that the lower limit of the bending angle errors is increased from 3 microradians to 12 microradians. This affects the assimilation of all bending angles above $\sim$ 20 km. The 6_MIC experiment is the same as the 12_MIC experiment, except that 6 microradian noise is added to the Metop-B GRAS observations. Again, lower limit of the bending angle errors is increased from 3 microradians to 6 microradians when assimilating the data.

In one experiment (HI_WT), the weight given to the Metop-B GRAS measurements has been increased by reducing the lower limit of the assumed bending angle error from 3 microradians to 1.5 microradians. The purpose of this experiment is to account for the fact that the assumed minimum error of 3 microradians used above $\sim$ 30 km at the moment is a conservative estimate, and it is possible that more information could be retrieved from the Metop-B GRAS measurements in the future. No additional noise is added to Metop-B GRAS measurements in this experiment.

The 6_CORR experiment is the same as the 6_MIC experiment, but the noise added to the measurements is vertically correlated. The Metop-B GRAS profiles are composed of 247 thinned bending angle values on a set of fixed impact heights. The correlation function is assumed to be triangular, which is appropriate for a box-car filter. For example, the correlation between the jth and $(j+k)th$ bending angles is assumed to be,

$$C_{j,j+k} = C_{j+k,j} = \mathrm{MAX}\left(\frac{100-\mathrm{k}}{100}, 0.0\right) \tag{1.6}$$

The assumed correlation “width” of 100 samples is based on simple arguments. The time required to measure bending angles with a tangent heights between 60 km and the surface is typically $\sim$ 60 s. MARQ13 consider applying filter windows of order 30 s to the (phase - pseudorange) differences, and this is likely to lead to very broad error correlations in the thinned bending angles provided in the operational BUFR files. Eq. 1.6 may not be an accurate representation of the the actual error correlations that would be produced in the processing, but at the very least it provides a means of testing the sensitivity of the results to error correlations.

The Metop-B GRAS measurements are currently not assimilated below h= 8 km in the northern and southern hemisphere extra-tropics ($ABS(lat) \geq 20°$), and below h = 10 km in the tropics, because the operational processing is still geometrical optics. This means that the impact of Metop-B GRAS in troposphere is probably smaller than would be expected for data processed with wave optics. In addition, the impact of the increased noise should be most evident above $\sim$ 50 hPa in the 12_MIC experiment, and above $\sim$ 30 hPa in the 6_MIC experiment. Consequently, we will focus on the forecast impact in the stratosphere in this study.

1.4 Results

Figure 1.1 shows the zonal mean (CONT-BASE) temperature analysis differences on a set of fixed pressure levels pressure levels from 1000 hPa to 1 hPa, averaged for the final 15 days of the experiment. This provides a clear illustration of how the GPS-RO measurements affect the mean analysis state when all GPS-RO data is available. There are significant differences in the polar regions, and above 10 hPa globally. Healy and Thépaut (2006) noted that the assimilation of the GPS-RO measurements improved a long-standing problem with unphysical structures in the temperature analyses in the polar regions, that were in the null-space of the radiance measurements assimilated at that time. As expected, the removal of GPS-RO measurements in the BAND experiment (Figure 1.2) has an impact on the mean state at higher latitudes, where the much of the structure shown in Figure 1.1 is lost. Similarly, although the bias structure above 10 hPa is reasonably well produced at low latitudes, the agreement is much poorer closer to the poles. The impact of assimilating the noisy, single frequency Metop-B GRAS measurements globally in the 12_MIC and 6_MIC experiments is shown in Figure 1.3 and 1.4, respectively. They both reproduce some of the features at high latitudes shown in the CONT-BASE results, but the size is reduced. For example, the 12_MIC experiment is $\geq$ 0.5 K warmer than the CONT experiment at 5 hPa, north of 50N. The vertical gradients of the temperature biases are not as strong with noisy GRAS data, but as expected in general the 6_MIC experiment produces sharper features than the 12_MIC experiment because the GPS-RO measurements have more weight. This is much clearer in the HI_WT experiment (Figure 1.5), which is the most with the CONT experiment. Overall, this provides evidence that the noisier single frequency data will not have the same ability to constrain the mean temperature state. This may be important in climate reanalysis applications (Poli *et al.* 2010).

The impact of reducing the number of GPS-RO data and/or degrading the quality of the measurements on the short-range (12 hour) forecast fit to radiosonde temperature measurements in the southern hemisphere is shown in Figure 1.6. Comparing the the CONT and BASE experiments, it is clear that the GPS-RO measurements generally improve the bias with respect to the radiosondes, in particular reducing sharp features above 100 hPa that are probably in the null-space of the radiances measurements that are also assimilated. For example, at 10 hPa, the bias 0.23 K lower in the CONT experiment than in the BASE experiment. In general, above 100 hPa the temperature biases are reduced as more weight is given to the Metop-B GRAS measurements in the 12_MIC, 6_MIC and HI_WT experiments. The results at 5 hPa should be viewed with some caution because the sample number (= 113) is an order of magnitude lower than the sample number at 10 hPa (= 1210). It is interesting to note that the GPS-RO measurements do not completely remove the bias in the stratosphere with, for example, the CONT experiment still having a residual bias of 0.47 K at 10 hPa. This probably relates to the null-space of the GPS-RO, because the measurements can correct sharp changes more easily than a bias that gradually increases with height.

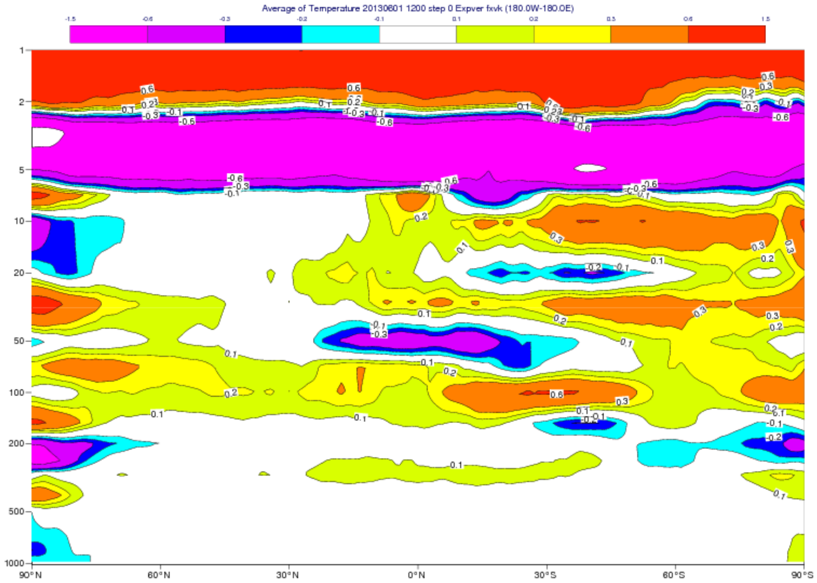

Figure 1.1: Zonally averaged (CONT-BASE) temperature analysis differences (K) on fixed pressure levels (hPa). The average is taken for the period June 1-15, 2013.

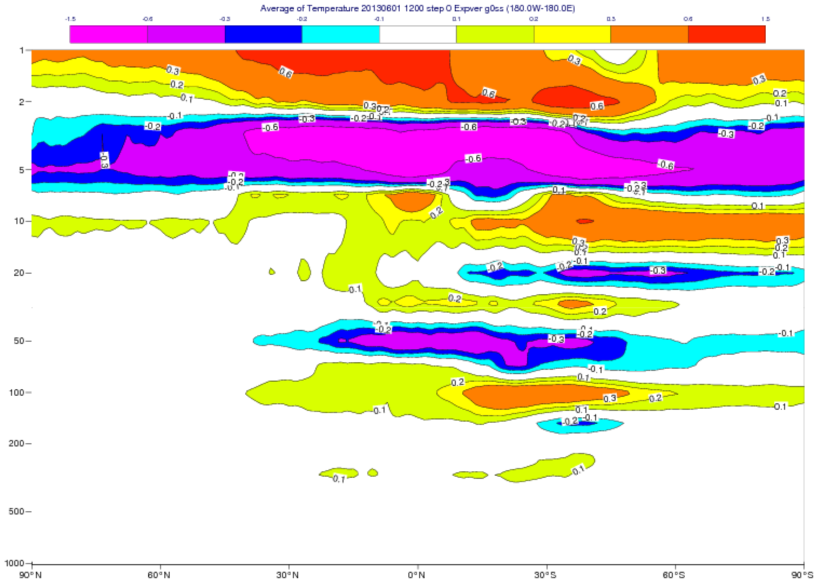

Figure 1.2: As Figure 1.1 but comparing the (BAND-BASE) mean analysis differences.

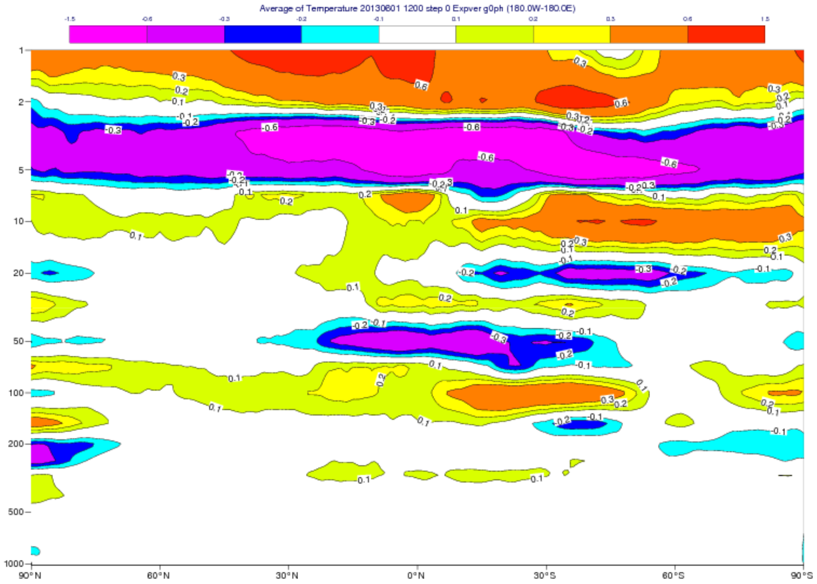

Figure 1.3: As Figure 1.1 but comparing the (12_MIC-BASE) mean analysis differences.

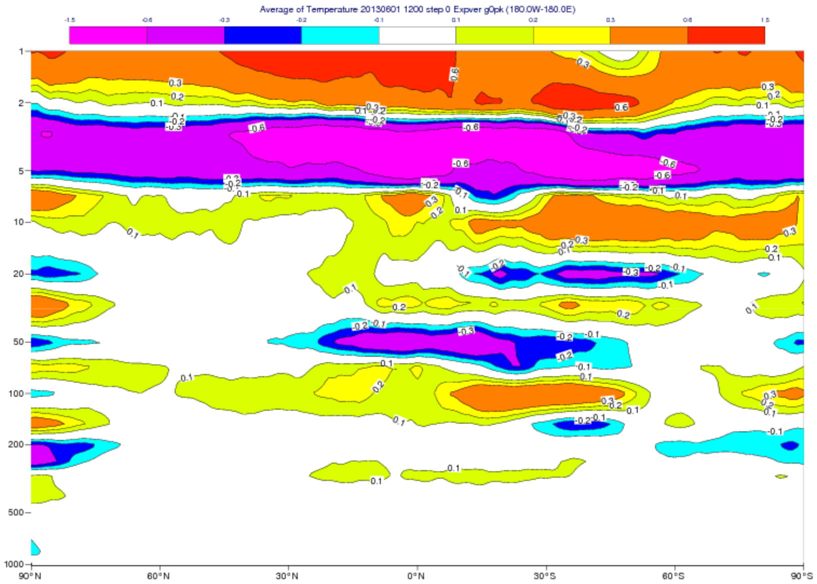

Figure 1.4: As Figure 1.1 but comparing the (6_MIC-BASE) mean analysis differences.

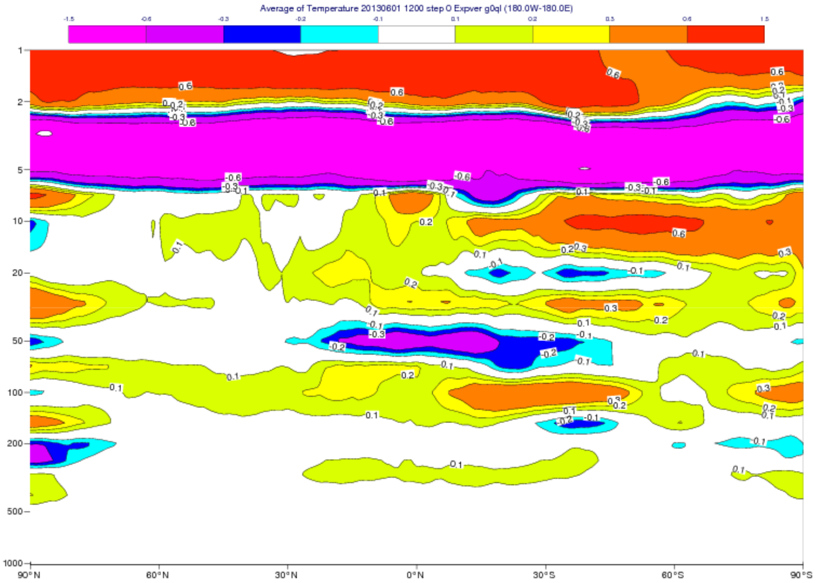

Figure 1.5: As Figure 1.1 but comparing the (HI_WT-BASE) mean analysis differences.

The change in the mean analysis state is also reflected in some of the bias corrections applied to the Metop-B AMSU-A radiances that are assimilated. Figure 1.7 shows the average bias corrections applied in the southern hemisphere for the June 1-15, 2013 period, noting that the channel 14 bias correction is fixed at zero at ECMWF to help anchor the system in the stratosphere. The differences between CONT and BASE experiments are comparable in size to the bias corrections themselves, noting that the size of the biases is of the order several tenths of Kelvin. The largest difference is 0.33 K for channel 13, which peaks near 5 hPa. It is interesting to note that bias corrections used in the BAND, 12_MIC and 6_MIC experiments are quite consistent with each other. In fact, the magnitude of the largest difference between the either the 12_MIC or 6_MIC values and the BAND bias corrections is less than 0.03 K. This seems to indicate that the bias correction model is spreading information outside the $\pm 40^\circ$ band quite effectively, and that the degraded GRAS data is not providing much additional information. This again suggests that the additional structure in the mean temperature analyses shown in Figures 1.3 and 1.4 is in the null-space of the radiance measurements. In contrast, the HI_WT versus BAND bias correction differences are much larger. The bias correction differences for channels 13 and 10 (peaking near 50 hPa) are 0.15 K and 0.1 K, respectively, and the HI_WT experiment is the most consistent with the CONT experiment. There is no general theory of “anchoring”, that defines how many anchoring measurements are required, or how much weight they must have in the NWP system to be effective. However, Figure 1.7 is a clear example of this sensitivity.

The impact of the degraded data on the forecasts has been studied by verifying against observations for the day-1 to day-10 forecast-range. Figure 1.8 shows the fractional difference in root-mean-square (RMS) error for the HI_WT and BAND experiments in the northern hemisphere, for temperatures on the 200, 100, 30 and 50 hPa pressure levels. The error bars show the 95 $\%$ confidence interval. The improvement in the RMS error is $\sim$ 1 $\%$ for the 100 hPa and 30 hPa levels, and 0.5 $\%$ on the 50 hPa, but this improvement is statistically sig-

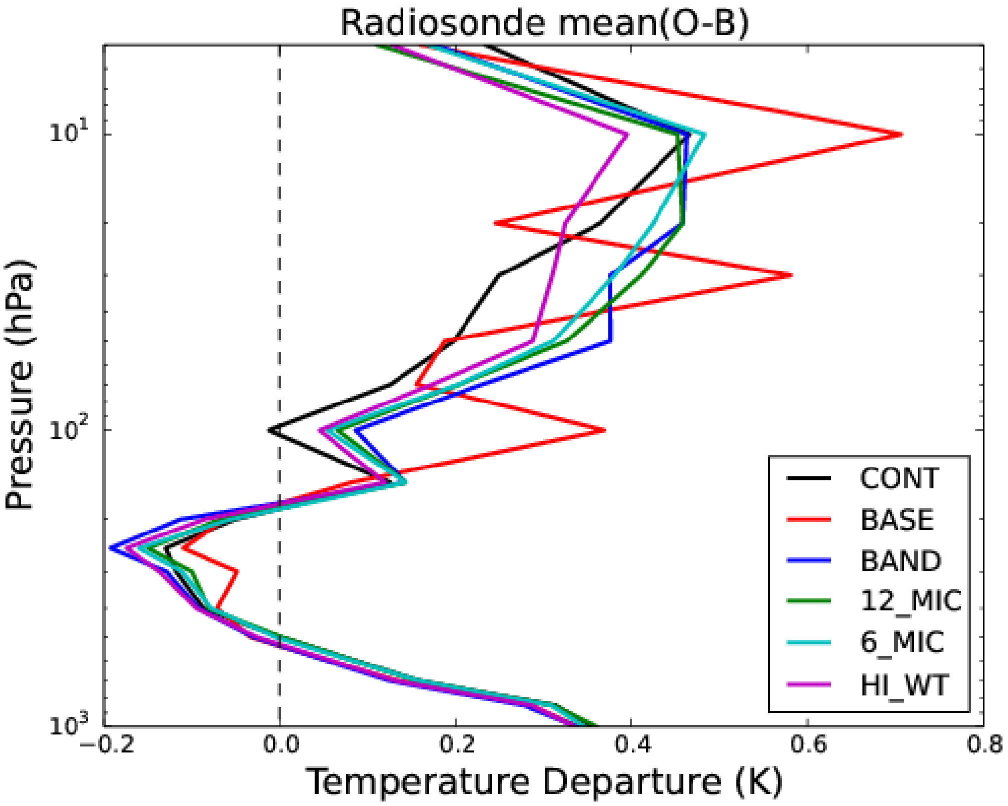

Figure 1.6: The mean (radiosonde minus short-range forecast) temperature differences (K) on pressure levels (hPa). The mean values are computed for the southern hemisphere, for the period June 1-15, 2013

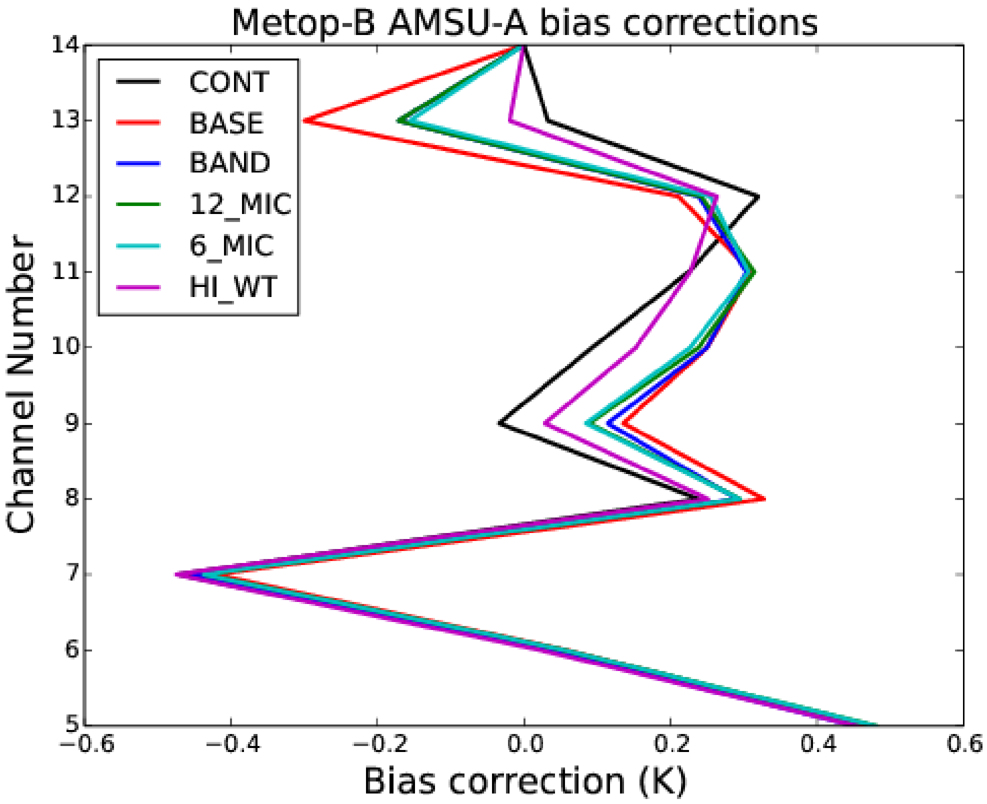

Figure 1.7: The mean bias corrections applied to the Metop-B AMSU-A radiances in the southern hemisphere, for the period June 1-15, 2013. The bias correction of channel 14 is fixed at 0K in all experiments.

nificant only around day-4. These improvements are from reduced biases, and in fact there is no clear improvement in the the standard deviation of the forecast errors on these levels. This demonstrates that the GPS-RO measurements have an impact on stratospheric temperature scores when they are used aggressively assuming a 1.5 microradian minimum standard deviation value. We are now interested in how much information is lost as a result of using the degraded data. Figures 1.9 and 1.10 show the corresponding fractional RMS difference plots for the (6_MIC - BAND) and (12_MIC - BAND), respectively. Both of these experiments produce a similar improvement to the HI_WT experiment at 100 hPa, presumably because bending angles in each experiment have the same weight near this level ($\sim$ 17 km). The additional noise/reduced weight only becomes significant above $\sim$ 26 km in the 6_MIC experiment, and above $\sim$ 21 km in the 12_MIC experiment. The HI_WT 50 hPa temperature forecast errors are slightly better than the 6_MIC and 12_MIC experiments, but the results are not statistically significant. However, at 30 hPa the HI_WT results are clearly superior, with the 6_MIC results being neutral and the 12_MIC results being slightly negative. The climatological height of the 30 hPa levels is $\sim$ 24 km, just below the increased noise in the 6_MIC experiment, but within the region of increased noise in the 12_MIC experiment. In summary, these results show there will be statistically significant degradation of the forecasts at 30 hPa if the measurement noise increases to either 6 or 12 microradians.

One concern noted in section 1.3 was that the additional smoothing required to produce the 6 microradian data should broaden vertical error correlations. Perhaps surprisingly the use of vertically correlated noise, using the triangular correlation function given in eq. 1.6, did not significantly affect the results. Figure 1.11 compares the RMS forecast scores for the for the 6_CORR and 6_MIC experiments. The differences are not statistically significant.

1.5 Discussion and Conclusions

A series of assimilation experiments have been performed in order to estimate the impact of degraded Metop GRAS GPS-RO measurements, produced with a single frequency processing method. The impact of this degradation has been assessed in a worst case scenario where, in addition to all non GPS-RO used in ECMWF operations, only degraded GPS-RO data from Metop-B is available globally. All other non GRAS GPS-RO data confined to a latitude band between $\pm 40^{\circ}$. The aim is to reproduce the situation where measurements from only the first six tropical COSMIC satellites are available.

The Metop-B GRAS measurements have been degraded in two experiments by adding 6 microradian (6_MIC) and 12 microradian (12_MIC) Gaussian random noise to the data on the standard 247 fixed impact heights. The weights given to the measurements in the data assimilation has been reduced in order to be consistent with additional noise levels. The impact of vertical error correlations has been investigated, and the main results do not seem to be sensitive to their inclusion.

In addition, we have performed an experiment where the weight has been increased by assuming the minium standard deviation of the bending angle errors is 1.5 microradians (HI_WT) compared to the 3 microradians currently used at ECMWF. The routine operational monitoring of the departure statistics at ECMWF suggests a more aggressive use of the data in the stratosphere should be investigated, and this reduction would bring the errors used in the assimilation closer to the GRAS instrument specifications. The results presented in

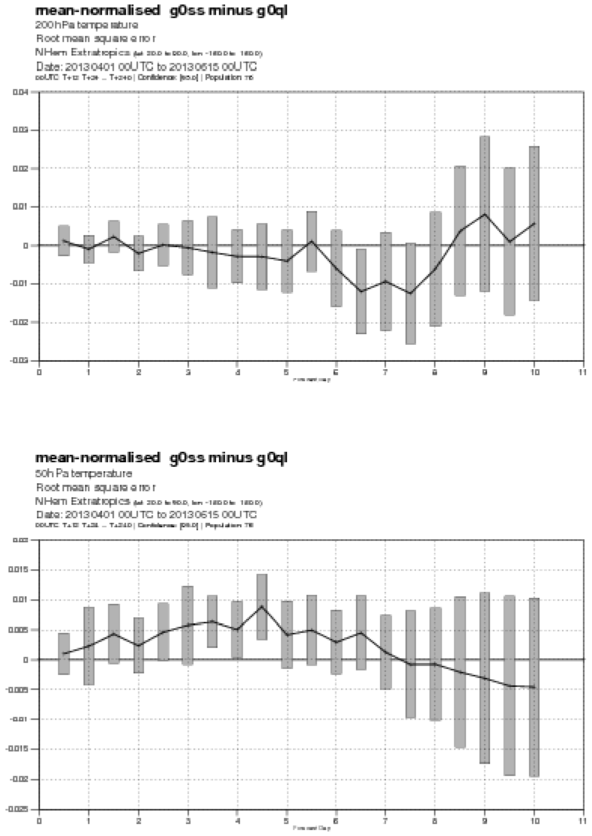

Figure 1.8: The northern hemisphere RMS forecast score differences for temperature on the 200, 100, 50 and 30 hPa pressure levels. They show the fractional improvement in the RMS score for the HI_WT versus the BAND experiments, with a positive value indicating a positive forecast impact. The verification is against radiosonde measurements, and the statistics are computed for the period April 1 - June 15, 2013. The error bars are 95 % confidence interval.

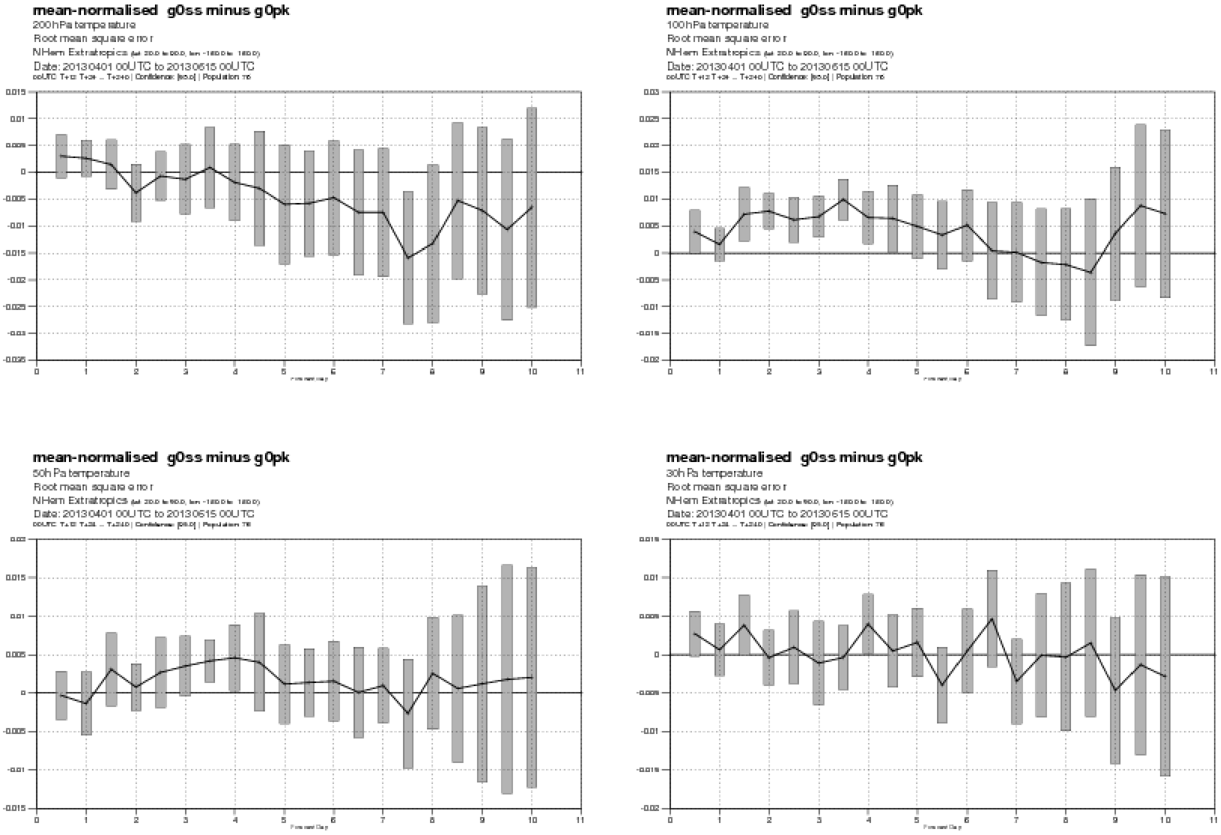

Figure 1.9: As Figure 1.8 but comparing the 6_MIC versus BAND experiments.

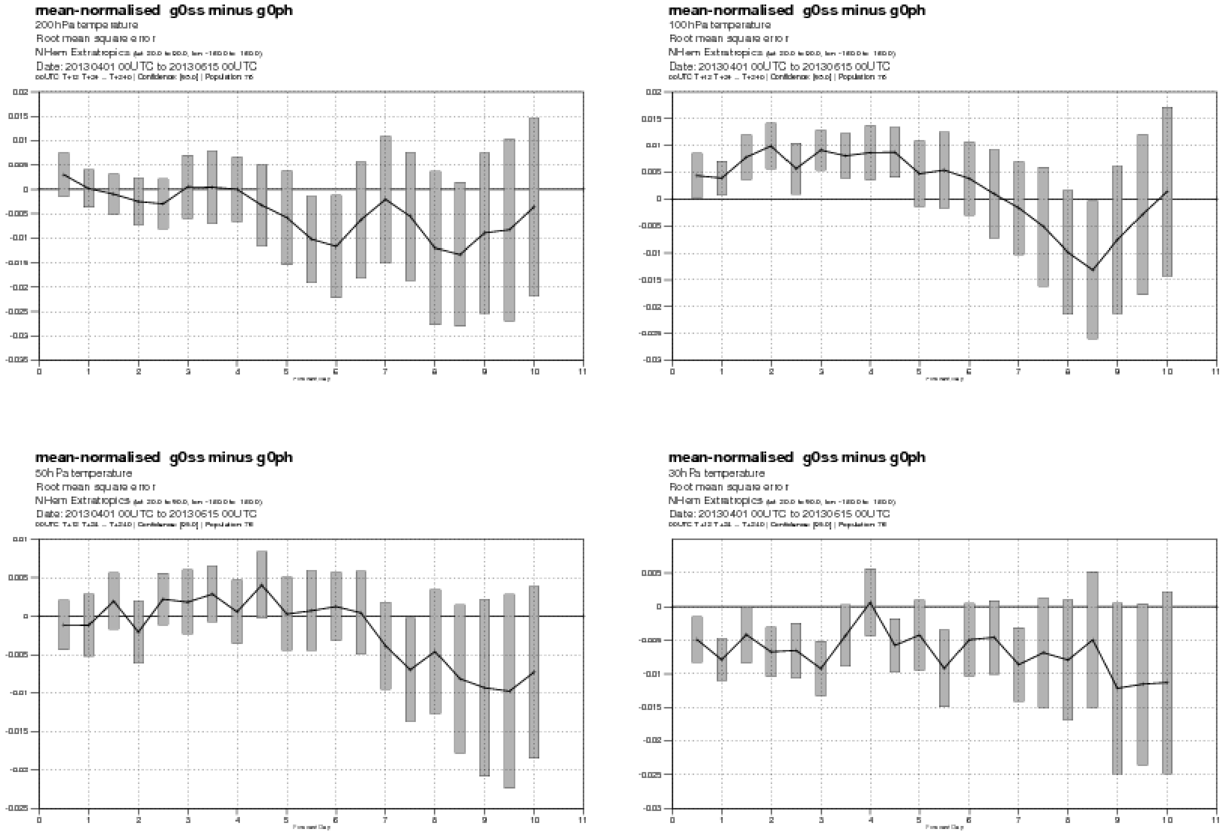

Figure 1.10: As Figure 1.8 but comparing the 12_MIC versus BAND experiments.

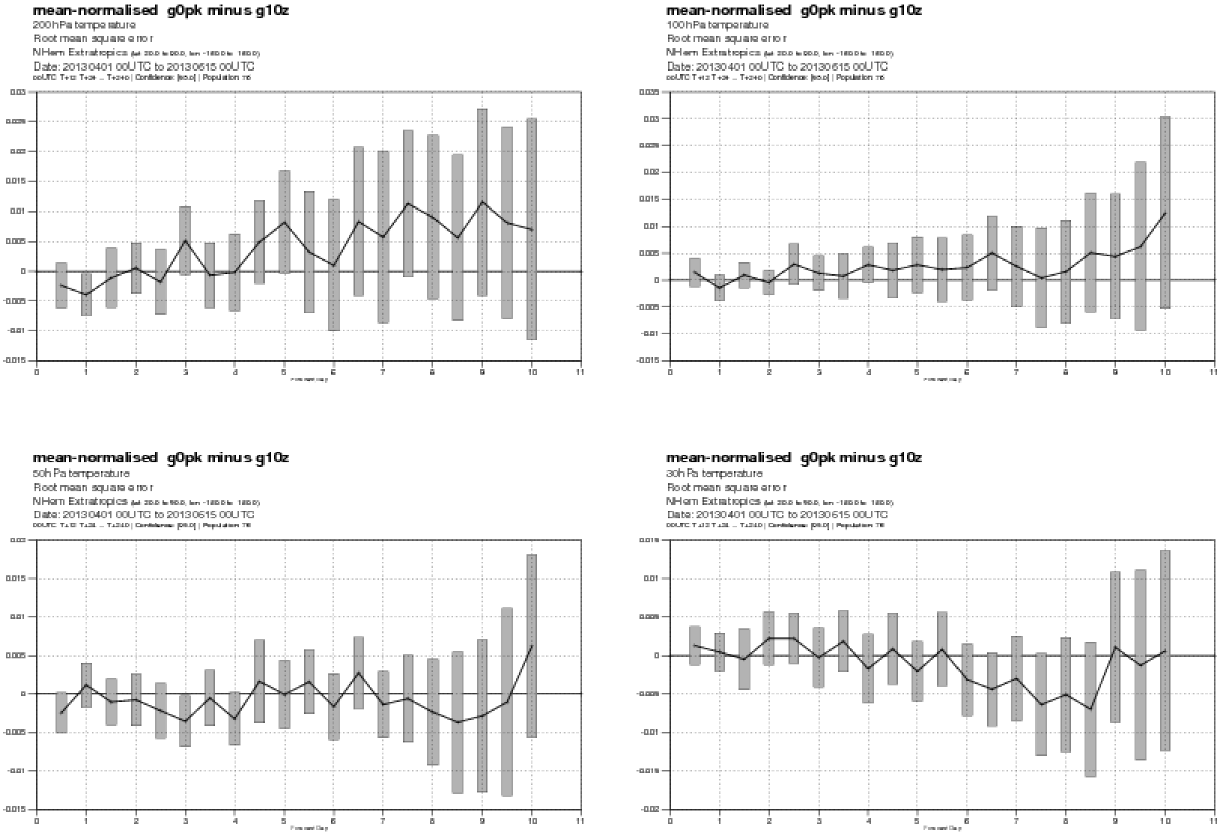

Figure 1.11: The northern hemisphere RMS forecast score differences for temperature on the 200, 100, 50 and 30 hPa pressure levels. They show the fractional improvement in the RMS score for the 6_CORR versus the 6_MIC experiments, with a positive value indicating a positive forecast impact in the 6_CORR experiment. The verification is against radiosonde measurements, and the statistics are computed for the period April 1 - June 15, 2013. The error bars are 95 % confidence interval.

this study would support the case for give Metop GRAS measurements more weight in the assimilation system. For reference, we have also performed experiments using all available GPS-RO data with the current operational error model (CONT), with all GPS-RO blacklisted (BASE), and only using non-GRAS GPS-RO data only with $\pm 40^{\circ}$ latitude band.

The increased noise levels will have the biggest impact in the stratospheric temperatures. There are clear differences in the zonally averaged mean temperature analysis when comparing the 6_MIC and 12_MIC experiments with the HI_WT experiment (Figures 1.1-1.5). The HI_WT experiment is the most consistent with the CONT, where all the available measurements are assimilated. The bias corrections applied to Metop-B AMSU-A radiances in the BAND, 6_MIC and 12_MIC experiments agree to within 0.03 K in the southern hemisphere, suggesting that the noisy measurements are not additional bias correction information relative to that provided in the BAND experiment. However, the HI_WT experiment the channel 13 bias correction differs by $>$ 0.1 K, and it is most consistent with the CONT experiment.

The biases in the short-range stratospheric temperature forecasts increase as the noise is added to the GPS-RO measurements (Figure 1.6). The RMS temperature errors at 30 hPa in the northern hemisphere are $\sim$ 1 $\%$ smaller in the HI_WT experiment than in both the 12_MIC and 6_MIC experiments, for day-1 to day-5 forecast range. This improvement in the RMS is because the biases are smaller. However, note that temperature errors for the three experiments are similar at 100 hPa. This seems reasonable because 100 hPa is below the level where the additional noise is expected to have a significant impact on the bending angle quality.

To summarise, the experiments have demonstrated that a degradation of the GRAS noise levels from $\sim$ 1 microradian to between 6 - 12 microradians would have a noticeable, statistically significant impact stratospheric temperature forecasts above $\sim$ 30 hPa, in a system where other GPS-RO measurements are confined to a $\pm 40^{\circ}$ latitude band. This information is clearly a useful component of any cost-benefit/risk analysis, when assessing the case for modifying the GRAS instrument for the new GPS signals.

For future work, it would be interesting to assimilate real data processed with the single frequency approach in order to check the assumed error models used here. It would also be interesting to see if any of the new ROM SAF Radio Occultation Processing Package (ROPP) ionospheric modelling tools could be adapted for use in the single frequency processing chain.

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