TECHNICAL MEMORANDUM

645

The use of variable CO_2 in the data assimilation of AIRS and IASI radiances

Richard Engelen and Peter Bauer

Research Department

March 2011

European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen

Series: ECMWF Technical Memoranda

A full list of ECMWF Publications can be found on our web site under:
http://www.ecmwf.int/publications/

Contact: library@ecmwf.int

Abstract

An important component of the assimilation of radiance observations from AIRS and IASI is the radiative transfer modelling. Currently, the RTTOV model used in the ECMWF IFS system uses a fixed value for CO_2. Neglecting the spatio-temporal variability of CO_2 introduces an error in the simulation of the satellite radiances, which could affect the quality of the analyses and forecasts. The current assumption is that variational bias correction corrects most of this error and therefore minimizes the impact on the forecast scores. This paper investigates the possibility of modelling CO_2 within the IFS to improve the radiative transfer modelling. Results show that the required bias correction is reduced when using more realisitc CO_2 values. The impact on the analysis quality and forecast scores is mostly neutral with some indication of improvement in the tropics and the stratosphere.

1 Introduction

An important observational constraint in the ECMWF numerical weather prediction system are the thermal infrared radiances measured by the Atmospheric Infrared Sounder (AIRS) and Infrared Atmospheric Sounding Interferometer (IASI) instruments. Through the mechanism of absorption and emission these radiances contain information about the thermal structure of the atmosphere as well as about the concentration of various atmospheric constituents such as water vapour, ozone, and carbon dioxide.

The information extracted by the analysis is obtained from the difference between the observed and simulated radiances that are derived using a radiative transfer model with input from model fields that have been interpolated to observation locations. The ECMWF Integrated Forecast System (IFS) uses the Radiative Transfer for the TIROS Operational Vertical Sounder (RTTOV) model for this purpose. RTTOV (*Matricardi et al.*, 2004) is a fast radiative transfer model using profile-dependent predictors, such as temperature and trace gas concentrations on a fixed pressure grid, to parameterise the atmospheric optical depths. The version of RTTOV used in the operational set-up of the IFS assumes fixed concentrations for the minor atmospheric constituents. In reality, gases like carbon dioxide, ozone, carbon monoxide, and methane show significant variability, both spatially and temporarily. Therefore, spectral channels sensitive to constituents that exhibit strong but unknown spatio-temporal variability are avoided, as is the case for carbon monoxide and methane.

Most information on atmospheric temperature is derived from the large CO_2 absorption complex near $15\mu m$ assuming fixed CO_2 concentrations. However, atmospheric CO_2 concentrations do show significant spatial and temporal variability. *Engelen et al.* (2001) already showed that neglecting these variations could have a significant impact on the quality of temperature retrievals from a single high-spectral-resolution sounder. Figure 1 illustrates the spatial variability of CO_2 by showing the August 2009 zonal-mean cross section as well as the geographical distributions for the ECMWF model levels 20 (ca. 37 hPa), 30 (ca. 210 hPa), and 40 (ca. 585 hPa) of the difference between simulated CO_2 and the value of 377 ppm as used by RTTOV. It is clear that there are significant horizontal and vertical gradients meaning that the current assumption in RTTOV of a well-mixed atmosphere is incorrect. The question therefore arises if this simplification in RTTOV has any impact on the analysis quality and the forecast skill since it must be assumed that a fixed, erroneous CO_2 concentration should alias CO_2 concentration errors into erroneous temperature increments. The atmospheric levels where deviations from the constant value of 377 ppm are large as shown in in Fig. 1 suggest that temperature errors can lead to degraded weather forecasts.

One other factor that plays a role in this study is the variational bias correction (VarBC), which is used to correct systematic differences between the AIRS and IASI observations and the model simulated

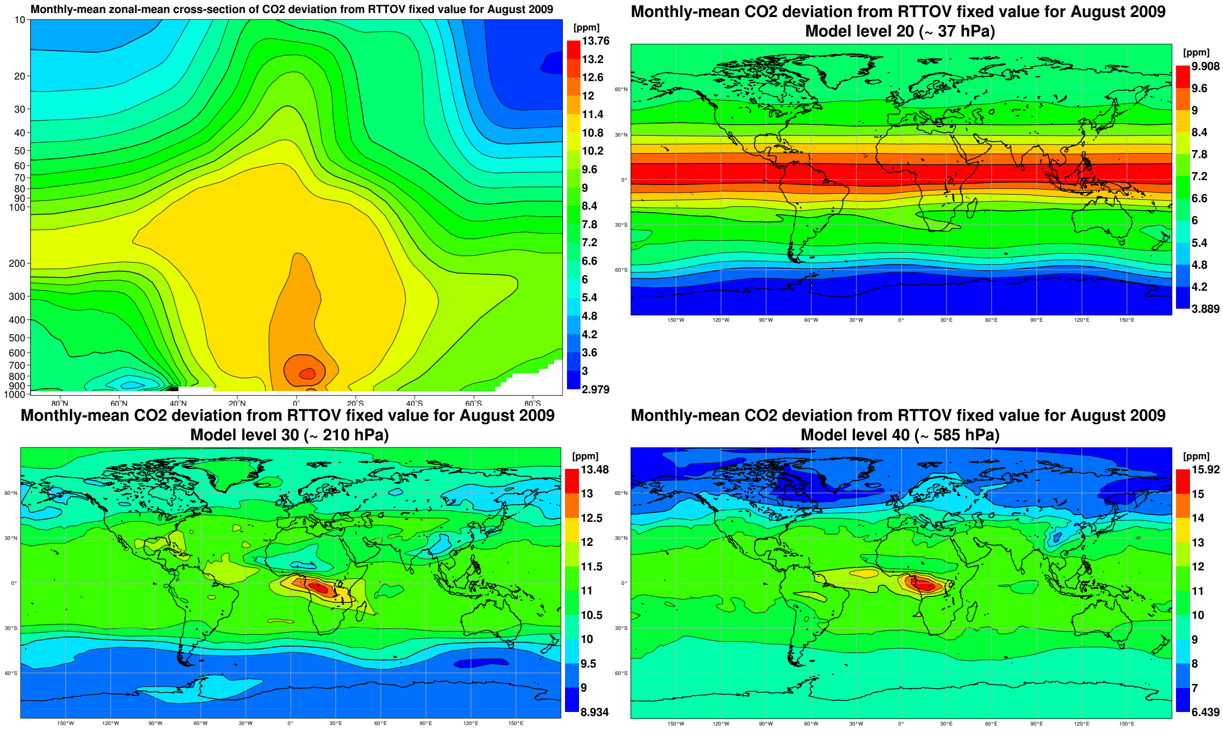

Figure 1: Monthly-mean zonal-mean cross section and geographical distributions for model level 20, 30, and 40 of the CO_2 perturbation relative to a global mean value of 377 ppm for August 2009.

equivalents in the analysis (*Auligne et al.*, 2007). It is very plausible that VarBC is able to correct at least some of the biases that are introduced through the assumption of fixed CO_2 levels by RTTOV. For most CO_2 sensitive AIRS and IASI channels a bias model is used that depends on air mass. Atmospheric CO_2 is significantly correlated with air mass, which was a reason for *Engelen et al.* (2009) not to use VarBC in their CO_2 data assimilation experimentation. While the bias correction using VarBC would minimise the impact of incorrect CO_2 values on analysis and forecast accuracy, it is in principle more desirable to correct the bias at source, through an improvement of the radiative transfer modelling, also accounting for the fact that bias corrections work on large scales and may not provide enough detail to correct for the CO_2 specific contributions. A reduction in the required bias correction by using more realistic CO_2 is therefore a potential improvement to the data assimilation system as well and can serve as a means of validation in this study.

In this study we have simply substituted the fixed value of 377 ppm for the CO_2 concentrations in RTTOV by fully modelled CO_2 values. This allowed to assess the effect of a better representation of CO_2 in the observation operator on the bias correction, the temperature analysis, and the forecast scores. The set-up and results of the experiments are described in Section 2. Section 2.1 describes the details of the experiments; Section 2.2 shows the resulting bias correction change; and Section 2.3 illustrates the impact of the variable CO_2 concentrations on NWP analysis and forecast skill. Section 3 concludes the paper by summarising the main results and by providing further recommendations for study.

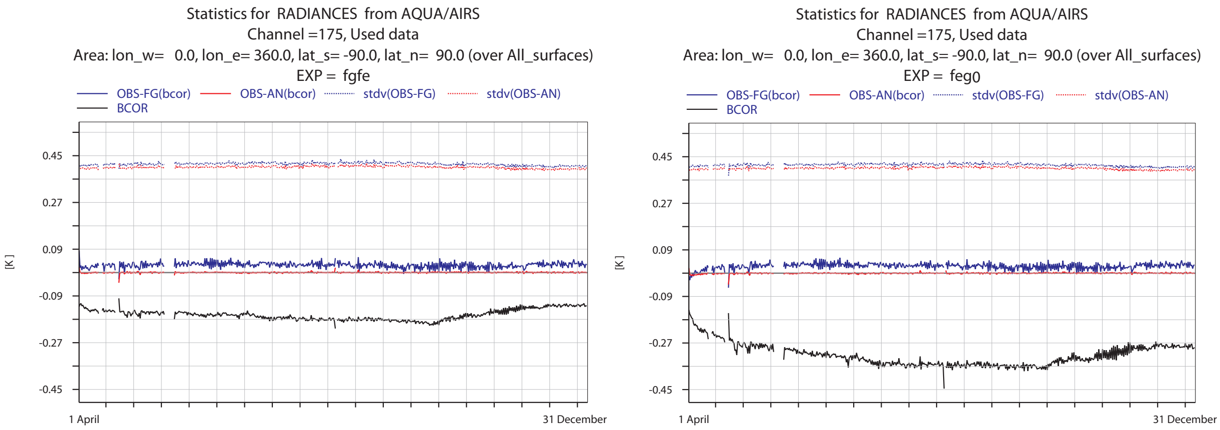

Figure 2: Global mean monitoring statistics for AIRS channel 175 as a function of time for the modelled CO_2 experiment (left) and the control (right). First-guess departures (observation minus model first-guess) are shown in blue, analysis departures (observation minus model analysis) are shown in red, and the calculated bias correction is shown in black.

2 Set-up and Results

2.1 Description of experiments

To investigate the basic idea of using realistic CO_2 values in the radiance assimilation we performed a set of assimilation experiments at spectral wavenumber truncation 159 (about 120 km) and with 60 model levels (T159L60) for the period 1 April 2009 to 31 December 2009. The experiments used a configuration similar to the one used in the Monitoring Atmospheric Composition and Climate (MACC) project (*Engelen et al.*, 2009). This configuration models CO_2 in addition to all the standard IFS variables as a tracer (like water vapour and ozone). CO_2 is advected by the modelled winds and transported vertically by the vertical diffusion and convection parameterizations. Surface fluxes for CO_2 are prescribed according to *Engelen et al.* (2009). The observation operator for the assimilation of the AIRS and IASI radiance observations consists of the RTTOV radiative transfer model as described in *McNally et al.* (2006). For our CO_2 assimilation experiments we applied the methods to include CO_2 as a profile variable in RTTOV that were developed for RTIASI (*Matricardi*, 2003).

Our test experiment (*fgfe*) used the fully modelled CO_2 fields in the radiative transfer modelling, while the control experiment (*feg0*) used fixed values of 377 ppm. The value of 377 ppm is currently used in the operational RTTOV coefficient files. Within the MACC project CO_2 is part of the full control vector in the minimization. In this study we only model the CO_2 values, because *Engelen et al.* (2009) showed that at higher latitudes problems can arise when assimilating temperature and CO_2 at the same time. Existing biases in the IFS stratospheric temperatures can be aliased into unrealistic CO_2 concentrations, which are then transported around to other areas of the globe. Modelling CO_2 without having incremental changes due to the observations was therefore deemed to be the safest way of introducing more realistic CO_2 values in the observation operator.

The first few months of both experiments were needed for spinning up the variational bias correction since the initial fields on the first day of both experiments contain the operational set-up and the bias corrections established with the constant CO_2 fields. This period is thus not used in the following results. Figure 2 shows an example of this spin-up for one of the AIRS channels for the variable CO_2 experiment on the left hand side and the control experiment on the right. Both experiments were initialized with the

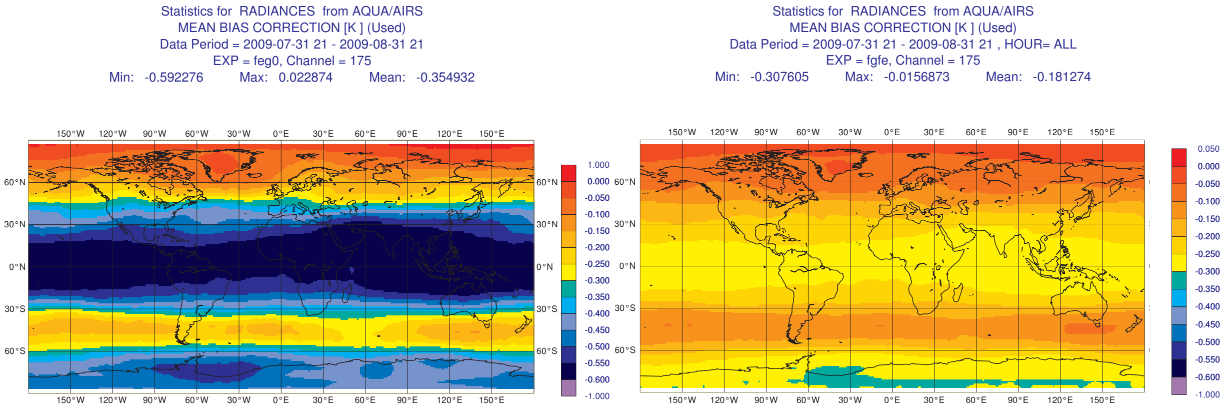

Figure 3: Mean bias correction for August 2009 for AIRS channel 175. The control experiment is shown on the left and the modelled CO_2 experiment is shown on the right.

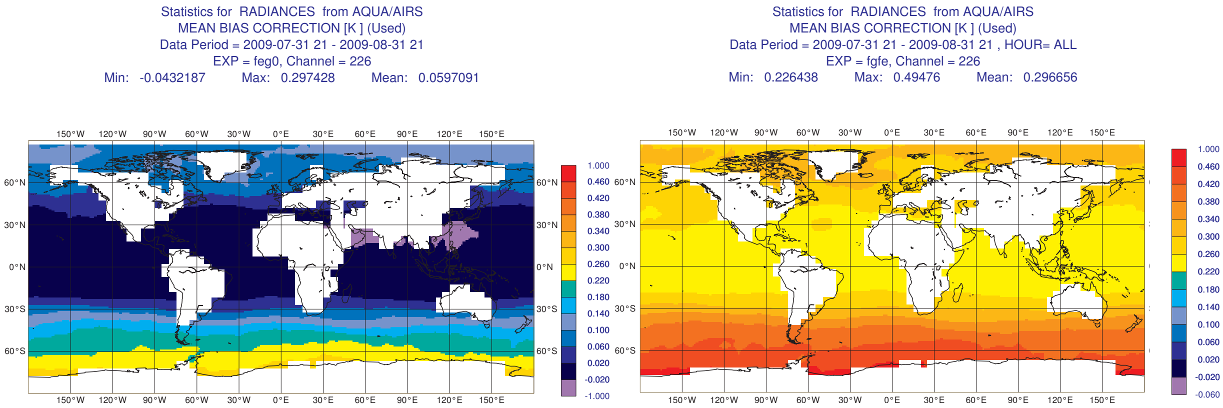

Figure 4: Same as Figure 3 but for AIRS channel 226.

ECMWF operational analysis on 1 April 2009. The channel shown in Figure 2 was among those needing the longest spin-up time. This example illustrates why only the period August-December 2009 has been used in the evaluation.

2.2 Bias correction

We first consider the impact of using realistic CO_2 values in RTTOV on the mean bias correction. Figures 3 and 4 show the mean bias correction for AIRS channels 175 (699.7 cm^{-1}; maximum temperature sensitivity around 200 hPa) and 226 (714.2 cm^{-1}; maximum temperature sensitivity around 700 hPa). The control is shown on the left and the variable CO_2 experiment on the right hand side, over the period 1-31 August 2009. Figures 5 and 6, show similar channels for IASI, namely channels 219 (699.5 cm^{-1}) and 278 (714.3 cm^{-1}). While these channels only show a very small subset of all used channels, they clearly illustrate one of the main results: the global mean bias for each channel does not necessarily become smaller, but the dynamic range of bias corrections does become smaller when CO_2 concentrations are explicitly modelled. This is also illustrated in Figure 7, which shows the change in the absolute value of the global mean bias correction for all AIRS channels in the long-wave CO_2 absorption band (between 600 and 800 cm^{-1}) on the left and the change in the dynamic range of bias values (maximum value minus minimum value) on the right hand side. From these figures it is clear that the global mean bias correction can change in both directions, but the bias correction variability, reflected by the bias correction range,

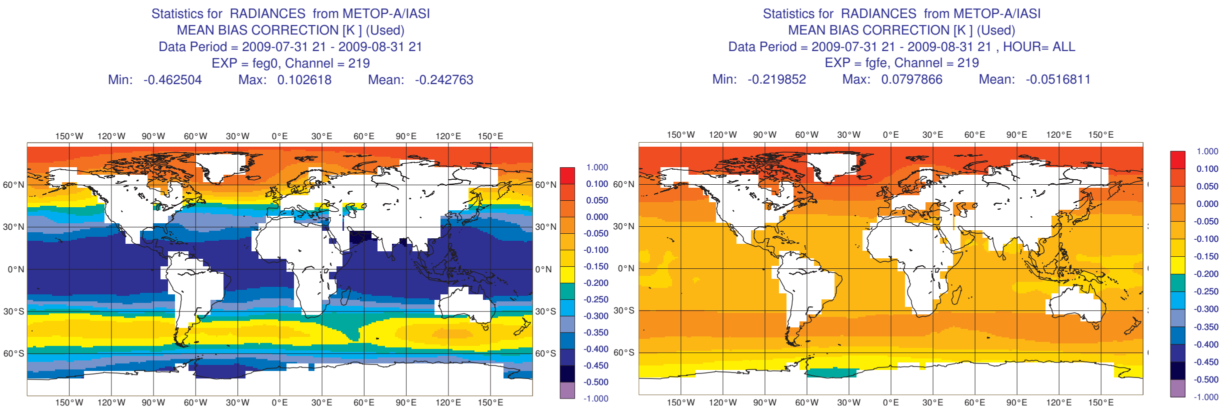

Figure 5: Same as Figure 3 but for IASI channel 219.

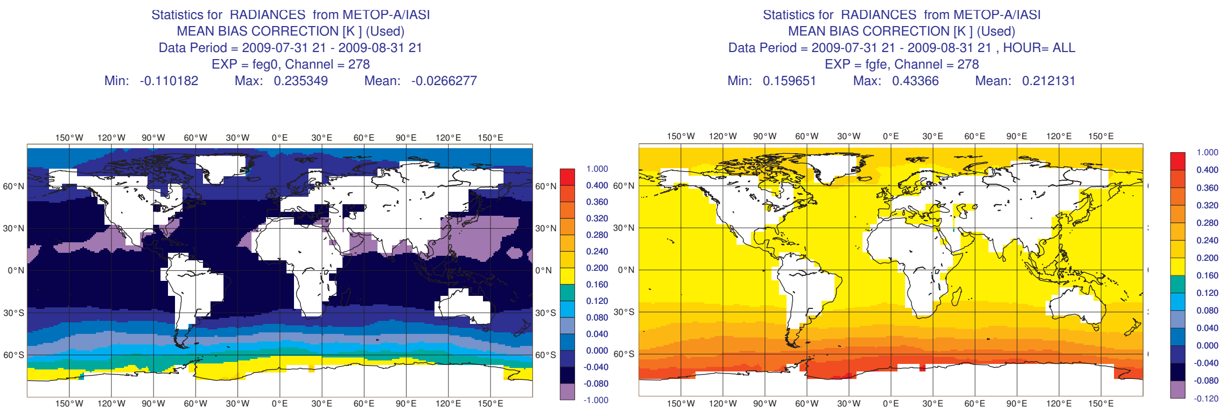

Figure 6: Same as Figure 3 but for IASI channel 278.

becomes smaller for most channels. Because the bias correction depends on various variables, such as spectroscopy errors, model errors, and the here studied CO_2 concentration errors, the global mean bias correction will not necessarily become smaller when more realistic CO_2 values are used in RTTOV. This is because some errors might compensate each other and by reducing one error component, other errors might become more visible. But the fact that the bias correction range has become smaller for almost all channels means that radiances modelled from the first guess fields are closer to the observations so that the bias correction has to perform less work. This also makes the case that a significant portion of the bias correction for AIRS and IASI is explained by incorrect CO_2 concentrations.

2.3 Temperature analysis and forecast scores

The effect on the meteorological analysis is more difficult to assess because the variable bias correction is likely to correct for the bulk of the above errors and the remaining signal may not significantly affect analyses and forecasts. If VarBC would not be able to fully correct the effect of constant CO_2 in the radiative transfer modelling, one would expect an improvement in the temperature analysis by using variable CO_2. However, many factors play a role here, such as data quality control and the remaining bias correction. Figure 8 shows a zonal mean cross section as well as monthly mean geographical fields at model levels 20, 30, and 40, respectively, of the difference between the temperature analysis of the variable CO_2 and control experiments for August 2009. The figure shows patterns that are similar to the CO_2 patterns shown in Figure 1. Largest differences are seen in the tropics, the southern high latitudes,

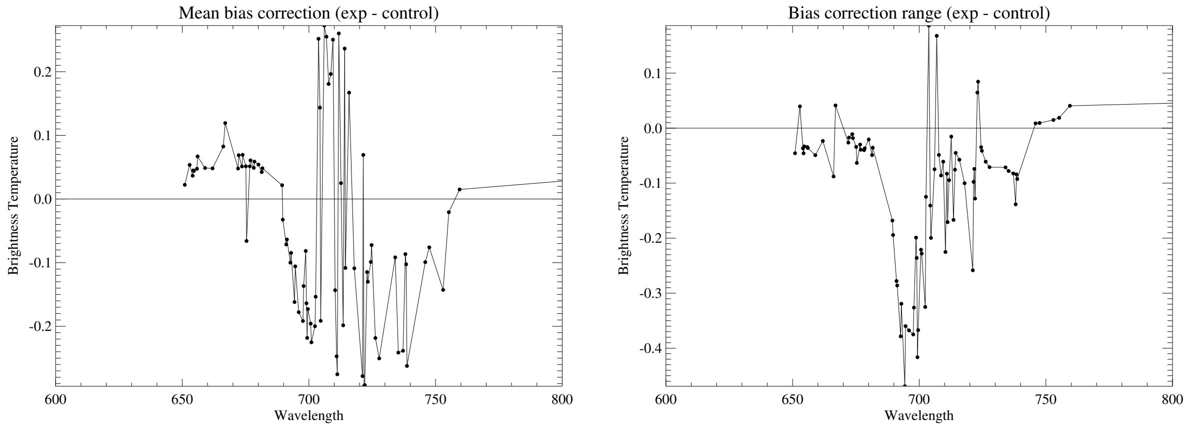

Figure 7: Mean bias correction difference between the CO_2 modelled experiment and the control as a function of spectral wavelength (left) and mean difference in bias correction range as a function of spectral wavelength(right).

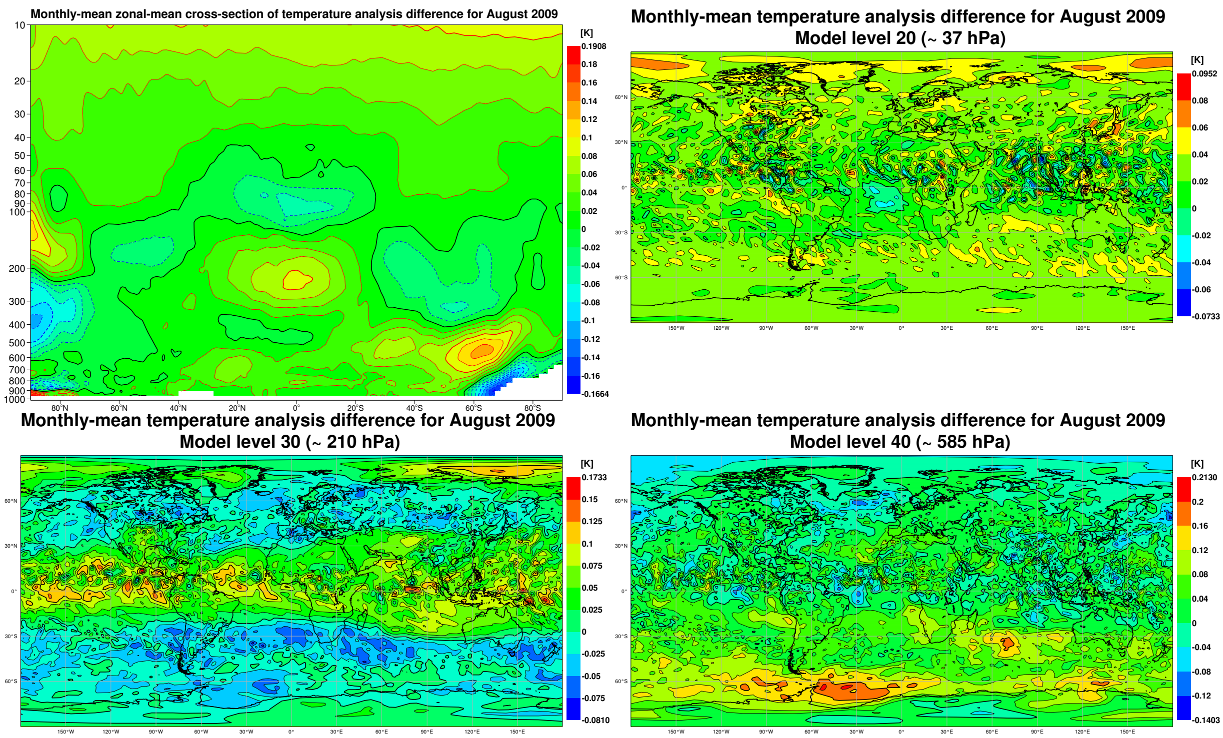

Figure 8: Monthly-mean zonal-mean cross section and geographical distributions for model level 20, 30, and 40 of the T analysis difference for August 2009.

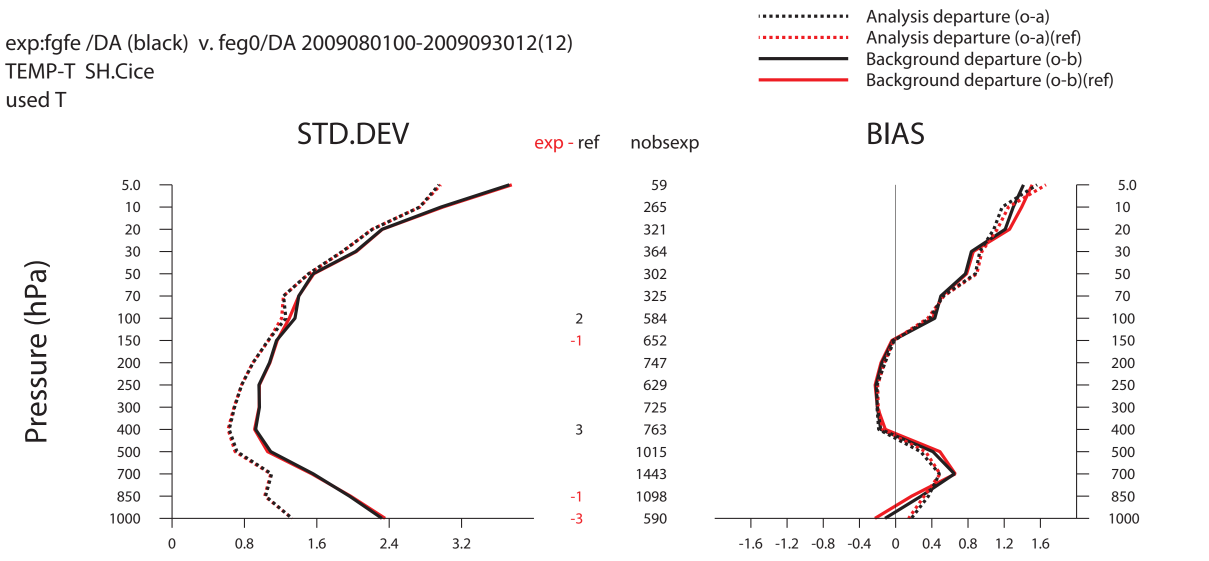

Figure 9: First-guess (background) and analyis temperature departure statistics against radiosonde observations for the area between 90S, 60W and 60S, 20E for the period 1 August to 30 September 2009. The modelled CO_2 experiment is shown in black and the control is shown in red.

and in the upper stratosphere.

Temperature analysis differences at model level 40 show the larger differences over the Southern Ocean, which is partly covered by sea ice. This is also visible in the zonal-mean cross-section, which shows a cooling close to the surface and a warming in the layers above. The figure does not show if these analysis changes are good or bad, however. Verification against radiosonde observations, as shown in Figure 9 for the area 90S, 60W and 60S, 20E, shows only very small differences between the modelled CO_2 experiment and the control, but most of the temperature changes occur over ocean or sea ice where not many radiosondes exist. However, the temperature bias relative to radiosonde observations does decrease in the modelled CO_2 experiment, with a small cooling close to the surface and a slight warming above. The smaller scale structure for model level 40 in Figure 8 is likely caused by the differences in the surface. AIRS and IASI channels sensitive to the surface are not assimilated over land (Antarctica), while the surface emissivity for ice is different from the surface emissivity for ocean water. Combined with the changed CO_2 values these factors will induce slightly diffferent responses in the temperature analysis.

The temperature analysis differences in the upper stratosphere were checked by calculating first-guess and analysis departure statistics for the AMSU-A instruments. Channels 10 to 14 are all sensitive to temperatures in the stratosphere, but not to CO_2 concentrations. The departure statistics therefore provide an independent check on the temperature analysis differences. In the current operational set-up at ECMWF there is no bias correction applied to channel 14, while bias correction of the other channels is calculated with the VarBC method. Figure 10 shows the statistics for the AMSU-A instrument on board of the Aqua satellite for August 2009. All the other AMSU-A instruments show similar results. While the actual bias-corrected first-guess and analysis departures for channels 10 - 13 are not different between the two experiments, the needed bias correction has been reduced significantly. This indicates that the stratospheric temperatures in the modelled CO_2 experiment are more in line witht the AMSU-A observations than those in the control.

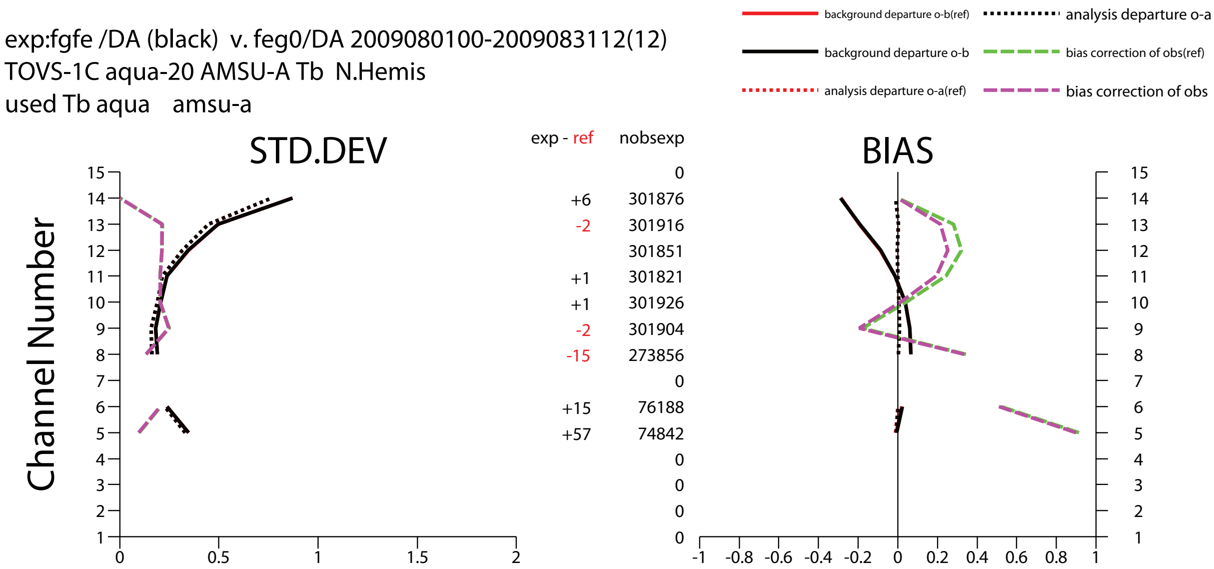

Figure 10: First-guess (background) and analyis brightness temperature departure statistics against AMSU-A observations for the period 1 August to 31 August 2009. The modelled CO_2 experiment is shown in black and the control is shown in red.

When forecast scores for the period 1 August to 30 September 2009 are calculated a neutral impact is found. Figure 11 shows the difference in the 500 hPa geopotential height forecast anomaly correlation between the two experiments for the globe (left) and the northern hemisphere extra-tropics (right). Each experiment has been verified with its own analysis based on the mean analyses differences shown in Figure 8. Beyond day 3-4 this choice should be irrelevant because forecast errors become much larger than the difference between the two analyses. Figure 12 shows the same scores for the tropical 200 hPa (left) and 850 hPa (right) temperature forecast anomaly correlations.

Only the tropical 200 hPa temperature forecast anomaly scores show a significant positive impact at the 95% confidence level. The same scores for the period 1 November to 31 December 2009 show very similar results (not shown). This impact is quite significant given the efficiency of VarBC in removing biases introduced by erroneous CO_2 concentrations. The experiments also demonstrate that the aliasing of CO_2 errors into temperature errors is affecting both analyses and forecasts. The experiments further

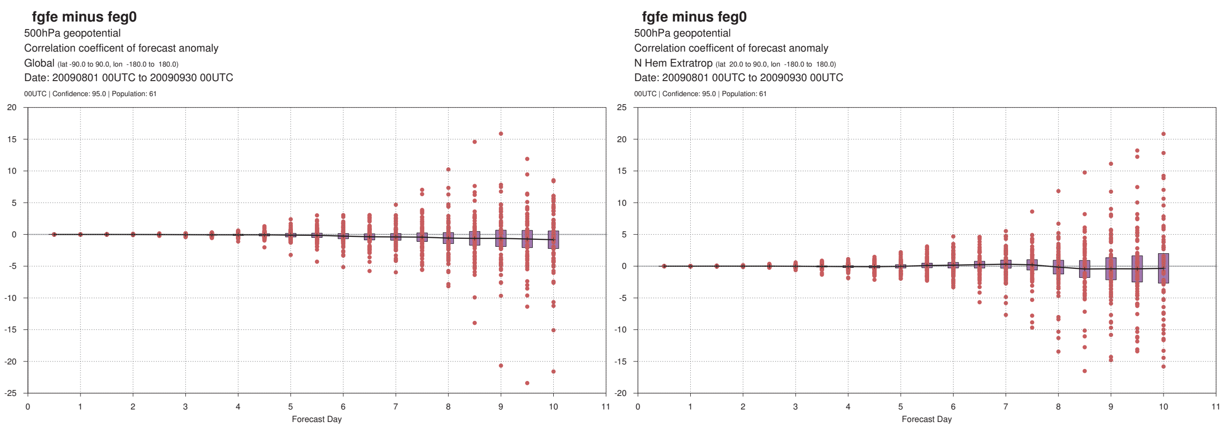

Figure 11: 500 hPa geopotential forecast anomaly scores of the variable CO_2 against the control experiment for the globe (left) and the northern hemisphere (right).

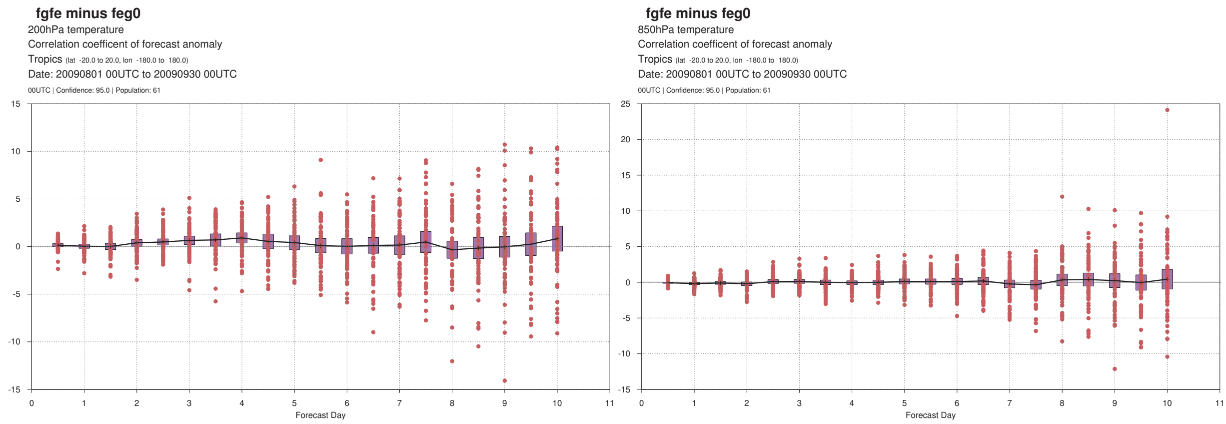

Figure 12: Tropical temperature forecast anomaly scores of the VarCO2 exeriment versus the control for 200 hPa (left) and 850 hPa (right).

demonstrate that the interaction between tracer and temperature lasts into the forecast and that it leaves a signature on the dynamics. Similar mechanisms act on water vapour and dynamics with a shorter life cycle because of very efficient moist physics, but certainly between ozone and temperature in the stratosphere and, potentially, other trace gases with large spatio-temporal variability such as methane and carbon monoxide.

3 Conclusions

An important component of the assimilation of satellite radiance data is the radiative transfer model used in the observation operator. While certain variables are part of the minimisation (such as temperature, humidity, and ozone) and therefore can be changed, other variables are fixed (such as the spectroscopy and the concentrations of minor trace gases). This study assessed the impact of a better representation of CO_2 values in the radiance assimilation of AIRS and IASI on the needed bias correction, the quality of the temperature analysis, and the forecasts scores. Using modelled CO_2 based on the system used within the MACC project reduced the needed bias correction as estimated by VarBC. Global mean bias correction values did not always become smaller, but the range of values defined by the difference between the maximum and the minimum bias correction value did reduce for almost all channels in the CO_2 absorption band. The impact on the temperature analysis is small, but not negligible, especially in the tropics. This was also reflected in the forecasts scores, which are mostly neutral apart from the tropical 200 hPa temperature anomaly scores.

The results presented here suggest that it would be beneficial to replace the current fixed value for CO_2 in the RTTOV radiative transfer model by more realistic values. Although the VarBC bias correction method is capable to correct most of the error related to the assumed CO_2 values, it is preferable to reduce the needed bias correction by introducing more realistic treatment of the true atmosphere. The ECMWF IFS system could benefit here from the developments done as part of the MACC project. Modelling CO_2 requires only one extra tracer in the IFS, which is computationally not very demanding. The most critical aspect of introducing CO_2 is the definition of the surface fluxes. This could very likely be based on the same climatologies as are being used for the MACC delayed-mode system. Any developments within MACC, which is expected to grow into a long-term operational service itself, could be easily introduced in the operational IFS system. Also, any remaining differences between the modelled CO_2 values and the true atmosphere will be corrected by the VarBC system where possible.

References

Auligne, T., A. P. McNally, and D. P. Dee (2007), Adaptive bias correction for satellite data in a numerical weather prediction system, *Q. J. R. Meteorol. Soc.*, *133*, 631–642, doi:10.1002/qj.56.

Engelen, R. J., G. L. Stephens, and A. S. Denning (2001), The effect of CO_2 variability on the retrieval of atmospheric temperatures, *Geophys. Res. Lett.*, *28*, 3259 – 3262.

Engelen, R. J., S. Serrar, and F. Chevallier (2009), Four-dimensional data assimilation of atmospheric CO_2 using AIRS observations, *J. Geophys. Res.*, *114*, D03303, doi:10.1029/2008JD010739, doi:10.1029/2008JD010739.

Matricardi, M. (2003), RTIASI-4, a new version of the ECMWF fast radiative transfer model for the infrared atmospheric sounding interferometer, *Technical memoranda*, ECMWF, 425.

Matricardi, M., F. Chevallier, G. Kelly, and J.-N. Thépaut (2004), An improved general fast radiative transfer model for the assimilation of radiance observations, *Q. J. R. Meteorol. Soc.*, *130*, 153–173, doi:10.1256/qj.02.181.

McNally, A. P., P. D. Watts, J. A. Smith, R. Engelen, G. A. Kelly, J.-N. Thépaut, and M. Matricardi (2006), The assimilation of AIRS radiance data at ECMWF, *Q. J. R. Meteorol. Soc.*, *132*, 935–957, doi:10.1256/qj.04.171.