TECHNICAL MEMORANDUM

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Assimilation of MIPAS limb radiances in the ECMWF system. Part I: Experiments with a 1-dimensional observation operator

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Abstract

Emitted infrared limb radiances from the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) are for the first time assimilated directly in a global Numerical Weather Prediction system, using a fast radiative transfer model that assumes local horizontal homogeneity. The study reports on the monitoring of the observed MIPAS radiances against model equivalents, and the subsequent assimilation experiments within a 4-dimensional variational data assimilation system. The impact of the limb radiance assimilation on the resulting analyses and forecasts is assessed by considering the fit to other observations assimilated in the system and by comparing the resulting analyses with independent data.

The results demonstrate the feasibility of direct assimilation of emitted infrared limb radiances and highlight how information on stratospheric temperature, humidity, and ozone can be extracted from the radiances directly within the assimilation system. The assimilation of MIPAS radiances leads to considerable differences in the mean stratospheric analyses, without a significant degradation of the fit to other observations used in the assimilation. The assimilation of MIPAS limb radiances appears to correct temperature biases with an oscillatory structure above 10 hPa in the analyses, and the assimilation leads to a considerable moistening of the stratosphere, typically by 20-40 %. For ozone, the assimilation causes an increase in the tropical ozone maximum in the analysis, and a reduction of ozone over the poles. The changes to the humidity and ozone fields are retained in the subsequent 10-day forecast.

The changes introduced in the analyses are overall supported qualitatively and quantitatively by independent retrievals of temperature and humidity, whereas results for ozone are more mixed. Analyses with MIPAS radiances agree better with independent ozone sondes or retrievals over the North Polar region, whereas over the tropics the changes to the mean ozone analyses are not supported by other observations. The limb radiance assimilation shows considerable sensitivity to the bias correction applied to the limb radiances prior to the assimilation, suggesting that the assimilation would benefit from refinements in the bias correction method.

1 Introduction

This memorandum reports on experiments with direct assimilation of infrared limb radiances from the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) onboard the Envisat satellite (Fischer and Oelhaf 1996). It is the first time that limb radiances are directly assimilated into a Numerical Weather Prediction (NWP) model. In its original configuration, the MIPAS instrument is an interferometer with very high spectral resolution (0.025 cm^{-1} unapodised, equivalent to 59,604 spectral points, subsequently referred to as channels). It provides limb radiances in the tangent height range 6-68 km (in the nominal scanning configuration) with a field of view at the tangent point of 3 km in the vertical and 30 km in the horizontal (perpendicular to the viewing plane). The MIPAS radiances are assimilated with a view to obtain temperature, humidity, and ozone information in the upper troposphere to lower mesosphere region.

Information from MIPAS has been assimilated before into NWP or chemical transport models (CTM) in the form of retrieved profiles. Mostly, this has been confined to the assimilation of ozone retrievals, whereas the humidity or temperature retrievals have been assimilated less. For example, Dethof (2003) reports on the assimilation of near real-time MIPAS ozone profiles within the ECMWF system and notes improvements in the development of the ozone hole over Antarctica in the analyses and an improved fit to ozone sondes not used in the assimilation. Wargan et al. (2005) have assimilated MIPAS ozone profiles within the CTM of the National Aeronautics and Space Administration (NASA), and also found improved fits to independent ozone sondes and other independent ozone retrievals. Geer et al. (2006) report on assimilation of MIPAS ozone profiles in a range of European assimilation systems.

The developments to directly assimilate emitted clear-sky limb radiances from MIPAS have been prompted by the success of the assimilation of nadir radiances. In radiance assimilation, the radiance observations are directly used in the analysis scheme, rather than separately retrieved profiles of atmospheric variables (e.g., Andersson et al. 1994, McNally and Vesperini 1996). This typically requires a 3-dimensional or 4-dimensional variational assimilation system (3DVAR or 4DVAR, e.g., Rabier et al. 2000), and employs a fast radiative transfer model in the analysis, to provide the link between the model variables and the radiance observations (e.g., Saunders et al. 1999). Radiance assimilation has a number of advantages (e.g., Eyre et al. 1993), most notably: the radiances are used together with all other observations and the latest background information, combining the best possible information to perform an analysis/retrieval. Also, the assimilation does not need to account for *a-priori* information or other assumptions used in the retrieval step which can lead to complicated error and bias characteristics in the retrieved profiles. As a result, the specification of observation errors is usually considered easier in radiance space than in retrieval space. Given these advantages, most major NWP centres are now assimilating information from infrared or microwave sounders or imagers in the form of radiances rather than retrievals.

Of course radiance assimilation has its own challenges. One issue is the finding that model-simulated and observed radiances almost always show systematic deviations or biases (e.g., Harris and Kelly 2000). Some of these may be due to biases in the model fields. However, a large proportion of the bias is most commonly attributed to so called “radiance biases”, i.e., biases in the spectroscopy, in the assumed concentrations of well-mixed gases, or in the instrument characterisation. The presence of such radiance biases is particularly well-established for channels which sound the well-observed troposphere. Radiance biases need to be corrected prior to the assimilation, as the assimilation system assumes unbiased observations. A range of methods has been developed over the years, including the use of regression models of First Guess (FG) predictors (e.g., Harris and Kelly 2000), or the so-called γ/δ method (e.g., Watts and McNally 2004) which employs scaling factors for the optical depths. Another challenge in radiance assimilation is that the errors inherent in the radiative transfer model used in the assimilation introduce spectrally and spatially correlated errors. These are difficult to quantify and add a component to the observation error that is difficult to handle in the assimilation (e.g., Sherlock 2000). As a result, correlated errors are frequently ignored, and inflated uncorrelated observation errors are used (e.g., McNally et al. 2006). All of these challenges will otherwise be encountered in the retrieval process, but for some of them more sophisticated solutions may be available or feasible in a separate retrieval step.

The present study also covers a range of other new aspects, in addition to being the first about direct assimilation of limb radiances. The assimilation of humidity information in the stratosphere has only recently become possible in the ECMWF system through developments by Hólm et al. (2002) regarding a new humidity control variable which accounts for the large variability of humidity in the atmosphere. Our study is one of the first to make use of these developments for the assimilation of stratospheric humidity information from radiances or retrievals. In addition, assimilation of ozone information at ECMWF has so far been based on assimilating retrievals. Nadir radiances sensitive to ozone such as High-resolution Infrared Sounder (HIRS) channel 9 or a range of Atmospheric Infrared Sounder (AIRS) channels are excluded from the assimilation. This is for a number of reasons, such as problems with modelling the surface contribution in the radiances, a lack of confidence in the formulation of background errors for ozone, and to avoid aliasing of errors in the poorly constrained ozone FG into the temperature analysis.

The structure of the report is as follows: We first outline the methodology used to assimilate MIPAS limb radiances and describe the MIPAS data used in this study. This is followed by a summary of our experience from passive monitoring of MIPAS radiances, and the development of a correction of MIPAS radiance biases. We then discuss in detail the analysis and forecast impact. This includes a comparisons of analyses with and without MIPAS radiances to independent data, and a sensitivity study regarding the bias correction applied to MIPAS radiances. Finally, a summary of findings and our conclusions are given in the last section.

2 Methodology and data

2.1 Radiance assimilation concept

The concept of radiance assimilation with variational data assimilation systems has been described extensively elsewhere (e.g., Lorenc 1986, Eyre et al. 1993, Andersson et al. 1994), and here we recall only the main points. Variational assimilation systems aim to minimise a cost-function $J(\mathbf{x})$ with respect to the atmospheric state $\mathbf{x}$. The cost-function measures the misfit of $\mathbf{x}$ to the background state and the observations, and if the errors in both are Gaussian and unbiased, the cost function becomes:

$$J(\mathbf{x}) = (\mathbf{x}-\mathbf{x}_B)^T\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_B)+(\mathbf{y}-\mathbf{H}(\mathbf{x}))^T\mathbf{R}^{-1}(\mathbf{y}-\mathbf{H}(\mathbf{x})) \qquad (1)$$

Here, $\mathbf{x}_B$ is the background state with its error covariance $\mathbf{B}$, $\mathbf{H}$ represents the observation operator or forward model which links the atmospheric state $\mathbf{x}$ to the observations $\mathbf{y}$. $\mathbf{R}$ is the error covariance for the observations, and it includes the error in the observation operator.

The above framework also allows the direct assimilation of observations which are linked to model fields indirectly through sophisticated observation operators such as a radiative transfer model. For radiance assimilation, $\mathbf{H}$ incorporates a fast radiative transfer model, the spatial interpolation to the observation location, and - in case of 4DVAR - also the forecast model integration from the time associated with $\mathbf{x}$ and $\mathbf{x}_B$ to the observation time.

The minimisation of J is usually performed iteratively, using a gradient descent algorithm. The gradient is typically calculated using the adjoint method (e.g., Thépaut and Moll 1990).

2.2 Assimilation system and experiments

The experimentation with the assimilation of MIPAS radiances is performed with the ECMWF 4DVAR system (Rabier et al. 2000). The assimilation scheme is incremental 12-hour 4DVAR, with an analysis resolution of T159 ($\approx$ 125 km), a model resolution of T511 ($\approx$ 40 km), and 60 levels in the vertical up to 0.1 hPa. Ozone and humidity are advected using a semi-lagrangian transport scheme in the forecast model. Ozone chemistry is parameterised using version 1.2 of the Cariolle scheme (Cariolle and Déqué 1986), including a heterogeneous depletion term. An ozone climatology (Fortuin and Langematz 1995) is used in the radiation scheme. For humidity, a simple parameterisation accounts for the water vapour source due to stratospheric methane oxidisation, and for water vapour loss through photolysis in the mesosphere.

The assimilation system is based on that used operationally in autumn 2005, with the modifications as follows: the experimental stratospheric humidity analysis is activated, following the work of Hólm et al. (2002). The control variable is normalised relative humidity, reducing to normalised specific humidity in the stratosphere. The formulation of the background error is that used operationally in 2003 for all variables.

Two assimilation experiments are discussed here: in the control experiment (CTL) MIPAS data are passively monitored, but not assimilated. In the RAD experiment, MIPAS radiances are actively assimilated as described in the following subsection. Both experiments cover the 43 day period 18 August - 29 September 2003, and 10 day forecasts were performed for each 0 UTC analysis.

Other assimilated observations in both experiments are based on the operational data selection in autumn 2005, with following modifications: Global Positioning System (GPS) radio occultation (RO) bending angles from CHAMP were assimilated with a 1-dimensional observation operator. These data have been shown to correct temperature biases in the analyses for the upper troposphere/lower stratosphere region (Healy and Thépaut

2006). Also, data from 4 Atmospheric Microwave Sounding Unit (AMSU)-A instruments are used in the analysis, from NOAA[1]-15, 16, 17, and from the AMSU-A on the Aqua satellite. For ozone, the only other data assimilated are retrievals from the Solar Backscatter Ultra Violet (SBUV) instrument onboard NOAA-16, and only data with solar zenith angles less than 84°are considered. The SBUV data provide profile in formation in 12 layers, but these are combined to 6 layers for the assimilation (0.1-1 hPa, 1-2 hPa, 2-4 hPa, 4-8 hPa, 8-16 hPa, 16 hPa-surface).

2.3 Assimilation of MIPAS radiances

The observation operator for the limb radiance assimilation is the fast radiative transfer model RTMIPAS (Bormann et al. 2005). RTMIPAS uses regression models for the effective layer optical depths to calculate convolved transmittances, and these regression models have been derived from line-by-line calculations for a set of diverse profiles. The approach is similar to that of RTTOV which is commonly used in the assimilation of nadir radiances (Saunders et al. 1999, Matricardi et al. 2001). RTMIPAS takes into account the effects of variable humidity and ozone, and uses a fixed climatology for all other relevant atmospheric gases. The model assumes local thermal equilibrium and a cloud-free atmosphere. Validation against line-by-line radiances for a profile set not used in the derivation of RTMIPAS show that the error introduced by the fast parameterisation is well below the noise level of the MIPAS instrument for most channels and tangent altitudes. More details can be found in Bormann et al. (2005). The radiative transfer calculations consider layers of the atmosphere up to 0.0037 hPa, and to extrapolate above the top of the forecast model (0.1 hPa) we hold humidity and ozone constant and use a fixed mesospheric lapse rate for temperature.

Tangent pressure information for the forward calculations is fixed during the assimilation, and level-2 tangent pressures are used instead of the level-1 engineering pointing information. The level-2 tangent pressures are used as considerable errors and biases have been found in the engineering pointing information for MIPAS (von Clarmann et al. 2003). This approach of handling the tangent altitude information has some disadvantages: it introduces an undesirable dependence on the level-2 data, and errors or biases in the retrieved tangent pressure will create spectrally correlated errors or biases in the forward calculations. Alternatively, the tangent altitude could be retrieved in a pre-processing step or it could be included as a control variable in the main analysis. We have pursued neither of these options, as they were considered beyond the scope of this first implementation of limb radiance assimilation.

The quantity assimilated in our experiments is radiances, instead of brightness temperatures mostly used in nadir radiance assimilation. This was found more appropriate for the specification of observation errors. Observation error covariances are assumed to be diagonal, with the errors set to 4 times the MIPAS instrument noise reported for the well-studied orbit 2081 (see Bormann et al. 2005 for a display of the instrument noise used). The observation error includes contributions from measurement error and errors in the forward model, and a somewhat larger value has been chosen to reduce the effects of neglected correlated observation errors. Such a conservative choice is consistent with approaches taken for nadir radiance assimilation (e.g., McNally et al. 2006). Radiance observations are considered erroneous outliers when they differ from the FG equivalents by more than 5 times the expected standard deviation of the departures, and such outliers are removed from the assimilation. Variational quality control is also applied (Andersson and Järvinen 1999). Our approach to correcting MIPAS radiance biases is described in section 3.2.

[1]National Oceanic and Atmospheric Administration

2.4 Assimilated MIPAS radiance data

The assimilation considers only radiances from 325 selected single-channel microwindows of MIPAS data[2]. The necessity to select a subset arises as it is currently technically unfeasible to assimilate all MIPAS channels, and because many channels are sensitive to atmospheric constituents whose concentrations are only poorly known or which are not part of our control variable. The selected subset is the same as used in Bormann and Healy (2006) and the wavenumbers as a function of channel index are shown in Fig. 1. The set has been selected using the method of Dudhia et al. (2002) which iteratively grows microwindows which maximise information content of the set of selected radiances relative to the estimated error in the *a priori* data. The method uses linear theory to estimate the retrieval error, given estimates for the error in the *a priori* data, the instrument noise, and error estimates from so-called systematic errors. The systematic errors include uncertainties or assumptions in the radiative transfer model, such as uncertainties in the spectroscopic data, neglecting the variability of certain gases, uncertainties in the instrument line shape, etc. The 325 single-channel microwindows have been chosen for a simultaneous derivation of temperature, humidity, and ozone information. The estimate for the ECMWF background error covariance matrix served to define the error in the *a priori* data, and in-flight values for orbit 2081 were used to specify the MIPAS apodised instrument noise. For further details on the channel selection the reader is referred to Dudhia et al. (2002) and Bormann and Healy (2005). The theoretically-based data selection was subsequently revised after practical experience from radiance monitoring against the FG used in the assimilation as described below. All MIPAS data used in this study have been taken from the version 4.61 reprocessed MIPAS dataset.

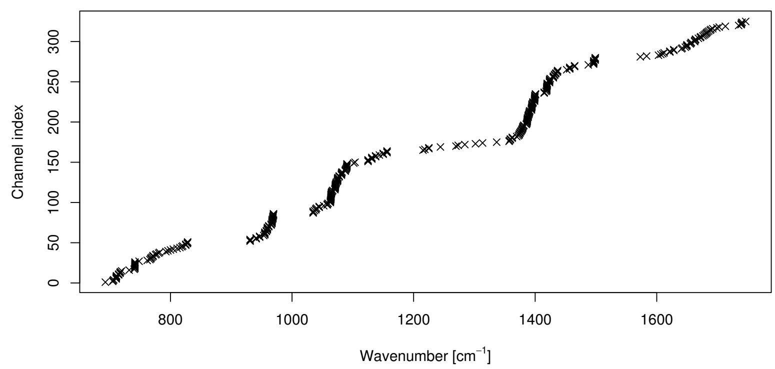

Figure 1: Wavenumbers [cm^{-1}] for the selected channels.

Cloud screening is performed based on the approach of Spang et al. (2004) and an additional threshold check on the clearest MIPAS channel (radiance in the 960.700 cm^{-1} channel below 100 nW/(cm^2 sr cm^{-1}); Dudhia 2004, pers. communication). Also, data with considerable sensitivity to layers above the top of the assimilation system (0.1 hPa) are excluded. This means in practice very few radiance observations with tangent altitudes above 50 km are assimilated. Similarly, radiances with tangent altitudes less than 12 km are also excluded, mainly to avoid errors introduced through the assumption of horizontal homogeneity in the observation operator and to limit effects from residual cloud contamination.

[2] A microwindow is a contiguous set of radiances described by a spectral region and a tangent altitude range.

3 Radiance monitoring and correction of radiance biases

3.1 Monitoring of MIPAS radiances

Departure statistics for MIPAS radiances against model-simulated equivalents from the CTL experiment are shown in Fig. 2. Standard deviations of FG departures show values that are within expected values given the background error, the instrument noise, and the forward model error for most channels. Somewhat larger deviations are found for channels 17-26 (around 740 cm^{-1}) at tangent altitudes between 33 km and above, and at high tangent altitudes in the ozone region of 1020-170 cm^{-1}. The larger standard deviations for lower tangent altitudes in the water vapour band are partially a result of forward model error arising from the assumption of horizontal homogeneity.

The most striking feature in the FG departures is the presence of considerable biases between the observed and the simulated radiances for most channels. For tangent altitudes below 39 km, simulated radiances tend to be too low (below 30 km in the 1125-1150cm^{-1} ozone band), frequently by about 3-4 times the instrument noise. For tangent altitudes of 47 km and above, simulated radiances appear too large by similar amounts in the CO_2 band 685-830 cm^{-1}, and in the ozone region 1020-170 cm^{-1}. The bias shows some geographical variation, with larger biases over Antarctica (not shown).

Time-series of the FG bias show some temporal variability in channels from the MIPAS A and AB bands, with features which can be related to updates in the MIPAS gain calibration (e.g., Fig. 3). The A band shows the largest variability, with sudden jumps (for instance, at 25 August 2003, 1 September 2003), followed by slow drifts towards smaller bias. The jumps are present in most channels of the A band at all tangent altitudes, and the magnitude of the jump is often around the noise level of the instrument. The jump in the bias is not accompanied

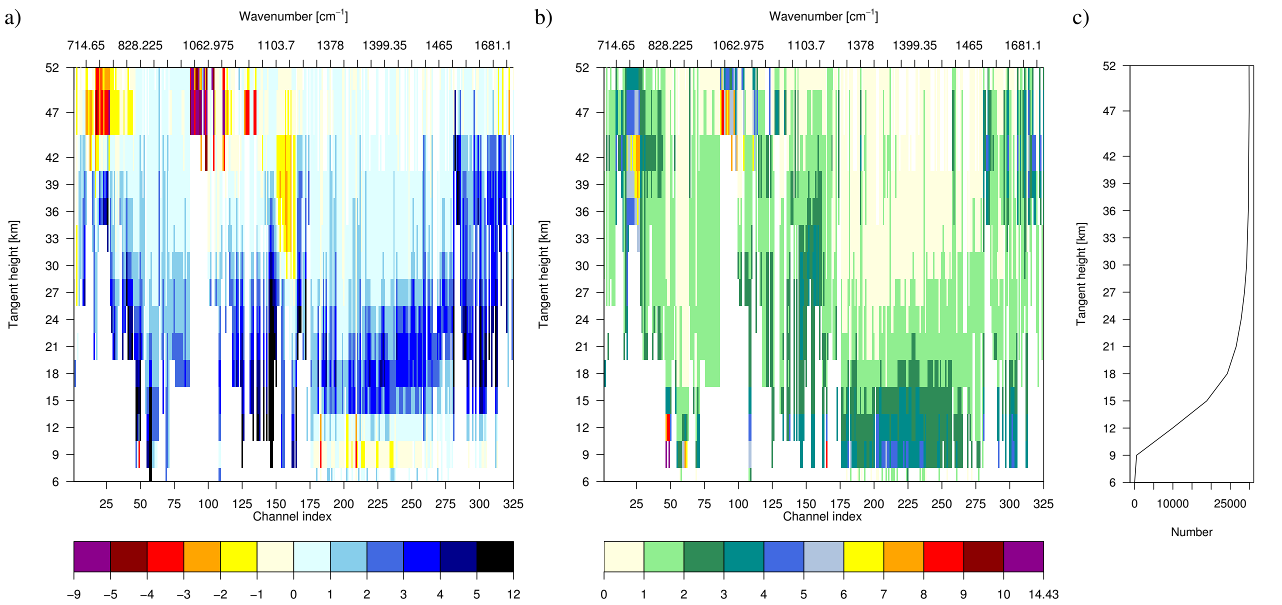

Figure 2: a) Global-mean observation minus FG bias for cloud-screened MIPAS radiances from the experiment CTL as a function of channel index and nominal tangent altitude. The bias has been normalised by the instrument noise in each channel. Only data for the channel/tangent altitude combinations chosen in the channel selection are shown; other areas appear white. Wavenumbers of selected channels are provided in the top axis for orientation. No correction of radiance biases has been applied. b) As a), but for the standard deviation. c) Number of clear sweeps per tangent altitude.

with a jump in the standard deviation (Fig. 3). The times of the jumps correspond to updates in the MIPAS gain calibration which, during the period considered, was usually performed weekly. The monitoring suggests that the practice of relatively infrequent updates of the calibration introduces a considerable radiance error. This error is difficult to account for in our assimilation framework, and may negatively affect the assimilation of the channels in the A-band. Some jumps in the biases can also be seen in the AB-band, and, to much smaller extent in the C-band. The D-band shows fairly stable biases.

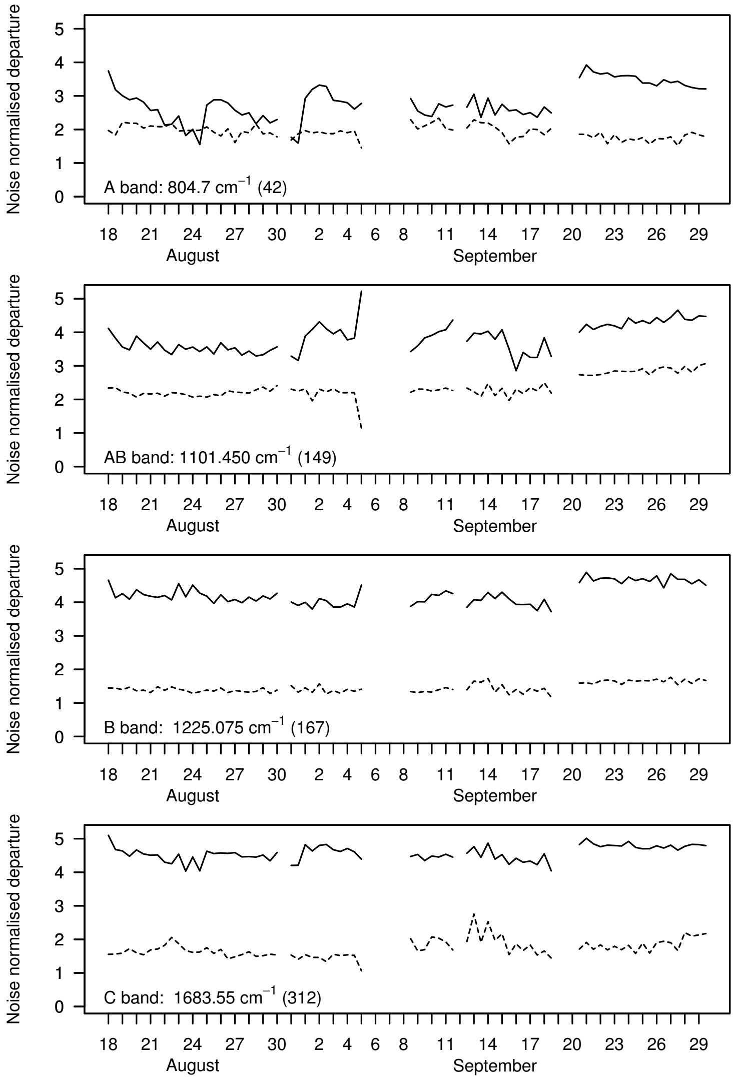

Figure 3: Time-series of global-mean observation minus FG biases (solid) and standard deviations (dashed) from the CTL experiment for four typical MIPAS channels, representative of the four MIPAS bands, as indicated in each panel. Numbers in brackets give the channel index as used in this study. Statistics are for data with a nominal tangent altitude of 27 km, and the bias has been normalised by the instrument noise. No correction of radiance biases has been applied.

3.2 Correction of MIPAS radiance biases

Early experimentation with MIPAS radiances revealed that a large proportion of the bias seen in Fig. 2a can be explained through biases in the FG in the stratosphere. However, biases in the FG can not explain *all* the bias pattern observed, suggesting that MIPAS radiances, like nadir radiances, exhibit so-called radiance biases, arising from errors in the spectroscopy, the instrument characterisation, etc. For instance, if MIPAS radiances are assimilated without a correction for these biases, biases in the radiance departures against the resulting analyses show inconsistencies for MIPAS channels whose weighting functions peak at similar altitudes. As the assimilation system assumes unbiased data, such radiance biases need to be removed prior to the assimilation.

Further investigations found that the γ/δ method (e.g., Watts and McNally 2004) provides a good first model for the observed radiance biases for most channels. This method uses a channel-specific scaling factor γ for the optical depths calculated in the forward model, and models the remaining bias with a channel-specific constant δ. The scaling factor γ can be interpreted as uniform correction to either the absorption coefficient or the absorber amount, whereas the constant δ is essentially a radiometric offset. The method is currently employed operationally at ECMWF for a number of infrared and microwave instruments, and more discussion on the method and the derivation of the γs and δs can be found in Watts and McNally (2004). Figure 4 compares the observed bias in the analysis departures with differences in simulated radiances resulting from a small 5 % perturbation in γ for some sample channels. Figures 4a-c highlight how for the channels shown most of the bias in the analysis departures can be removed by choosing an appropriate channel-specific γ, tuned with data from a range of tangent altitudes. However, some channels also show additional features in the biases, not captured by the γ/δ method. For instance, in Fig. 4b biases for tangent altitudes 36-42 km are somewhat lower than what would be expected from the regression line, and biases in the channel displayed in Fig. 4d show an altogether different structure. These features may arise from biases in the analyses or from other contributions to radiance biases not modelled by the γ/δ method.

The calculation of the γ and δ parameters for the bias correction of *nadir* radiances is usually done on the basis of FG or analysis departures from experiments for which the data to be bias-corrected are not assimilated, under the assumption that the FG or the analysis is unbiased (e.g., Watts and McNally 2004). This approach was not considered appropriate for MIPAS radiances as these are mainly sensitive to the stratosphere which is much less constrained in the ECMWF system than the troposphere. Model fields in the stratosphere can therefore exhibit considerable biases, especially the humidity and ozone fields, as can be seen in comparisons of ECMWF fields with independent data. To circumvent this problem we calculated channel-specific γs and δs from a lower-resolution 2-week experiment (covering 18-31 August 2003) which actively assimilated MIPAS temperature, humidity, and ozone retrievals. Analyses from this experiment were found to be less biased against independent data (e.g., Bormann et al. 2006). By using data from a range of tangent altitudes to estimate an appropriate γ and δ for each channel we also reduce the danger that biases at certain levels in the analyses are aliased into the correction of the radiance biases. The drawback of the approach is that the bias correction used for the radiance assimilation is dependent on MIPAS retrievals.

The experience from the radiance monitoring and bias tuning prompted a revision of the theoretically-based data selection. We excluded channels which show too large biases or standard deviations in the FG departures, arising either due to problems with the radiance observations themselves or due to inadequate modelling of these radiances in the assimilation system. As a result, only 260 of the 325 channels channels were considered in the assimilation trials reported here.

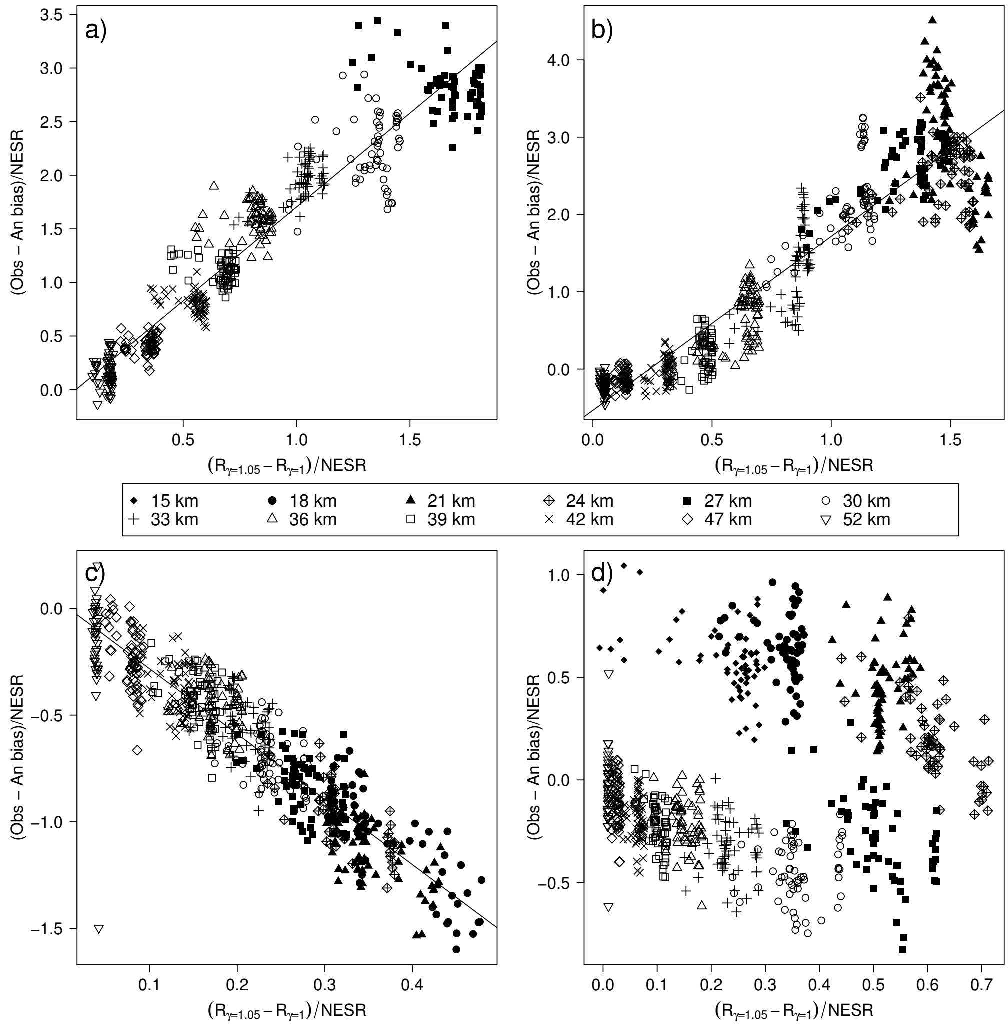

Figure 4: Biases in the analysis departures versus differences resulting from a 5 % perturbation in γ for four sample channels. The statistics are taken from an experiment in which MIPAS radiances were assimilated without bias correction (covering the period 20-31 August 2003). The radiances have been scaled by estimates of the MIPAS instrument noise. Each point in the plot represents statistics over a 30° × 20° longitude/latitude box. To avoid polar areas with known model biases, only data for the region between 50S and 50N are shown. The different symbols indicate the closest nominal tangent altitude, as specified in the legend. A regression line is also shown where appropriate. The displayed channels are a temperature-sounding channel at 711.050cm^{-1} (a), an ozone-sounding channel at 1101.450cm^{-1} (b), and two humidity-sounding channel at 1434.275cm^{-1} (c) and 1419.000cm^{-1} (d).

4 Analysis and forecast impact

4.1 Departure statistics

Statistics for MIPAS radiances generally show a reduction in the FG departures when MIPAS radiances are assimilated, compared to the CTL experiment. The bias observed in Fig. 2a largely disappears, and there is also a reduction in the standard deviation (cf Figures 5 and 2). This suggests that the analysis is able to incorporate the information from the MIPAS radiances, and information from the MIPAS radiances is retained in the short-term forecast. Biases are now within the MIPAS instrument noise for the majority of channels and tangent altitudes, except for some spectral regions, such as the ozone band around 1103 cm^{-1}, and for channels 17-26 around 740 cm^{-1} in the CO_2 region. The much smaller bias is a combined effect of adjusting the model fields to MIPAS radiances and the bias correction applied to the radiances. The remaining bias for some channels indicates some discrepancy between the bias diagnosed by these observations, either amongst themselves or with other aspects of the analysis system. It may point to deficiencies in the bias correction method for these channels. Analysis departures for MIPAS radiances are generally smaller than FG departures when MIPAS radiances are assimilated, as expected for an analysis that draws well to the observations (not shown).

Overall, the better fit to MIPAS radiances does not seem to be at the expense of a poorer fit to other observations. While a degraded fit does occur for some observations in some areas, such degradations tend to be balanced with improvements elsewhere. The largest changes occur for FG or analysis biases against observations of the stratospheric temperature or ozone field, while observations of the troposphere show little or no change.

For stratospheric radiosonde temperature observations, biases appear smoother in the vertical above 50 hPa, with improvements at some levels and degradations at others, while standard deviations are unchanged (e.g., Fig. 6). It is not clear how reliable radiosonde temperature measurements and especially bias estimates from radiosondes are at these high levels, but the smoother bias pattern is considered a positive aspect. Similarly, standard deviations for radiance departures for AMSU-A show little to no change over the Northern Hemisphere

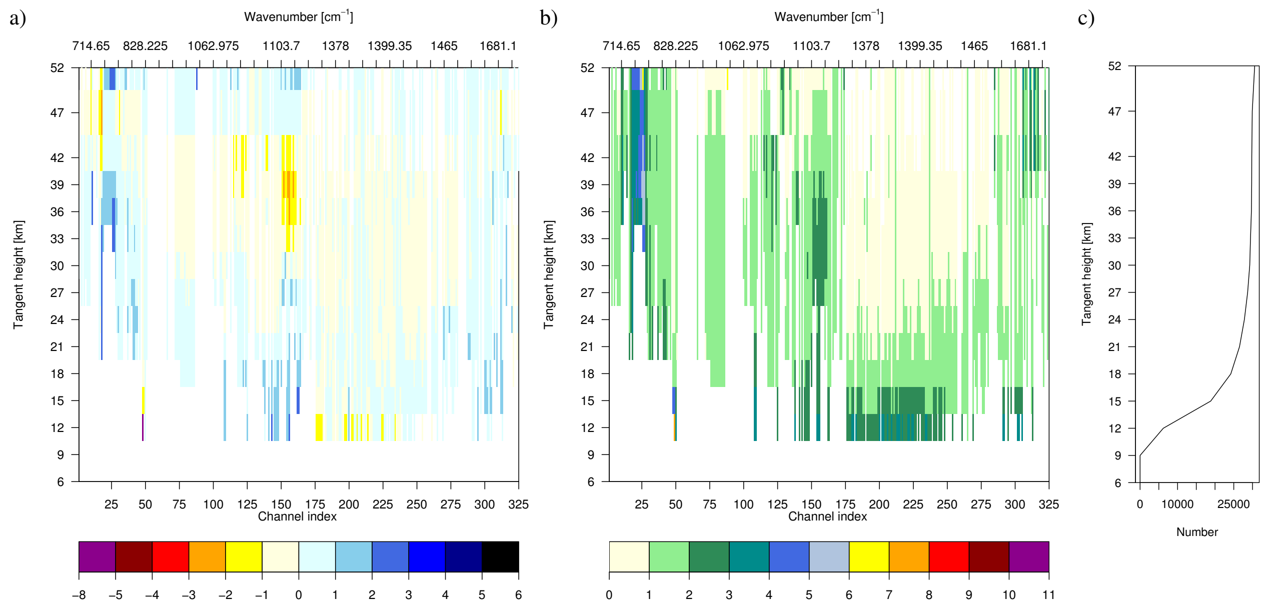

Figure 5: As Fig. 2, but for used data from the RAD experiment with assimilation of MIPAS radiances and after correction of radiance biases.

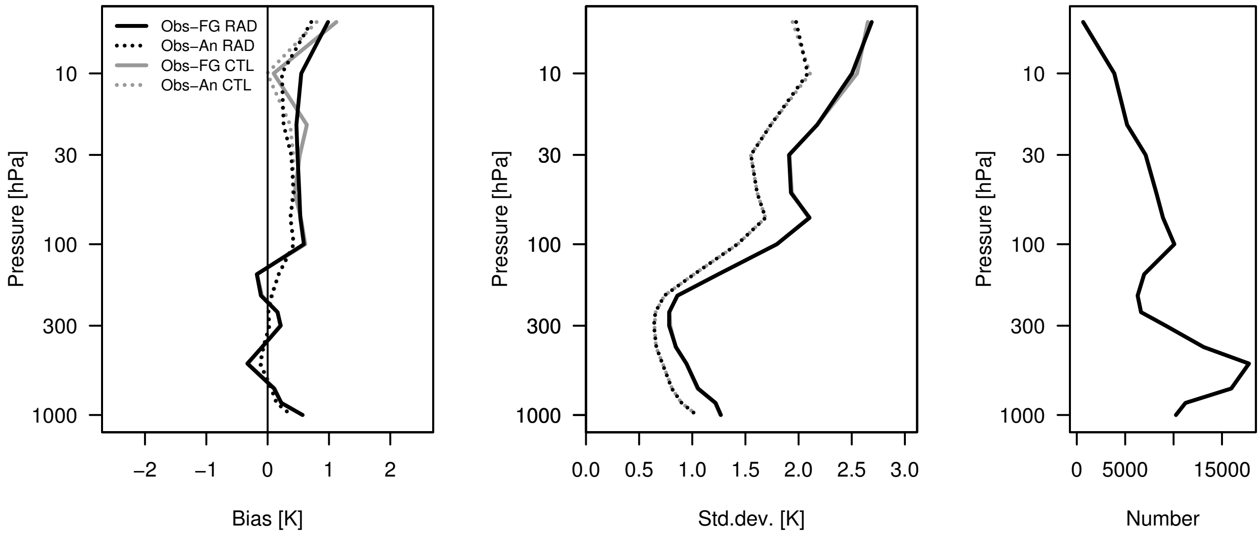

Figure 6: Departure statistics for used radiosonde temperature observations over the tropics for the period 1-29 September 2003. Solid lines indicate statistics for FG departures, dotted lines statistics for analysis departures. Statistics for the RAD experiment are in black, for the CTL experiment in grey. From left to right the three panels show the bias (sonde minus FG or analysis), standard deviation, and the number of observations, respectively.

and the Tropics, whereas biases in stratospheric channels show differences of up to 0.1 K (not shown). Data from four AMSU-A instruments are used in our experiments, and these observations determine to a large extent the temperature analysis in the stratosphere. Given the uncertainty in the bias correction for AMSU-A channels, small changes in the bias against these instruments are not surprising. The most noteworthy degradation in the fit to other temperature observations occurs for some AMSU-A channels over the Southern Hemisphere (Fig. 7). Standard deviation of analysis departures for channel 14 (peaking at 2 hPa) and, to a lesser extent, channel 13 (peaking at 5 hPa) are slightly increased, indicating that the analysis is pulling away from these data in this region in order to fit the MIPAS radiances. However, at the same time, the standard deviation of FG departures is not changed for channel 14, suggesting a similar quality of the FG. The poorer analysis fit may therefore be a result of increased variability in the stratospheric temperature field and is not considered a negative aspect.

For ozone, the only other observations assimilated in our experiments are retrievals from SBUV on NOAA-16. The retrievals show smaller FG and analysis departures when MIPAS radiances are assimilated, especially in the 8-16 hPa layer and above 2 hPa (Fig. 8). Most of the reduction originates from the higher latitudes (note, that high solar zenith angles mean that SBUV data are not used north of 80N and south of 70S for our experiments). The smaller FG and analysis departures are a positive aspect, as the smaller departures, both in terms of bias and standard deviation, suggest that changes introduced through the MIPAS radiance assimilation are supported by the SBUV data.

The fit to other humidity-sensitive observations is not significantly altered in our experiment. These observations include radiances from AIRS, AMSU-B, and SSMI, as well as humidity estimates from sondes. Most of these are primarily sensitive to tropospheric humidity, and therefore no changes in the FG or analysis fit are expected.

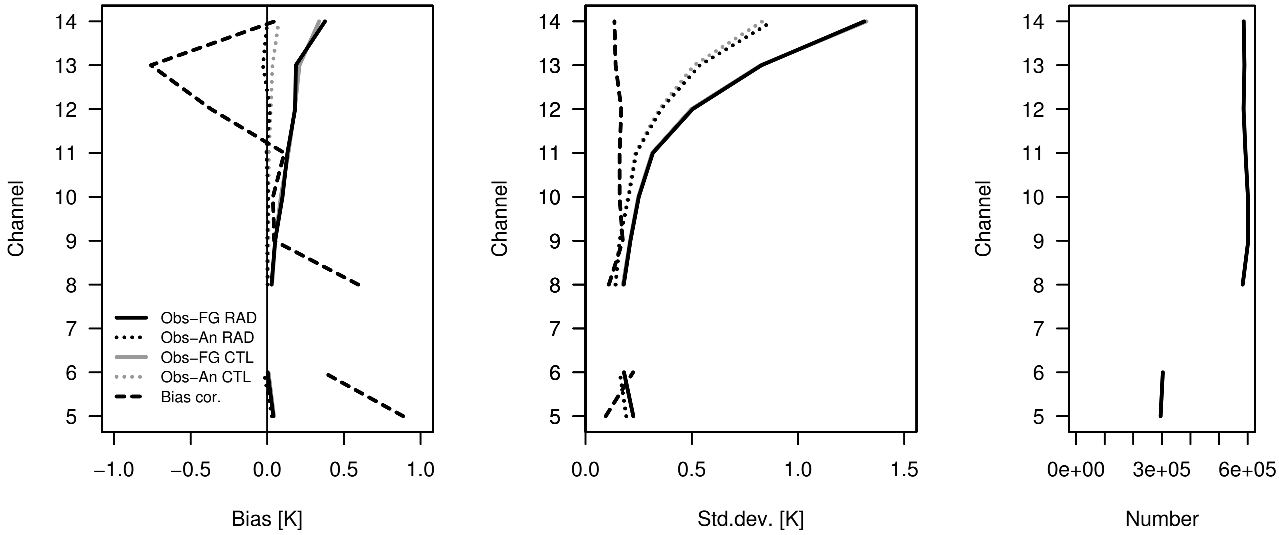

Figure 7: As Fig. 6, but for brightness temperatures from AMSU-A onboard NOAA-17 over the Southern Hemisphere. Statistics for the bias correction applied to the brightness temperatures are also shown with a dashed line.

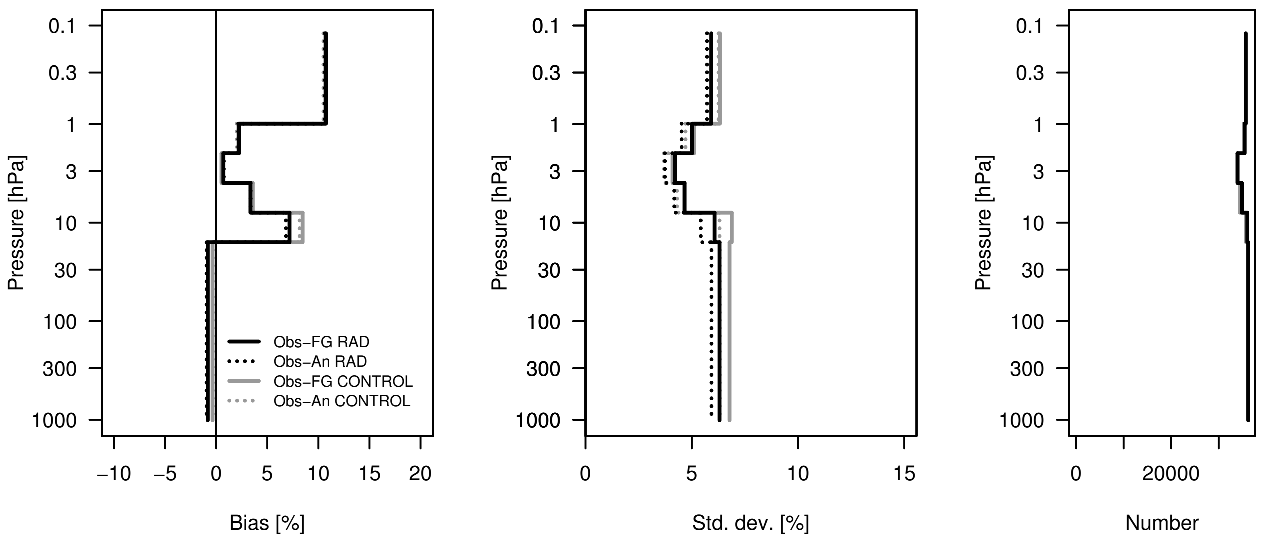

Figure 8: As Fig. 6, but for used SBUV ozone retrievals from NOAA-16 (global). Statistics have been normalised by the mean observation.

4.2 Impact on mean analyses

The assimilation of MIPAS radiances has a substantial impact on the mean analyses of temperature, humidity, and ozone in the stratosphere (Fig. 9). For temperature, most changes are confined to the region above 10 hPa, reflecting that the temperature field below 10 hPa is well constrained by other observations in the system. Differences tend to exhibit oscillatory structures in the vertical, with some zonal mean differences exceeding 5 K, especially over the South Polar region. Oscillations have previously been noted in the lower stratosphere in work regarding the assimilation of GPS RO data (Healy and Thépaut 2006). The humidity field is substantially moistened throughout the stratosphere through the assimilation of MIPAS radiances, typically by 1 ppmv or 20-40 %, exceeding 60 % around 30-40 hPa over the southern mid-latitudes. Further investigation shows that the model fields adjust to the wetter state within 3-6 days (depending on level) of the experiment, and after this a relatively constant level is reached. Some drying can be reported around the extratropical tropopause. For ozone, most changes occur around 10-20 hPa, with increases in ozone volume mixing ratios. A reduction in ozone is apparent at various levels over the polar regions.

The levels for which large changes to the analysis fields occur are consistent with the regions for which MIPAS radiances are expected to have the largest impact. These regions have been identified in a theoretical linear error analysis which takes into account background errors, instrument errors, and systematic errors (Bormann and Healy 2005). The study suggests that the largest impact of MIPAS can be expected above 10 hPa for temperature, and throughout the stratosphere for humidity and ozone.

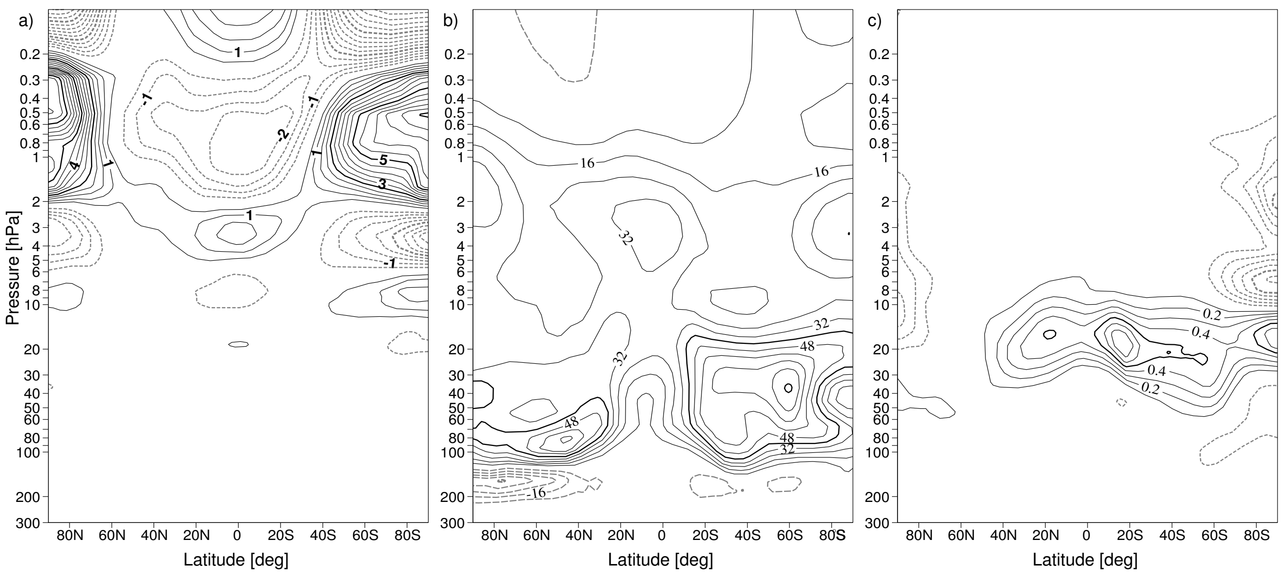

Figure 9: a) Zonal mean temperature differences between the experiments with and without assimilation of MIPAS radiances. Contour interval is 0.5 K, with positive values shown by solid black contour lines and negative values shown through dashed grey lines. b) Same as a), but for humidity (relative to the experiment without MIPAS radiance assimilation), with a contour interval of 8 %. c) Same as a), but for ozone volume mixing ratio with a contour interval of 0.1 ppmv.

4.3 Comparison to MIPAS retrievals

We will now compare FG and analysis fields from the RAD and CTL experiment with v4.61 MIPAS retrievals of temperature, humidity, and ozone. These retrievals are derived assuming horizontal homogeneity, as described in Ridolfi et al. (2000). The MIPAS retrievals have not been assimilated in either experiment. MIPAS retrievals of course do not provide an entirely independent assessment of the assimilation of MIPAS radiances, but it should be noted that the retrievals are based on different parts of the MIPAS spectrum, use a different radiative transfer model, and deal differently with radiance biases. A comparison of our assimilation results with MIPAS retrievals provides a useful first consistency check.

For temperature, standard deviations of analysis departures for the RAD experiment are generally smaller than those of FG departures above 30 hPa, demonstrating that the MIPAS radiance assimilation brings the analysis in better agreement with the retrievals (Fig. 10). Also, standard deviations of the FG departures for the RAD experiment tend to be smaller than those for the CTL experiment above about 3 hPa, confirming that the information added in the RAD experiment is successfully retained in the short-term forecast. This is especially the case in the extra-tropics, whereas for the tropics the reduction in FG departures is less pronounced. In terms of biases against the MIPAS temperature retrievals, the situation is less clear. For the tropics and the South polar region, biases of the FG or the analysis against MIPAS retrievals appear smaller above 10 hPa for the RAD experiment, whereas in other regions the CTL experiment shows better agreement (not shown).

For humidity, we see a strong reduction in the bias against MIPAS retrievals, reflecting the considerable moistening of the stratosphere through the assimilation of the MIPAS radiances. FG or analysis departures show a dry bias of 15-30 % for the CTL experiment throughout the stratosphere, whereas the bias is within ±5 % for the RAD experiment (Fig. 11). The good agreement with MIPAS retrievals in terms of bias is not too surprising, given that the correction of the radiance biases used in RAD has been calculated from an experiment that assimilated MIPAS retrievals. Comparisons with independent data will have to be used to further assess whether the amount of moistening in the stratosphere is a positive aspect. The standard deviation of FG or analysis departures is hardly changed between the CTL and the RAD experiment, with a tendency for larger standard deviations in the RAD experiment, especially between 3-10 hPa. In any case, standard deviations

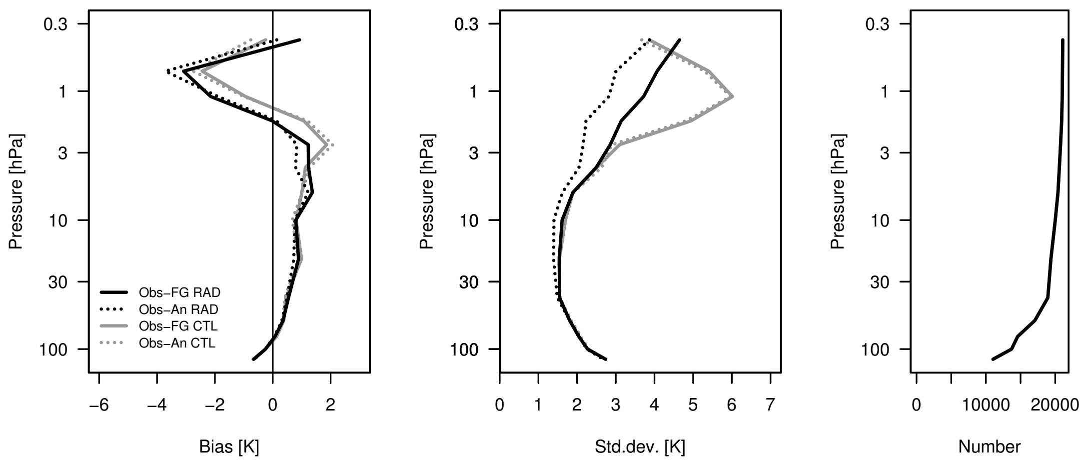

Figure 10: Departure statistics for MIPAS temperature retrievals (global) for 1-29 September 2003. Solid lines indicate statistics for FG departures, dotted lines statistics for analysis departures. Statistics for the RAD experiment are in black, for the CTL in grey. From left to right the three panels show the bias (retrieval minus FG or analysis), standard deviation, and the number of retrievals, respectively.

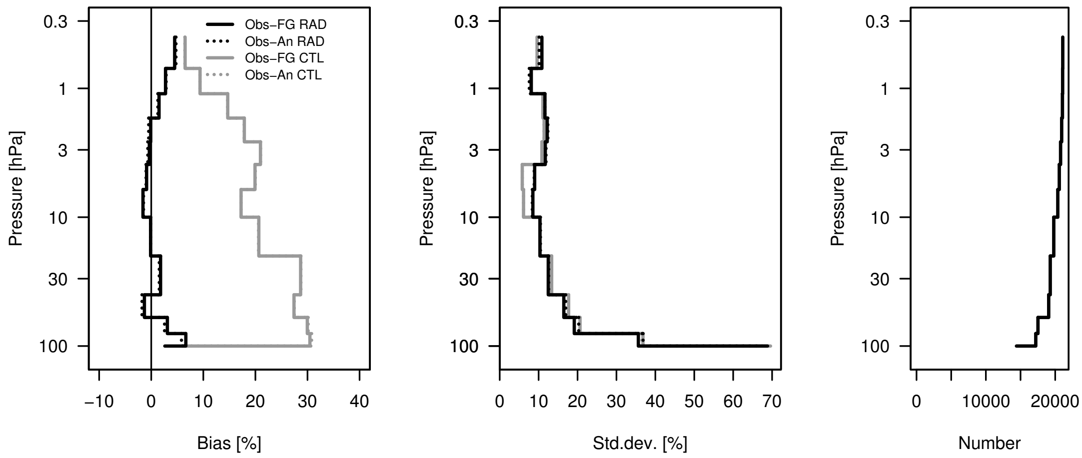

Figure 11: As Fig. 10, but for humidity. Bias and standard deviation [%] are shown relative to the mean observation, using data for partial columns.

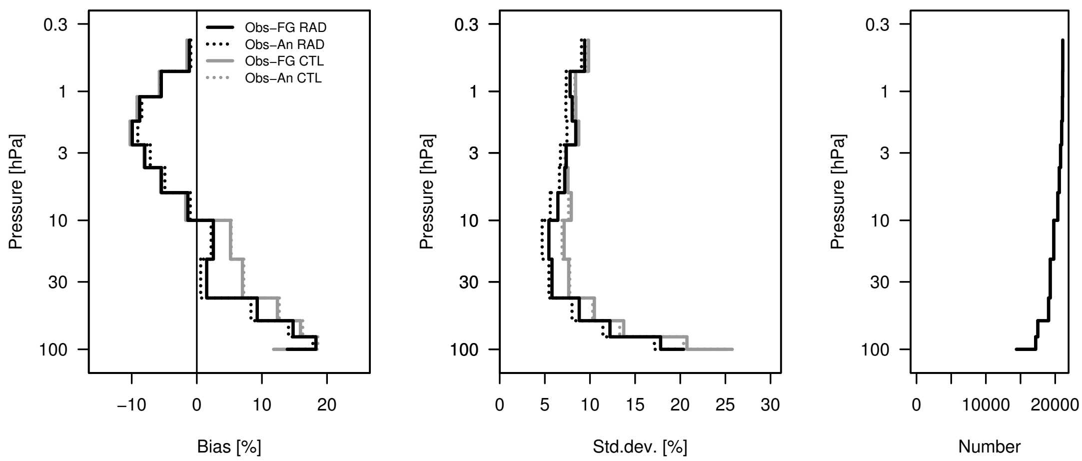

Figure 12: As Fig. 11, but for ozone.

are rather small (around 10 %) throughout most of the stratosphere, rising to larger values in the troposphere, probably due to larger variability in general and cloud contamination in the MIPAS data.

For ozone, the RAD experiment again agrees better with the MIPAS retrievals than the CTL in terms of the FG as well as the analysis. Standard deviations of analysis departures are smaller than those of the FG departures in RAD, and these in turn are smaller than standard deviations of FG departures in the CTL (Fig. 12). There is also a reduction in the bias below 10 hPa, but both the RAD and the CTL experiment show more ozone above 10 hPa than would be suggested by the MIPAS retrievals, with little difference between the two experiments.

In summary, the analysis and FG from the RAD experiment agree on average better with MIPAS retrievals than those from the CTL. The findings suggest that the radiance assimilation is able to extract information from the MIPAS radiances consistent with what has been derived in the MIPAS retrievals, and, more importantly, the extracted information is also maintained in the short-term forecast. Note, however, that MIPAS retrievals do not provide an independent assessment of MIPAS radiance assimilation; to do so we will now compare the resulting analyses with independent data from different instruments not used in the assimilation.

4.4 Comparison with independent data

To further evaluate the results of the radiance assimilation and the changes introduced through MIPAS data we will now compare the analyses from CTL and RAD to independent data not used in the assimilation system. Unfortunately, the choice of independent good-quality observations of the stratosphere covering the globe is relatively limited. Here we use retrievals from the Halogen Occultation Experiment (HALOE), the Stratospheric Aerosol and Gas Experiment (SAGE) II, and the Polar Ozone and Aerosol Measurement (POAM) III retrievals, and data from ozone sondes. HALOE measures profiles by solar occultation in the infrared, whereas POAM III and SAGE II use solar occultation in the ultraviolet and visible. All three retrievals are therefore

Table 1: Main characteristics of correlative retrieval data.

	HALOE	POAM III	SAGE II
Version used	19	4	6.2
Quantities used	Temp. (above 35 km), H_2O, O_3	H_2O, O_3	H_2O, O_3
Typical number of profiles per day	30	15	15
Geographical coverage in Sept. 2003	60-71 N and 0-45 S	64-71 N and 80-87 S	58-74 N and 59-62 S
Vertical resolution	3-4 km for temp., 2 km for H_2O and O_3	1-2.5 km	1 km
Total retrieval error:			
Temperature	2-5 K for 0.1-5 hPa	-	-
O_3	10-20 % for 1-100 hPa	5-10 % for 3-100 hPa (3-50 hPa for NH)	5-10 % for 3-100 hPa
H_2O	15-25 % for 1-100 hPa	15-20 % for 3-100 hPa (3-30 hPa for SH)	15-30 % for 3-100 hPa
Reference	Russell et al. (1993)	Lucke et al. (1999)	Thomason et al. (2004)

based on limb measurements, and horizontal homogeneity is assumed in the retrieval. The retrievals have been extensively compared to other data such as ozone sondes and other retrievals (e.g., Bhatt et al. 1999, Randall et al. 2003, Wang et al. 2002, Thomason et al. 2004, Kley et al. 2000). An overview of the main characteristics is given in Table 1. Note that below 35 km HALOE temperature retrievals represent the model background used in the retrieval process and are therefore not suitable for our evaluation.

The set of ozone sondes used for comparisons is the same as used in Geer et al. (2006). It aims at global coverage by combining data from various sources. As pointed out in Geer et al. (2006), the dataset is somewhat heterogeneous, given the different types of sondes and processing included, a tradeoff for coverage. Sondes typically measure up to 10 hPa, with a total error of 5 % in the lower stratosphere, rising to about 15 % in the upper troposphere and around 10 hPa.

Retrievals and analyses are compared in the following way: First, the analysis profile closest (in time and space) to the retrieval or sonde profile was extracted from a $1^\circ \times 1^\circ$6-hourly dataset. Then this analysis profile and the retrieval were both interpolated linearly in log(pressure) onto a common pressure grid. This allows the accumulation of difference statistics over the period of the experiment.

4.4.1 Temperature

The oscillatory changes to the mean temperature analysis above 5 hPa observed in Fig. 9 appear to be supported by temperature retrievals from HALOE, at least in areas where these data are available. Biases against HALOE temperatures tend to be reduced when MIPAS radiances are assimilated over all regions covered by HALOE, and standard deviations between analyses and HALOE profiles are reduced over the latitudes 20-41 S, but fairly unaltered elsewhere (Fig. 13). Note, however, that HALOE retrievals for this month cover only a limited range of latitudes, and HALOE do not cover the polar extremes with some of the largest changes in the

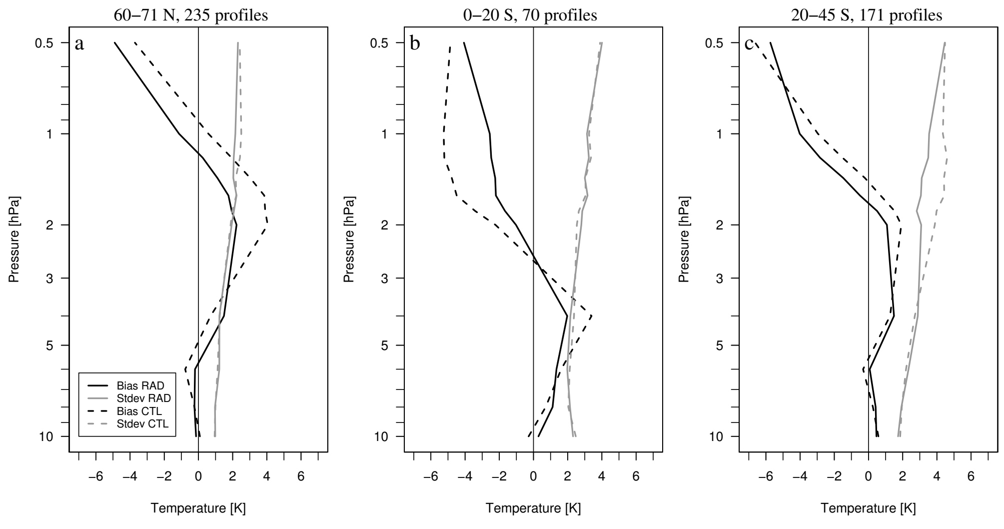

Figure 13: a) Statistics for differences between HALOE temperature retrievals and analyses [K]. Black lines indicate HALOE minus analysis biases, grey lines show standard deviations of the differences. Solid lines are for statistics for analyses from the RAD experiment, whereas dashed lines show statistics for the CTL analyses. Data cover the period 1-29 September 2003 and the north polar region. b) As a), but for the southern tropics. c) As a), but for the southern mid-latitudes.

mean temperature analyses. Nevertheless, the findings give some additional indication about the realism of the temperature changes introduced through the MIPAS radiance assimilation.

4.4.2 Humidity

Evaluation of stratospheric humidity analyses is somewhat hampered by the considerable disagreement between the independent data available for comparison, as is apparent from Kley et al. (2000). Comparison between retrievals from different instruments (including the three used here) indicate mean differences between each other in the range of ± 10 % or even higher. While generally considered as highly accurate, HALOE retrievals tend to be slightly drier than the average, whereas POAM III retrievals tend to be somewhat wetter. Version 6.2 of the SAGE II retrievals have been tuned with a HALOE climatology over the stratosphere, so, on average, agree well with HALOE over the stratosphere, yet show somewhat larger values than HALOE towards the mesosphere. Mean agreement between the correlative data and our analyses within the ± 10 % range must therefore be considered acceptable.

All independent retrievals suggest that the stratosphere in the CTL experiment is too dry, and instead they support the moister stratosphere in the RAD experiment. The North Polar region is covered by all three types of retrievals considered, and here the CTL analysis is, on average, drier by about 10-25 % against HALOE and SAGE II data, and by about 15-35 % against POAM III retrievals (Fig. 14). In contrast, the RAD analysis shows hardly any bias against HALOE or SAGE II data throughout most of the stratosphere over the North Polar region, and it is about 10 % too dry against POAM III retrievals in the same area. HALOE as well as POAM III retrievals suggest a wet bias in the RAD analyses around the stratopause over the North Polar region, by around 15 % and 10 %, respectively, whereas SAGE II data show no such feature. Other regions covered by the correlative datasets considered here show similar statistics, generally supporting the moistening introduced

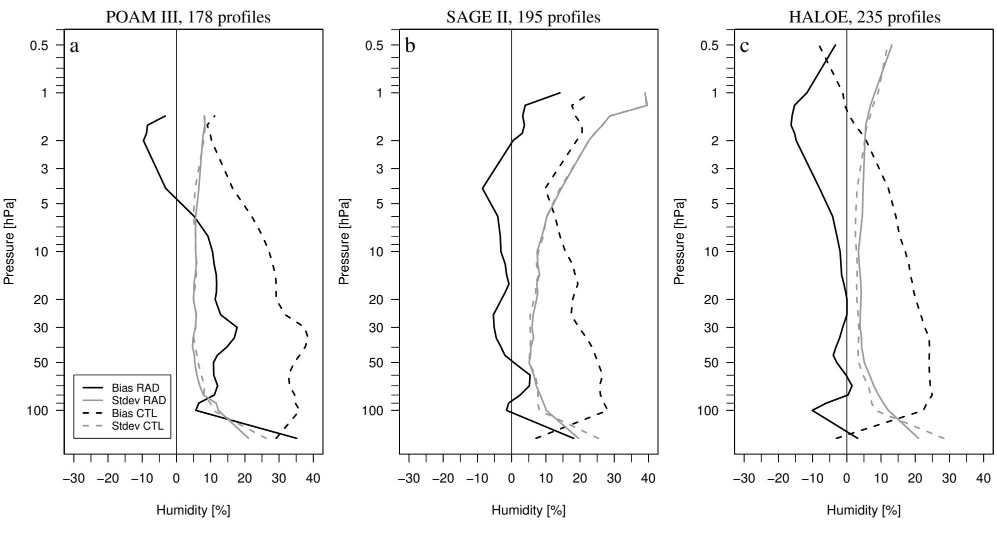

Figure 14: a) Statistics for differences between POAM III humidity retrievals and analyses, normalised by the mean observation. Black lines indicate POAM III minus analysis biases, grey lines show standard deviations of the differences. Solid lines are for statistics for analyses from the RAD experiment, whereas dashed lines show statistics for the CTL analyses. Data cover the period 1-29 September 2003 and the region 64-71N. b) As a), but for SAGE II retrievals over the region 60-74N. c) As a), but for HALOE retrievals over the region 60-71N.

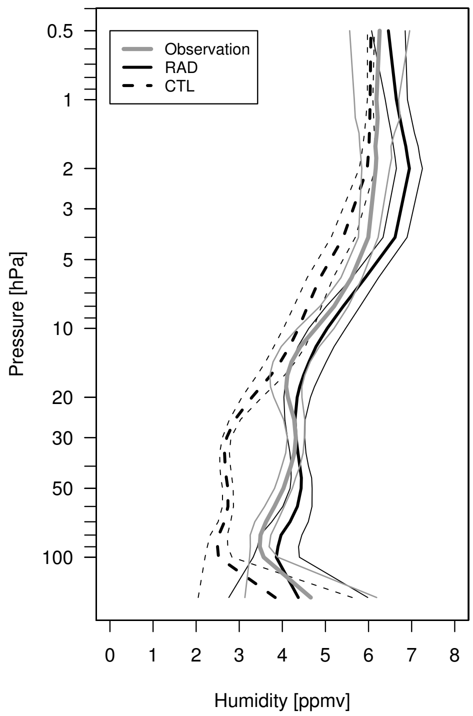

Figure 15: Humidity profiles from HALOE retrievals (grey), compared to humidity profiles from the RAD analyses (solid black) and the CTL analyses (dashed black), both interpolated to HALOE. Thick lines indicate the mean over 171 profiles covering the period 1-29 September 2003 and the region 20-45S, with thin lines showing plus/minus one standard deviation.

in RAD, with some indication of a slight wet bias in some areas. Within the uncertainty inherent in the retrievals used we can conclude that the moistening noted in Fig. 9b is qualitatively and quantitatively supported by the independent data used.

The radiance assimilation also improves the vertical structure of the stratospheric humidity field and brings it more in-line with what is observed in the correlative data. For instance, comparisons with HALOE retrievals over the southern midlatitudes support the somewhat larger moistening in the 30-40 hPa region noted earlier, and they also support the vertical structure with two minima present in the RAD analyses, but not in the CTL analyses (Fig. 15). The drying observed in the upper troposphere in the RAD experiment over the Northern Hemisphere (Fig. 9b) is largely outside the range for which the retrievals used are reliable, but there is some indication in SAGE II as well as HALOE data that this is indeed a realistic feature (e.g., Fig. 14)

Standard deviations of the differences between the analyses and the retrievals are typically around 5-7 %, with larger values towards the mesosphere and troposphere (e.g., Fig. 14), except for SAGE-II data over the South Polar region where standard deviations can be about twice that. These standard deviations differ little between the CTL and the RAD experiment, with small increases at some levels (for instance for HALOE in Fig. 14c) and in some regions and marginal reductions in others. This is largely because the size of the standard deviations is close to the random error associated with the retrievals, and we therefore cannot expect to detect improvements in the standard deviations of differences to these data.

4.4.3 Ozone

Comparisons between ozone analyses and independent data give somewhat more mixed results. The analyses from the RAD experiment compare best with independent data over the North Polar region. In this region, the RAD analyses compare substantially better against all three types of retrievals than the CTL analyses, both in terms of biases and standard deviations in the 5 to 150 hPa range (e.g., Fig. 16a).

Over the South Polar region, results are less clear when comparing the ozone analyses against the available sonde data or POAM III retrievals. The RAD analyses capture better the ozone maximum around 20 hPa (albeit in too broad fashion), and the region of depleted ozone below 70 hPa is also represented in a somewhat better way (e.g., Fig. 16c). The latter leads to a reduction in a positive bias of the analyses against data from the Total Ozone Mapping Spectrometer (TOMS) in terms of total column ozone over the South Pole (not shown). However, overestimation of ozone remains a problem in this area in the CTL and the RAD experiments. This is largely a shortcoming of the ozone parameterisation, as it does not capture the extreme ozone depletion over the Antarctic during this time of the year (e.g., Dethof and Hólm (2004). Also, standard deviations of the differences between the analyses and POAM III retrievals or sondes are fairly large and remain in the 20-40 % region for the RAD as well as the CTL analyses over the South Polar region (not shown).

Probably the poorest performance of the RAD ozone analyses is found in the Tropics. While the size of the ozone maximum is better represented, the height of the maximum is too low and the analyses fail to capture the vertical structure below 20 hPa, as can be seen against sonde observations or HALOE retrievals (e.g., Fig. 16b).

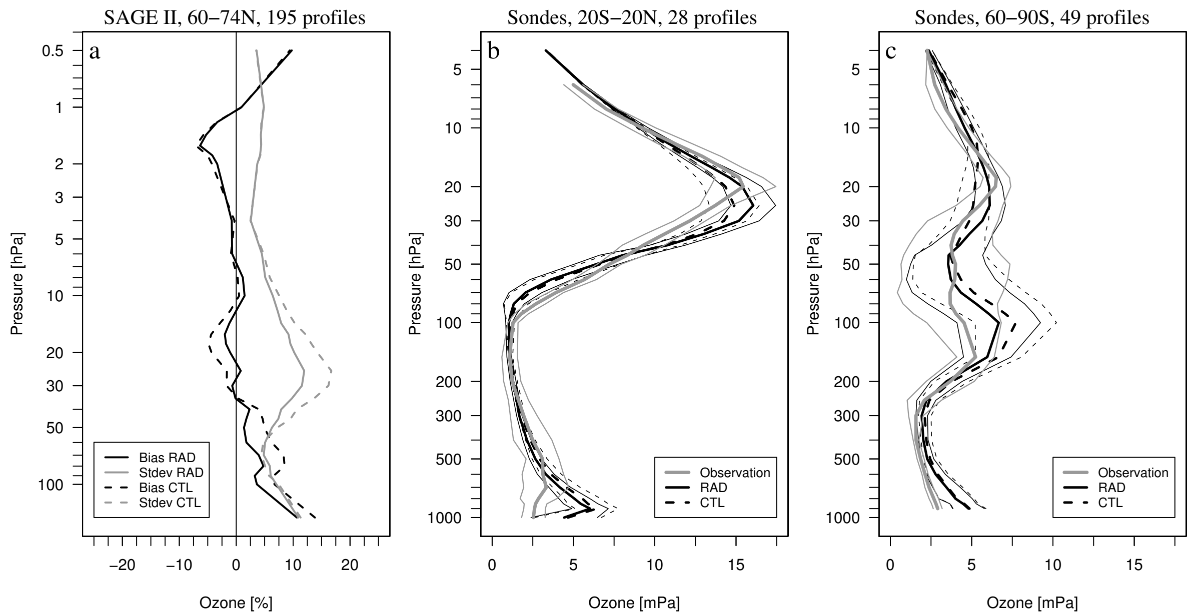

Figure 16: a) Statistics for differences between SAGE II retrievals and analyses, normalised by the mean observation. Black lines indicate SAGE II minus analysis biases, grey lines show standard deviations of the differences. Solid lines are for statistics for analyses from the RAD experiment, whereas dashed lines show statistics for the CTL analyses. Data cover the period 1-29 September 2003 and the region 60-74N. b) Ozone profiles from ozone sondes (grey), compared to ozone profiles from the RAD analyses (solid black) and the CTL analyses (dashed black), both interpolated to the sonde profiles. Thick lines indicate the mean over the period 1-29 September 2003 and the tropical region, with thin lines showing plus/minus one standard deviation. c) As b), but for the south polar region.

There is considerable underestimation of ozone in the tropical lower stratosphere in both the CTL and the RAD experiment, made somewhat worse in the RAD experiment. In general, the increase in ozone in a fairly broad layer noted in Fig. 9c are not supported by independent observations which instead suggest a more complex vertical structure. This is a somewhat disappointing result, as it is in contrast to the high vertical resultion we expect to obtain from MIPAS data.

There are a number of possible reasons for the poorer performance in terms of assimilating ozone information. As noted earlier, analysis or FG departures show some of the largest remaining biases in the ozone channels, especially around channel index 150-160, suggesting that the system is less consistent for these channels, possibly due to deficiencies in the radiance bias correction. Uncorrected radiance biases from a range of tangent altitudes may explain the broad biases in the ozone analyses noted above. Another area of uncertainty are the ozone background errors. These play an important role in radiance assimilation in terms of separating temperature and ozone information. Given the sparsity of ozone observations used in the ECMWF system, the estimates of the background errors used are less reliable. Also, biases in the temperature FG can alias into biases in other fields in the case of radiance assimilation. Offline 1DVAR experiments suggest that retrieved ozone information is particularly sensitive to temperature biases for our channel set and background errors.

4.5 Sensitivity to correction of radiance biases

To test the sensitivity of the assimilation to the radiance bias correction we performed another experiment which used bias correction parameters calculated in an alternative way, without using analyses with MIPAS retrievals. We recall here that given considerable biases in the model fields in the stratosphere, a bias correction calculated from passive monitoring of MIPAS radiances is not considered appropriate. Therefore, for the alternative bias correction we calculated the bias parameters through an iterative approach, based on a series of lower resolution 2-week experiments (covering 18-31 August 2003) which actively assimilated MIPAS radiances. In the first experiment, MIPAS radiances were assimilated without bias correction, and the resulting biases in the analysis departures were used to calculate channel-specific γs and δs. These γs and δs were then employed in the next experiment for the same period, and this experiment was again used to calculate revised parameters. The procedure was repeated until little change in the bias parameters was observed. Using this approach we aim to separate between analysis and radiance biases on the basis of MIPAS radiance data alone by using the fact that limb sounding and MIPAS especially provide many channels which peak at similar altitudes. We found that the estimates for γ and δ did not change very much after three iterations of the approach described above. We then reran the experiment RAD, but with bias parameters for MIPAS radiances from this third iteration. The experiment is referred to as RADa.

Little difference can be seen in the departure statistics for RAD and RADa for observations used in the system. Statistics for MIPAS radiances show that the alternative bias correction is equally suited to produce similarly consistent mean analysis departures (not shown). There are small changes in the bias against temperature-sensitive observations, with the effect that these biases appear more similar to those in the CTL experiment (not shown). The fit to SBUV data from NOAA-16 is further improved in RADa compared to RAD, whereas departure statistics for humidity-sensitive observations are not significantly altered (not shown).

Nevertheless, using different bias parameters has a significant impact on the analyses. Zonal mean differences between RADa and the CTL show a significantly different picture than the differences between RAD and CTL (cf, Figures 17 and 9), especially for humidity and ozone. The stratospheric humidity analyses from RADa are significantly wetter than from RAD, with a typical moistening of 20-50 % throughout most of the stratosphere compared to the CTL experiment, about 10-20 % more than in RAD. For ozone, the alternative bias parameters result in a larger increase of ozone around 20-80 hPa in RADa. Temperature shows the smallest changes, with little difference in the general structure of the mean analysis differences between RADa or RAD and the CTL.

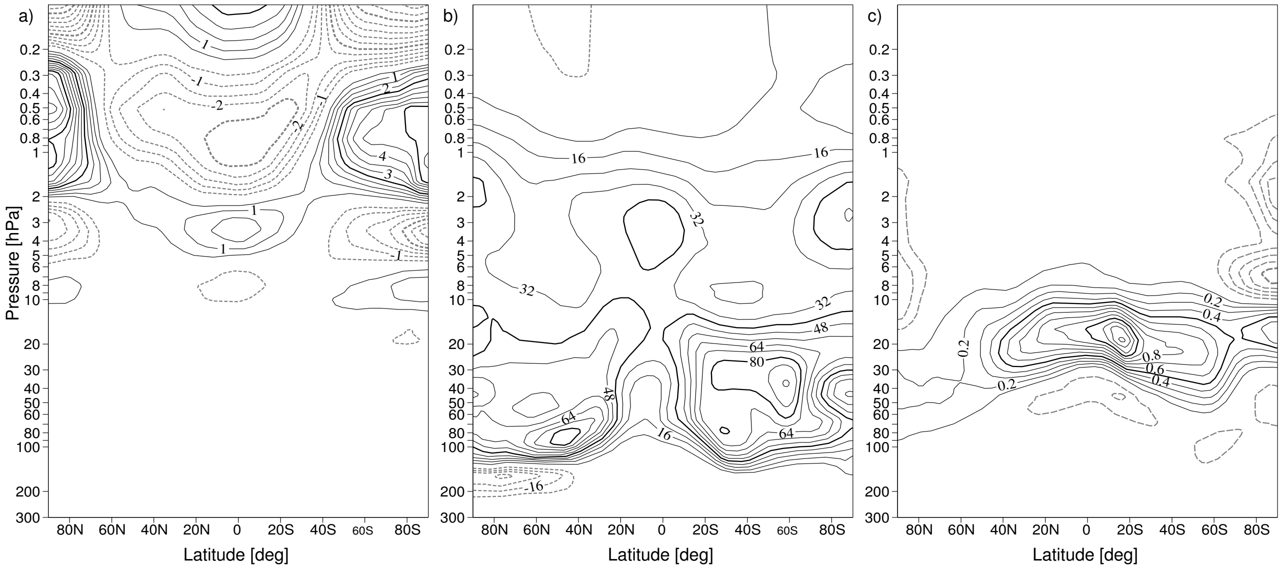

Figure 17: As Fig. 9, but for the zonal mean differences for the experiment RADa and the CTL.

Comparison against independent data also reveals considerable differences between the analyses from RADa and those from RAD (not shown). In some areas the analyses from RADa agree slightly better with independent retrievals than the RAD analyses, for instance the temperature analyses compared to HALOE data, or ozone fields over the South Polar regions against the available retrievals or sonde data. However, there are also significant degradations. For instance, most of the humidity retrievals indicate that the wetter analysis in RADa is too wet by 10-20 % (except for POAM III data over the North Polar region). Also, ozone retrievals or sondes over the midlatitude or tropical regions suggest that RADa now significantly overestimates ozone in the 20-80 hPa range, and standard deviations of the difference to the analyses are increased in the same regions.

The findings demonstrate considerable sensitivity of our results to the bias correction applied to MIPAS radiances, and they highlight the difficulty of estimating the radiance biases in the context of relatively poorly constrained model fields in the stratosphere. Both bias corrections lead to very similar departure statistics for the MIPAS radiances as well as the other observations, with neither bias correction leading to significant disagreement of the analysis or FG with other observations. This means the observing system present in these experiments gives little indication which of the two bias corrections is preferable, despite the two bias corrections leading to significant analysis differences.

4.6 Forecast impact

We will now assess the impact of the MIPAS radiance assimilation on medium-range forecasts. To do so, we will focus on a comparison between experiments RAD and CTL. Our main method of assessing forecast error will be a comparison of forecasts against analyses, but comparisons against the independent retrievals are also presented where appropriate. Given the large differences in the analyses from RAD and CTL pointed out earlier, the choice of verifying analysis for forecast evaluation is crucial for our evaluation. We have chosen the analyses from RAD as verifying analyses. While this choice somewhat favours the RAD experiment, our previous evaluation has shown the analyses from RAD to be more accurate than those from CTL, and it is therefore the appropriate choice for forecast verification.

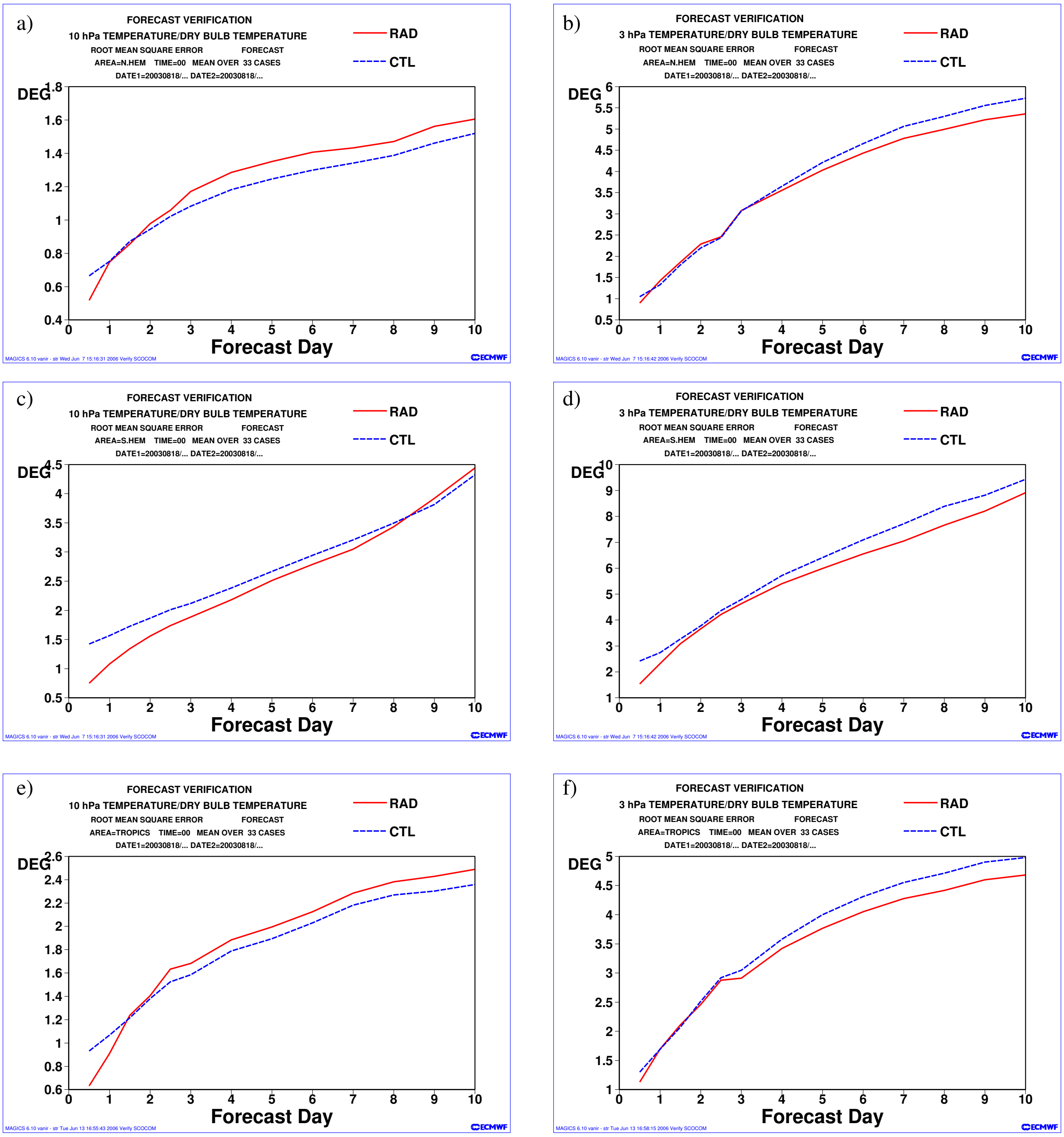

Figure 18: Root mean square errors for temperature forecasts from RAD (red solid) and CTL (blue dashed) as a function of forecast range. The panels show scores for the Northern Hemisphere (a, b), the Southern Hemisphere (c, d), and the Tropics (e, f) at 10 hPa (a, c, e) and 3 hPa (b, d, f).

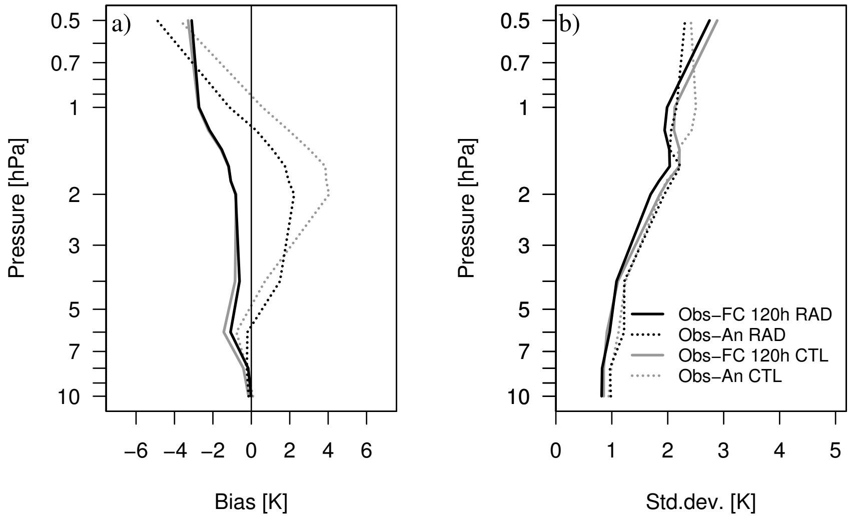

Figure 19: Comparison of forecast and analyses against HALOE temperature profiles over the area 60-71 N. The left panel shows the bias, the right panel the standard deviation of the retrieval minus model field differences. Black lines indicate statistics for the RAD experiment, grey lines the CTL experiment. Statistics for analyses are shown by dotted lines, and those for 5-day forecasts are displayed by solid lines. The sample covers analyses or forecasts initialised during the period 1-29 September 2003, with 235 colocations for the analyses, and 201 for the forecasts.

The impact of the MIPAS radiance assimilation on temperature forecasts is somewhat inconclusive. Verification against the RAD analyses show improvements in the upper stratosphere and at 200-100 hPa over the Northern Hemisphere, but also degradations in the middle stratosphere around 10-30 hPa over the Northern Hemisphere and the Tropics (e.g., Fig. 18), with a neutral impact elsewhere. The improvements or degradations are largely due to mean errors rather than standard deviations. Surprisingly, comparisons against HALOE temperature profiles show that the 5-day forecast agrees better with HALOE data in terms of biases as well as standard deviations than the analyses, with slightly better agreement between the RAD experiment and HALOE (e.g., Fig. 19). In particular, the oscillatory structure in the biases noted earlier is not present for the forecast. This suggests that the radiance assimilation corrects an analysis problem which appears to diminish in influence during the integration of the forecast model.

Stratospheric humidity forecasts from the RAD experiment generally compare better with the verifying analyses than those from the CTL throughout the globe (not shown). Improvements can be reported down to about 150 hPa; below this level the impact is mainly neutral. The better agreement is mostly due to the much wetter stratosphere in RAD which is retained throughout the 10-day forecast. The finding that the wetter stratosphere is retained is a positive aspect, as it shows that the strong moistening of 20-30 % is not rejected by the forecast model on 10-day time-scales. Note, however, that time-scales for the evolution of humidity in the stratosphere are a year or longer, far beyond the length of forecast runs considered in this study. The finding that the wetter stratosphere is retained in the forecast is also supported by a comparison of forecasts against the independent humidity retrievals introduced in section 4.4 (Fig. 20). In particular, these show that the bias between the retrievals and the analyses or 5-day forecasts are very similar.

For ozone, information introduced through the MIPAS radiances is also retained throughout the forecast. For instance, root mean square errors (RMSE) of total column ozone are consistently reduced almost everywhere

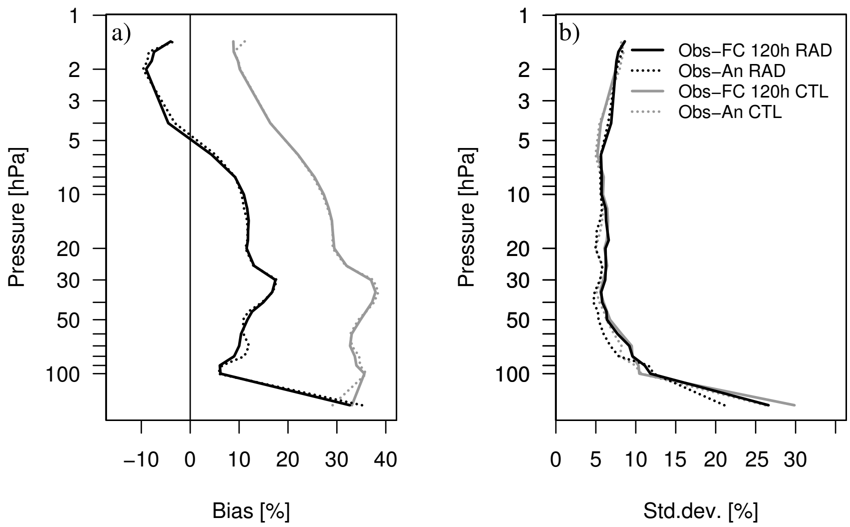

Figure 20: As Fig. 19, but for statistics for a comparison of forecast and analyses against Poam III humidity profiles over the area 60-71 N. Biases and standard deviations have been normalised by the mean retrieval. The sample covers 178 colocations for the analyses, and 179 for the forecasts.

at day 2 in the RAD experiment compared to the CTL, especially over the South Polar region, where the reductions reach 9 DU (Fig. 21a). In many areas the reduction is of the order of 20-50 % of the forecast error in total column ozone. Smaller errors in forecasts of total column ozone are also present in the 5-10-day range, especially over the South Polar region, but elsewhere the situation is more mixed (e.g., Fig. 21b). Most of the improvements in the RMSE are again due to smaller biases between the forecasts and the verifying analyses. Similar findings have been reported by Dethof (2003) for the assimilation of MIPAS retrievals over a similar period. The ozone forecasts have also been compared to data from independent ozone sondes and ozone retrievals, confirming the above findings (not shown).

5 Conclusions

This paper reported on the first trials with direct assimilation of MIPAS limb radiances, using a fast radiative transfer model that assumes local horizontal homogeneity. The assimilation aims to extract information on temperature, humidity, and ozone from the MIPAS radiances, primarily in the stratospheric region. To achieve this, radiances from up to 325 channels were considered, over channel-specific tangent altitude ranges. The main findings are:

- Passive monitoring of MIPAS radiances shows considerable biases against radiances simulated from FG fields. The biases appear to be a mixture of biases in the FG fields (especially humidity and ozone), and radiance biases. Monitoring of the temporal consistency of MIPAS radiances against FG radiances shows that the infrequency of the calibration updates (weekly during our study period) allows biases of up to the order of the instrument noise in the MIPAS A and AB bands.

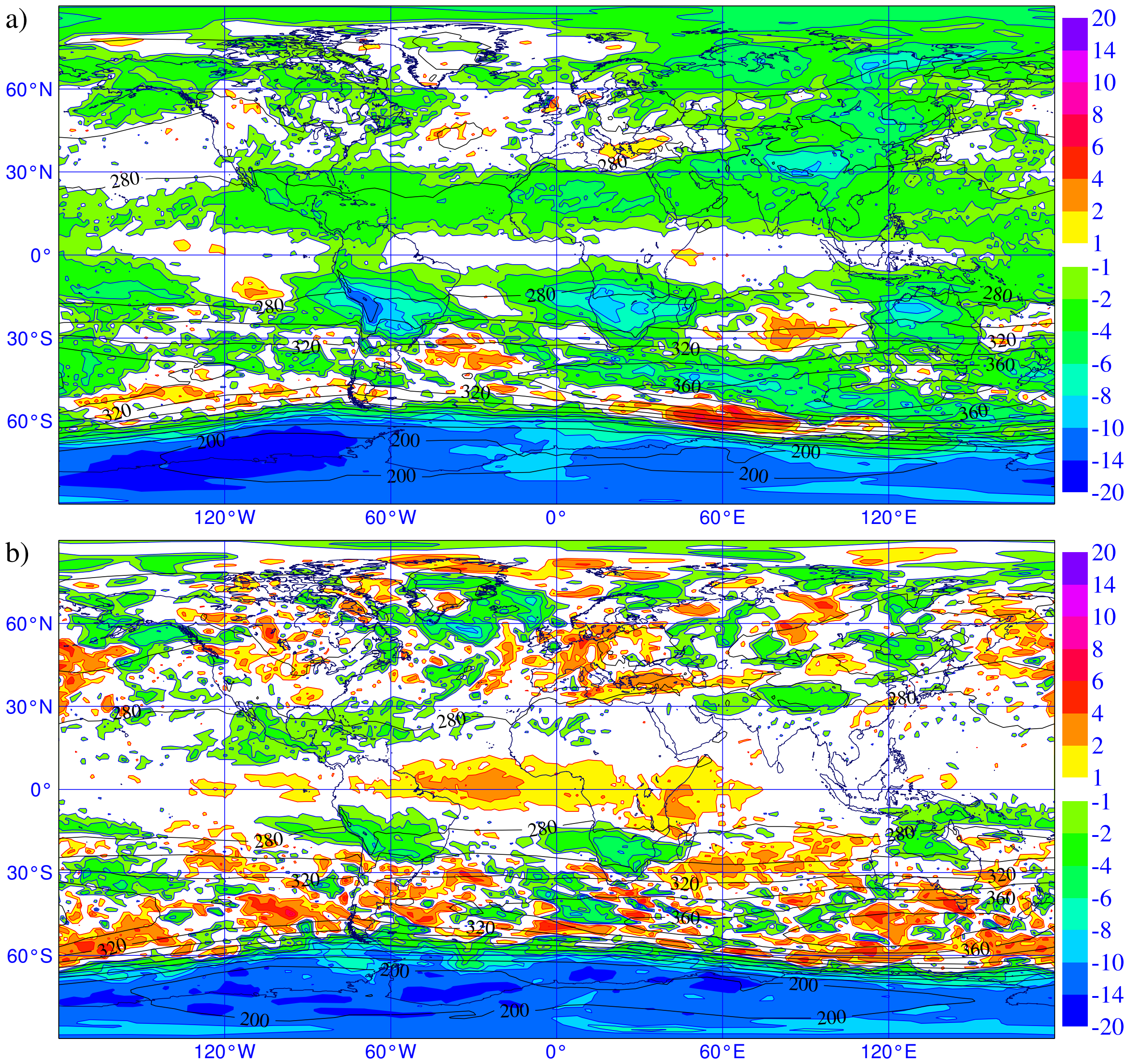

Figure 21: a) Differences in the 2-day root mean square forecast error of total ozone [DU] between the RAD experiment and the CTL. Green and blue indicate a reduction in the forecast error. b) As a), but for the 5-day forecast.

- Assimilation of MIPAS radiances has a considerable impact on the temperature analyses above 10 hPa and on humidity and ozone analyses throughout the stratosphere, lower mesosphere and upper troposphere. This is achieved without significantly degrading the fit to other observations.
- Analyses and short-term forecasts with MIPAS radiance assimilation compare better with MIPAS retrievals not used in the analysis than analyses and short-term forecasts without assimilation of MIPAS data. This is true for temperature, humidity, and ozone, and the finding provides a first consistency check of the radiance assimilation.
- MIPAS radiances appear to correct temperature biases with oscillatory structures in the vertical above 10 hPa over the Polar regions and, to a lesser extent, over the tropics, leading to better agreement with HALOE retrievals not used in the assimilation.
- Assimilation of MIPAS radiances produces a wetter stratosphere, in better agreement with independent humidity retrievals not used in the assimilation.
- Ozone analyses with MIPAS radiances agree better with ozone retrievals not used in the assimilation over the North Polar region, whereas mean ozone increments appear too broad in the vertical elsewhere.
- The results show considerable sensitivity to the bias correction applied to MIPAS radiances, with different bias models leading to similar fits to all assimilated observations in the system, yet large differences in the resulting analyses.
- The information added to the analyses through the MIPAS radiance assimilation is at least partly retained throughout the forecast, leading to improved forecasts in the stratosphere.

The study demonstrates the feasibility of direct assimilation of emitted infrared limb radiances and highlights how useful information can be extracted from the radiances within the assimilation system. Many aspects of the stratospheric analyses of temperature, humidity, and ozone are improved through the assimilation of MIPAS radiances, as shown through comparisons with independent data. This is especially encouraging as the study covers a number of novel aspects, such as performing a stratospheric humidity analysis in an NWP system, the direct assimilation of ozone-affected radiances, and assimilation of observations in the presence of relatively poorly known background error characteristics. The experiments presented here suggest that useful stratospheric humidity analyses can now be performed following the development of a new humidity control variable as described in Hólm et al. (2002). Assimilation of MIPAS radiances corrects a dry bias otherwise present when no stratospheric humidity soundings are assimilated.

Our experience also shows the relevance of a bias correction for MIPAS radiances, together with the difficulty of deriving an appropriate correction within the framework employed in our study. It appears that other observations present in our experiments do not sufficiently constrain the analysis in the stratosphere to detect and correct biases in MIPAS radiances in a robust way. This is especially true for the humidity field. The situation is very different from that for nadir radiances which are sensitive to the much better observed troposphere or to temperature in the stratosphere for which radiosonde observations provide some anchor points. In the nadir case, the radiance bias correction in fact provides a powerful tool for cross-calibrating sensors in agreement with conventional observations. The situation in our case could be improved if more observations of the stratosphere were available and were assimilated in our experiment. Another option is to improve the bias model used, based on a better understanding of the source of the biases. For instance, in the ESA retrieval processing a calibration offset and continuum-like bias features are retrieved for each scan on the basis of 1-3 cm^{-1}-wide microwindows (Ridolfi et al. 2000). This approach also reduces the possibility of interpreting residual cloud contamination as radiance biases. The methods could also be applied in the radiance assimilation, and they may lead to a more robust correction of radiance biases for MIPAS.

The experiments reported here were performed with an observation operator that assumes local horizontal homogeneity. Bormann and Healy (2006) have shown that assuming horizontal homogeneity can introduce a considerable forward model error, especially for lower altitudes and strongly absorbing channels. Such errors could be avoided by using a radiative transfer model that takes into account horizontal gradients by operating on the limb-viewing plane. Data assimilation is well-suited to extracting information from MIPAS by using such a 2-dimensional radiative transfer model as global 3-dimensional information is readily available. A companion paper discusses the use of a 2-dimensional operator compared to the 1-dimensional approach taken here. Another aspect not covered here is the comparison between assimilating MIPAS radiances versus MIPAS retrievals. This will be reported on in a companion paper (Bormann et al. 2006).

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