TECHNICAL MEMORANDUM

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Assimilation of MIPAS limb radiances in the ECMWF system. Part II: Experiments with a 2-dimensional observation operator and comparison to retrieval assimilation

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August 2006

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

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Abstract

This study applies and compares three different ways of assimilating MIPAS data in a global Numerical Weather Prediction system. The three methods are: direct assimilation of emitted infrared limb radiances with a 1-dimensional radiative transfer model that assumes local horizontal homogeneity, direct assimilation of radiances with a 2-dimensional radiative transfer model which takes into account horizontal gradients in the atmosphere, and assimilation of retrieved profiles of temperature, humidity, and ozone. The three methods are intercompared by contrasting the resulting analyses against each other and against independent retrievals.

The use of a 2-dimensional radiative transfer model in the radiance assimilation leads to relatively small differences in the analyses compared to using a 1-dimensional observation operator in our experiments. Nevertheless, the results show that the 2-dimensional operator correctly takes into account the effect of tangent point drift, is capable of extracting a limited amount of horizontal structure from a single MIPAS scan, and leads to smaller First Guess departures for lower tangent altitudes and more strongly absorbing channels. As a result, humidity and ozone increments from a 2-dimensional operator are smaller in the lower stratosphere and upper troposphere in areas where considerable horizontal gradients prevail, and forecasts of humidity and ozone are improved in these regions.

In these first trials with assimilation of limb radiances, both the radiance and the retrieval assimilation, appear capable of incorporating useful information from MIPAS in the analyses. Both methods introduce broadly similar changes to the mean analyses, with little indication which method should be favoured. Nevertheless, results from the retrieval assimilation compare better to independent ozone data in the tropics and over Antarctica. For the radiance assimilation, there are many areas with scope for improvement, and these are discussed at the end of the paper.

1 Introduction

This memorandum reports on assimilation experiments with a 2-dimensional (2d) radiative transfer model employed to directly assimilate infrared limb radiances from the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) onboard the Envisat satellite (Fischer and Oelhaf 1996). The work complements our earlier study of assimilating MIPAS radiances with a 1-dimensional (1d) observation operator which assumed local horizontal homogeneity for the radiative transfer calculations (Bormann and Thépaut 2006). The report includes a comparison between the assimilation results with the 2d and the 1d radiative transfer model, and comparisons with the assimilation of MIPAS retrievals. It is the first time that radiances are directly assimilated into a Numerical Weather Prediction (NWP) model with a 2d radiative transfer model.

Our previous experiments with a 1d observation operator demonstrated the feasibility of directly assimilating infrared limb radiances from MIPAS in a NWP system (Bormann and Thépaut 2006). Experiments were performed over a 43-day period in August/September 2003. The assimilation of MIPAS radiances introduced considerable changes to the stratospheric analyses, without significantly degrading the overall fit to other observations used in the assimilation. For instance, the stratosphere was significantly moistened by 20-40 % through the assimilation of MIPAS radiances, and the MIPAS data corrected oscillatory structures in the vertical in analyses of the upper-stratospheric temperature field. Comparisons with independent data suggested that both aspects were an improvement of the stratospheric analysis, at least in the areas covered by the independent data. Results for the ozone analysis were more mixed, with improvements over the North Polar region and a better representation of the ozone hole over the South Polar region, but mean tropical ozone adjustments which appeared too broad in the vertical. The results showed considerable sensitivity to the bias correction applied to MIPAS radiances. Nevertheless, information on humidity and ozone introduced through the MIPAS assimilation was retained in the subsequent 10-day forecasts.

Studies have shown that the assumption of local horizontal homogeneity can introduce a considerable error in the forward calculations for infrared limb radiances (e.g., Bormann and Healy 2006). The error is smallest for radiances with along-path weighting functions which are approximately symmetric around the tangent point (e.g., for optically thin spectral regions), and it is largest for radiances from lower tangent altitudes and more strongly absorbing spectral regions, for which along-path weighting functions tend to be asymmetric around the tangent point. The effect of tangent point drift also brings additional dependence on the horizontal structure for one limb scan (Bormann and Healy 2006). Consequently, there has been some interest in using 2d radiative transfer models to develop tomographic retrieval schemes for limb sounding data (e.g., Livesey and Read 2000, Carlotti et al. 2001, Reburn et al. 2003). Improvements in terms of the horizontal resolution that can be retrieved compared to treating each limb scan individually have also been shown (Ridolfi et al. 2004).

Given the benefits of using a 2d radiative transfer model, there is some interest in employing such a model for the direct assimilation of limb radiances, in order to improve the representation of horizontal structure in the forward model. Variational data assimilation is well-suited to account for the horizontal characteristics, as it aims *per-se* to estimate a 3-dimensional or even 4-dimensional state of the atmosphere, and a 3-dimensional or 4-dimensional First Guess (FG) of the atmosphere is readily available. This is in contrast to tomographic retrieval methods which tend to start the retrieval iteration from a horizontally homogeneous atmosphere, and which assume that a series of limb scans all view the same plane. For MIPAS, the latter assumption is not always true, as the instrument mostly views slightly off-rearward.

Another aspect not studied previously is the comparison between results from the assimilation of retrievals versus an assimilation of limb radiances. The experience with nadir data suggests that assimilating radiances with their simpler error characteristics and errors that do not depend on the *a priori* information or other assumptions used in the retrieval should also be beneficial in the case of the limb viewing geometry. However, radiance assimilation crucially relies on an adequate correction of radiance biases (e.g., Harris and Kelly 2000, Dee 2004) and a good formulation of background error covariances in order to assist the separation of radiance information into temperature, humidity, and ozone information. Both of these aspects are currently areas of considerable uncertainty in the case of limb radiance assimilation over the stratosphere (Bormann and Thépaut 2006). For ESA's MIPAS retrievals bias correction is performed by retrieving microwindow-dependent continuum-like features and channel offsets (Ridolfi et al. 2000). The separation into geophysical variables is achieved during the sequential retrieval process, with the aid of channel subsets which focus on temperature/pressure, humidity, and ozone information, respectively (Ridolfi et al. 2000). MIPAS retrievals have most commonly been assimilated as profiles of level or layer values, with simple horizontal and vertical interpolation providing the link between model fields and retrievals (e.g., Dethof 2003, Wargan et al. 2005). This is also the approach used in the current study. More recently, methods have been employed that more adequately address the retrieval characteristics by taking into account the averaging kernels (e.g., Rodgers 2000).

The structure of the memorandum is as follows: we first introduce the assimilation system, observation operators, and assimilation experiments used in our study. We then discuss results of our experiments. This includes a discussion of increments obtained with a 1d and a 2d operator from a single MIPAS scan, comparisons between using 2d and 1d radiative transfer models for the radiance assimilation over an extended trial, and a comparison between results from the radiance and the retrieval assimilation. Finally, a summary and discussion of our findings is provided in the last section.

2 Assimilation approach

The general assimilation framework for this study is the same as in Bormann and Thépaut (2006), and only a brief summary is provided here. We use ECMWF's global incremental 4DVAR system (Rabier et al. 2000), with an assimilation window of 12h, 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. Ten-day forecasts are performed for each 0Z analysis. The experimental stratospheric humidity analysis was activated, following the work of Hólm et al. (2002). Assimilated observations were selected using the criteria used operationally in autumn 2005, with the addition of AMSU[1]-A data from NOAA[2]-17 and Aqua , and GPS radio occultation (RO) bending angles from CHAMP. The latter were assimilated with a 1d operator which assumes horizontal homogeneity (Healy and Thépaut 2006).

All MIPAS radiances and retrievals used in this study have been taken from the version 4.61 reprocessed MIPAS data. MIPAS radiance assimilation uses data from 260 selected channels over channel-specific tangent altitude ranges, as in Bormann and Thépaut (2006). 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. Cloud screening is based on Spang et al. (2004) and an additional threshold check on the clearest MIPAS channel (sweeps with the 960.700 cm^{-1} radiance above 100 nW/(cm^2 sr cm^{-1}) are considered cloudy; Dudhia 2004, pers. communication). Tangent pressure information is taken from the level-2 data. Bias correction for MIPAS radiances is based on the γ/δ method (e.g., Watts and McNally 2004), as discussed in Bormann and Thépaut (2006).

2.1 Observation operators for MIPAS radiances

The observation operators used in this study are RTMIPAS for the experiments with a 1d operator (Bormann et al. 2005), and RTMIPAS-2d for the experiments with a 2d operator (Bormann and Healy 2006). RTMIPAS was previously employed in our assimilation experiments with direct assimilation of MIPAS radiances under the assumption of local horizontal homogeneity (Bormann and Thépaut 2006). Both models use the same regression-based transmittance parameterisation. The main difference is that RTMIPAS-2d accounts for the horizontal structure in a limb-viewing plane by using path conditions (including scene temperatures for the radiative transfer integral) calculated with a 2d ray-tracer, whereas RTMIPAS assumes horizontal homogeneity. RTMIPAS-2d has been shown to reproduce line-by-line radiances with a level of accuracy that is below the MIPAS instrument noise for most channels, at least for tangent pressures less than 350 hPa. For lower tangent altitudes, some parameterisation errors occur due to variability not captured during the training of the regression models which are based on line-by-line calculations for horizontally homogeneous atmospheres. However, these tangent altitudes are not used in our study.

It is worthwhile to summarise here some of the technical aspects of the implementation of RTMIPAS-2d and its tangent linear and adjoint in the ECMWF system, given the multi-processor environment of the assimilation system. In the ECMWF system, observations and model fields are distributed over the memory of a number of processors. However, the processor which owns a given observation may not hold the region of the model fields surrounding the observation location. To apply observation operators on the processor which owns a given observation, message passing is performed to supply the information from the model fields. For the 1d observation operators, the processor with a given observation sends a request to the processor which owns the model fields for the relevant region of the globe. The processor which owns the model fields for the relevant region then performs a spatial interpolation, and the interpolated profile is subsequently passed to the processor which owns the observation. For the 2d operator, we adopt the same strategy, but now a series of profiles representing the limb viewing plane is accumulated at the processor which owns the limb observation. This series of profiles may originate from several different processors, depending on which processors own the relevant regions of the globe. Again, the spatial interpolations to the locations of the series of profiles is

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performed on each processor that owns the relevant model fields. Care has to be taken that the interpolation and message-passing is performed in a reproducible order, in order to accurately perform the corresponding adjoint operations.

In our experiments the limb-viewing plane is specified through the azimuthal angle calculated from the sub-tangent point and satellite position for the central sweep of each scan. Deviations from this viewing plane for other sweeps are neglected. The plane is represented by 31 profiles, centred at the sub-tangent point of the central sweep, with a spacing of approximately 40 km, consistent with the model resolution. Tangent point drift is taken into account in the RTMIPAS-2d calculations, based on a zonal projection of the tangent point onto the limb-viewing plane.

2.2 Assimilation experiments

As a first sanity check we performed two single-scan experiments for a single analysis cycle at 30 August 2003 0Z, using, respectively, the 1d- and the 2d-operator to assimilate just one scan of MIPAS radiances. Such single scan experiments allow a detailed comparison of the increments (i.e., the adjustments to the FG introduced through the assimilation of observations) obtained with a 1d and a 2d observation operator, in order to highlight the role of the forward model together with that of the background error covariances in the assimilation. To further simplify the interpretation, these experiments used the 3DVAR version of the ECMWF system, with the FG calculated at the appropriate time. This excludes the evolution of the background error covariances which complicates the shape of increments in a 4DVAR system. The sub-tangent point of the central sweep of the assimilated MIPAS limb scan is located at 49.2W, 52.8S, east of Patagonia, in an area of strong gradients in the stratosphere (e.g., a temperature gradient of 15 K/1000 km at 30 hPa). The sub-satellite point is northward of this location, and all sweeps down to 12 km tangent altitude passed the cloud screening. The FG for both experiments was the same, and it was taken from the experiment with radiance assimilation with a 1d-operator discussed in Bormann and Thépaut (2006).

In addition, we present results from longer trials, all of which cover the 43-day period 18 August - 29 September 2003. The following experiments were performed: the control experiment (CTL) is the baseline in which MIPAS data are only passively monitored and not assimilated. In the experiment RAD, MIPAS radiances are actively assimilated using a 1d observation operator which assumes horizontal homogeneity. CTL and RAD are the same experiments as in Bormann and Thépaut (2006). In the experiment RAD-2d, we assimilated MIPAS radiances with the 2d observation operator outlined above.

We also performed an experiment in which we assimilate ESA's MIPAS level-2 retrievals of temperature, humidity, and ozone. This experiment will be referred to as RETR. In these experiments we assimilate profiles of partial columns for humidity and ozone, and temperature on tangent pressure levels. The retrievals were derived under the assumption of horizontal homogeneity, and the retrieval algorithm is described in Ridolfi et al. (2004). Diagonal error covariances were used for the MIPAS retrievals, with the diagonal based on the retrieval errors provided with the data or a minimum threshold if the retrieval errors are below this threshold. The thresholds are 0.6 % for temperature (1-1.5 K), 10 % for humidity, and 5 % for ozone. Experimentation with doubling the retrieval error to take systematic errors in the retrievals into account resulted in little difference in the resulting analyses.

3 Results

3.1 Single-scan experiments

We will first discuss the results of the single-scan experiments to provide some further insight to the expected behaviour of the assimilation with a 2d operator.

Figure 1a and b compare humidity increments at around 80 hPa from a 1d operator and from a 2d operator. Several aspects are striking: While the general shape of the increments is similar, the magnitude is smaller with the 2d operator, and the centre of the increment is shifted northward. The smaller increments with the 2d operator can be traced back to smaller FG departures for this particular case, so smaller adjustments to the FG are necessary. Similar findings can be reported for many other levels and also for ozone and temperature increments at the majority of levels (though not all) for this case. Given the smaller FG departures noted as a result of a reduction in forward model error in our earlier study (Bormann and Healy 2006), such smaller increments are likely to be typical for the 2d operator in general. The northward-shift of the centre of the increments reflects that tangent point drift is taken into account in the 2d operator. This causes a shift of the tangent point (and therefore the most sensitive area) of typically 160 km towards the sub-satellite point between the sub-tangent point of the central sweep and that of the lowest sweep. The 1d operator is unable to represent this aspect.

The general shape of the analysis increments is worth further discussion. In general, the shape of the analysis increments appears similar for the 1d and the 2d operator (cf, Fig. 1a and b), as this shape is largely determined by the background error. However, at some levels and for some variables there is evidence of limited additional horizontal structure in the increments. An example of this is given in Figures 1c and d. Here, the temperature increments obtained with a 2d operator appear somewhat tighter along the limb-viewing plane, and additional positive increments occur on either side of the limb-viewing plane, and these positive increments are not present in any form in the experiment with the 1d operator. Note as well that for this particular level, the absolute value of the peak increment is larger for the 2d operator, but it is associated with an increment of the opposite sign nearby. Slight tightening or broadening of the increments along the limb-viewing plane can be reported for other levels, suggesting that the 2d operator is able to retrieve a limited amount of horizontal structure along the limb-viewing plane.

The amount of horizontal structure that can be retrieved could be optimised at the channel-selection stage. Our channel selection was based on maximising information content using 1d simulations (but without a penalty for channels sensitive to horizontal structure) and therefore information on horizontal structure is included in our channel set largely by chance. An optimised channel selection would maximise the information content retrieved over a limb-viewing plane and the resulting set is likely to consist of a mix of channels with along-ray weighting functions peaking at as well as away from the tangent point. The generation of such a channel set is beyond the scope of the present study and is left for future work.

A single-scan experiment has also been performed for a tropical MIPAS scan, in an area of very small horizontal gradients in the stratosphere (not shown). Here, the size of the increments was mostly similar for the 1d and the 2d operator, as the FG departures were also fairly similar. However, the effect of tangent point drift, and some broadening and tightening of increments along the limb-viewing plane were also observed in this case.

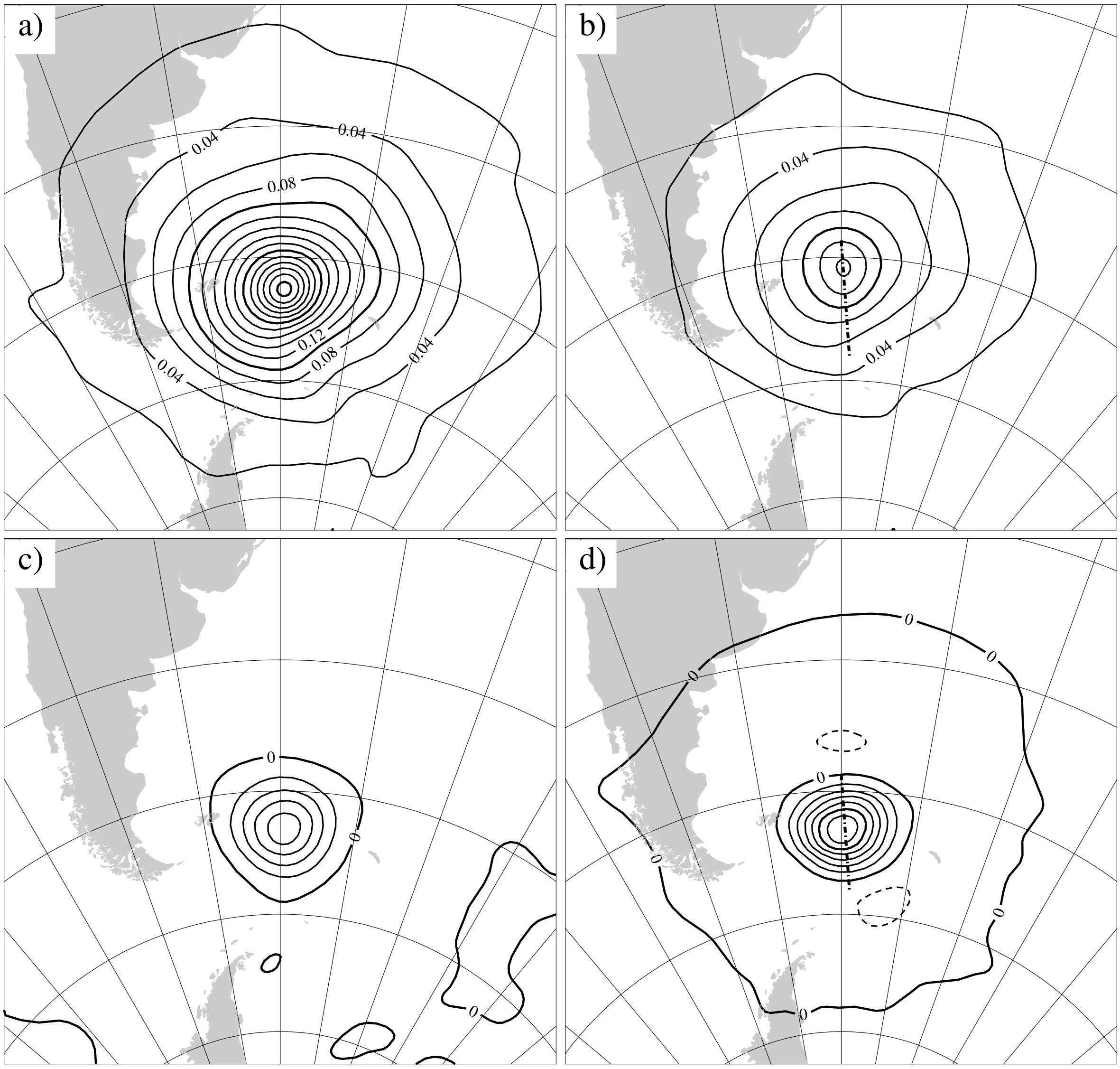

Figure 1: a) Humidity increments [ppmv] obtained with a 1d operator at model level 24 (approx. 80 hPa) in the single-scan experiment. Contour interval is 0.02 ppmv. b) As a), but obtained with a 2d operator. The dash-dotted line indicates the location and orientation of the limb-viewing plane used in the operator. c) Temperature increments obtained with a 1d operator at model level 16 (approx. 15 hPa) in the single-scan experiment. The contour interval is 0.1 K, with solid contours indicating negative values and dashed contours indicating positive values. d) As c), but obtained with a 2d operator. Again, the dash-dotted line indicates the location and orientation of the limb-viewing plane used in the operator.

3.2 Analysis impact over extended trial

3.2.1 2d versus 1d operator

We will now discuss the results of our extended trial with radiance assimilation over a 43-day period in August/September 2003. This is to assess the differences in the analysis impact from using a 2d operator compared to a 1d operator over a longer period.

FG statistics for assimilated MIPAS radiances show smaller FG departures for the 2d operator compared to the 1d operator for radiances from lower tangent altitudes and more strongly absorbing channels (Fig. 2 which can be compared to Fig. 5b in Bormann and Thépaut 2006). The reduction reaches $1\frac{1}{2}$ times the instrument noise for the lowest tangent altitude used (12 km). At the same time, no channel shows a significant increase in the FG departures at any tangent altitude, with the largest increase reaching only $\frac{1}{14}$th of the instrument noise. Smaller departures are particularly prominent over the polar and mid-latitude regions. The reduction is a result of reduced forward model error in the 2d operator, and it is consistent with earlier findings from passive monitoring of MIPAS radiances against the ECMWF FG (Bormann and Healy 2006). Note, however, that for the channels selected for assimilation the tangent altitudes where Bormann and Healy (2006) showed the strongest horizontal gradient error tend to be excluded from our assimilation. Analysis departures also show a reduction in the standard deviations for the same radiances when a 2d operator is used (not shown). As expected, most reduction is in terms of the standard deviation, whereas biases for FG or analysis departures are virtually unchanged (not shown).

Apart from the smaller FG departures, the most striking difference between the RAD and RAD-2d experiments

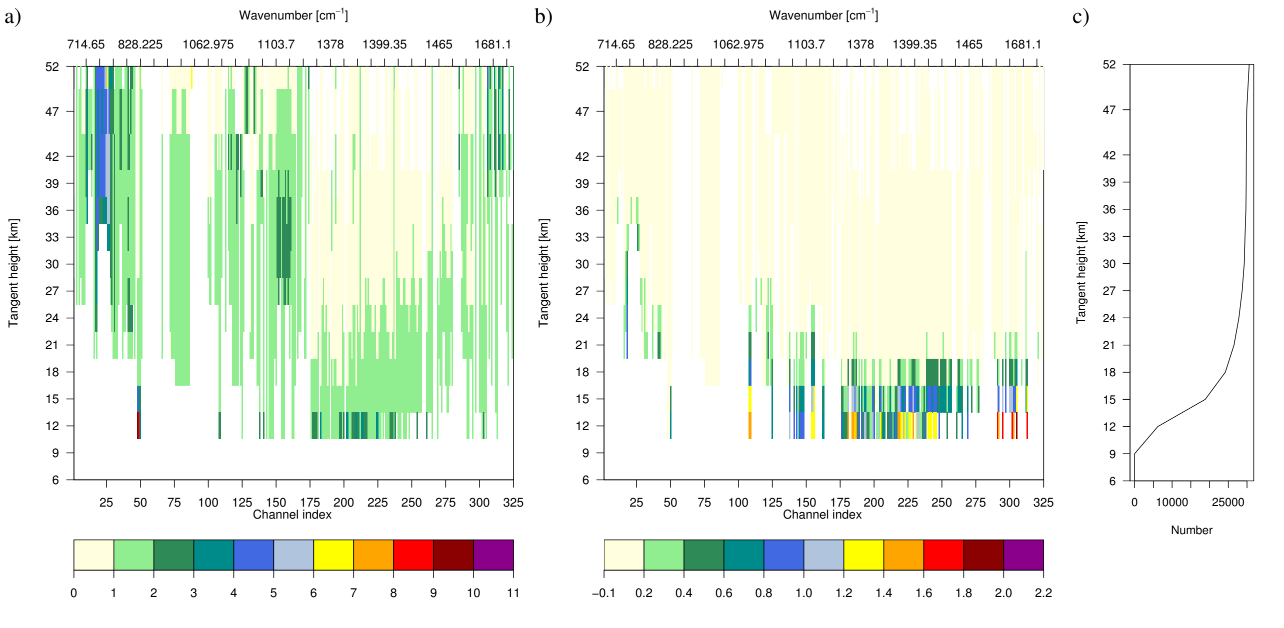

Figure 2: a) Standard deviation of observation minus FG departures for used MIPAS radiances from the experiment RAD-2d as a function of channel index and nominal tangent altitude. The values have been normalised by the instrument noise in each channel. Wavenumbers of selected channels are provided in the top axis for orientation. Correction of MIPAS radiance biases has been applied. The Figure can be compared with Fig. 5b from Bormann and Thépaut (2006). b) Difference between the standard deviation of FG departures for the experiment RAD and the experiment RAD-2d as a function of channel index and nominal tangent altitude. The values have again been normalised by the instrument noise in each channel. c) Number of clear sweeps per tangent altitude.

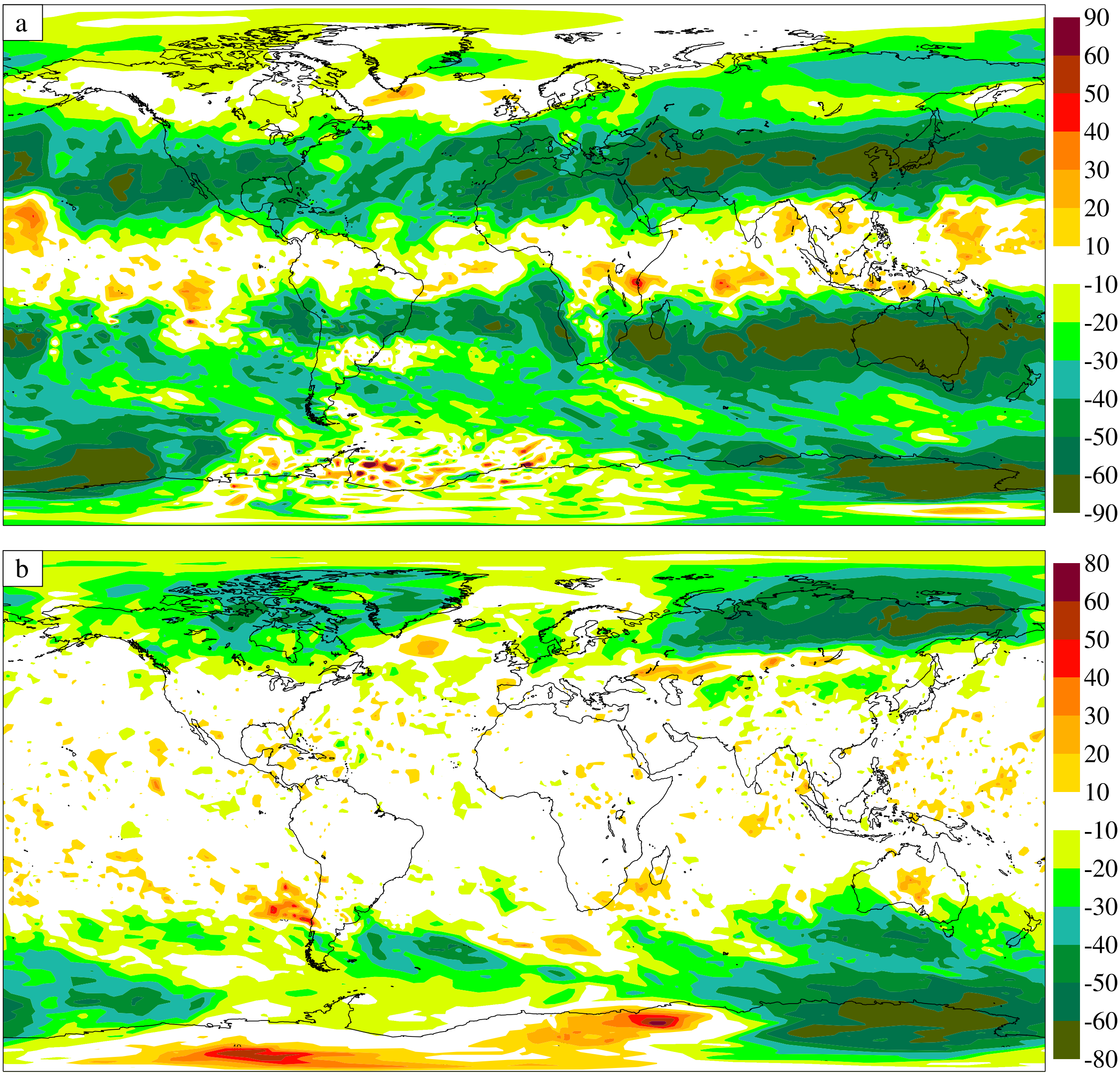

Figure 3: a) Differences in the root mean square (RMS) of the humidity increments at model level 21 (approx. 44 hPa) between the experiment RAD-2d and the RAD experiment, relative to the RMS of the increments in RAD [%]. Green areas indicate a reduction of increments from using the 2d operator. b) As a), but for ozone increments.

is a significant reduction in the size of the analysis increments for humidity and ozone. In and around the polar vortex and in the mid-latitudes humidity and ozone increments tend to be reduced by 30-60 % over large parts of the stratosphere in the 5-125 hPa range, whereas the size of the increments is similar around the equator (e.g., Fig. 3). The reduction is most prominent for humidity, whereas little difference is found for temperature. The reduction of the increments occurs predominantly in areas with considerable horizontal gradients, where the 2d operator is expected to make the most difference. The reduction in the increments is related to the smaller FG departures for MIPAS radiances noted earlier, and it suggests a better consistency of the assimilation system, as a result of using an improved forward model as it allows better use to be made of the model background information. Note, however, that the observation errors for the RAD and RAD-2d experiments were unchanged, even though the larger forward model error in RAD would suggest that the observation errors used for MIPAS radiances in RAD should be larger than those in RAD-2d, at least for lower tangent altitudes and some strongly absorbing channels. Larger observation errors in RAD would also result in a reduction of the size of the increments.

Otherwise, there are only relatively small differences in the behaviour of the analysis system between RAD and RAD-2d. Departure statistics for other observations used in the system are hardly changed between the experiment RAD and RAD-2d. The only exception are departures for ozone retrievals below 8 hPa from the Solar Backscatter Ultra Violet (SBUV) instrument onboard NOAA-16. These show a small reduction in the standard deviation of the FG or analysis departures below 8 hPa over the southern mid-to-higher latitudes when the 2d-operator is used, suggesting that the FG is slightly improved in the RAD-2d experiment (e.g., Fig. 4) Also, zonal mean analyses from the experiment with a 2d operator are rather similar to those from a 1d operator, suggesting that mean analyses are relatively insensitive to the use of a 1d or a 2d operator. Figure 5 shows the difference between the zonal mean analyses from the RAD-2d experiment and that from the CTL, and the Figure can be compared with Fig. 9 in Bormann and Thépaut (2006). The largest differences in the zonal mean analyses of RAD-2d and RAD occur around the tropopause for the humidity field, where the differences can reach 5 %.

3.2.2 Retrieval assimilation

We will now contrast the analysis impact found in RAD or RAD-2d against that obtained when assimilating the MIPAS retrievals in the experiment RETR. A full discussion of the impact of the retrieval assimilation is beyond the scope of this paper; instead we provide an overview of the points relevant to the comparison with the results of the radiance assimilation.

The FG or analysis fit to MIPAS retrievals is generally improved in the experiment RETR compared to CTL, suggesting that the analysis is able to extract and retain information from the retrieved profiles (Figures 6-8). For temperature, standard deviations of the FG departures in RETR are typically less than 2.5 K in the Tropics and over the Northern Hemisphere. For the Southern Hemisphere, standard deviations of the FG departures are also improved, but remain high above 5 hPa (up to 6 K), suggesting some discrepancy between the MIPAS retrievals and the model fields. While biases between the MIPAS temperature retrievals and the FG or analysis are generally improved as well over various geographical areas, an oscillatory structure in the vertical with extremes of ± 4 K is still present in the RETR experiment. For humidity, the assimilation draws well to the MIPAS retrievals, with only small biases against the FG or the analysis in the 2-100 hPa range, and standard deviations of the FG departures well below 10 %. Some larger departures can be found towards the mesosphere or the upper troposphere, where also some discrepancy in the bias between model fields and MIPAS retrievals are apparent. For the top-most MIPAS layer at 0.1-0.2 hPa, departure statistics show that the MIPAS retrievals are still 20 % wetter than the RETR analyses, whereas for the layer just below this MIPAS retrievals are drier than the model fields by around 10 %. It appears that the analysis is struggling to find a compromise

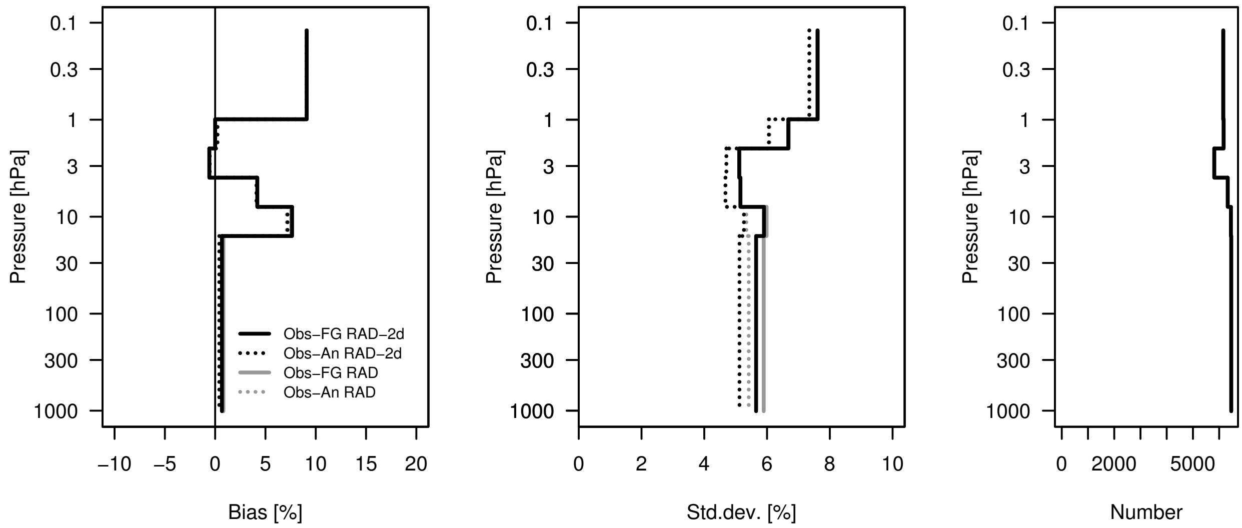

Figure 4: Departure statistics for used SBUV ozone retrievals from NOAA-16 over the latitude band 30-60S for the period 1-29 September 2003. Solid lines indicate statistics for FG departures, dotted lines statistics for analysis departures. Statistics for the RAD-2d experiment are in black, for the RAD experiment 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. Departure statistics have been normalised by the mean observation.

between such conflicting bias information, under the additional constraints imposed by vertical correlations in the background errors. For ozone, the fit to the MIPAS retrievals is also improved in the experiment RETR compared to CTL, but biases of the order of 5-10 % are still common. Standard deviations of the FG departures are markedly reduced below 5 hPa in the RETR experiment compared to the CTL.

It is interesting to compare the departure statistics for MIPAS retrievals in RETR with those obtained in RAD or RAD-2d (cf, e.g., Figures 6 to 8 with Figures 10-13 from Bormann and Thépaut 2006). Generally speaking, the reduction in the standard deviation between FG and analysis departures tend to be larger in the RETR experiment than in RAD or RAD-2d, as might be expected since RETR actively assimilates the MIPAS retrievals. FG departures on the other hand provide a more independent assessment. For ozone below 30 hPa and for humidity in the middle stratosphere, the FG from the RETR experiment tends to agree better with the MIPAS retrievals than the FG from the experiments with radiance assimilation. This may indicate some inconsistency between the radiance and retrieval assimilation. Elsewhere, standard deviations of FG departures against MIPAS retrievals are very similar for RETR, RAD, and RAD-2d, and for temperature above around 3 hPa and for ozone above 10 hPa they even tend to be smaller for the radiance experiments than for the retrievals. This indicates excellent consistency of the radiance assimilation with the MIPAS retrieval processing.

Overall, the better fit to the MIPAS retrievals in RETR is not at the expense of a poorer fit to other observations compared to the CTL experiment. Generally speaking, the alterations in the fit to other observations are very similar to the changes observed in RAD or RAD-2d compared to CTL, with smoother biases against stratospheric temperature observations from radiosondes, and an improved FG fit to SBUV data. However, some differences to RAD or RAD-2d are worth mentioning: the larger standard deviations of the analysis departures against AMSU-A channel 14 over the Southern Hemisphere noted in the experiment RAD and also present in the experiment RAD-2d are not present in the RETR experiment for which these values are unaltered compared to the CTL experiment (not shown). Also, biases and standard deviations against temperature observations from radiosondes over the South Polar regions appear somewhat smaller around 5-10 hPa in RETR than in RAD (not shown). This gives some indication that the temperature analysis over the Antarctic region is more consistent in the RETR assimilation than in RAD or RAD-2d.

The changes introduced to the mean analyses by the MIPAS retrievals are qualitatively similar to the changes noted for the radiance assimilation for temperature and humidity, but with considerable differences for the ozone field. Note that the bias correction for the experiments with radiance assimilation was calculated from an experiment with retrieval assimilation, so some similarities in the changes to the mean analyses are to be expected. For temperature, the differences versus the control show an oscillatory structure in the vertical for the retrieval as well as the radiance assimilation, with somewhat smaller differences for the retrieval assimilation, especially towards the top of the model and over the polar regions. For humidity, the retrieval as well as the radiance assimilation lead to a considerable moistening of the stratosphere, typically by 20-30 %, with similar magnitudes for the retrieval as well as the radiance assimilation. Differences are noticeable towards the mesosphere and in the lower stratosphere over the Southern Pole, for which the differences introduced by the radiance assimilation are much smaller than those introduced by the retrieval assimilation. Note also the different structure in the lower stratosphere in the tropics, for which the retrieval assimilation introduces smaller changes. For ozone, the changes introduced to the mean zonal ozone analysis by the retrieval assimilation show rather different structure over the tropics than those obtained in the experiments with radiance assimilation. While all three MIPAS experiments put the maximum increase in tropical ozone at around 15 hPa at 18S, the retrieval assimilation also shows some decrease in ozone around 20 hPa at the equator, and this decrease is not present in the experiments with radiance assimilation.

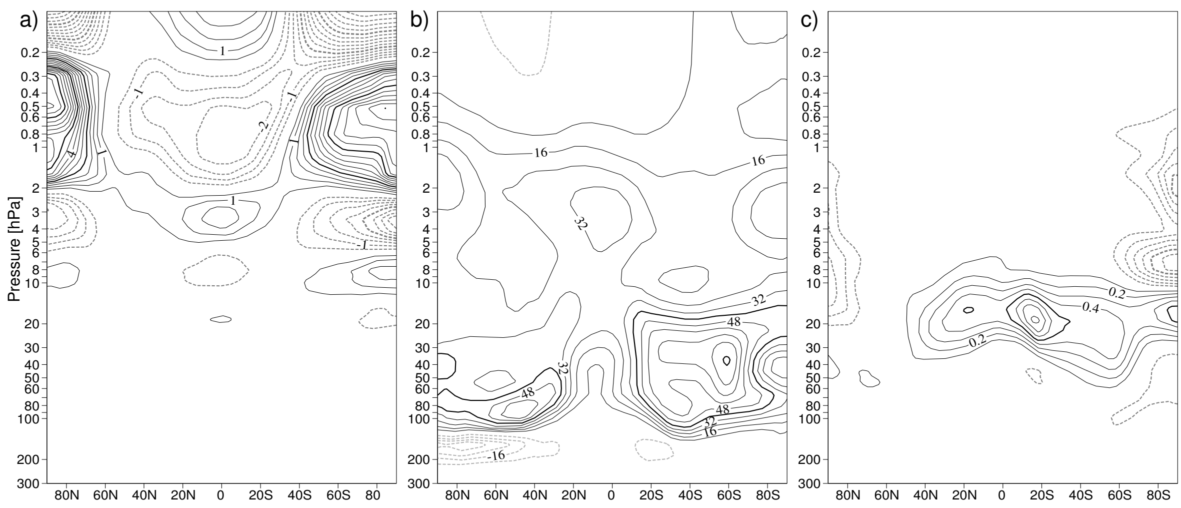

Figure 5: a) Zonal mean temperature differences between the experiment RAD-2d and the CTL. Contour interval is 0.5 K, with positive values shown by solid black contour lines and negative values shown through dashed grey lines. b) Same as a), but for humidity (relative to the CTL), with a contour interval of 8 %. c) Same as a), but for ozone volume mixing ratio with a contour interval of 0.1 ppmv.

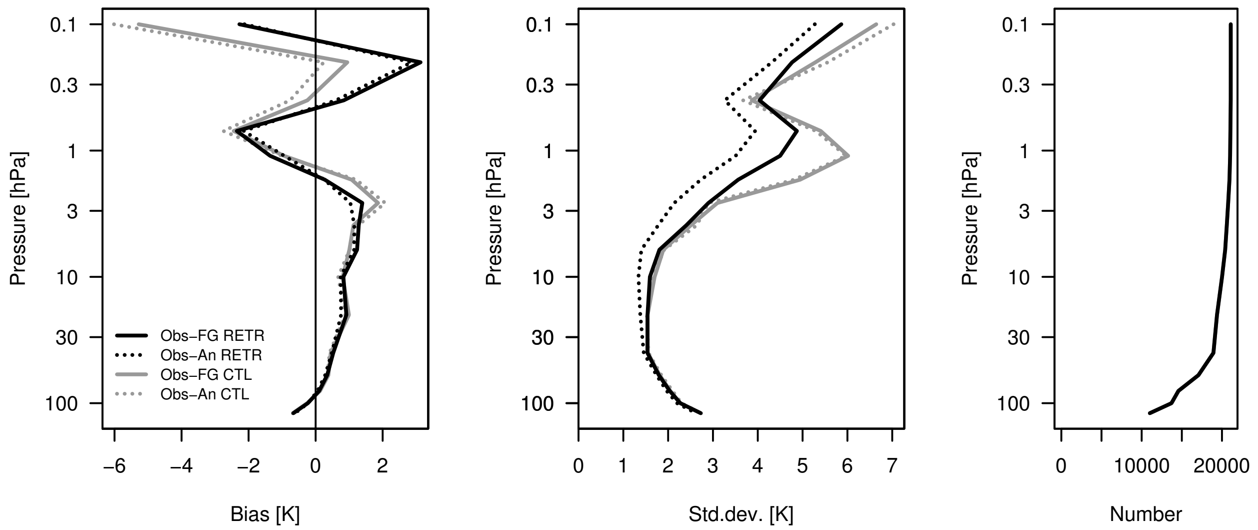

Figure 6: Departure statistics for MIPAS temperature retrievals (global) for 1-29 September 2003. Solid lines indicate statistics for FG departures, dotted lines statistics for analysis departures. Statistics for the RETR experiment are in black, for the CTL in grey. From left to right the three panels show the bias (retrieval minus FG or analysis), standard deviation, and the number of retrievals, respectively.

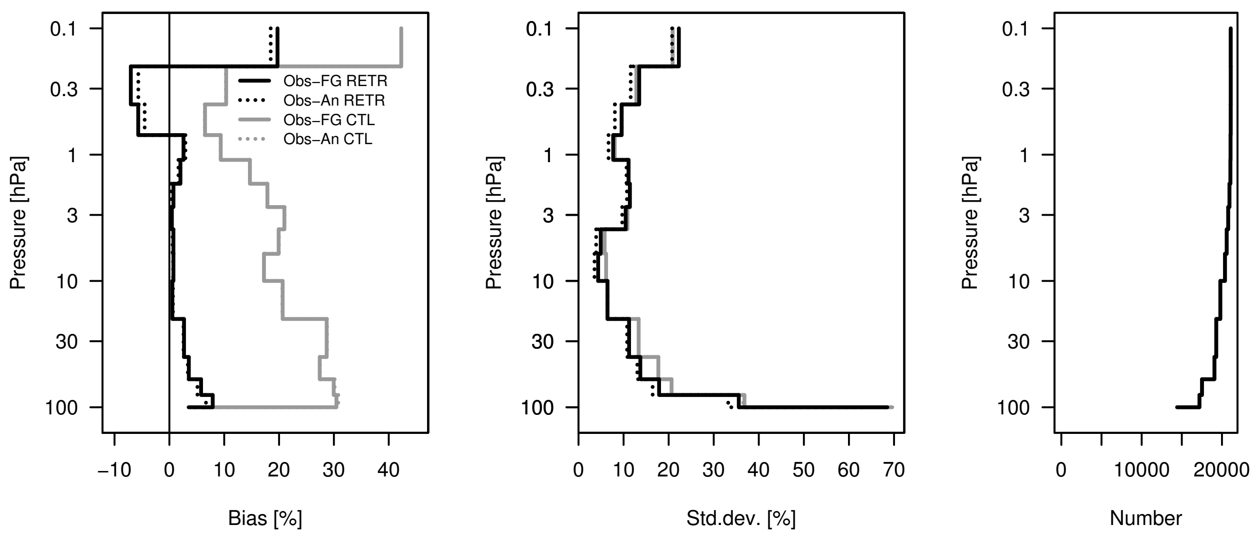

Figure 7: As Fig. 6, but for humidity. Bias and standard deviation [%] are shown relative to the mean observation, using data for partial columns.

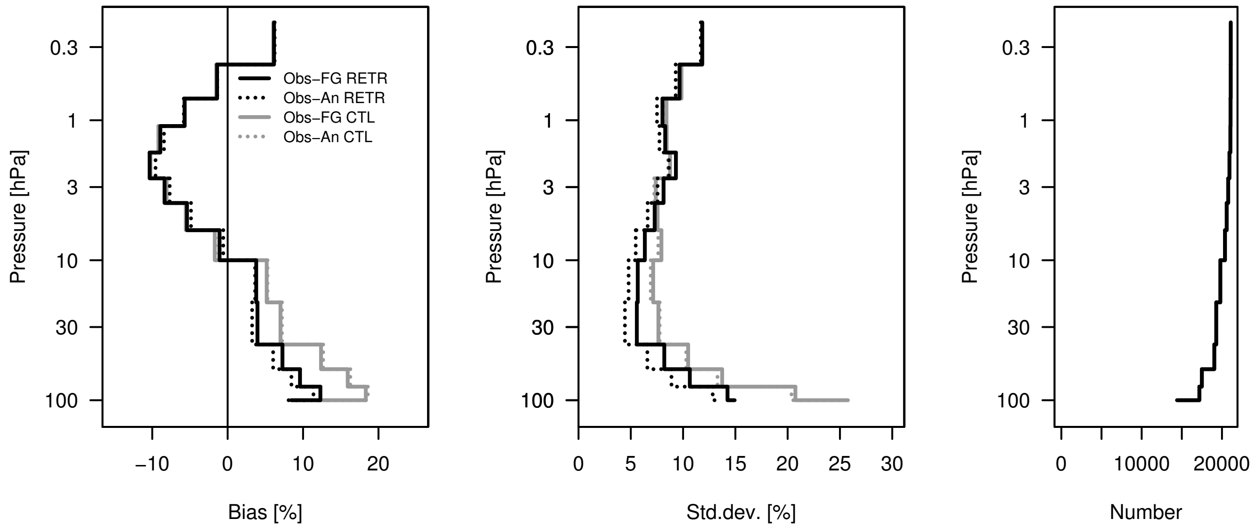

Figure 8: As Fig. 7, but for ozone.

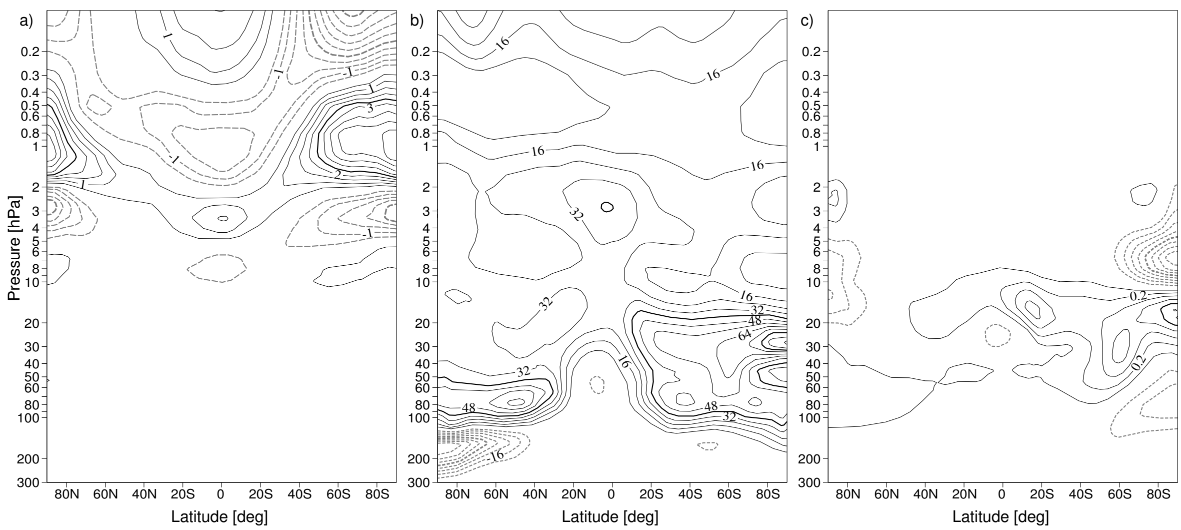

Figure 9: As Fig. 5, but for the zonal mean differences for the experiment RETR and the CTL.

3.3 Comparison of radiance assimilation and retrieval assimilation to independent data

We will now compare the analyses from the four experiments (RAD, RAD-2d, RETR, CTL) with independent retrievals and ozone sondes in order to evaluate the changes introduced by different methods of assimilating MIPAS data. The independent data are the same as used in Bormann and Thépaut (2006), that is, ozone sondes as well as retrieved profiles of humidity and ozone from the Halogen Occultation Experiment (HALOE), the Stratospheric Aerosol and Gas Experiment (SAGE) II, and the Polar Ozone and Aerosol Measurement (POAM) III. HALOE retrievals of temperature are also used to assess the upper stratospheric and mesospheric temperature fields; note that below 35 km HALOE data represent the model background used in the retrieval process and are therefore not suitable for our evaluation.

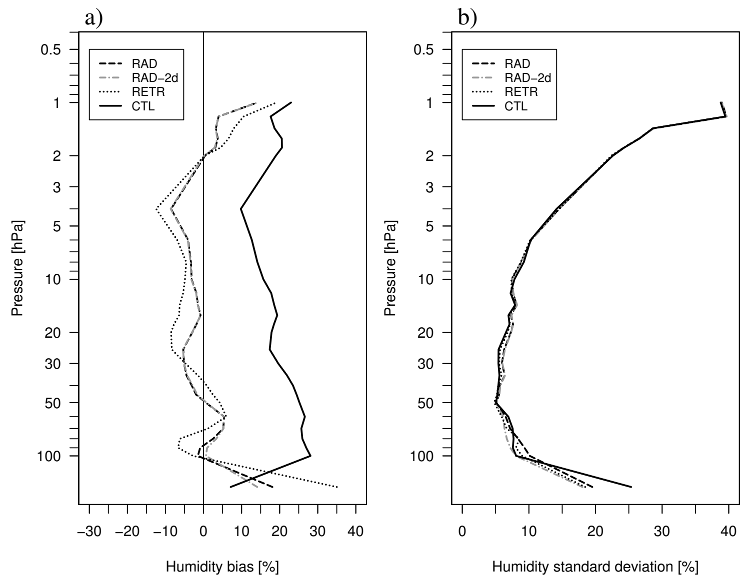

Figure 10: Comparison between Sage II humidity retrievals over the North Polar region (60-74N) against analyses from the CTL (solid black), RAD (dashed black), RAD-2d (dash-dotted grey), and RETR (dotted) experiment. The data covers the period 1-29 September 2003 (195 profiles), and the two panels show the bias (a) and the standard deviation of the retrieval minus analyses differences, normalised by the mean retrieval value.

Statistics of analyses against the correlative data are very similar for the RAD and the RAD-2d experiment, suggesting that improvements in the analyses from using a 2d observation operator in the assimilation are relatively small. The only exception are statistics for humidity for the troposphere/lower stratosphere region below about 70 hPa over the polar or mid-latitude regions. Here, standard deviations of the differences to the three types of correlative data are consistently 3-5 % lower for the RAD-2d experiment than in the RAD experiment (e.g., Fig. 10b). While the effect is small, the consistency of the finding for the three types of retrievals nevertheless provides some evidence that accounting for horizontal gradients in the observation operator for MIPAS radiances leads to better humidity analyses in these regions. Note that polar and mid-latitude regions are also the areas for which we found significantly smaller humidity increments. For ozone, smaller analysis departures in the RAD-2d experiment as noted for SBUV data are not present in any of the correlative data.

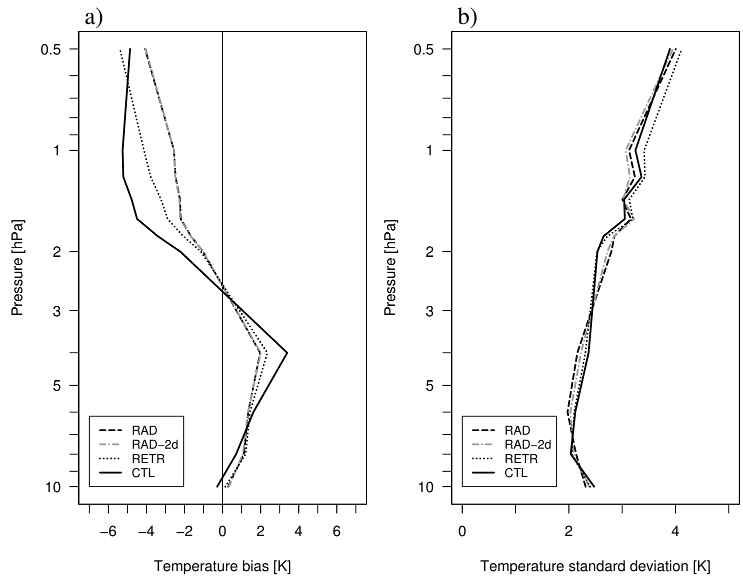

Figure 11: Comparison between HALOE temperature retrievals over the tropical region (0-20S) against analyses from the CTL (solid black), RAD (dashed black), RAD-2d (dash-dotted grey), and RETR (dotted) experiment. The data covers the period 1-29 September 2003 (70 profiles), and the two panels show the bias (a) and the standard deviation of the retrieval minus analyses differences.

3.3.1 Temperature

The experiments with the assimilation of MIPAS radiances or retrievals are comparing similarly well with HALOE temperature retrievals over the upper stratosphere and lower mesosphere, with a slight advantage for the experiments with the radiance assimilation over the tropical region. HALOE data appear to support the oscillatory changes introduced to the temperature analyses in all three MIPAS experiments compared to the CTL. Over the tropics, the bias versus HALOE profiles is almost halved in the RAD or the RAD-2d experiment, whereas biases in RETR are improved as well, but not quite as much (e.g., Fig. 11a).

3.3.2 Humidity

Overall, humidity analyses from the three MIPAS experiments compare similarly well with the independent data, with little preference for one or the other experiment. The most prominent change introduced through the assimilation of MIPAS data is the moistening of the stratosphere. Overall this is similarly supported qualitatively and quantitatively by the independent data (Figures 10 and 12), within the uncertainties inherent in these retrievals as discussed in Bormann and Thépaut (2006).

Nevertheless, there are noteworthy differences. Over the North Polar region, all three types of correlative humidity profiles support the weaker drying around the tropopause in RAD or RAD-2d compared to CTL, and the independent data suggest that RETR is too dry in this area (e.g., Fig. 10). While the correlative data tend to be less reliable at these levels, the signal is the same for all three retrieval types, providing additional confidence in the result. For the tropics, the drier lower stratosphere in the RETR experiment is in better agreement with HALOE retrievals than the result from the radiance assimilation (e.g., Fig. 12). Analyses with MIPAS radiances

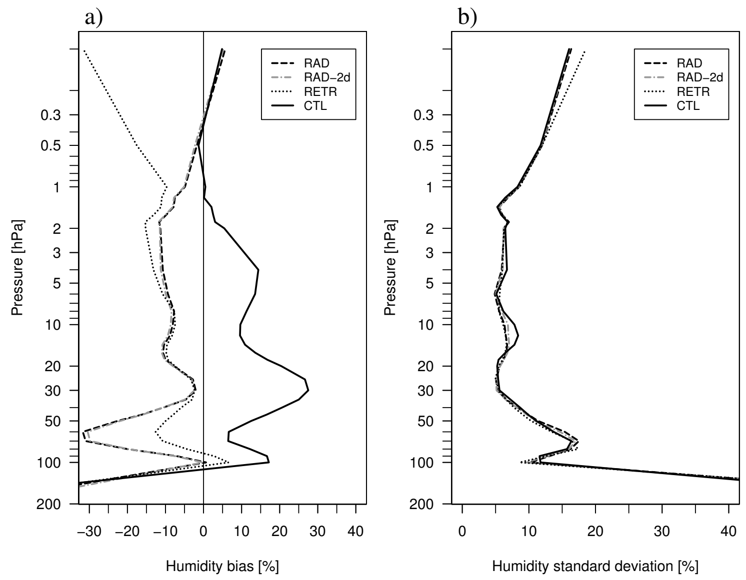

Figure 12: As Fig. 10, but for humidity profiles from HALOE over the tropical region (0-20S; 70 profiles).

show a wet bias of up to 30 % against HALOE around 60 hPa over the tropics, whereas the wet bias in RETR is only around 10 %. In contrast, over the mesospheric region, HALOE indicates that the analysis from RETR is too moist by up to 30 % over all areas covered by HALOE (e.g., Fig. 12). This suggests in turn that the MIPAS retrievals are too wet for the highest layer provided, and it would likely be beneficial to exclude this layer from the assimilation. Inconsistencies in the upper MIPAS layers were already apparent from the bias against the FG or the analyses displayed in Fig. 7. In contrast, there is better agreement between HALOE retrievals and humidity analyses from RAD or RAD-2d over the mesosphere. Note, however, that very few MIPAS radiances with mesospheric tangent altitudes are assimilated in RAD or RAD-2d, so the better results for the radiance assimilation in the mesosphere reflect, to some extent, a better bias against HALOE of the CTL experiment.

3.3.3 Ozone

Results of comparisons of ozone sondes or retrievals with the analyses discussed here are somewhat more mixed. Analyses of all three experiments with MIPAS data clearly compare better with independent data over the North Polar region (e.g., Fig. 13). Biases as well as standard deviations of differences between analyses and any of the correlative data are considerably improved through the assimilation of MIPAS data, indicating a better ozone analysis in this region. The retrieval assimilation appears to lead to somewhat larger ozone values around the tropopause than the radiance assimilation, but it is not clear which is better.

Over the South Polar region, the analyses from the retrieval assimilation agree better with the observations from ozone sondes. Standard deviations of the differences between ozone sondes and analyses are smaller by about 5 % for the RETR experiment than for the CTL, which exhibits standard deviations similar to those of the two experiments with radiance assimilation (Fig. 14). Also, ozone depletion in the 60-200 hPa range is considerably better represented in RETR than in RAD or RAD-2d, which still exhibit considerable positive biases of up to 50 % in this area. It appears that the radiance assimilation is less successful in extracting information from MIPAS data in this region than the retrieval assimilation.

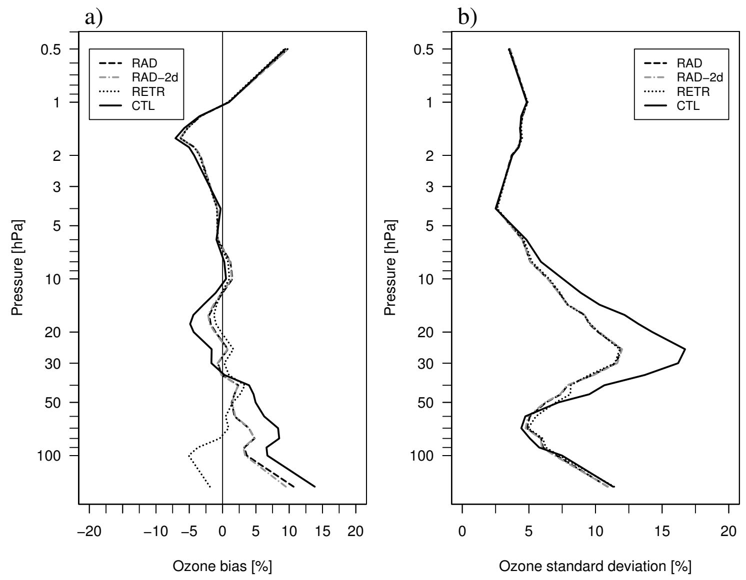

Figure 13: As Fig. 10, but for ozone profiles from SAGE II over the North Polar region (60-74N; 195 profiles).

Outside the polar region, standard deviations of the differences between analyses and correlative data are largely unaltered whether MIPAS data are assimilated or not, suggesting that neither MIPAS radiances nor MIPAS retrievals are significantly reducing the random error in the ozone analysis. The main differences appear instead in the bias between the correlative data and the analyses. Over the tropics, for instance, the retrieval assimilation leads to smaller biases against sondes or HALOE retrievals, somewhat reducing the oscillatory structure otherwise present in the CTL experiment (e.g., Fig. 15). The radiance assimilation in contrast enhances the oscillatory structure in the bias. Note, however, the rather limited sample of 28 ozone sondes available for this comparison, making the statistics less reliable.

3.4 Forecast impact

We will now compare the forecast performance of the experiments RAD, RAD-2d, RETR, and CTL. Given the better agreement of analyses with MIPAS data with independent data, we will validate the RAD, RAD-2d, and the RETR forecasts against their own analyses, whereas the CTL experiment will be verified against the RAD analysis. Note that the differences between the validating analyses introduces some uncertainty in the verification.

Broadly speaking, forecasts from the three experiments with MIPAS data compare to the CTL forecasts in a similar way as the RAD experiment which was discussed in Bormann and Thépaut (2006). For humidity and ozone, the information introduced through the assimilation of MIPAS radiances is at least partially retained throughout the forecast. This is especially so for the moistening throughout the stratosphere, and the reduction of total ozone over the South Pole. The largest benefit stem from a reduction in the mean error. For temperature, the results are less conclusive, as the assimilation of MIPAS data reduces large temperature biases in the upper stratosphere in the analyses, but these temperature biases appear to be less of a problem later in the forecast in the CTL experiment or the other three experiments.

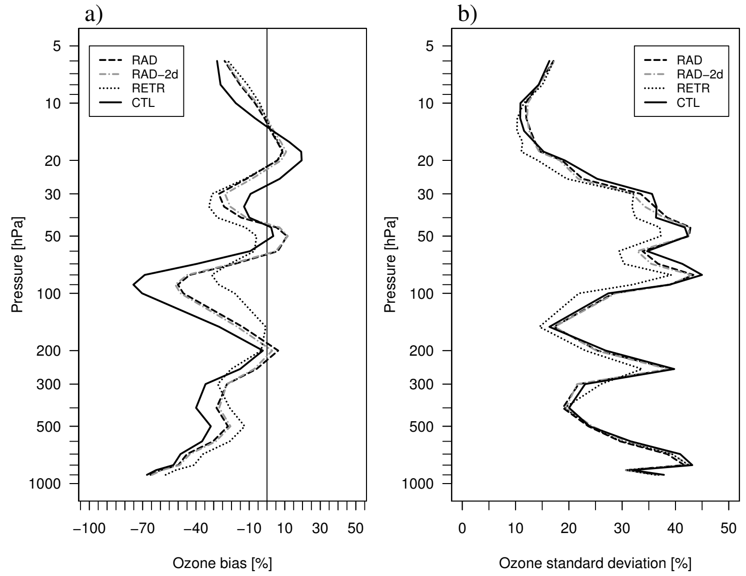

Figure 14: As Fig. 14, but for 49 ozone sondes over the South Polar region (60-90S).

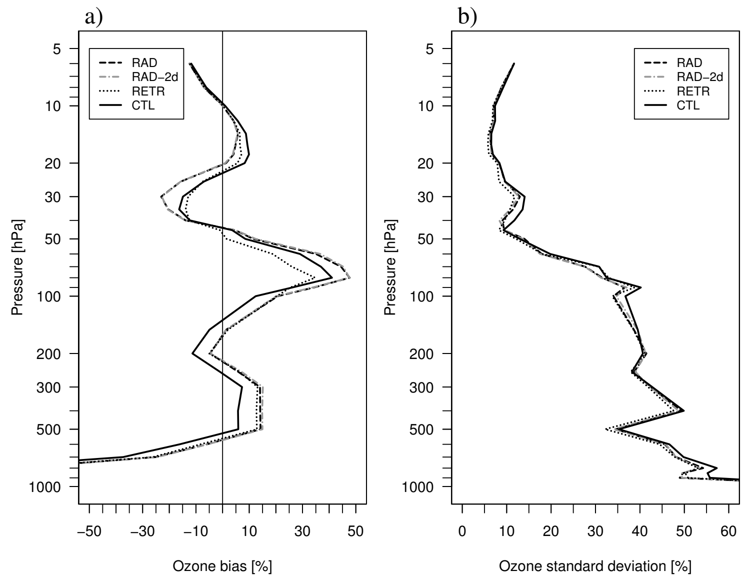

Figure 15: As Fig. 15, but for 28 ozone sondes over the tropical region (20S-20N).

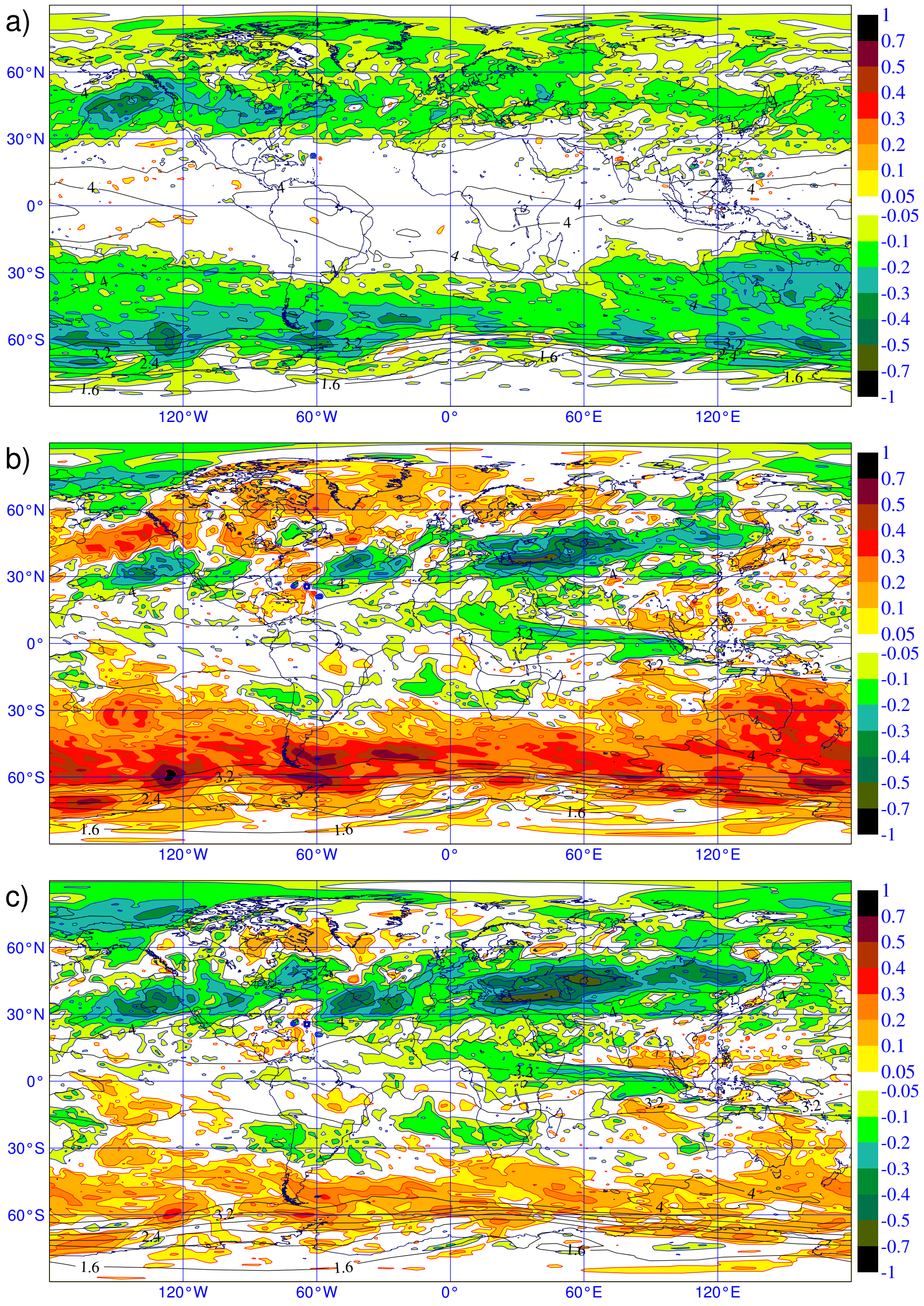

Figure 16: a) Difference in the RMS of the humidity forecast error [ppmv] for the 5-day forecast at model level 24 (approx. 80 hPa) between the RAD and the RAD-2d experiment. Green indicates a reduction in the forecast error for the RAD-2d experiment compared to RAD. Both forecasts have been verified against their own analyses. Black contours indicate the mean humidity field of the RAD experiment [ppmv]. b) As a), but for the RMS of the RAD forecast error compared to RETR. Black contours indicate the mean humidity field of the RETR experiment [ppmv]. c) As b), but for the RMS of the RAD-2d forecast error compared to RETR.

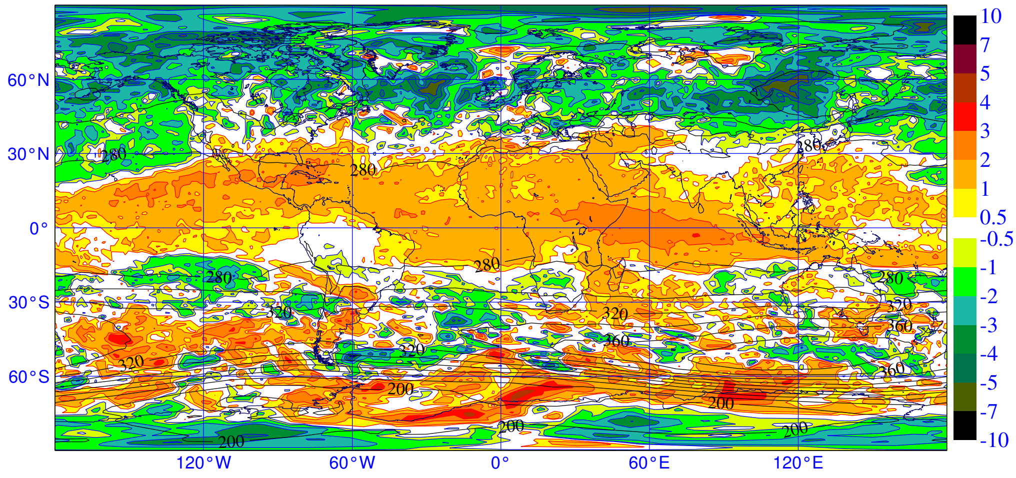

Figure 17: As Fig. 16c, but for the difference in the RMS error of the 5-day forecast of total ozone between RAD-2d and RETR.

Comparing forecasts from RAD and RAD-2d, the largest benefits from using a 2d operator for the radiance assimilation again appear in the humidity field in the lower stratosphere and upper troposphere region between 40 and 150 hPa. The root mean square (RMS) forecast error is considerably reduced in the mid-latitudes around the polar vortices in regions where large horizontal gradients in temperature or humidity prevail (e.g., Fig.16a). This is an encouraging result, as it indicates that the improvements in the humidity field in the RAD-2d experiment are retained in the forecast even after interaction with transport. Smaller reductions in similar areas can also be reported for the ozone field (not shown), whereas temperature forecasts from RAD and RAD-2d show little difference in quality.

As a result of the better humidity forecasts in RAD-2d over the mid-latitudes, humidity forecasts from RAD-2d also compare better to those from RETR than forecasts from RAD over these areas (cf, Figures 16b and c). However, the benefit of using a 2d operator in the radiance assimilation compared to assimilating retrievals which were derived under the assumption of horizontal homogeneity is not clear. While the radiance assimilation with a 2d operator leads to smaller forecast errors over the Northern Hemisphere compared to RETR, it shows larger errors over the Southern Hemisphere when both are verified against their own analyses. Note, however, that both experiments show similar levels of forecast error in the southern midlatitudes when both are verified against the RAD-2d analyses, highlighting the role of the verifying analyses in this comparison. The reasons why the radiance assimilation with a 2d operator performs relatively better over the Northern Hemisphere than over the Southern Hemisphere are not quite understood. A possible reason is that larger errors in the temperature background fields may alias into humidity errors in the radiance assimilation. Over the Southern Hemisphere, fewer conventional observations are available, and the background fields are therefore more prone to temperature biases. On the other hand, the good performance of the RETR forecasts compared to RAD-2d over the Southern Hemisphere indicates that the microwindow selection used for the retrievals successfully limits the effect of horizontal gradient errors. The microwindow selection used in the ESA retrievals specifically aims to avoid spectral regions and tangent altitudes with large horizontal gradient error, whereas our channel selection purposely did not include such a constraint. The poorer performance of the RAD experiment over the southern midlatitudes compared to RETR appears to be the result of a combination of horizontal gradient errors and other shortcomings in the radiance assimilation, for instance, suboptimal specification of observation errors or radiance biases.

For ozone, the forecasts from the RAD-2d experiment also show smaller forecast error than RETR over the

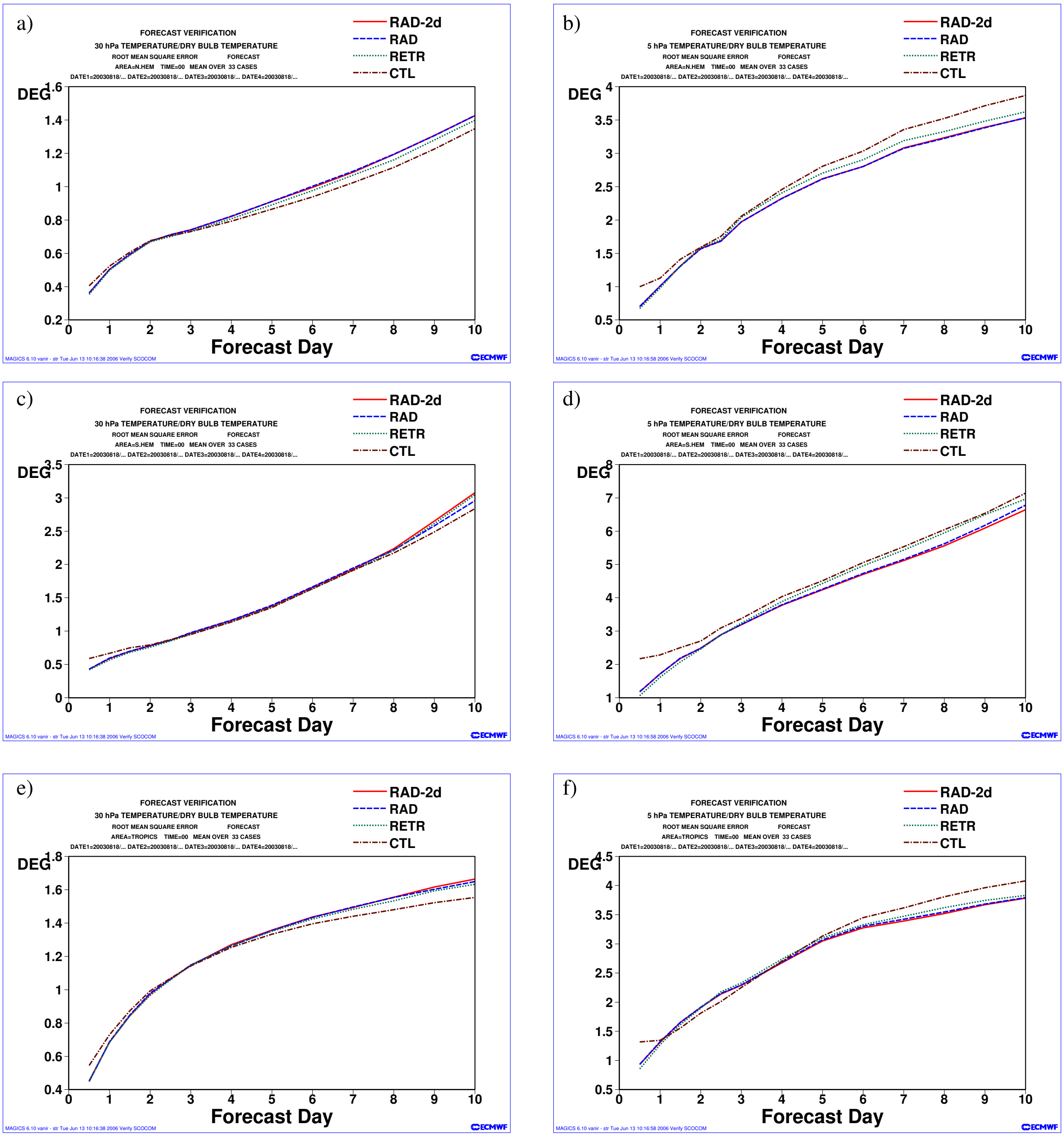

Figure 18: RMS errors for temperature forecasts from RAD-2d (solid red), RAD (dashed blue), RETR (dotted green), and CTL (dash-dotted brown) as a function of forecast range. The panels show scores for the Northern Hemisphere (a, b), the Southern Hemisphere (c, d), and the Tropics (e, f) at 30 hPa (a, c, e) and 5 hPa (b, d, f).

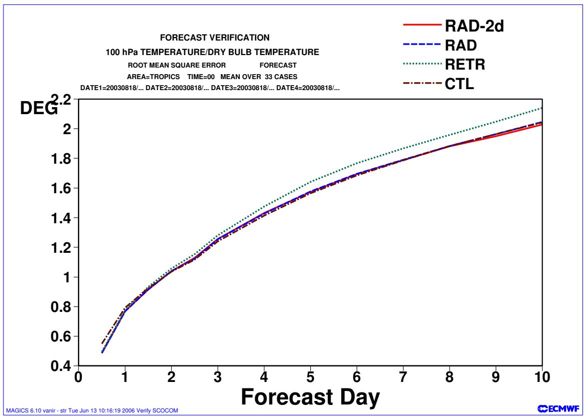

Figure 19: As Fig. 18a, but for the RMS forecast error for temperature over the tropics at 100 hPa.

Northern Hemisphere, whereas larger errors occur over the tropics and the Southern Hemisphere (e.g., Fig, 17). The poorer performance of RAD-2d over the tropics may be a result of the poorer ozone analyses in RAD-2d compared to RETR noted earlier. Over the Southern Hemisphere, the areas of larger forecast errors in RAD-2d for ozone coincide with areas of larger humidity forecast errors (cf, Figures 17 and 16c). This may point to a common origin in the analyses, for instance the quality of the temperature background which affects the extraction of both ozone and humidity information in the radiance assimilation.

For temperature forecasts, the intercomparison between RAD-2d, RAD, and RETR is somewhat inconclusive. The three experiments with the assimilation of MIPAS data share many similarities, such as similarly degraded forecasts compared to CTL for the middle stratosphere around 10-30 hPa over the Northern Hemisphere and the Tropics, and similarly improved forecasts in the upper stratosphere in the same regions (Fig. 18). Nevertheless, there are areas with noteworthy differences. For instance, over the Southern Hemisphere, RAD and RAD-2d show smaller forecast errors than RETR from day 4 onwards, and RETR performs only slightly better than the CTL (Fig. 18d). Also, temperature forecast errors at 100 hPa show that errors in RETR are larger than in CTL, whereas RAD and RAD-2d show a neutral impact (Fig. 19). This may indicate some problems with the assimilation of MIPAS temperature profiles around the tropical tropopause.

4 Conclusions

This paper employed different ways of assimilating limb sounding data from MIPAS within the ECMWF 4DVAR assimilation system, namely: radiance assimilation with a 1d observation operator which assumes local horizontal homogeneity; radiance assimilation with a 2d operator which takes into account horizontal gradients along the limb-viewing plane; and retrieval assimilation. We jointly assimilated information on temperature, humidity, and ozone. We compared the radiance assimilation with a 2d operator against results obtained with a 1d operator, and contrasted the resulting analyses with those achieved through the assimilation of MIPAS retrievals. The main findings are:

- Assimilation of MIPAS radiances with a 2d operator leads to smaller FG departures than when a 1d operator is used, as a result of smaller forward model error. The smaller FG departures translate to smaller analysis increments for humidity and ozone in mid-latitude and polar regions if the same observation errors are employed. These regions are areas where considerable horizontal gradients prevail, so that the forward model error arising from neglecting horizontal temperature gradients is largest.

- In the mid-latitude and polar areas, analyses which employed a 2d operator agree slightly better to independent humidity retrievals in the lower stratosphere/tropopause region, and assimilated SBUV ozone retrievals also show small reductions in FG and analysis departures when the 2d operator is used. Otherwise, there is little difference in departure statistics for other assimilated observations or between analyses and independent data between using a 1d and a 2d operator.

- Use of a 2d operator leads to better forecasts for humidity and, to a much smaller extent, ozone in the lower stratosphere and upper troposphere in the mid-latitude regions.

- Experiments with assimilation of a single MIPAS scan show that radiance assimilation with a 2d operator accurately depicts the effect of tangent point drift. There is also some indication that radiance assimilation with a 2d operator is capable of extracting some information on the horizontal structure from a single limb scan, even though the general structure of the increments is largely determined by the background error covariances.

- In the current configuration, it is not clear that the assimilation of MIPAS limb radiances produces superior analyses than the assimilation of MIPAS retrievals; both approaches appear to be capable of improving stratospheric analyses of temperature, humidity, and ozone. Ozone analyses from the retrieval assimilation compare somewhat better to independent ozone observations than analyses from the radiance assimilation, especially in terms of biases over the tropics. For temperature and humidity, our findings indicate little difference in the quality of the analyses or forecasts.

The results obtained in this study are based on experiments performed over a 43 day period. More experimentation, and especially an investigation of the long-term performance of the assimilation over several seasons are required to corroborate our findings. This includes a study of the long-term effects of our assimilation on, for instance, the representation of transport processes in the stratosphere in the system. However, some conclusions can already be drawn.

Our results indicate that using a 2d operator for the assimilation of MIPAS radiances has a small benefit for analyses and forecasts of humidity and, to a lesser extent, ozone over the midlatitudes in the lower stratosphere and the upper troposphere region. However, the improvements over using a 1d operator are much smaller than the improvements noted from assimilating MIPAS radiances with a 1d radiative transfer model in the first place, or the differences observed from using an alternative radiance bias correction in Bormann and Thépaut (2006). It appears that improvements in the bias correction applied to MIPAS radiances are likely to be more beneficial than using a 2d operator.

However, it is likely that our current experimentation does not reflect the full benefit that can be achieved with a 2d operator. The current channel selection is not specifically optimised for the retrieval of horizontal structure, and more benefits from a 2d operator are likely with a more tailored channel selection. Our single-scan experiments already suggest that the retrieval of some horizontal structure is possible with the 2d operator, as along-ray weighting functions for limb radiances can peak away from the tangent point. This situation is notably different from, for instance, GPS RO limb sounding, for which weighting functions are always approximately symmetric around the tangent point, and therefore retrieval of horizontal structure with a 2d operator is not possible (Healy et al. 2006). Consequently, more benefits from using a 2d operator for limb radiance assimilation are expected as the effective horizontal resolution of the analysis increases. It should also be noted that the influence of 2d/1d forward model error has not been taken into account in our specification of observation errors; smaller observation errors for lower tangent altitudes may be more appropriate for the

2d operator, or larger ones for lower tangent altitudes for the 1d operator. Furthermore, the assimilation was restricted to radiances from tangent altitudes above 12 km; the 2d operator may lead to larger benefits if the assimilation was extended to lower tangent altitudes.

Our results so far do not support the hypothesis that the direct assimilation of MIPAS radiances leads to superior analyses than the assimilation of MIPAS retrievals. On the one hand, this may be because some benefits of radiance assimilation are less clear in the limb case than in the nadir case. For instance, for MIPAS limb sounding under the assumption of horizontal homogeneity, the resulting retrieval is much less affected by *a priori* data from a model or climatological background (e.g., Ridolfi et al. 2004), making incestuous use of model information less of a problem when the retrievals are assimilated. Also, the power of radiance assimilation appears to be best realised when cross-calibration of sensors against other observations is possible. This cannot be achieved with the current relatively sparse observation network for stratospheric constituents.

On the other hand, the experiments discussed in this report are the first ones with direct assimilation of MIPAS radiances, and many areas are in need of further research and development, providing scope for improvements in the radiance assimilation. In this context it is encouraging that even this first approach of MIPAS radiance assimilation provides analyses which are rather similar to those obtained with the assimilation of retrievals.

One area of particular scope for improvement in the radiance assimilation is the bias correction applied to the MIPAS radiances, as highlighted in the sensitivity study performed in Bormann and Thépaut (2006). Improvements could be achieved by employing a revised bias model, based on a better understanding of the origin of the radiance biases, for instance following approaches used in the ESA retrieval processing (Ridolfi et al. 2004). Here, continuum-like features and channel offsets are retrieved on the basis of microwindows that are 1-3 cm^{-1} wide. This method could be adopted for assimilation purposes, and may provide more robust estimates of the bias. The approaches should also reduce the influence of residual cloud contamination, an area that may gain importance if the radiance assimilation is extended to lower tangent altitudes. Improvements may also be achieved from retrieving tangent altitude information within the main analysis rather than using the tangent pressures from the level 2 data. Since the retrieval of tangent pressure relies on an estimate of the CO_2 profile, the availability of a CO_2 analysis as described by Engelen et al. (2004) may be an advantage. While it seems preferable to retrieve the tangent altitude information in the main analysis, care has to be taken that biases in the FG data are not aliased into tangent altitude information when taking this approach. Furthermore, observation errors for MIPAS radiances have been specified in a rather ad-hoc way for our study, and tuning of these is likely to be beneficial.

Other areas should also lead to a better assimilation of MIPAS data. Improved background errors for the stratosphere are likely to lead to larger benefits for the radiance assimilation than the retrieval assimilation, given the influence of the background errors in separating the radiance information into temperature, humidity, and ozone. There is currently considerable uncertainty about the representation of ozone background errors, and poor background errors for ozone are probably a contributing factor for the poorer performance of the radiance assimilation in terms of ozone. Also, our study indicates that the ECMWF model fields also exhibit considerable biases, and a correction of these biases (either through improvements in the model or by diagnosing the model error in the assimilation) is expected to be beneficial. In addition, ECMWF recently increased the number of model levels to 91, raising the top of the model to 0.01 hPa. This should allow the assimilation of MIPAS radiances with higher tangent altitudes which are currently excluded. In turn, MIPAS radiances may help to better constrain the analysis at the mesospheric levels for which otherwise very few observations are available. For the retrieval assimilation, data characteristics could be better represented in the assimilation by taking averaging kernels into account. In addition, the Microwave Limb Sounder (MLS) on-board the Aura mission offers the opportunity to extend the current investigation to the assimilation of microwave limb radiances.

Acknowledgements

Niels Bormann was funded through the ASSET project (Assimilation of Envisat Data), a shared-cost project co-funded by the Research Directorate General of the European Commission within the activities of the Environment and Sustainable Development sub-programme of the 5th Framework Programme. Sean Healy is supported through the EUMETSAT/ECMWF Fellowship agreement. Comments provided by Adrian Simmons and Jean-Noël Thépaut are gratefully acknowledged. All MIPAS data used © ESA. SAGE II data were obtained from the National Aeronautics and Space Administration (NASA) Langley Distributed Active Archive Centre. The provision of HALOE data by Lance E. Deaver on http://haloedata.larc.nasa.gov/home/index.php is gratefully acknowledged. POAM data were obtained from http://wvms.nrl.navy.mil/POAM/poam.html. Ozone sonde data was kindly compiled by A. Geer. The ECMWF system is the product of many staff members and consultants at ECMWF and Météo France.

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