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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Retrieval of temperature profiles from CHAMP for climate monitoring: intercomparison with Envisat MIPAS and GOMOS and different atmospheric analyses" *by* A. Gobiet et al.

A. Gobiet et al.

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Final Response to the Comments of Referee 1

(referee's comments are given in italics)

1. **Answer to General Comments**

   (a) *Throughout the paper the authors suggest that the CCR does not overweight the a priori information, but it is difficult to quantify the importance of the a priori information in the CCR retrieval in the stratosphere from the results* *presented [. . .].*

We agree that improved quantification of the influence of a priori errors on retrieval errors is useful and therefore expanded the paper accordingly. Please refer to our answer to specific comments (b) and (c) for details.

(b) *The paper would also be improved by more details on the CCR. Eg, how are the ECMWF and MSIS data combined at 65 km? In addition, although the authors claim that the temperature is initialised at 120 km, I suspect that the hydrostatic is effectively initialised at a much lower height than this.*

More details about the retrieval, particularly concerning the specific questions of the Referee are given in Section 2.3 of the paper now. For the discussion of the specific points, please refer to our answers to the specific comments.

(c) *The authors also need to consider the implications of ECMWF operationally assimilating GPSRO measurements, on the use of ECMWF information in the CCR.*

See specific comment (g).

(d) *I also suggest that they contact GFZ to discuss an other possible reasons for the CCR - GFZ differences in the stratosphere.*

After personal communication with Dr. Wickert of GFZ we learned that a part of the systematic GFZ - CCR difference could be due to a numerical incorrectness in the most recent operational version of the GFZ retrieval (version 005). How much of the differences between the CCR and GFZ retrievals are caused by the numerical incorrectness, and not by the high-altitude initialisation scheme, could not be verified as no sufficient description is available so far on the recent improvement of the GFZ temperature profiles (GFZ informed they plan further improvements before a larger-scale application of the new scheme). Independent of this, other studies [e.g., Gobiet and Kirchengast, 2004] clearly have demonstrated that different imple-

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mentations of high altitude initialization create such differences in the temperature profiles as we showed and discussed. Furthermore, the depicted cold bias in the ECMWF analyses is consistent with explaining a significant part of the bias in the GFZ retrieval results. To give a balanced view on this issue we cite Dr. Wickert's expert judgement that a part of the bias in GFZ version 005 operational data is due to a numerical incorrectness and that an improved operational temperature product is scheduled for release later in 2007 (J.Wickert, pers. communications, 2007). More details are given in our answer to Dr. Wickertâ128;153;s comment (Gobiet et al., 2007; Wickert, J., 2007) and in our answer to the specific Referee's comment (l). The paper has been adapted accordingly in Sects. 3.3.1 and 4.1.

2. Answer to Specific Comments

(a) *Section 2.2, page 3237, no "2nd initialisation" is needed to initialise the hydrostatic integral. The hydrostatic integral is initialised at 120 km, so you do perform a 2nd initialisation. Please clarify.*

We agree that the wording on page 3237 was not ideal with respect to what we wanted to express: The initialisation of the hydrostatic integral at 120 km is an initialisation in a technical sense but has no noticeable effect on the retrieval results; 120 km can be regarded as being "outside of the atmosphere" from a RO-retrieval point of view. The "outside of the atmosphere assumption" is valid at 120 km since initialisation of the hydrostatic integral with zero pressure at that height yields essentially identical temperature profiles at any height of interest below the stratopause as the initialisation with MSIS pressure. The fundamental difference of CCR to most other RO retrieval schemes is that we effectively don't introduce any further background information after statistical optimization. In order to clarify this issue we refocused the concerned paragraph in Sect. 2.2 of the paper following the argumentation above.

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(b) *"This ingests minimal a priori and allows for clear tracing of the amount of non-observed information entering the retrieval.". This "clear tracing" is not currently obvious to the reader. You need to present averaging kernels for the temperature retrieval to enable clear tracing of the non-observed information. These should be included in the paper.*

Please see answer to the next comment.

(c) *Page 3239, end of first paragraph, last sentence, the transition between background and observation dominance. Please quantify what is meant by "background dominance". [. . .] It would be useful to plot the diagonal values of the averaging kernel, R_{ii}, as a function of height for 2 cases where the background dominance starts at 45 and 65 km, respectively. This might help quantify "background dominance" for the reader.*

The two comments above point to an important topic that was only briefly treated in the submitted version of the paper but not studied in more detail. Originally, we wanted to point out that the presented retrieval scheme allows for error tracing and leave the realisation of this error tracing for a later study. Since both Referees asked for more details on this topic, we implemented an error tracing scheme in CCR using the error propagation of matrices given in Syndergaard (1999). Starting from bending angles, the observation error, background error, and retrieval error $(B^{-1}+O^{-1})^{-1}$ covariance matrices are transformed via refractivity to temperature errors. Rather than showing the diagonal of the averaging kernel $B(B+O)^{-1}$, we display the square root of the ratio of the diagonal of the retrieval error to the background error matrix (q_r; "retrieval to a priori error ratio"), i.e., the fraction of the retrieval error stemming from the background error following Rieder and Kirchengast (2001) (their equation 8). The "observation dominated" altitude range is then defined by the region where q_r is below 0.5. The results of this additional study confirmed (also for a larger dataset) that the transition height from background dominated to observation dominated in the bending

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angle profiles generally lies between 60 and 45 km and that the transition height for temperature profiles lies about 4 km below that. Following the suggestion of Referee 1, we added a Figure and discussion regarding the "low" and "high" transition height cases in Sect. 2.3 of the paper.

(d) *Section 2.3 Gobiet and Kirchengast (2004) employ a search strategy to find the MSIS bending angles that give the best fit to observations in the 45 to 65 km and also introduce an ad-hoc scaling factor. Are these still used?*

The library search strategy and the scaling were not used for the present processing version of the CCR retrieval. The MSIS-based version of Gobiet and Kirchengast (2004) employing library-search and scaling is still available as option in the CCR, however, as noted in Table 1 of the paper. MSIS is not a very well diversified search library (regarding the diversity of atmospheric conditions included), in particular for high latitudes, but we keep the option for improved libraries and comparison-test reasons.

(e) *How do you deal with the transition and inconsistencies between ECMWF and MSIS at 65 km?*

The transition from ECMWF to MSIS is realised by converting the model's temperatures and pressures to refractivity, then combining the ECMWF refractivity profile from the second highest model level upwards (avoiding the highest level which basically constitutes a boundary condition) with the MSIS refractivity, using a half-Gaussian weighting with 7.5 km vertical scale length to ensure a smooth transition. This ensures physical consistency of the combined profile regarding temperature and pressure, which are available from the (combined) refractivity via using the hydrostatic equation and the equation of state. The description in the paper has been updated (Sect. 2.3).

(f) *Is the Gobiet (2005) reference generally available? I feel that more details of the CCR are required in the paper.*

Yes, the cited report is available at the website of the Wegener Center

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(www.wegcenter.at → Data and Info Center → Wegener Center Verlag).

(g) *The use of ECMWF between 30 – 65 km. ECMWF now assimilates GPSRO measurements operationally, so the GPSRO observations used in CCR and the ECMWF a priori will not be independent from Dec 2006. How will this be accounted for in your retrieval for climate monitoring beyond 2006?*

Due to ECMWF having started RO data assimilation with operational system upgrade Cy31r2 as of 12 Dec 2006, the WegCenter RO climate retrieval scheme is scheduled to no longer use ECWMF analyses as a priori information beyond 2006. It is scheduled to use ECMWF short-range forecasts instead (24h and 30h forecasts for 00/12 UTC and 06/18 UTC time layers, respectively; forecasts are started 00/12 UTC, twice every day). Using the forecasts will provide sufficiently independent a priori profiles, as required by the $>$ 30 km optimal bending angle estimation, yet the a priori will continue to be a physically consistent state with "good" error characteristics. Also, effects of different initialization (analysis vs. forecast vs. climatology-library-search) will be cross-checked at least over Jun 2006-May 2007 to ensure to quantitatively understand any potential residual differences. An according note has been added to Sect. 2.3 of the paper.

Related remark: The currently prepared tropospheric retrieval ("moist air 1D-Var retrieval", not part of this paper), for optimal estimation of temperature and humidity from the RO refractivity at $<$ 8-14 km, will use the same ECMWF forecast states as the $>$ 30 km bending angle estimation scheme.

(h) *Page 3238, 2nd paragraph. Estimating the errors from the variance. It is noted that a widely adopted approach, estimating the errors from the RMS relative to the a priori, can overestimate the observation errors if the a priori is biased. Can you quantify the magnitude of the overestimation?*

The overestimation of observation error due to the usage of RMS instead of the variance is small. At 65 km, the background bending angle amounts to between 1 to 3 micro radians whilst the typical CHAMP error amounts

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to 1 or 4 micro radians. Assuming a 15% background bias this would increase the observation error estimate by less than 10%. Only a severely biased background profile (i.e., larger than 15%) combined with a observed profile featuring a small variance-error would have a strong influence on the observation error estimate (e.g., increase it by about 50%).

The overall effect of using a RMS instead of a variance observation error estimate in CCR was tested in a one-day sample and it was found that the observation error estimate increased by 10 - 20% and the mean altitude where q_r equals 0.5 decreased by 1.9 km (from 50.3 to 48.4 km). The paper has been updated accordingly in Sect. 2.3.

(i) *At and above some height, say h_b, the optimised bending angles will be effectively equal to the a priori bending angles. [...] Can you estimate h_b for the cases where background dominance starts 45 km and 65 km? This will be a more realistic temperature initialisation height than the 120 km that is quoted in the paper.*

In the presented version of the CCR retrieval h_b can be defined in a quite straight forward manner, since the CHAMP profiles are cut off according to technical criteria (e.g. negative phase delays, ...) at the upper end. This cut-off altitude lies often around 65 km and automatically marks h_b since above the a priori constitutes 100% of the later retrieval result.

This altitude could be termed “effective temperature in initialisation height” as the Referee suggests. However, we believe that this notation would be misleading since our retrieval scheme uses “no” temperature initialisation (except the initialisation of the hydrostatic integral at 120 km, see answer to specific comment (a)). Background information is exclusively introduced at the bending angle level and no other background information for hydrostatic integral initialisation below 120 km is used. Of course, this doesn’t mean that the observation contributes to the retrieval results above h_b, but still this is an important difference to other RO retrieval schemes and enables

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improved traceability of errors (see also our answer to specific comments (b) and (c)).

(j) *Section 3.3.1, the use of "three different sources of information (one observational and two a priori) leading to an overemphasis of the a priori ...". But the CCR also uses 3 sources of information, observation, ECMWF and MSIS, so 3 sources does not necessarily lead to an overemphasis of the a priori. Please explain what you mean here.*

We mean that the inclusion of a second set of a priori information for the initialisation of the hydrostatic integral at a rather low altitude without regarding error characteristics (i.e., assuming zero a priori error at that altitude) overemphasises background information. We reformulated our misleading sentences in Sect. 3.3.1 of the paper accordingly:

"The GFZ retrieval employs statistical optimisation of bending angle profiles using the MSISE-90 climatology (Hedin et al., 1991) as a priori data and adds further a priori information derived from operational ECMWF analyses by initializing the hydrostatic integral at 43 km (i.e., the systematic and random error of ECMWF at 43 km is assumed to be zero). This results, similar to other double-initialisation schemes described in literature (e.g., Hajj et al., 2004), in overemphasis of ECMWF a priori information and physically inconsistent refractivity and temperature profiles near the "2^{nd} initialisation" upper boundary."

(k) *Section. 3.3.2., "MIPAS data is not biased against ECMWF, since the latter is used as a smoothing constraint rather than for Bayesian combination" This is misleading. [. . .]*

This topic has been discussed in detail in the answers of co-author G.P. Stiller and an additional reviewer comment (Stiller, 2007a; Stiller 2007b; Anonymous Referee, 2007) concluding that the MIPAS retrieval is indeed not sensitive to "flat" ECMWF biases, but that biases varying with height could

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to some degree enter the MIPAS retrieval results. Wang et al. (2005) have demonstrated that the ECMWF cold bias between 30 and 45 km does not affect the MIPAS retrievals. However, the original wording “entirely independent” is too strong and has been replaced. The paragraph under discussion (Sect. 3.3.2) reads now:

“Though ECMWF analyses are used as a priori in the retrieval process, MIPAS is not biased against ECMWF, since the latter data are used within a smoothness constraint matrix of the type $\gamma L_1^T L_1$, where γ is a scaling factor and L_1 is a first order finite differences operator. The use of the first order finite differences operator does not constrain the column information but only how this information is distributed over altitude (von Clarmann and Grabowski, 2007). For the focus of this study, inspection of biases, MIPAS can be regarded as independent from CCR and ECMWF for biases in those data being vertically resolvable by MIPAS.”

(l) *Section 4.1, If the biases in the GFZ - CCR retrievals are caused by the GFZ retrievals being attached to the ECMWF a priori more strongly, why are these biases bigger than the CCR - ECMWF biases (Fig 7)? This suggests that other factors are biasing the GFZ data. Please consider.*

Since we don’t have the code of the GFZ retrieval scheme available we can only hazard a guess here. However, three factors might contribute: First, the numerical incorrectness in the GFZ retrieval mentioned by Dr. Wickert in his comment (Wickert, 2007) seems to contribute. Second, the background information used in the statistical optimization of bending angels (MSIS) by GFZ might lead to significantly biased refractivity profiles (even below the hydrostatic integral initialisation height at 43 km) which can enhance the cold bias introduced by ECMWF at 43 km. This argument is based on our experience gained by using MSIS instead of ECMWF as background information in a CCR-like scheme (Gobiet and Kirchengast, 2004) where we found significant cold biases down to below 30 km. Third, the initialisation height of the hydrostatic integral at 43 km in the GFZ retrieval might be a sub-optimal choice. Assuming a large cold ECMWF bias at that height quickly decreasing below, the GFZ temperatures might even be colder than ECMWF around 40 or 35 km. However, this third argument is very speculative and is only expected to significantly contribute in combination with the second argument. An according comment has been added to Sect. 4.1 of the paper:

"Parts of this bias can be attributed to the treatment of a priori information in the GFZ retrieval (see Sect. 3.3.1). As will be shown in Sect. 4.4 later, the source of this bias is a general cold bias (except southern JJA high latitudes) in ECMWF temperatures above 30 km, to which the GFZ retrieval is stronger attached than the CCR. Additional causes could be a numerical incorrectness found in the GFZ retrieval (J. Wickert, personal communication, 2007) and the influence of the MSIS a priori information used for statistical optimization in that retrieval."

(m) *The 1 to 2 K standard deviation below 26 km seem large - any explanation?*

We mainly attribute the larger standard deviation of CCR compared to the GFZ retrieval to CCR. CCR operates approximately at the original measurement altitude levels, which is an oversampling regarding the physical vertical resolution of the RO measurements (1 to 1.5 km). In the version presented in the paper, we did not apply a filter removing resulting numerical noise. Tests with Hanning filtering, for filtering noise at wavelength less than 1 km, are promising and we expect that the CCR standard deviation is reduced this way. A further reason could be that we follow a mild outlier rejection strategy on phase delay level (only data points outside the 3σ range of 1-second intervals of the profile are rejected). Those rather technical factors are currently further investigated and improved for the next processing version of CCR and are expected to reduced the standard deviation (while leaving the averages unchanged).

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Anonymous Referee 1: Interactive comment on “Retrieval of temperature profiles from CHAMP for climate monitoring: intercomparison with Envisat MIPAS and GOMOS and different atmospheric analyses” by A. Gobiet et al., Atmos. Chem. Phys. Discuss., 7, S621-S622, 2007.

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We want the thank the Referee for his/her instructive comments that considerably helped to improve the quality of the paper!

A. Gobiet and co-authors.

Interactive comment on Atmos. Chem. Phys. Discuss., 7, 3229, 2007.