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6, S6508–S6522, 2007

Interactive Comment

Interactive comment on “Improved ozone profile retrievals from GOME data with degradation correction in reflectance” *by* X. Liu et al.

X. Liu et al.

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We would like to thank the two anonymous referees for their constructive comments on our paper. We have carefully considered their comments and have addressed them as follows and made changes in the revised manuscript.

Responses to referee 3

GENERAL COMMENTS

G1. Although the paper is already quite complete in the presentation of the new technique itself, I believe the paper would benefit from a better introduction in which the purpose and potential usage of GOME ozone profiles is outlined. This introduction should then lead to requirements for the accuracy of the retrievals which are then tested after applying the degradation correction. The authors show that their new degradation

EGU

correction has an impact on the retrieval but do not show substantial proof of improvements in the retrieval of global 3D ozone fields. Perhaps not the full validation exercise is required here but their thoughts and requirements should at least be outlined in the conclusions. As in the 'Short Comment' of Mark Weber, there is currently not enough focus on the profile quality and the checks performed show total column assessments which is not the main goal of this retrieval scheme. Validation including lidar data would be appropriate, especially as the degradation generally affects the shortest wavelengths ...

At the beginning of second paragraph, we added "As a follow-on of the GOME instrument, the GOME-2 series has started with the launch of the first Meteorological Operational satellite (MetOp) in October 2006. One of the keys to continuously monitoring the vertical distribution of ozone is ensuring consistent high-quality ozone profiles retrieved from the GOME record." We added a paragraph to discuss future work to improve the quality of our ozone profile retrievals from GOME at the end of the article.

The main focus of our study is on the consistency of retrieved tropospheric ozone during the GOME record. Because the initial offset in GOME level 1 data (channel 1) could not be corrected by our proposed method, we do not mainly focus on the quality of retrieved profiles. We include some on-line corrections to reduce the effects on retrievals. These corrections are not perfect and lead to altitude-dependent biases (usually within 15 percent) relative to SAGE data (Liu et al., 2006a) in the stratosphere during 1996-1999 when the degradation is insignificant. However, the retrieved tropospheric column ozone has been shown to agree very well with other correlative datasets (Liu et al., 2005, 2006b) during 1996-1999. We have attempted to correct the initial offset by performing radiative transfer simulations with climatological ozone profiles and ozonesonde measurements. However, the results are not satisfactory because we find that the derived correction varies significantly with latitude and ozonesonde stations. Therefore, we use this simple method to correct degradation only to derive GOME profiles and tropospheric ozone for the GOME record, with similar quality to retrievals in

ACPD

6, S6508–S6522, 2007

Interactive Comment

1996-1999 when no degradation correction is necessary.

We did not compare our retrievals with LIDAR measurements (reliable ozone profile information in the altitude range 20-50 km) for several reasons. Because of the on-line calibrations in channel 1a, the effects of degradation correction on our retrievals in the stratosphere (or above 15-20 km) is quite small (usually within 10 percent; see our Figs. 3, 5, and 7) although the degradation at those short wavelengths can be more than 20 percent. In addition, ozone information above 40 km from the retrievals is weak because we do not use measurements below 289 nm.

G2. I have examined the validation results presented in Figure 3 and 5 (page 8296 and 8298) with those recently published by Meijer et al. (2006). The degradation results seem to remove the observed biases in the comparisons presented by Meijer et al. (2006), or at least move in the desired direction. However, the results of Meijer et al. are based on a period (1997-1999) for which it was concluded that the degradation didn't yet have an effect. Can you comment on this?

The altitude-dependent bias for the 1997-1999 period shown in Fig. 6b of Meijer et al. (2006) is due to the initial wavelength-dependent biases in channel 1. Note that these results were based on retrievals of our previous algorithm, in which no on-line calibration is applied. The reason why degradation correction offsets biases in Meijer et al. (2006) is likely that the initial offset and degradation are in the same direction for channel 1.

G3. I am not a native speaker of English, but I believe it would be better to rephrase some of the sentences that start with a verb, i.e., 'To show..' and 'To apply..'. In addition there are quite some instances in which it is better to place the adverb before the verb (except for conjugations of 'to be'), see e.g., page 8287 line 6 'differs substantially' and page 8287 line 20 and 27. Page 8286, line 25, change 'damage' to 'damaging' Page 8287, line 1-2, 'Although' should be removed and perhaps after the comma you could use something like 'but then it is assumed' Page 8287, line 4-5, sentence should be

ACPD

6, S6508–S6522, 2007

Interactive Comment

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Interactive Discussion

Discussion Paper

EGU

rephrased and use of ‘however’ should be reconsidered.

We did not make these changes as they have been proofread by our second author who is a native English speaker.

G4. The authors should explain how they have dealt with the change in channel 1a/1b border ...

We added a paragraph to describe this.

G5. It would be good if it is possible to distinct the presented degradation correction scheme from the correction already taken into account by the radiometric calibration in their retrieval algorithm. This is important for showing the wider use of this technique and its effect ...

We originally thought about this. However, most of the retrievals are not successful due to negative ozone values (our radiative transfer model could not handle negative ozone absorption) during the period of significant degradation (e.g., July 2000-2002) if we do not perform degradation correction or on-line radiometric calibration. Therefore, we could not separate the effects on retrievals due to on-line calibration from those due to degradation correction for all the time period.

G6. Although the authors mention that this calibration has specifically an effect on the tropical regions, they didn’t use this in their Response to the Short Comment of Mark Weber on why they select the 60S-60N range instead of the 15S-15N.

We think that these two things are unrelated. The reason why we did not choose 15S-15N is that there is larger atmospheric variability than in 60S-60N. The larger effect of on-line calibration on retrievals in the tropics is due to stronger a priori constraint.

SPECIFIC COMMENTS

S1. Page 8286, line 4, it would be good to add a year (in brackets) after ‘beginning of GOME observations’. Page 8286, line 5-6, I believe it is confusing to use the wording ‘positive degradation’ without further explanation. Page 8286, line 13, the adverb ‘generally’ significantly weakens your abstract.

We added “(July-December 1995)”, changed “positive degradation” to “positive biases” and removed “generally.”

S2. Page 8286, line 13-15, it should be noted here that the retrieval improvement was observed in comparisons with one station. What is meant with ‘consistency’?

We added “at Hohenpeisenberg” before “during 2000-2003” and changed “retrieval consistency” to “spatiotemporal consistency of retrieval quality.” We also added a sentence “In addition, retrieval biases due to degradation vary significantly with latitude” to justify the word “spatio”

S3. Page 8286, line 22, please add the upper limit as well (mention stratosphere or 50-km)... Page 8286, line 26, is it sure that the layer consists of ice?

We added “from ˜50 km” before “down to” and changed the reason for degradation to “and contaminants that fill voids in the MgF_2 coating of the scan mirror”

S4. Page 8287, line 25 and 28, as mentioned in the general comments, the use of the verb and word ‘proceed’ and ‘consistent’, respectively, seem to indicate a certain goal or retrieval requirement which has not been specified. The paper would benefit from some specific additional comments.

We added “; otherwise, retrievals are often unsuccessful during 200-2003 due to negative ozone values caused by the degradation” after “proceed for all measurement periods.” We also added a few sentences to summarize the retrieval performance during 1996-1999: “Retrieved ozone profiles are usually consistent with SAGE ozone profiles to within 15 percent during 1996-1999, despite a systematic altitude-dependent bias which exists as a result of the initial offset in GOME channel 1 (van der A et al., 2002; Krijger et al., 2005). The retrieved TO and TCO agrees well with TOMS, Dobson and ozonesonde measurements to within 6 DU (2 percent) and 3 DU (15 percent), respectively"

S5. Page 8288, line 22-23, how much do your results depend on these settings...? I am a bit confused whether the overall ratio is compared to July 1995 or July-December 1995 ...

The final reference period is July-December 1995. We have made it consistent in the abstract and summary. We added discussion about the effect of these settings: "The initial reference period and the length of the running mean are empirically selected. They minimally affect the results; the degradation changes are within 1.5 percent when changing the reference period by 3 months and the length of running mean by 1 month"

S6. P 8289, l 13-14, this sentence is confusing and I don't understand the date March 96.

We added ", when the integration time of channels 1b to 4 is changed from 0.375 s to 1.5 s" to explain this.

S7. Page 8290, line 1-2, this is a very important drawback and should perhaps also appear in the abstract as a limitation or further investigated.

We added the two drawbacks of this approach "However, because this method assumes that the deseasonalized globally-averaged reflection does not change much with time, retrievals with this correction may be inadequate for trend analysis. In addition, it does not correct for instrument biases that have occurred since launch"

S8. Page 8290, line 16, add 'near the Hohenpeissenberg station' after 'selected months'. Page 8290, line 19-20, in the ranges mentioned here it is not clear whether you indicate the range of the average values or the individual biases. In either case the supplied ranges do not reflect the values presented in Figure 4. P. 8291, l. 5, the use of 600 km is inconsistent with the use of longitude ...

We made both changes. The numbers are approximate for individual values (excluding 1 or 2 extreme values). We changed the longitude range to "+/-8 longitude"

ACPD

6, S6508–S6522, 2007

Interactive Comment

S9. Page 8291, line 6-7, the applied method for integrating to the GOME grid and use of the averaging kernels (AKs) should be clarified ... In addition, how is the TO and TCO calculated for the correlative data? For the TCO, I would advocate the use of integrated columns based on the high-resolution sonde data avoiding the effect of AKs that information of higher layers is attributed into the troposphere (see Meijer et al, 2006).

The procedure has been described in Liu et al. (2006a) so we changed the original sentence to "Ozonesonde measurements are convolved with GOME retrieval averaging kernels to the GOME vertical resolution following the procedure described in Liu et al. (2006). Ozonesonde TCO is integrated from the convolved profiles to reduce the smoothing from the stratosphere." We found that GOME TCO agrees better with convolved ozonesonde TCO because it contains similar smoothing from above.

S10. P 8291, end of section 3, I believe a short table would be appropriate in order to distinguish between all the different periods and values. The selection of certain time periods appears somewhat random but ... It should also be noted that the overall TO bias, as printed in Figure 6a, has become worse using the correction (1.8 vs. 2.4 DU).

We added a table, mentioned the selected periods in table caption and rephrased the text. The difference of 0.6 DUis very small, within retrieval uncertainties of both data.

S11. P. 8291, l. 9, what about the comparison with results of van der A et al. (2002).

We added a few sentences "van der A et al. (2002) showed degradation only up to early 2000 before significant degradation starts for longer wavelengths. At shorter wavelengths, their results usually show larger degradation in early 2000. For example, the degradation is ˜1.16 at 289 nm, 6 percent and 4 percent larger than the values in this study and Krijger et al. (2005), respectively." It is difficult to compare how their correction improves retrievals because of different correlative datasets, time periods and retrieval algorithms.

S12. Furthermore, as degradation is considered a major problem for ozone profile retrieval and a dedicated study has been performed in the CHEOPS project ... good to extend the discussion here a bit further and compare the results.

Note that we didn't have access to their report when we submitted our paper. In the revision, we introduced a little bit more about this study in the introduction: "In the Climatology of Height-resolved Earth Ozone and Profiling Systems for GOME (CHEOPS-GOME), Krijger et al. (2005) performed a dedicated study to derive GOME reflectance degradation over the GOME lifetime using a combination of ozonesonde observations and climatology." We added a detailed comparison between that study and our results in several places: (1) The degradation patterns and their magnitudes for different positions agree very well with the derived degradation using a forward model approach by Krijger et al. (2005). For example, their derived degradation values at 325 nm are ˜1.30, 1.18, and 1.10, respectively (2) The main characteristics are very consistent with the results of Krijger et al. (2005). Both show the forward shift of maximal degradation with increasing wavelengths and second peaks in early 2003 for shorter wavelengths. For example, at 289 nm, both show a first maximal value of ˜1.22 in July-August 2000 and a second maximal value of ˜1.23 in April-May 2003; at 324 nm, both show maximal degradation of ˜1.19 in February-March 2001. One main difference occurs at 385 nm; our degradation curve shows a maximal value of 1.13 in February 2002, while their degradation curve shows a broad maximum of ˜1.09 during 2002-2003. (3) The results of Krijger et al. (2005) also show variations of similar magnitudes before 1998. They also show similar variations for 301 and 307 nm during 1998 and 1999.

S13. Page 8294, can you comment on the seasonal variation observed in some of the wavelengths in Fig.1b and on the gap around 312-314 nm ... in Fig. 1b?

We added discussion about the season variation: "During the period when we expect no degradation (i.e., before 1998), we still see slight annual variations. However, the values are generally within ś3 percent. At 301 and 307 nm, there are stronger seasonal variations during 1996-1999 with negative degradation of up to 7 percent. The results

ACPD

6, S6508–S6522, 2007

Interactive Comment

EGU

of Krijger et al. (2005) also show variations of similar magnitudes before 1998. They also show similar variations for 301 and 307 nm during 1998 and 1999; but the results of van der A et al. (2002) show opposite degradation between 300-307 nm. These variations are likely due to non-seasonal variations of atmospheric conditions including ozone" We did not show the channel 1b/2b overlapping region 312-314 nm for clarity. In addition, measurements in the overlapping region are subject to much larger calibration errors.

S14. Page 8296, please specify that the presented comparison of for coincidences around the Hohenepeissenberg station. Page 8298, the range 0-10N is missing in this Figure.

We added "around Hohenpeisenberg" in the figure caption. We only show differences for selected latitude bins (every other 10 degree latitude bin) to avoid too many lines.

We made the suggested technical changes except for those addressed above.

Responses to referee 4

General comments

G1. The underlying assumption that the mean reflectance does not change in time is mention in the paper. ... Why is this valid and under which condition? Why choose a given latitude region?

In the revision, we specifically mentioned the assumption: "The underlying assumption is that the deseasonalized global average reflectance does not change in time" and have added detailed discussion to support this: (1) "According to the International Satellite Cloud Climatology Project radiative flux data (ISCCP-FD), the largest differences in the deseasonalized monthly mean planetary albedo are within 2 percent during the GOME life time to date (http://isccp.giss.nasa.gov/projects/browse_fc.html). The ISCCP-FD data also illustrate that the fluctuations in the reflected shortwave radiation averaged in the tropics are larger than that averaged over the globe due to El Nino

ACPD

6, S6508–S6522, 2007

Interactive Comment

processes (Gupta et al., 2006). Therefore, it is generally valid to assume a relatively invariant global average reflectance to derive the large degradation in GOME data, which can be larger than 20 percent (Krijger et al., 2005). Due to the lack of solar-illumination at high latitudes in some seasons, we average the reflectance over 60N-60S (excluding the South Atlantic Anomaly region)." (2) "We tried using GOME data averaged in other latitude ranges (i.e., 60N-30N, 15N-15S, and 60N-30S) or averaged in other ranges of brightness (i.e., 20 percent darkest and 20 percent brightest), and we found that using all GOME data averaged over 60N-60S better reduces the effect of atmospheric variability, leading to less oscillations before 1998, when the degradation is insignificant."

G2. The authors assume that only the radiance response of the instrument is changed due to the degradation. However, it is very likely that also the polarization sensitivity is changed. For example, this can be studied looking at a dependence of the correction on solar zenith angle ...

Note that our derived degradation agrees very well with that by Krijger et al. (2005), in which they used a vector radiative transfer model to account for degradation in polarization sensitivity in GOME data. This suggest that its effects on radiance spectrum (i.e., usually angle dependent) are greatly reduced in our analysis because we average all reflectance spectra in 60N-60S.

The degradation in polarization sensitivity is not corrected in this study because we still use the same extraction software (i.e., the same polarization correction) for retrievals with and without degradation correction. In addition, even if polarization sensitivity is not degraded, the dependence of the correction will depend on solar zenith angle, because the information about ozone and its vertical distribution from the measurements strongly depends on solar zenith angle. Furthermore, the effect of on-line radiometric calibrations (or constraints) in channel 1a in our retrievals also depends on solar zenith angle. Therefore, it would be very difficult to separate the effect of polarization sensitivity from other effects in our retrieval algorithm.

ACPD
6, S6508–S6522, 2007

Interactive Comment

G3. I miss a more extended validation of their approach. ... It would be interesting to see here a more extended validation. For example how does the retrieval perform at higher latitude? Also a time series of a validation at particular altitude may help to see if a seasonal dependence ...

Although we showed comparisons only at Hohenpeissenberg stations, we actually compared retrievals (with and without degradation correction) with ozonesonde measurements at seven other locations (i.e., Scorsbysund, Boulder, Wallops Island, Hilo, America Samoa, Lauder, and Neumayer) during 1996-2003, and we have plotted the comparison (similar to Fig. 6) for each individual layer (layer 1 to 7 or from surface to ~35 km). The reason why we selected the Hohenpeissenberg station is that there are a lot more GOME-sonde coincidences than at other locations and the effects of degradation correction on retrievals represent other mid-latitude locations. At the two high-latitude stations, the number of GOME-sonde collocations is less than 62 during the whole time period and there is a lack of coincidences during the winter season. In addition, retrievals in the troposphere are less sensitive to the degradation because of large solar zenith angles, and retrievals in the stratosphere are also less sensitive to the degradation due to the initial offset in GOME data and the on-line radiometric correction implemented in our algorithms. Therefore, it is difficult to see the dependence of correction on solar zenith angle. For the two tropical stations, the effect of degradation on our retrievals is relatively small as has been shown in Figs. 4 and 5 and explained in the text. In addition, the large differences of 20-60 percent in the UT/LS region between our retrievals and ozonesonde observations, resulting from both ozonesonde measurements retrievals (see detailed discussion in Liu et al., 2006a) make it difficult to show the improvements.

The seasonal dependence of the comparison for those layers where the effects of degradation are largest (e.g., second and third layers) are very similar to the time series of validation of tropospheric column ozone (Fig. 6b). Therefore, we did not show the comparison for individual layers.

ACPD
6, S6508–S6522, 2007

Specific comments

S1. Page 8287 line 16-17: I think the surface fit does not present the main drawback of the 'forward model' approach. The surface albedo is used, to the best of my knowledge, in all algorithms as a kind of nuisance parameter ...

Here we meant that in the forward model approach (e.g., in van der A et al., 2002) to correct for degradation correction, the surface albedo derived from uncorrected spectral region (e.g., 400 nm) is used as fixed (not varied) input to simulate radiance. Error in surface albedo directly propagates into the simulated radiance spectrum and therefore into the derived degradation correction.

S2. To my opinion, the disadvantage of the 'forward model' approach is that one assumes that the atmosphere can be characterized with independent measurements ... Overall, I miss here a more detailed discussion of the pro and contras of the different approaches.

We added discussions about the pros and cons of these two approaches according to your comments. We changed the last two sentences in the second paragraph of the introduction to "Although these forward model approaches can be used to check both instrument calibration at any time period and instrument degradation, there are several disadvantages. First, due to the uncertainties and inhomogeneous performance of ozonesonde observations, especially in the upper troposphere and lower stratosphere (Liu et al., 2006), the derived correction parameters can vary significantly with latitude or vary from location to location. Second, one has to assume an ozone distribution above the ozonesonde by combing other different types of measurements (e.g., lidar measurements). This requires careful collocations of different ozone measurements as well as GOME; however, the number of such triple collocations is very limited. Third, if surface albedo is derived from uncorrected measurements, error in derived surface albedo directly propagates into the simulated spectra, leading to incomplete degradation correction (Krijger et al., 2005). One approach to performing degradation

ACPD

6, S6508–S6522, 2007

Interactive Comment

correction in the spectral region for deriving surface albedo is to use measurements in regions with nearly constant surface albedo and little cloud coverage such as the Libyan Desert (Krijger et al., 2005). Finally, the forward model approach does not allow one to distinguish between forward model errors and instrument errors." At the end of section 2, we added "van der A et al. (2001) and Krijger et al. (2005) identified an over-estimation of ˜10 percent in reflectance below 300 nm that has occurred since launch. Because our method uses measurements at launch as a reference, it could not correct those instrumental errors."

S3. Fig 1a: caption: "coadd refers to the average degradation of the for scan positions" Do you average four individual curves or do you average the corresponding spectra. ... may be the reason for the jump at 307 nm in Fig1 c.

We averaged the spectra. To clarify this, we change the caption to "refers to the derived degradation of the reflectance averaged from four scan positions." We looked carefully at the jump; it is caused by two operational changes: (1) March 1996, when the integration time of channels 1b to 4 is changed from 0.375 s to 1.5 s. (2) June 1998, when the channel 1a/1b boundary is changed from 307 nm to 283 nm. The jump is also shown in the results of van der A et al. (2002). We added discussion about the jump in the text.

S4. Fig1 c: Too many lines. Use 2 panels for Fig. 7. would be better.

We reduced the number of lines in Fig. 1c and made the change in Fig. 7

S5. Page 8289 line 12-13: Does the radiance jump at the subchannel boundaries of channel 1 cause a problem in the retrieval? ...

We added "It does not cause problems in our retrievals, because our algorithm does not use the spectral region 307-312 nm."

S6. Page 8289 line 21-23 This point was not clear to me? It has probably something to do that you removed the solar zenith angle dependence from your data ... At one

ACPD

6, S6508–S6522, 2007

geo-location both are correlated, but this is not necessarily true for the whole data set ...

The final degradation is derived after removing components dependent on solar zenith angle and seasonal variation; it no longer depends on solar zenith angle and will be similarly applied to every reflectance spectra measured at the same time. We changed the sentence to “To perform degradation correction in retrievals for a particular time period, we multiply the parameterized wavelength-dependent degradation at that time with the corresponding solar spectra before retrievals start.” I agree that these 2 components are related. However, we treated them differently when removing their effects. We have clarified this in the text: “We use non-linear least squares fitting to remove the components related to solar zenith angle (a 3rd-order polynomial of the cosine of solar zenith angle) and seasonal variation (a 3rd-order polynomial of the time within a year).”

S7. P 8290 l 21-24: Do you mean that due to a stronger constrain less information is extracted from the measurement ... If so, the smaller retrieval bias in the tropics can not be explained by the fact that ‘the on-line degradation correction works better’ ...

Yes. We rephrased “thus the on-line ...” to “so less information is extracted from the measurements and retrievals are less sensitive to spectral biases.”

S8. Fig. 4: Why this difference at 60S and 60N in the TOC but not in TC?

We added explanations in the revision: “Around 60S and north of ˜70N, the differences are much smaller in TCO, suggesting that the retrieved TCO is less sensitive to degradation. This is because radiance measurements at larger solar zenith angles (i.e., higher latitudes) usually contain less tropospheric ozone information.”

S9. Fig. 5 There is a clear degradation present at the shortwave UV. ... I would mention that errors at the longwave UV are of crucial importance for the retrieval due to the low sensitivity of the measurement whereas errors at the shortwave UV are less critical ...

The main reason why stratospheric ozone is less affected by degradation is that we

ACPD
6, S6508–S6522, 2007

applied a 2nd-order polynomial correction to radiances between 289 and 307 nm in the retrieval. Without this correction, retrievals would be very sensitive to measurement errors in shortwave UV as shown in the first column of Fig. 6b of Meijer et al., 2006 (our previous retrievals without this correction). We added explanations in the text.

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ACPD

6, S6508–S6522, 2007

Interactive Comment