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Reply to the referee # 2
Cloud sensitivity studies for stratospheric and lower mesospheric ozone profile retrievals from measurements of limb scattered solar radiation

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1 AMTD Criteria

1. This paper addresses a very relevant scientific question regarding the effect of clouds upon retrieved ozone profiles. This fundamental question has been asked since the advent of the limb scattering technique and is clearly within the scope of AMT.
⇒ Thank you.

2. These studies are one of the first done systematically for ozone profile retrievals.
⇒ Thank you.

3. Many results are presented for various aspects of the problem, but the level of explanation and discussion could be more in-depth.
⇒ See replies to specific comments below.

4. Assumptions are clearly outlined.
⇒ Thank you.

5. The results are sufficient to support the limited conclusions made.
⇒ Thank you.

6. The authors have done a good job of detailing the conditions and assumptions of the calculations. Thus, enabling others to repeat these same studies.
⇒ Thank you.

7. The authors clearly indicate their own original contributions.
⇒ Thank you.

8. The title clearly states the content of the article.
⇒ Thank you.

9. The abstract is clear and concise.
⇒ Thank you.

10. Overall, the presentation is well structured and clear.
⇒ Thank you.

11. The language is fluent.
⇒ Thank you.

12. For the most part, the math is correct.
⇒ Thank you.

13. Several figures could be re-done to enhance readability.
⇒ Fig. 1-3 have been changed.

14. The references tend to be SCIAMACHY-centric and not necessarily the most appropriate, but maybe representative of what the authors have read.
⇒ Acknowledged.

15. Appendix A could be eliminated without much loss of information.
⇒ Appendix A is needed to prove that the derivative of the triplet with respect to the cloud parameters has commonly the same sign as the derivative of the intensity of the solar radiation reflected by clouds which is essential when discussing the results. We see no reason to eliminate the Appendix because it provides useful information to the readers interested in the mathematical background and can be easily skiped by others.

2 GENERAL:

Referee: This article examines a question that has existed since the advent of the limb scattering technique, i.e. how does scattering by clouds cause errors in profile retrievals. A systematic approach is used to study the problem and many results are generated. The use of an approximate model to gain better physical insight into the problem is a wise choice.
The depth of the explanations should be increased, but overall the article is an important one in the field of limb scatter observations and subsequent ozone profile retrievals.
Author: We have tried to offer explanations for the observed effects wherever possible. However, we found that due to the complicated nature of the retrieval problem (in combination with the complex RT) simple attempts to explain the found dependencies of the ozone retrievals errors on clouds are often incorrect. We therefore decided to limit the discussion of many observed dependencies to a mere description of the effects seen in the sensitivity studies, without offering simply explanations that may be entirely incorrect. If the referee could point out specific aspects that should be discussed in more detail, we will attempt to do so.

3 Specific Comments:

Referee: Page 381, line 2: Is the cloud fraction truly equal to 60%? Some studies say as high as 80%.
Author: We changed the value to "about 50%" and included the references.

Referee: Cloud coverage is dependent upon the threshold of what constitutes a cloud, i.e. optical depth limit, and the pixel size. What is really relevant for limb scatter?
Author: This is a good question, and we're not sure, whether *the* answer to it exists. Qualitatively, the effect of clouds on the retrievals will certainly increase with increasing cloud optical thickness (if clouds are ignored in the retrieval process, as in our study). We feel it is not possible to give a threshold value of the cloud optical thickness that is generally valid, because different science applications will require different accuracy, precision and long-term stability of the retrieved data product.

Referee: Page 381, lines 15-19: Yes, the limb scatter observation geometry can be complex due to multiple scattering, but not simply because there is multiple scattering. The same observation geometry is fairly straight forward for wavelengths with strong atmospheric absorption, i.e. less than 300 nm, and single scattering is the primary pathway for sunlight to reach the observer. While multiple scattering also occurs for the nadir observation geometry, at wavelengths greater than 300 nm, it is less complex than the limb scatter geometry for two main reasons: scattering must be modeled in a spherical atmosphere, not a plane-parallel atmosphere, and the major source that diffusely illuminates the observation line of sight is not directly observed. For the later factor, this region of influence in the Earths atmosphere can be 1000km in length and 500 km or more in width [Oikarinen et al., 1999], as a consequence heterogeneity of the region around the tangent point becomes an issue. While scattering in a spherical atmosphere and the adjacency effect do occur for the nadir geometry, generally one can do quite well in modeling with scattering in a plane parallel atmosphere occurring within the field of view (pixel).
Author: We completely agree with the referee, and the text has been modified accordingly.

Referee: Page 384, Line 16: Need to state upfront that you are referring to limb scatter measurements here.
Author: OK, done.

Referee: Page 386, line 10: Id classify 675nm as within the Chappuis band (400-700 nm).
Author: OK, we changed it to Chappuis bands.

Referee: Page 386, last paragraph: Does $y_c(h_i)$ represent the combined measurement for all the wavelengths, but a single tangent height (the reference tangent height aside)?
Author: $y_c(h_i)$ represents the measurements at all wavelengths and all tangent heights, but we realize that our notation here is not fully consistent, because we only list h_i as an argument of the retrieval vector. The sentence has been changed in order to reflect that measurements at all tangent heights and wavelengths are included.

Referee: Section 7 and Figure 1: Since the Chappuis triplet is actually created in two steps: normalization and wavelength ratioing, it would be instructive to add additional plots to Fig. 1. Curves for both independent processes should show reduced errors, but not necessarily the same reduction or altitude dependence.
Author: This is a very good suggestion. The plot was added to Fig. 1–3 showing the quantities for the normalized limb radiance profile at 602 nm.

Referee: Page 394, line 23: You should go a little deeper here in the explanation. Where have the pathlengths been changed that lead to increased absorption? Is it due to scattering within the cloud and subsequent absorption by ozone within the cloud? This has long been a suspect for error in total ozone estimation from nadir observations. The motivation for the approximate model was to better understand what is physically happening in the retrieval process. So, please discuss, even in a qualitative fashion, why the curves look that way they do. For example, the absolute radiance plot

where the absorption error term is positive because the cloud-free model needs more larger ozone concentrations to match the increased path-absorption. Likewise, the scattering term (first term in Eq. 21) is negative because the clouds increase the observed 602 nm radiance, but the only way the cloud- free model can match the observed radiance is to decrease the ozone concentration.
Why does the gaseous absorption term or second term have a negative sign when the Chappuis triplet is used? You make the case that the approximate model is similar, although not completely robust, to the more rigorous method. So, make the most of it and gain as much physical insight about the problem as you can. I really feel that understanding Fig. 1 will go along ways toward understanding the root of the error, rather than just saying the problem is that clouds arent modeled properly, i.e. not at all.
Author: The additional explanations were added to the text of section 7.

Referee: The other key to the problem can be found in Fig. 9, where the errors approach zero for an albedo in the cloud-free case that matches the cloudly Chappuis value, by definition. The triplet/pair approach outlined in Flittner et al. (2000) and expounded upon in Loughman et al. (2005) stresses the need for an estimate of the surface albedo based upon the particular scene in order that the upwelling diffuse light in the retrieval process be modeled in a more appropriate manor. The estimate of the scene albedo is needed in the inversion process to better estimate the mix of multiple vs. single scatter for each tangent height for an individual wavelength and to refine the spectral dependence of the radiance. Whether this is done with a cloud or a Lambertian surface with a variable albedo should be a minor issue. The authors certainly have the means to test the validity of using a Lambertian surface with a variable albedo. The use of a Lambertian surface with an albedo estimated directly from the limb radiances has been used in the analysis of data from SOLSE/LORE, SAGE III and OSIRIS, and is the baseline approach for the future OMPS instrument.
Author: This is another very good point. We agree that the estimation of an effective albedo is in principle possible from the limb measurements themselves, and that other teams already included this in their retrieval schemes. We realize that this currently is a limitation of the approach outlined in this paper, and we're working on the implementation of a simultaneous estimation of the scene albedo. Despite this limitation, we believe that the current manuscript is relevant.

Referee: Table 3: The Figs. column is extremely helpful in navigating the article. Great idea!
Author: Thank you.

Referee: Fig. 1: I found it hard to discern the symbols. Maybe if each particular symbol was a constant color, i.e. X always red.
Author: Done.