Answers to Anonymous Referee #1

This paper consists of two parts: At first, a new retrieval of cloud top height through Oxygen A-Band spectroscopy is introduced and validated (part I). Secondly, a seven year climatology of this parameter is derived, and an analytical parameterization is provided (part II). Apart from minor comments, I found the paper relatively clear and easy to follow. However, there were a few places where further explanations are needed. On many occasions, one could only understand the current manuscript when also reading Kokhanovsky 2007a (or Rozanov and Kokhanovsky 2004). However, if the current manuscript is more than a mere "add-on" to the 2007 manuscript, more details are needed, as specified below. In general, the retrieval section is too short, as is the validation aspect.

In the new version of the manuscript we address both issues. The retrieval section has been made clearer and additional validation has been added.

MAJOR COMMENTS
Part I - retrieval and validation p4996: As pointed out earlier, all of this work is based on the assumption of water clouds. Therefore, the optical thickness (p4996,l1) may be off. As long as optical thickness is not provided as a final product, that is probably fine, as long as the spherical albedo is correct, which does seem to be necessary for the retrieval (although it's not explained what role it takes for the determination of CTH; Eq. 8 is not based on albedo, but on reflectance).

(A.1) The optical thickness can not be neglected and is provided as cloud product. Its validation was given in Nauss et al. [2005] (see also response to Joiner, point A.4). Moreover, its value is needed for the correct calculation of forward reflectances, because the depth of the O_2 line depends also on the cloud optical thickness. The asymptotic relations of radiative transfer enable its retrieval in the case of optically thick clouds, as it is in the continuum at wavelength 758 nm, where its influence on reflectances is more pronounced as compared for wavelength 761 nm.

p4997, Eq. 8 and explanation.
In my opinion, there are several shortcomings in this paragraph: (1) It is unclear how the retrieval actually works. The spectral reflectance comes from Eq. 1, ok. Although it isn't specified in the manuscript (this needs to be done!), I assume that R(h_0) is calculated with the forward model, in this case the analytical formulae from Eq. 2-5. Obviously, R(h_0) and R'(h_0) (Eq. 7) are calculated across the entire Oxygen A-Band wavelength range - is this correct? If so, what is the wavelength range?

(A.2) Yes, it is correct. The wavelength range is [758 – 772] nm. The spectral reflectance is

$$R_{\text{mes}} = \frac{\pi I}{\mu_0 E_0} \tag{1}$$

where E_0 is the spectral irradiance, I the measured radiance and μ_0 the cosine of solar zenith angle.

What is not described well enough is how the formulae for asymptotic theory serve as a forward model that accounts for Oxygen absorption within and above the cloud layer. The authors do mention that the correlated-l concept is used, but how does that work in asymptotic theory? Please provide the missing explanation / formulae.

(A.3) We address this in answer A.5.

(2) How is the correlated_k method implemented within asymptotic theory?

(A.4) The structure of the oxygen band, convolved with the instrument response function, is reproduced adopting the method of the "exponential sum fitting coefficients" given by Buchwitz et al. [2000]. Five precalculated profiles of molecular oxygen cross-section (T-,P- and λ-dependent) are calculated, multiplied by tabulated constants [Buchwitz et al., 2000], and summed up to give the convolved wavelength-dependent monochromatic TOA intensity. In this work, the wavelength step of 0.05 nm is used. This method enables fast calculations with an accuracy within 2% as compared with line-by-line calculations [Buchwitz et al., 2000].

How is the radiative transfer performed above the cloud layer, with single scattering approximations that are outside the framework of asymptotic theory?In Rozanov and Kokhanovsky (2004), a *semi*analytical algorithm was presented, based on SCIATRAN (which can account for molecular scattering and absorption). How is this done with asymptotic theory alone?

(A.5) There is no difference in the forward parameterizations of R_{TOA} presented in Rozanov and Kokhanovsky [2004] and used in this work. The TOA reflection function is expressed as

$$R_{\mathrm{TOA}} = R_0 + T_1 R_b T_2 \tag{2}$$

where R_0 gives the reflection function of the part of atmosphere above the cloud in the single scattering approximation, due to its weak signal. The Rayleigh and aerosol scattering and absorption coefficients are considered. R_b is the reflection function of the cloud-underlying atmosphere system together with surface contribution, while the multipliers $T_{1,2}$ are the transmission coefficients from the Sun to a cloud and from the cloud to a satellite, respectively. Accounting in $T_{1,2}$ for gaseous absorption only diminishes the total extinction along the light-path and results in the increase of the second term of the right hand side of the above equation. This procedure enables the account of multiple scattering above the cloud. Moreover, the contribution of the atmospheric layer below the cloud is not neglected. Equations 7-20 in Kokhanovsky and Rozanov [2004] illustrate how the aerosol-gaseous medium and underlying surface can be approximated by an effective Lambertian surface with albedo A^*.
The Oxygen absorption within the cloud layer is taken into account in the term R_b. The main parameter is the single scattering albedo ω_0, which changes in the presence of the cloud top, as depicted in Fig.(7) of Kokhanovsky and Rozanov [2004]. Moreover ω_0 depends on height inside the gaseous absorption band under study and it can be

written as

$$\omega_0 = 1 - \frac{\sigma_{\mathrm{abs}}^{\mathrm{O_2}}}{\sigma_{\mathrm{ext}}}$$

where aerosol and cloud absorption in the visible are neglected. The effective value ω_0^* is then calculated iteratively (the formulae are in appendix A of Kokhanovsky and Rozanov [2004]). One can think at this procedure as finding the homogeneous analogue SSA of the inhomogeneous SSA profile inside the cloud. The accuracy of this approach was given in Yanovitskij [1997].

> (3) Although the reference Rozanov and Kokhanovsky (2004) is given on line 5, this does not explain how the retrieval of h,l is actually done *here* - in the same way? In Rozanov and Kokhanovsky, SCIATRAN is used, which is not mentioned in the current paper. Is it correct (as explained in Kokhanovsky et al. 2007a) that one imagine to write the cost function in vectorial form where the rank of the matrix is determined by the number of wavelengths used, and where h_0 is a parameter? If so, this needs to be stated. Also, the wavelength index cannot just be dropped without explanation. Follow the Rozanov and Kokhanovsky 2004 paper (around Eq. 17) to explain this.

(A.6) We address point 3 and 4 together in the following answer.

> (4) In Eq. 8, I am missing "l" as a parameter. How, then, can "l" be found by minimizing F?

(A.7) Firstly, the h_0 is just a start CTH value for the retrieval. Tests have shown that the retrieval is almost insensitive to different start values of h_0 in range of [1-10] km. This is due to the fact that the solution for the 2-parameter (namely h, l) inverse problem is performed iteratively. The first step is to fix the geometrical thickness l and then calculate h with equations 6 and 7. The value l is chosen as 100 m, being a typical cloud extinction coefficient $\epsilon = 50$ km^{-1} and the COT lower limit 5 (i.e, $l = \frac{\tau}{\epsilon}$). The value of minimum difference $\delta(l_k)$ between the forward and measured spectrum is iteratively looked for along the whole band (therefore the wavelength index is dropped), with the following equation

$$\delta(l_k) = \left|\left|\vec{R}_{\mathrm{mes}}(h, l_k) - \vec{R}(h_0) - \vec{R}'(h, l_k) \cdot (h - h_0)\right|\right|^2$$

where the index $k = 1 \ldots N$ is the needed iteration number. We will update the manuscript accordingly and missing clarification will be given.

> (5) How do asymptotic theory and the minimization described in Eq. 8 account for the fact that photons do, in fact, penetrate into clouds, and that clouds are not just a simple "reflector"?

(A.8) Please see point A.5 and the appendix A in Kokhanovsky and Rozanov [2004].

> p4998,l25: A 1% variability of the asymmetry parameter is introduced. Three clarifications are needed: (1) A 10% variability would be more appropriate since the cloud can be composed entirely of ice.

(A.9) Cirrus clouds are excluded from the beginning, by filtering the reflection function for a value lower than 0.15, so the algorithm should not be triggered. Moreover, in order to not introduce spurious values in the statistics, we check the quality flag of the retrievals as discussed in response to Joiner, point A.1. Please see also point A.5 in response to referee #2.
For low level ice clouds (which may be in mixed-phase too), we are able to retrieve them. As can be seen in the figure of Joiner/A.1, the presence of an ice layer does not inhibit the algorithm to retrieve CTH/CBH values. However, we are not able to discriminate them in the statistics.

> (2) Is there any spectral dependence of the asymmetry parameter across the Oxygen-A band?

(A.10) The asymmetry parameter is barely wavelength-dependent in the visible. Spectral changes can be seen close to the water absorption band around 3 μm, where extinction drops to its minimum, as shown in Kokhanovsky [2006]. We report below the relevant figure for completeness.

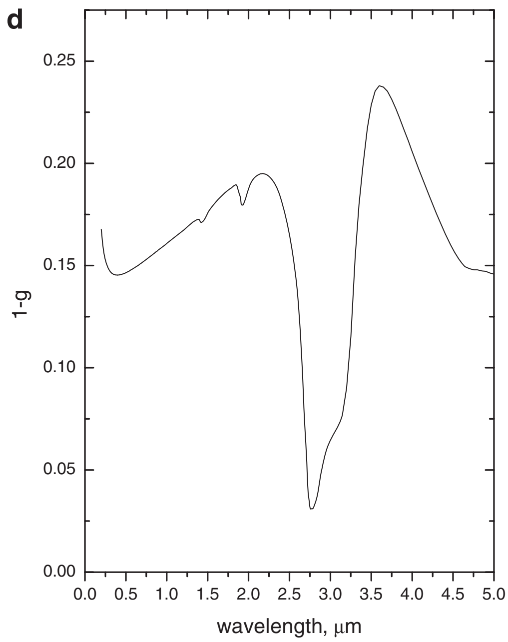

Figure 1: The parameter $(1-g)$ as function of wavelength for the Deirmendjian's C1 cloud model employed in this work.

> (3) What does Figure 1 actually show? Where does CTH_retrieved come from, where does CTH_true come from? Without clarification, one can only assume that a model cloud was placed at altitude CTH_true, and the spectrum was calculated using asymptotic theory. The CTH was then retrieved. Clarifications needed: (3a) Is this the way it was done?

(A.11) Yes, it is correct. We will explain in more details this issue in the updated manuscript.

(3b) Wouldn't is be more appropriate to calculate the spectrum with an independent RT model?

(A.12) The forward reflectances are modeled using the scalar discrete ordinate method (S-DOM) implemented in SCIATRAN. This is because polarization effect play a very little role in the O_2 A-band (see Fig. 2). Accordingly only the scalar Stokes vector $\vec{I}$ was calculated, whereas, using the vector discrete ordinate method (V-DOM), all four Stokes vectors are computed. The retrieved reflectances were calculated with analytical approximate equations of radiative transfer instead. Therefore we consider the two models separate and independent.

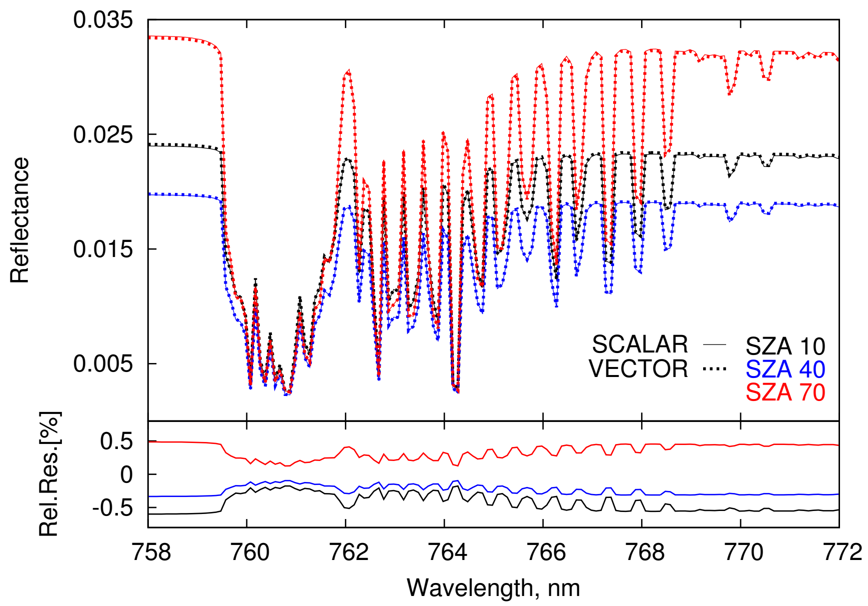

Figure 2: **[Upper plot]** Reflectances in the O_2 A-band in Scalar (S-DOM, solid lines) and Vector (V-DOM, dotted lines) SCIATRAN mode for three different solar zenith angles (10° black, 40° blue, 70° red). **[Lower plot]** Relative residuals between reflectances calculated from the Stokes vector $\vec{I}$ in Scalar (S) and Vector (V) mode. The error is defined as $100 \cdot (S - V)/V$, for the corresponding solar zenith angle. Wavelength step: 0.1 nm.

(3c) Is it possible to test various different cloud fractions? Was the cloud fraction in the validation runs set to 1?

(A.13) Yes, the CF is set to 1. Owing to the results of Kokhanovsky et al. [2007], we ingested in the algorithm reflectances which are already weighted by CF itself. The absent correlation between CF bias and CTH bias (as presented in the response to referee #2, point A.35) indirectly corroborate this approach.

(4) Likewise, what does Figure 2 show? Was the forward calculation (using CTH_true) run with one particular g, and the retrieval with another?

Again, the range of g's should be larger to account for the possibility of ice clouds, or ice clouds should be excluded from the beginning. Also, further validations should be conducted such as the dependence on cloud fraction.

(A.14) Firstly, we have redone Fig.2 (following the suggestion of referee#2/A.32). With this regard, see also point A.16.
As previously stated, the cirrus clouds are excluded from the very beginning. Moreover, owing to the arguments and results presented in Kokhanovsky et al. [2007] and the comparison of CF bias versus CTH bias between the ATSR and the O_2 A-band algorithms (please, see response to referee #2, point A.35) we are persuaded that CF plays a little role in this context.

p4999,l1: Phase functions are mentioned here. But isn't the radiative transfer based on asymptotic theory which relies only on the asymmetry parameter?

(A.15) In the framework of asymptotic theory, the reflection function R is not only dependent on the asymmetry parameter g, but on the phase function p itself. We report here Eq.11, p.167 of Kokhanovsky and Rozanov [2003]

$$R(\tau,\xi,1) = \frac{0.37+1.94\ \xi}{1+\xi} + \frac{p(\pi+\arccos\xi)}{4(1+\xi)} - \frac{27}{49}\Big(\frac{1}{1.07+0.75\ \tau\ (1-g)} - t_c\Big)(1+2\xi)$$

where τ is the optical thickness, ξ the cosine of the solar zenith angle, and t_c is the cloud transmittance, corrected in order to achieve the required accuracy for $5 < \tau < 10$.

Why would rainbow features show up in g? Possibly the only way to interpret the red dots in Figure 2 is to assume that the authors did, indeed, use a different model for calculating the spectra that does allow using the full phase function as input, and asymptotic theory for the retrieval. If so, this needs to be stated somewhere.

(A.16) Yes, indeed. The forward spectra are calculated with full Mie theory. This consideration impacts Fig. 2 (p.5022) and Fig. 3 (p.5023). Since GOME is not equipped with IR channels functional to the droplet size determination, the retrieval of COT with only one channel (758 nm) and with Eq. 5 (p. 4996) is strongly sensitive to phase function changes (please see also the responses to Joiner/A.9 and to referee#2/A.18).
The COT is then used to retrieve CBH/CTH values. Therefore we expect an error propagation. Nevertheless, the influence of bow angles is less evident than those in Fig.3 (we have redone the plot following the recommendation of referee#2/A.32). The error mitigation arises from the dual fact that only the ratios $(R_{758} - R_\lambda)/R_{758}$ are ingested in the algorithm and that the CTHs are calculated along the O_2 A-band, using 67 spectral points.

The validation part should be expanded. The best Figure seems to be Figure 6. But only Delta CF is shown, not CF itself. I would highly recommend to discuss the error in CTH as a function of CF and optical thickness, as well as thermodynamic phase. The dependence on phase is especially important since the entire retrieval algorithm seems to be based on water.

(A.17) We have redone the analysis following your recommendation and we plotted CF bias versus CTH bias. Please see response to referee #2, point A.35.
We are not able to direct retrieve informations on the thermodynamic phase, due to the lack of infrared channels of GOME.

For the depth of the Oxygen-A Band, there are two factors besides the Oxygen absorption itself that matter, both of which are mentioned by the authors, but not sufficiently explained (a) multiple scattering in clouds;

(A.18) Please see point A.20.

(b) 3D effects (i.e., modifications of the path length distribution through heterogeneous clouds, especially in scenes with CF$<$1).

(A.19) 3D effects are, in fact, neglected. It is certainly true that, for CF$<$1, they play a role, but on the other side the coarser the instrumental footprint, the less influence they have. For instance, for a assumed cloud of 1 km and 320 $\times$ 40 km^2 of vertical and horizontal extent (as sensed by GOME), its reflectance (weighted in the IPA equation) will receive more contribution from the light scattered back by the plane along the nadir direction than from the light scattered in the horizontal direction.
The opposite holds true when the spatial resolution of the sensor becomes finer (e.g. MODIS). Clouds can not be modeled as plane parallel slabs anymore and 3D effects must be taken into account.

(a) Although mentioned as an advantage of the current algorithm to account for multiple scattering in clouds and the associated deepening of the Ox A Band (p5002,l24), I do not find an explanation how that's done. This needs to be made clear.

(A.20) Multiple scattering is inherently accounted for when calculating R_b in Eq.(2), because of the nature of the analytical theory (please see derivations of the formulae and error analysis in Kokhanovsky and Rozanov [2003]).

(b) p4994,l21-l22 states that 3D calculations are not necessary to account for cloud heterogeneities since GOME has such coarse resolution. This is not the correct explanation. Instead, Kokhanovsky et al. (2007a) state that since the CTH retrieval involves spectral ratios, it is not affected very much by 3D effects, as long as CF is known from an independent source. This statement should be true regardless of cloud fraction and of satellite resolution. I am surprised about the results of Kokhanovsky et al. (2007a) (I would expect a deepening of the Oxygen A absorption lines when running RT in full 3D mode, and not IPA mode), but this is not of relevance for this review. However, Kokhanovsky et al. (2007a) should be cited correctly.

(A.21) This part will be updated in the manuscript.

Part II - climatology * In part one, the algorithm is only introduced for water clouds, but the CTH in the paper have a maximum altitude of 14 km - how does this work?

(A.22) The reanalysis of the dataset (please see response to Joiner, point A.7) shows that the maximum of Fig. 8 is placed now at $\approx$ 12 km. Nevertheless, the occurrence of 2.5% clouds at heights 14 km can be explained as supercooled water clouds, which are lifted up by deep convection in the tropics [Hogan, 2004].

* Revise the statement "The reliability of the dataset for studies on a regional scale has been illustrated." As stated by the authors (p4998,l16), the GOME retrieval does not work for thin high clouds, and it possibly does not work for ice clouds.

(A.23) In answer Joiner/A.1 we provided a synthetic test for a two layer system with a ice layer covering a water layer. It can be concluded, by comparison of the two plots, that the algorithm works for ice clouds, given a $\tau > 5$. What is not known beforehand is the ice phase function and this will introduce errors in the retrievals.

While a validation of the algorithm was provided for a case study in part I, the climatology in part II was not validated by an independent dataset. Therefore, I don't think that this statement would be adequate, unless more validation is provided.

(A.24) In the new version of the paper, we provide a comparison with the ROCINN dataset. Please see the response to referee #2 point A.22. The comparison with the other O_2 A-band algorithm FRESCO, pertinent to the spectrometer family of GOME and SCIAMACHY, will be given in the ensuing work, in which GOME-2 measurements are employed.

* Is it correct to say that clouds with an optical thickness < 5 are not part of the climatology? This means that Ci are almost entirely excluded, correct?

(A.25) Yes, it is correct.

* When providing an average CTH, provide the range of optical thickness for which this was provided, and whether the "average" CTH is weighted with respect to optical thickness.

(A.26) The average COT for the provided average CTH (which now amounts to 5.6 ± 1.8 km (variance)) is 19.11 ± 3.77 (variance). The CTH was not weighted by the respective COT distribution.

MINOR COMMENTS
p4992,l2: "clouds": specify which clouds (water/ice)
l12: Insert "the" before "Pacific"
l19: delete comma after "but"
p4993,l5: replace "moderate high" with "a"
p4998,l9: replace "through" with "throughout"

l20: replace "particles" with "particle"
l20-l21: "For this reason. . .appreciably." Fix English - is the word order off?
l26: replace "discloses" with "show"
p4999,l19-l20: Provide a little bit more detail about this. p5003,l18-20: I don't understand this statement. Does it imply that even though the retrieval is only valid for water clouds, it will function because water clouds are somewhere to be found in this data set?

(A.27) The statement was meant to underline that, even with such a coarse spatial resolution, the typical patterns of cloud fields are well depicted in the dataset. This part will be rephrased in the new version of the manuscript.

p5004,l29: replace "hemisphere" with "hemispheres"
p5004(l29)-p5005(l1) Fix word order ("appear") should not be placed at the end of the sentence.
p5005,25: replace "variations, nevertheless" with "variations. Nevertheless"
p5007,l1: replace "as well" with "either"

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