Cloud Discrimination in Probability Density Functions of Limb Scattered Sunlight Measurements

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We thank both reviewers for helpful and encouraging comments. We have addressed these with a revision of the paper and our reply to these comments in given in the text below, with reviewer comments in bold. The most significant change that we have made is to add a new set of modelled results to Figure 2 that show the scattering residual expected at the threshold optical depth for subvisible cirrus clouds, which helps to clarify the expected behaviour for cloud versus aerosol scattering.

Response to comments by Referee 1:

- **Abstract, p 6492, l 10 and ff: the abstract should contain at least one figure about the results achieved in the study.**

  Abstracts typically do not contain figures. This abstract refers implicitly to results shown in the figures; specifically figures 5 and 7.

- **Sect 1, p 6492, l 20 and ff: the introduction mainly lacks in two aspects: a proper problem setting regarding cloud retrieval in limb geometry is missing and relevant references to previous works too are missing, even if do not address directly clouds. For instance MIPAS (Semhbi et al., Spang et al., 2012) SCIAMACHY (von Savigny et al. 2005, Rozanov et al 2011) where a multi-wavelength color index method is described (SCODA, Eichmann et al, 2010) and the new OMPS (aboard NPP). Additionally also occultation instruments can retrieve informations on clouds (SCIAMACHY again and GOMOS, for instance). When citing Sassen and Cho (p 6493), the grouping of cirrus clouds as function of tau sounds detached from the narrative of the paper.**

  To help cohere the paragraph, two sentences were added at the end of the second paragraph of the introduction saying that limb scatter, though a passive technique, is able to detect the presence of these very optically thin clouds.

  "Optically thin clouds are below the detection threshold of passive nadir-viewing instruments, yet they scatter light sufficiently to bias their trace gas retrievals. By contrast, in limb-scattering or occultation geometries even very optically thin clouds can produce a measurable effect on the measured brightness profile."

  The introduction has also been updated to include references to relevant limb scattering and cloud measuring works:

  "Limb scatter measurements have been used previously with other techniques for cloud detection. For example SCIAMACHY (SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY) measurements were used by Eichmann et al. (2010) in a multi-wavelength approach to determine global cloud top heights, and von Savigny et al. (2004) developed a technique for detection of noctilucent clouds. Limb emission measurements in the infrared have also been employed for studying clouds. Greenhough et al. (2005) use MIPAS (Michelson Interferometer for Passive Atmospheric Sounding) measurements to retrieve a cloud detection index and Sembhi et al. (2012) study MIPAS detection limits for cloud and aerosol particles."

- **Sect 2, p 6494 , l 23 and ff: which aerosol models are accounted for in SAKSTRAN? See point (Sect. 3.2) below.**

  SASKTRAN is capable of modelling the scattering and absorption behavior of sulphate aerosol, ice clouds, and dust. However, as described in Section 2, for the cloud discrimination technique, we only require SASKTRAN to model the limb radiance due to the molecular atmosphere. This then allows for a comparison of the limb-scattered radiance measurements from OSIRIS to the molecular background radiance within a cloud- and aerosol-free atmosphere to obtain the scattered radiance contribution from clouds and aerosols alone. This is explained in detail in Section 3.1.

- **Sect 2.1, Eq (1): $\tilde{I}_1$ is not defined. I assume it is the direct illumination term. It is not really clear why it should vanish, even if it's explained (line 13 and ff, page 6495) that's because light propagation is not aligned to the satellite line-of-sight. Does this really enforce that no direct sunlight is reaching the sensor?**

  Indeed, $\tilde{I}_1$ is the direct illumination term. For the satellite line of sight this will vanish as the narrow field-of-view never directly views the sun. However for the multiple scattering terms, I_1 accounts ground scattering for rays that strike the surface; this explanation was added into Section 2.1 where the terms are first introduced.

- **Sect 2.1: despite the fact that SAKSTRAN is introduced as capable of accounting for multiple scattering and aerosols, this section introduces radiative transfer in single scattering approximation. Some question arise: what happens to the integration term of Eq.(1) (2nd of r.h.s.) when a cloud/aerosol layer is below the tangent point or when the tangent point resides within the scattering layer? Does the approximation still hold or is multiple scattering just proportional to N (number density), stated at line 12, page 6496)? Where does N come from? Is it an a-priori?**

  The optically thin single scatter theory is used to motivate the idea of the scattering ratio between the total measured signal and the modelled radiance for a cloud and aerosol free atmosphere. The molecular number density is taken from ECMWF reanalysis. This is now stated in the revision. The actual radiance calculations shown in the work are for total converged multiple scattering for the molecular atmosphere only. The single scatter approximation is indeed less applicable for the cases where there is a cloud in the line of sight; however, in this case the scattering residual will still be larger than one and is therefore still characterized by the statisical approach used here. It may no longer be proportional to the number density of cloud particles, but it will still be dependent in a positive sense and the approach remains valid. For the case where a cloud is below the tangent point, the coupling to higher tangent altitudes is very small at the 800 nm wavelength as the Rayleigh optical depths are very small.

- **Sect. 3.2: the success of the method described in this paper relies on the threshold's choice between cloud/cloud-free conditions. At line 12 (p.6499) it is said that some residual scattering is still present and the mirroring of a gaussian distribution gets rid of it. As reported by Rozanov et al 2011 (fig. 16), some aerosol models trespass a cloud/aerosol discrimination threshold. It is therefore reasonable to ask whether your method is not overestimating this residual scattering (therefore missing some clouds) or underestimating it (and contaminating the statistics with aerosol). The sentence "the position 2-sigma was found to be a reliable demarkation ..." (line 19, p 6499) has to be justified somehow quantitatively. SAKSTRAN is indeed capable to model both aerosol and clouds. Is it possible to assess this threshold's sensitivity as function of aerosols, otherwise how can someone be sure that all the following results pertain to clouds only?**

  It is possible that some strong aerosols may be detected by this technique as a cloud and have added a brief discussion to this effect in the revision. For instance, volcanic plumes can have strong scattering characteristics with optical depths on the same order as clouds. However, except during the early evolution of the volcanic plume the aerosol will typically be quite ubiquitous throughout a latitude band and in this case the cloud-free distribution will shift towards higher residual values. In the cases where clouds cannot be distinguished from aerosols, the cloud-free (including aerosols) and cloudy distributions merge in which case the technique fails. The advantage with this technique is that because of the shifting background distribution the technique itself gives an indication when clouds can no longer be discriminated from background aerosol.

Determining the 2-sigma position to denote the position of the cloud-free threshold line was not a trivial task. The position was selected based off of numerous visual inspections of probability density functions of scattering residuals. Several PDF plots were made on a monthly basis for many months and years at varying tangent altitude levels and it was determined the 2-sigma position generally fell within the minimum region lying between the cloud-free and cloudy distributions. In order to strengthen this aspect of the analysis we have used SASKTRAN to model the scattering residual that would be expected from a cirrus cloud with an optical depth of 0.03, which is the threshold value for subvisible cirrus. This is shown in a new version of Figure 2 shown below and we have added the following text to the manuscript:

"The validity of the cloud-free threshold curve is illustrated by computing the residuals, R, from simulated OSIRIS measurements through cirrus clouds. This radiative transfer modelling of simulated OSIRIS measurements was done with SASKTRAN by assuming cloud scattering properties from the in-situ database of Baum et al. (2005). The cloud particle number density profile, $n(h)$, is assumed to be Gaussian and is scaled to give a prescribed value of cloud optical thickness, τ_c. The vertical extent of the cloud is defined as the full width at half maximum (FWHM) of the distribution. Both the use of a single effective particle size and horizontal homogeneity within the cloud layer are assumed. For more details on model configurations, see Wiensz et al. (2013).

Simulated OSIRIS measurements were constructed for 15 August 2007 using the solar geometry for a typical descending-node OSIRIS scan at a latitude of 7°N. Simulated tangent altitudes were fixed with respect to the local tropopause altitude. To study the perturbation to the values of R from a cirrus cloud at varying altitudes, successive model runs were done with a given cloud (with fixed vertical and optical thickness) as it moved upward through the tangent altitudes. The cloud ‘bottom’ in each case is made to coincide with the line of sight tangent altitude to ensure that each line of sight passes directly through the bulk scattering region of the cloud as it is shifted. Residuals were computed from the modelled radiances by Eqn. 5. For each set of modelled radiances, which correspond to varying cloud altitude, the maximum residual occurs at the tangent altitude passing through the bulk of the cloud. This value is taken as the residual for the cloud altitude. The curve of computed residual, R, as a function of cloud altitude is shown in Fig. 2 for cirrus optical thickness $\tau_c = 0.03$, which is the subvisual cirrus detection threshold (Sassen and Cho, 1992). Simulations were done for cloud effective particle size $D_e = 40\ \mu$m and vertical thickness 200 m.

The figure illustrates several key points. First, the cloud-free threshold lies at values of R well below those for subvisual cirrus clouds. This suggests that the threshold indeed forms a demarcation between regions that contain, relatively, weakly- and strongly-scattering particles. Second, it is notable that the area of decreased probability between the two ‘branches’ in the figure lies at altitudes and residuals between the threshold curve and the subvisual cirrus curve. This indicate an increased occurrence of thin clouds at values $\tau_c \geq 0.03$ relative to lower τ_c values."

- **Fig.(3b): the second peak is monotonic w.r.t. ROI (height), that is the lower**

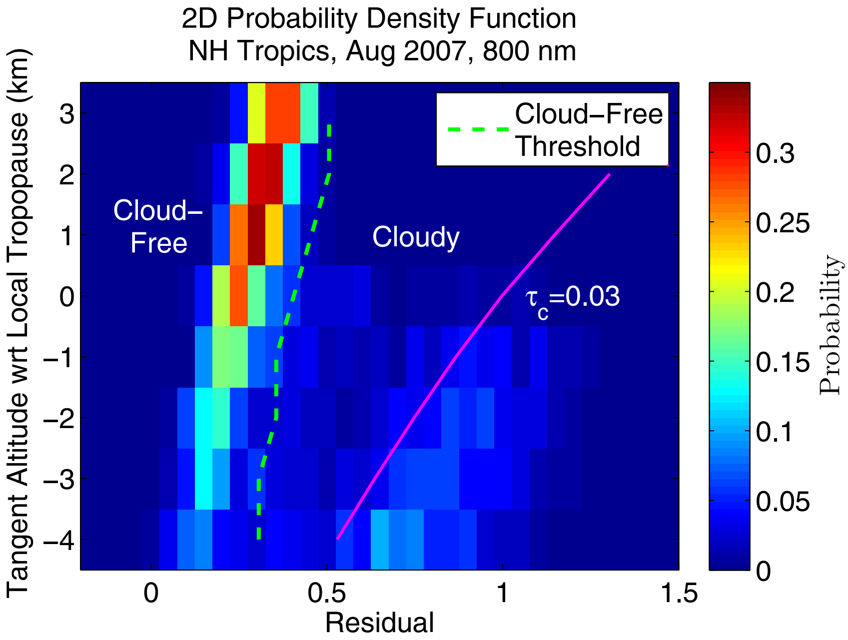

Figure 2: Two-dimensional residual probability density function with the cloud-free threshold curve (dashed green) and corresponding modelled subvisual cirrus curve for cirrus optical thickness $\tau_c = 0.03$ (solid magenta) for scans within the Northern Hemisphere tropical latitudinal band in August 2007 at 800 nm. The vertical axis is shown with respect to the local tropopause.

below the local tropopause, the higher the maximum. Why does this happen? Is this an indication of water cloud contamination of your PDF?

The cloudy distribution is monotonic with respect to height as should be expected. Indeed at lower tangent altitudes the technique is likely detecting optically thick water clouds. As altitude increases toward the tropopause, the frequency of occurrence of clouds generally typically falls off and gives this monotonic behavior.