Responses to Referee # 3

Anonymous Referee #3

Received and published: 13 July 2018

I can only echo the findings of the other two reviewers. This paper is well organized and well written and certainly of interest to the broad cloud/radiation/remote sensing communities.

I do have one additional point to make though. It concerns the constrained retrieval in ice clouds. I am familiar with a the following paper: "Reverdy, et al. (2015), An EarthCARE/ATLID simulator to evaluate cloud description in climate models, J. Geophys.Res. Atmos., 120, 11,090–11,113, doi:10.1002/2015JD023919". If one looks in the appendix of this paper, there are some observations and lidar Monte-Carlo calculations that suggest that for small particle semi-transparent cirrus that the Rayleigh return below cloud may suffer from (small but sometimes not-insignificant) multiple-scattering induced decaying tails.

Remembering the Reverdy paper made me realise that I was not able to find any discussion of how the below cloud return altitude range [is determined?] for the constrained retrieval procedure in this submission. Accordingly, I think the addition of a few lines somewhere describing this and the possible (but likely limited) effect of multiple-scattering tails would not be out of place in this paper.

We certainly agree that it is possible that there may occasionally be some conditions in which our parameterization of multiple scattering in cirrus clouds causes biases in constrained retrievals of optical depth. We have added material, shown in red, to Section 2.2.1 to describe how feature boundaries are refined and how clear air regions are identified.

Constrained retrievals use measurements of the effective two-way layer transmittance and its uncertainty that are determined by comparing signals from above and below the layer. The determination of the layer boundaries is detailed in Vaughan et al. (2005 and 2009). Briefly, the initial determination of cloud base is determined as that range at which the attenuated scattering ratio (the ratio of the normalized, range-corrected backscatter signal to a molecular backscatter model) drops below a range-dependent threshold that is determined largely by SNR and signal attenuation by the overlying atmosphere. This initial estimate of cloud base is further refined by continuing to search below this altitude for a region where the attenuated scattering ratio ceases to be a decreasing function of range. Depending on the SNR in the region below the cloud, this refinement sets cloud base below any readily detectable "leakage" of the signal into the assumed clear region caused by, for example, the transient recovery time of the detectors or by multiple scattering from small particles in dense clouds. Note that this multiple scattering leakage is not pulse stretching (Miller and Stephens, 1999), but instead occurs for instance because the forward scattering angle from the small ice crystals in cold cirrus can be wider than the CALIOP receiver field of view (Reverdy et al., 2015), so that the multiple scattering factor can be slightly larger below the ice clouds than in cloud (Winker et al, 2003). Once all features have been detected in a column, so called "clear air" regions above and below each feature are identified. To initiate a constrained retrieval, the V4 CALIOP extinction algorithm requires a minimum feature-free vertical extent of 2.48 km both above and below a candidate feature. The required effective layer two-way transmittance is then calculated as the ratio of the mean attenuated scattering ratios computed over these below-cloud and above-cloud clear air regions. The fidelity of these estimates relies on the supposition that the backscatter signals in the clear air regions are due solely to air molecules. If this condition is not met (and this is impossible to confirm with absolute certainty), then unless the mean particulate scattering ratios in the two clear air regions are identical, the transmittance measurements will be in error, no matter how small the reported uncertainty, and the constrained retrieval will also be in error. These are bias errors, not random errors, as discussed in Sect. 3b2 of Young et al. (2013), and by del Guasta (1998). Undetected particulate layers above the layer being analyzed can also affect the calculated lidar ratio. Extreme errors can cause the derived lidar ratios to approach and sometimes even exceed the physically acceptable limits of 0.05 sr to 250 sr imposed by the V4 retrieval scheme. Any constrained retrieval (bit 0 set to 1 in the extinction QC flag –

See Sect. 2.2.6) in which the derived lidar ratio is equal to either of these limits is to be treated as suspect. In these cases, the lidar ratio is set to the limit and an unconstrained retrieval is performed using this value. Such cases are indicated by the setting of bit 8 to 1 in the extinction QC flag (see Sect. 2.2.6 and Table 2), giving a total value of 257.

We have also added the following material after the current second paragraph of Section 3.6 (Caveats) and suggest that constrained retrievals of optical depth and lidar ratio be compared with adjacent unconstrained values if multiple scattering biases are suspected. Like Reverdy et al. (2015), we consider a detailed discussion of the intricacies of multiple scattering and its effects and treatment well beyond the scope of this paper.

There are some circumstances in which constrained retrievals may also be in error. As explained in Sect. 2.2.1, particulate scattering in regions used for normalization can lead to biased results. Also, as discussed by Reverdy et al. (2015), forward scattering from small ice crystals within a cloud can cause an enhancement in the backscatter signal measured below the cloud that decreases with range below cloud base. They further suggest that, for CALIOP signals, the rate of decay is so long that it is only really notable for cirrus that are composed of small particles (e.g., 10 µm – 20 µm) and have relatively high optical depths. When applying the CALIOP two-way transmittance estimation algorithm, the impact of such an enhancement would be to produce a constraint that is biased high, with the result that both the retrieved optical depth and lidar ratio would be biased low. However, these conditions occur relatively infrequently. For all V4 constrained retrievals of ice cloud profiles measured between 60° S and 60° N during the years 2011 – 2015, only 2.1 % have both centroid temperatures below –70 °C, where particles can be small (Heymsfield et al., 2014), and optical depths greater than 0.5.

If multiple scattering induced biases are suspected, the lidar ratios and optical depths where constrained retrievals are employed should be compared with the same parameters in adjacent columns that use unconstrained retrievals. In any case, constrained retrievals in which lidar ratios and optical depths have high relative uncertainties should also be regarded with caution. Finally, in order to assess the likely impact of these potential errors, we refer the reader to the comparison of CALIOP V4 and MODIS C6 optical depths presented in Section 3.3.2 and in Fig. 11. The generally very good agreement between the data sets gives a high degree of confidence that the approximations made in the CALIOP analyses have a relatively small impact on the quality of the CALIOP retrievals.

References

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