Interactive comment on "Liquid marine cloud geometric thickness retrieved from OCO-2's oxygen A-band spectrometer" by Mark Richardson et al.

Anonymous Referee #1

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This manuscript presents a method for the joint retrieval of cloud optical thickness, top pressure and geometric thickness from passive hyperspectral shortwave IR measurements combined with lidar observations. Overall the paper is well written and the presented methodology appears sound. The retrieval of the cloud geometric thickness from O2 A-band measurements is an important novel element of this method, even though it must be acknowledged that the validation of cloud geometric thickness looks much less robust than that of the other parameters. In particular, I find it difficult to understand what is the additional added value of the retrieved cloud geometric thickness compared to a reasonably chosen prior. Below are my complete comments.

Comments: Thank you for taking the time to review our paper. We completely agree that it is hard to test the robustness of our *H* retrievals, and suspect there are biases in it. We have worked on the phrasing to keep it clear that this research project requires further work and added two new figures, one showing indirect evidence of useful new information in our retrieved *H* and another showing comparison versus MODIS-implied *H*.

We agree with your overall point that our conclusions regarding *H* are tentative but think we show a serious advance, being the first hyperspectral A-band *H* retrieval attempted from space.

We are confident that we have addressed concerns that would prevent publication, but have been careful in our language so that readers can understand the limitations and future work required. A full redlined version of the manuscript is in the file submitted in response to RC1.

Changes: Please see individual responses below

MAIN COMMENTS

- The validation of the retrieved quantities is mostly focused on discussing biases and their most likely sources, but it would be also nice to see how well do the retrieved cloud optical thickness correlate with MODIS.

Comments:

Changes: We have added a new Figure 6 that shows retrieved τ veruss MODIS, ctP versus CALIPSO and *H* versus that implied from MODIS-retrieved LWP, using ECMWF profiles to derive c_w and assuming

- While correlative data are available for the validation of cloud optical thickness (MODIS) and cloud top pressure (CALIPSO), the only available verification for cloud geometric thickness is a comparison to the adiabatic prior. I know that independent measurements of cloud geometric thickness are difficult to obtain, but nevertheless don't you feel that just comparing the retrieval with the prior limits somehow our capability of assessing the added value of the retrieval? After all, if you carry out a retrieval it is because you would like to get better estimates than the prior. What I see from the paper is that your Delta P_c retrievals are sensitive to the choice of the prior. As you say at page 13, scaling the prior Delta P_c by 0.5 or 2 leads to posterior Delta P_c that are, in your own opinion, unrealistically small and unrealistically large respectively. Absent a dataset of independent measurements, though, it is difficult to corroborate this opinion. Would an experiment with synthetic data (running the retrieval on synthetic cloud scenes of which you know the geometric thickness) be of any help? And are there any instruments (e.g., ground-based lidars) available from which marine cloud base heights can be determined and combined with CALIPSO cloud top heights? Wouldn't that help you understand more precisely how your Delta P_c retrievals behave?

Comments: Richardson & Stephens (2018) shows a synthetic retrieval and error statistics, but the "true" clouds were vertically homogeneous too. Future work will test nonuniform vertical cloud profiles, a new wrapper for the RT code reduces difficulties related to cloudy profiles and r_{eff}, and should be working soon.

We couldn't find surface validation data but present indirect evidence for new & useful information. We binned H by both τ and estimated inversion strength from ECMWF then compute an adiabatic fraction relative to the H implied by MODIS-derived LWP. We see that our retrieved H is consistent with less-adiabatic conditions when EIS is weaker, although it's only at lower τ values where the retrieval greatly updates the prior as expected. Importantly, these changes are independent of and represent information independent of that from MODIS.

If our retrievals are good, we would expect this pattern of H in response to EIS. But observing this pattern obviously doesn't mean that our retrievals are good. So while we think this is promising evidence in favour of our retrieval approach being useful, we have tried to be clear in our phrasing that these results are tentative and are a first of a kind.

Changes:

- Text added to Section 2.1 to discuss validation data availability, including surface validation
- Text added to Section 5.2 and its title changed to "Cloud top pressure versus CALIPSO, geometric thickness versus MODIS and implied subadiabaticity"
- New Figure 7 added, showing changes in implied adiabaticity with EIS
- Modifications to Section 7 to summarise our evidence, new text: "Nevertheless, the small discrepancies relative to MODIS optical depth (Figure 4), the tendency to retrieve more subadiabatic clouds under weaker inversions, at least for optically thinner clouds (Figure 7), and the increased extinction coefficient in the marine stratocumulus regions (Figure 13) suggest that the OCO-2 spectra add useful information"

MINOR COMMENTS

- P4, L14. Try to avoid the repetition in "A term-by-term error analysis estimated H could be estimated..." (replace one of the two "estimated" with a synonym)

Comments:

Changes: Changed to "error analysis suggested that H could be estimated to…"

- P7, L7. "each I" -> "each I_i (i=1,...,75)"

Comments:

Changes: Change made.

- I think the description of the optimal estimation principles at page 7 is a bit too terse, and may not be help a non-expert reader to understand what this all is about. No context is provided for the invocation of Bayes' theorem. In my opinion, the following points should emerge from the description:

1. It is assumed that the state vector follows a Gaussian distribution with mean x_a and covariance matrix S_a
2. It is assumed that the measurement error is additive and follows a Gaussian distribution with zero mean and covariance matrix S_epsilon
3. The Bayes theorem is applied in order to express the posterior probability density of the state vector given the observations
4. The estimation procedure looks for the maximum of such probability density

Comments: You have persuaded us that these are important details. While we have tried to keep it short and sweet, we have added the requested details.

Changes: New introduction to Section 4.1:

"We begin with a prior cloud state vector whose components are Gaussian, represented by a mean state vector $\boldsymbol{x_a}$ and covariance matrix $\mathbf{S_a}$. Meanwhile the observational uncertainty is represented by a zero-mean Gaussian with covariance matrix $\mathbf{S_\epsilon}$. Optimal estimation produces a maximised posterior probability density of the posterior state given both the prior state and the observations, with appropriate weighting for their relative uncertainties. In our case the individual contributions to observational uncertainties are assumed to add in quadrature such that $\mathbf{S_\epsilon}$ is simply the sum of each term's covariance. The posterior is estimated by applying Bayes' theorem assuming a linear forward model encapsulated in the Jacobian matrix K whose elements are $\boldsymbol{K_{i,j} = \partial y_i / \partial x_j}$. "

- P7, L16. Please clarify that x_i is the iterate solution, and that K_i is the Jacobian matrix of the forward model evaluated at x_i

Comments: We missed how this was confusing, thanks for the careful reading.

Changes: Change time index to 'n' from 'i', leaving 'i' to refer to channel indices for observations/Jacobian.

- P7, L20. What convergence criterion did you adopt?

Comments: We did not use a convergence criterion for awkward computational reasons. The way in which the cloud retrieval code was "bolted on" to the OCO-2 L2FP code involves running a repopulating files and configurating everything every time the soundings to be done within a file changed. We found it easier to just run all of the soundings six times, so we did that and picked the lowest χ^2 step. Future versions with the new RT wrapper will follow a more standard approach.

Changes: Text added: "No explicit convergence criterion was adopted: all retrievals that did not trigger computational problems are reported and users are provided with both the state estimate and the χ^2 for the retrieval step used."

- P8, L31. Please specify what you mean by "correct for mu_0". I guess you divide I by mu_0, but it would be better to make this explicit.

Comments:

Changes: Changed to "..and divide by…"

- P9, L4. Could you explain the reason for applying a low cloud top pressure threshold? Is it because you assume ice clouds if p_top < 680 hPa?

Comments: Basically yes. There were a small number of these and we used this threshold to exclude potential egregious icy outliers in our liquid cloud retrieval.

Changes: Replace "whose P_{top} > 680 hPa. The CALIPSO P_{top} threshold limits our sample to the low cloud threshold of the International Satellite Cloud Climatology Project (Rossow and Schiffer, 1991) and helps to filter out non-liquid clouds."
→ "whose P_{top} > 680 hPa. The CALIPSO P_{top} threshold limits our sample to the low cloud threshold of the International Satellite Cloud Climatology Project (Rossow and Schiffer, 1991) and helps to filter out non-liquid clouds."

- P11, L1. I may have missed where I_wk and I_O2 are defined. If they weren't, please specify their meaning (I guess they represent radiances in the weak CO2 band and in the O2-A band respectively, but it should be made explicit).

Comments: This was an oversight

Changes: Section 4.3: "..(A-band 6×10^{19}, weak CO_2 band 1×10^{19} photons m^{-2} sr^{-1} μm^{-1})" → "(A-band $\mu_0 I_{O2}$ = 6×10^{19}, weak CO_2 band $\mu_0 I_{wk}$ 1×10^{19} photons m^{-2} s^{-1} sr^{-1} μm^{-1})"

Section 5.1: "the ratio of I_{wk}/I_{O2}" → "the ratio of the 10-channel continuum radiances in each band I_{wk}/I_{O2}"

- P11, L8-20. I had some difficulties trying to link the text with what is shown in Fig. 4. The subfigures (c) and (d) contain four plots each. In the legend, two plots are marked with "& flag" and two are not. Does the "& flag" mark mean I_wk/I_O2<0.28? It would be handy to have this information readily available in the figure caption (now you only mention a "radiance ratio warn flag"). Furthermore, at L13 you say that "for the full sample the median bias is 0.02 times the MODIS uncertainty and the 14-86% range is -1.15 to 0.99". Are you then referring to panel (b) of Figure 4? If so, there the 14-86% range reads -1.12 to 1.02. A similar question holds for the last sentence (L18-20). Are you referring to panel (d) of Fig. 4? If so, the numbers mentioned in the text seem slightly inconsistent with those reported in the figure. This is of course a minor issue, but it does not help readability.

Comments: You're right, these all needed fixing.

Changes:

(underlines are additions):

- Figure 4(c,d) legend labels changed to replace "flag" with Iwk/IO2 > 0.28 and add Iwk/IO2 < 0.28 when no flag.
- "For the full sample, the median bias…" → "For the full sample <u>in Figure 4(b)</u>, the median bias…"
- "For Quality_flag = 0, the median bias…" → "For Quality_flag = 0, <u>where SZA < 45° and Iwk/IO2 < 0.28, Figure 4(d) shows that</u> the median bias…"
- Discussion of Figure 4 numbers corrected.

- P15, L4. "we Section 5.3.3 linked" -> "in Section 5.3.3 we linked" ?

Comments:

Changes: Changed to: "we (Section 5.3.3) linked…"

- Wouldn't the material presented as supplement be more suitable as an appendix inside the manuscript?

Comments: We think that either work, but I (MR) prefer to keep this as SI. I don't see the benefit of switching to an appendix.

Changes: N/A