Authors' response to comments from reviewer 3

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We thank the reviewer for their thorough reading of our paper and for providing thoughtful comments. We have addressed each one below.

Reviewer's General Comments

1. This is a review on the manuscript entitled "Retrieving Vertical Profiles of Cloud Droplet Effective Radius using Multispectral Measurements from MODIS: Examples and Limitations" which deals with the retrieval of vertical cloud droplet effective radius profiles from multispectral measurements based on an adiabatic assumption. First, MODIS measurements are used and the retrieval results are compared to in-situ measurements from the VOCALS-REx campaign. A theoretical study then discusses the implications of the usage of more spectral measurements and measurements with a lower radiometric uncertainty.

2. In general, the paper is well written, mostly clear and good to understand. It also fits well into the scope of AMT and shows nicely how a reduced measurement uncertainty could improve the retrieval of cloud effective radii profiles from space. However, as already stated by the other two reviewers, I also think that the limitations of the retrieval method besides the measurement uncertainty should be discussed further before publication, in particular since this is also subject to the title. Hereby, I am missing the discussion on 3-D radiative transfer and partial cloud cover effects as well, which are known to impact spectral retrievals assuming 1-D plane parallel clouds.

    a. *Authors' response:* We agree that 3-D radiative effects and sub-pixel inhomogeneity should be discussed. See our responses to comments 1 and 2 from Reviewer 2 (Dr. Zhibo Zhang).

    b. *Proposed changes to the manuscript:* We will expand our Discussions and Conclusions section to include a review of previous work, such as Zhang and Platnick (2011) and Zhang et al. (2012), to highlight the drawbacks of using 1-D vertical cloud profiles and the implications of ignoring horizontal variation in cloud structure. We will discuss future work involving LES-generated cloud fields and 'step-function' cloud fields to more accurately simulate horizontal and vertical cloud inhomogeneity. We will outline the limitations of our method when applied to horizontally heterogeneous cloud fields. A thorough discussion of the biases introduced by sub-pixel inhomogeneity, along with expected impacts on our droplet profile retrieval and future work to mitigate these effects, will be included. This discussion is supported by previous results from Zhang et al. (2016).

3. In addition to that, I would ask the authors to discuss the implications of the constraints made for the optimal estimation method in more detail and further that the "validation" of the retrieval using in-situ measurements is only valid in an idealized world in which the cloud conditions match the ones supported by the retrieval. Particularly, constraining the effective radius at cloud top to be larger than the one at the bottom and both to values smaller than 25 μm limits the retrieval to clouds which do not contain any precipitation formation. Precipitation formation occurs throughout the cloud, and is hence specifically relevant for the here presented retrieval of the vertical cloud effective radius profile. Further, even the cloud top radius can be influenced by drizzle formation. For example, Pörtge et al. (2023) found cloud top effective radii larger than 25 μm for a stratocumulus cloud while simultaneous radar measurements showed precipitating droplets. In addition, the here presented method is also based on the assumption of a relatively narrow monomodal droplet size distribution as it is common in the field. However, the presence of drizzle will lead to the formation of a tail in the distribution (e.g. Zinner et al., 2010; Zhang et al., 2012), which might be an additional factor limiting the retrieval and should be discussed and pointed out more clearly in the conclusions. After consideration of those aspects, I would recommend the publication of the paper.

    a. *Authors' response:* We agree with the reviewer that the retrieval method we developed is only valid for non-precipitating clouds with droplet size increasing from cloud base to cloud top. These two constraints were made for different reasons. For the case of non-precipitating clouds, we are currently limited to retrieving droplet sizes up to 25 μm because this is the upper limit of the table of Mie calculations for liquid water droplets provided by libRadtran. To compute radiance for cloudy scenes, libRadtran utilizes a pre-computed table to convert cloud properties into optical properties. The next iteration of this work will use an expanded lookup table that ranges up to 50 microns.

       We assumed droplet size at cloud top was larger than at cloud base because both in-situ measurements and parcel theory show this to be true for non-precipitating stratocumulus clouds. At every iteration, the forward model computes the top-of-atmosphere reflectance for a cloudy scene with some vertical droplet profile. Since we retrieve only two values from this vertical profile, at cloud top and cloud base, we must make an assumption about how droplets change in size as a function of height. Future iterations of this work will investigate different assumptions, such as sub-adiabatic and linear growth (Platnick, 2000).

Remote measurements of polarized cloud reflectance are often used to retrieve the effective variance of the droplet distribution (Meyer et al., 2025; Pörtge et al., 2023). Since we investigated the retrieval of droplet profiles from measurements taken by MODIS, which measures unpolarized reflectance, we were unable to retrieve the effective variance. Thus, we assumed a standard value used in the community. We agree with the reviewer that this may introduce forward model error if the cloud under observation has a multimodal droplet distribution, such as the example in Pörtge et al. (2023). We will discuss the implications of this in our manuscript, however, multiple studies have shown that the presence of drizzle has only modest impacts on the retrieval of effective radius at various wavelengths (Painemal and Zuidema, 2011; Zhang et al., 2012; Zinner et al., 2010).

b. *Proposed changes to the manuscript:* We will update section 3 to include a discussion on the limited scenarios viable for retrieval with our constraints of non-precipitating adiabatic clouds with droplet sizes less than 25 μm. We will explain that these constraints stem from using the precomputed table of Mie calculations for liquid water droplets provided by libRadtran, which extends up to 25 microns. Therefore, we were limited to retrieving droplet profiles from non-precipitating clouds only. The next iteration of this work will use precomputed table of Mie calculations for liquid water droplets up to 50 μm. We note that while drizzle may be present in non-precipitating clouds, several studies have shown the impact on the retrieval of effective radius to be minor. We will also update the Discussion and Conclusions section of the paper to address our choice of an adiabatic droplet profile. Retrieving just two droplet sizes from seven MODIS spectral reflectance measurements is consistent with the results of Platnick (2000), who showed that using three MODIS spectral channels similar to the ones we used led to two unique pieces of information.

Reviewer's Specific Comments

1. L. 122f./Sec. 4.2: I was wondering why the authors did not simulate CPF spectra directly instead of the EMIT spectra? Since this part is a purely theoretical study, I think one could have used the CPF specifications directly to demonstrate how the smaller radiometric uncertainty and the usage of more spectral channels influences the solution space.

    a. *Authors' Response:* The EMIT spectral response functions are freely available, thus we can simulate TOA reflectance spectra without any guesswork. However, after your suggestion, we reached out to the instrument team that developed HySICS (the HyperSpectral Imager for Climate Science) for the CPF mission and asked if we could use the spectral response functions to simulate CPF sampled TOA reflectance.

    b. *Proposed changes to the manuscript:* We were given access to the HySICS spectral response functions and we will update the analysis in section 4.2 such that the TOA reflectance spectra used to generate the contour plots in Figures 7 and 8 will simulate the HySICS spectral channels. We will no longer use simulated EMIT measurements.

2. L. 106f.: In agreement to the first referee, I also think that it would be valuable to introduce the CPF instrument in more detail. In particular, if I have not overseen anything, I am missing the number of spectral channels and the horizontal resolution, please add if possible. And is there a spectral dependence of the measurement uncertainty? If so, the implications for the retrieval should also be addressed in the discussion.

    a. *Authors' Response:* We agree.

    b. *Proposed changes to the manuscript:* Spectral sampling and resolution, orbital geometry, spatial resolution, and swath width will be added to line 108. We will also include the CPF spatial sampling and swath width information in Section 4.1 to provide context to our discussion on comparing sampling volumes between in situ and remote measurements. Lastly, we updated Figure 6 to include an additional histogram with a length scale of $0.5km$, the spatial sampling of the CPF instrument at nadir. While the result is similar to the 1 km spatial sampling of MODIS when looking nadir, we found it useful to show that, as pixel size decreases, the average variability of effective radius with respect to the horizontal plane decreases. The measurement uncertainty of HySICS, the primary CPF instrument, was reported in Kopp et al. (2017), and showed that neighboring spectral channels strongly covary with one another. The Discussions and Conclusions section will review the implications of simplifying our model by assuming uncorrelated spectral noise.

3. L. 253: Are the partial derivative fractions presented only valid for the MODIS measurement uncertainty? And are they valid for all wavelengths? Please clarify in the manuscript.

    a. *Authors' Response:* The partial derivative fractions were derived using MODIS measurements. Through trial and error, we determined a set of fractions that would often exceed the MODIS measurement uncertainty of about 2%. We had to strike a balance between precisely estimating the Jacobian, defined as the rate of change of reflectance with respect to some infinitesimal change in one of the state variables, and the measurement uncertainty. For example, we found if Δr_{bot} was too small, then $\Delta R(\vec{x}, \lambda_i)$ was small and measurement uncertainty dominated. If Δr_{bot} was too large, we no longer accurately estimated the local slope. These fractions were used for all seven spectral channels because the MODIS measurement uncertainty at these channels is roughly constant. Adjustments should be made for use with other instruments. Lower radiometric uncertainty enables the detection of smaller changes in reflectance, which implies that the partial derivatives of the Jacobian can be estimated more precisely.

    b. *Proposed changes to the manuscript:* In section 2.3, we will expand on our description of how the Jacobian is estimated. The percentages listed were used for each spectral channel because the MODIS measurement uncertainty was nearly identical for the channels used. We will also make clear that these percentages must be adjusted when applying this retrieval method to measurements from instruments with different radiometric uncertainty than MODIS.

4. Table 1: In my opinion, it would be very valuable to add the resolution of each MODIS channel and the respective measurement uncertainty here.

    a. *Authors' Response:* We agree.

    b. *Proposed changes to the manuscript:* The table will be updated to include the spectral resolution and measurement uncertainty.

5. L. 323f.: Where do you see the shapes of the distributions from?

a. *Authors' Response:* We normalized the vertical dimension and discretized it into 30 bins for each in-situ profile. After doing this for all in-situ measurements without drizzle or precipitation, we found the median value for each bin, which is what we plotted in Fig. 2. Within each bin, we fit a distribution to the data. We found that for effective radius and liquid water content, a log-normal distribution best fit the measurements for most of the vertical bins, whereas a normal distribution was the best fit for number concentration for most of the bins. This explains why the shading in Fig. 2, which represents the average deviation from the median value, is symmetric for number concentration and asymmetric for the effective radius and liquid water content.

b. *Proposed changes to the manuscript:* In section 3, we will expand on our explanation of Figure 2 to describe how these distribution fits were made.

6. L. 336f.: Perhaps there might be something which I did not understand correctly, but why are you using the 2.13 µm weighting function for the cloud bottom here? To my understanding of Fig. 1, the effective radius derived from that one corresponds to the smallest optical thickness of all channels considered?

    a. *Authors' Response:* Thank you for bringing this up, indicating the need for a more detailed explanation in this section. The a priori value for the radius at cloud top was defined as the retrieved effective radius using MODIS measurements, and the a priori uncertainty as the associated retrieval uncertainty. The a priori value for the radius at cloud bottom is defined as 70% of the retrieved effective radius (the a priori value for cloud top radius). This percentage was derived from the median vertical profile of effective radius from the in situ measurements shown in Fig. 1, which shows that the median value of cloud bottom radius was 70% the value of the median cloud top effective radius. The bi-spectral retrieval of effective radius was computed using two MODIS channels centered at 645 nm and 2.13 μm, but is predominantly determined from the near-infrared wavelength. As the reviewer points out, most photons at 2.13 μm scatter near cloud top. Therefore, we need to express a higher uncertainty for the a priori value for the radius at cloud bottom. We used the 2.13 μm weighting function to determine that the portion of the total measured signal with a maximum penetration depth within the upper quartile of the cloud was six times that of the portion with a maximum penetration depth within the lower quartile. This is why we defined the a priori uncertainty for the radius at cloud bottom to be 6 times the value of cloud top.

    b. *Proposed changes to the manuscript:* In section 3, we will expand our discussion on the a priori values and their uncertainties by outlining how each value is defined, including a clearer description of the use of the bi-spectral retrieval of effective radius from the MODIS collection 6 cloud products to define the a priori at cloud top and bottom. We will also explain why the weighting function for 2.13 μm was used to determine the a priori uncertainty for the cloud bottom radius.

7. L. 375: Are the optical depths stated here derived from the retrieval? Please clarify, where those are derived from.

    a. *Authors' Response:* Those values were derived from the in-situ measurements.

    b. *Proposed changes to the manuscript:* The sentence has been rewritten with the source of the optical depth estimates made clear.

8. Fig. 3: In my opinion, it would be nice to have the corresponding MODIS pictures and an indication where the measurements took place in addition to the profiles. This would give the reader an overall impression of the cloud situation and scenery. Moreover, the measurement times would be interesting to know for the solar geometry for which the comparisons have been made. And how long did it take for the aircraft to sample the profiles, what was the flight distance/spatial coverage of the in-situ measurements?

    a. *Authors' Response:* This is a good suggestion that would provide further context for the results. Instead of including the RGB images of each MODIS scene, we will report the inhomogeneity index, along with the latitude and longitude of the measurements, within a new table that provides information on the MODIS and associated VOCALS-REx measurements used in our analysis.

    b. *Proposed changes to the manuscript:* We included a new table that outlines the time of each MODIS observation, the start and end times of the overlapping VOCALS-REx measurements, the time difference, the geographic location of the MODIS observations, and the sub-pixel inhomogeneity index.

Figure	MODIS Observation time (UTC)	MODIS Observation latitude and longitude	MODIS Sub-pixel inhomogeneity index H_σ	VOCALS-REx in-situ start time (UTC)	VOCALS-REx in-situ end time (UTC)	Time difference (min)
3a	Nov 11 2008 18:54:28	-24.0986, -75.0013	0.09	18:45:20	18:45:50	8.88
3b	Nov 11 2008 14:42:29	-22.8188, -73.0008	0.07	14:40:59	14:41:38	1.18
3c	Nov 9 2008 14:30:20	-22.8970, -73.0036	0.08	14:33:33	14:34:23	3.62

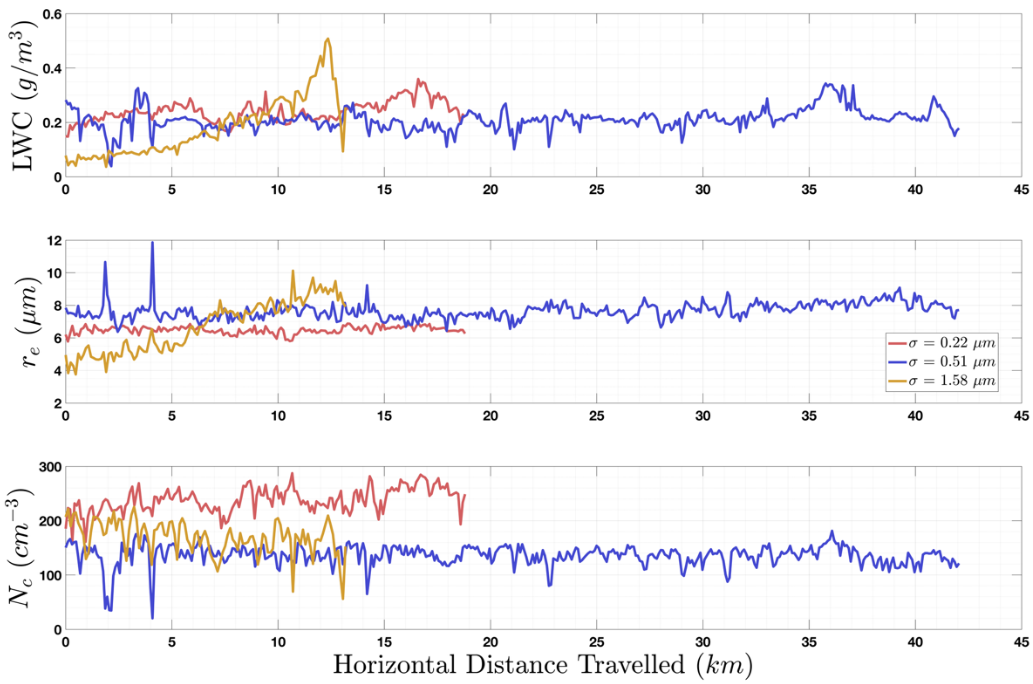
9. L. 400f.: One common issue of the bispectral retrieval is the overestimation of the effective radius due to 3-D cloud radiative effects and broken cloudiness. Could this be a reason for the effective radius profile showing larger values than the in-situ measurements? Here, it would also help to have a visualization of the cloud scenery.

    a. *Authors' Response:* We agree that 3-D radiative effects and sub-pixel inhomogeneity should be discussed. See our responses to comments 1 and 2 from Reviewer 2 (Dr. Zhibo Zhang). For the three cases used in our manuscript to retrieve droplet profiles (Figure 3), all had an inhomogeneity index of less than 0.1. According to Zhang and Platnick (2011), these values represent fairly homogeneous clouds and 3-D radiative effects are expected to be insignificant.

    b. *Proposed changes to the manuscript:* We will expand the Discussions and Conclusions section to review how 3-D radiative effects and broken cloudiness impact the retrieval of effective radius. We will expand section 4.1 to review the historical precedent of remote retrievals overestimating in situ measurements and discuss possible sources of this bias.

10. Fig. 5: Please make a comment on the two spikes which are very pronounced in the blue line. Where do they come from? I suspect that they also influence the derived standard deviation and calculated range quite a lot.

    a. *Authors' Response:* The reviewer is correct in pointing out that these two outliers affected the range and standard deviation of this horizontal profile. The in-situ measurements show decreases in the total droplet number concentration at the same moment the effective radius rapidly increases. Likely, these regions are associated with a shift in the droplet distribution towards larger droplets. Below is a figure showing the liquid water content, effective radius, and number concentration for the three horizontal legs shown in Figure 5 of our manuscript.



b. *Proposed changes to the manuscript:* We will replace Figure 5 with the version above that provides additional information on liquid water content and number concentration for three representative profiles. We also included an explanation for the sharp increase in effective radius shown in the blue curve above.

11. L. 484: What is the exact definition of "time difference" here? I guess the vertical profiles were sampled over some time as well, so when did MODIS pass over the scene and between which times were the profiles measured? Please clarify in the manuscript.

    a. *Authors' Response:* For each vertically sampled in situ measurement with a start and end time, we used the temporal halfway point to compute the time difference with the MODIS measurement. After reading the reviewer's comment, we revisited this calculation and learned that we could estimate the time difference more precisely by using the MODIS metadata to estimate the time each MODIS pixel within a swath recorded its measurement (thanks to Dr. Larry DiGiorlamo and Dr. Guangyu Zhao). We have updated the time differences using this more precise calculation in the table above (comment 9).

    b. *Proposed changes to the manuscript:* Section 4.1 will include a more thorough description of how the time difference between a MODIS measurement and the corresponding VOCALS-REx in-situ sampling is defined.

12. L. 39: “and has been used to verify …”

    a. *Authors’ Response:* Thanks for finding this mistake!

    b. *Proposed changes to the manuscript:* This has been fixed.

13. L. 270: “scalar”

    a. *Authors’ Response:* Thanks for finding this mistake!

    b. *Proposed changes to the manuscript:* This has been fixed.

14. L. 357: “shown”

    a. *Authors’ Response:* Thanks for finding this mistake!

    b. *Proposed changes to the manuscript:* This has been fixed.

References

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