Authors’ response to comments from reviewer 5

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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 manuscript presents a study on the retrieval of vertical profiles of the effective radius for non-precipitating warm clouds using multispectral solar reflectance measurements in the visible to shortwave infrared regions. Specifically, the study aims to retrieve three parameters: cloud optical thickness, the effective radius at the cloud top, and effective radius at the cloud base.

2. This study presents two key analyses. First, the three parameters are retrieved from the seven MODIS channels using a framework based on the optimal estimation method. The vertical profiles of the effective radius reconstructed from these parameters are then compared with in-situ measurements from the VOCALS-REx campaign. The second key analysis, based on simulations, examines how increasing the number of spectral channels and reducing the radiometric uncertainties can improve the retrieval accuracy of the three parameters. This analysis is particularly relevant to the upcoming CPF instrument, which will provide hyper-spectral imaging measurements.

3. This manuscript is generally well written and falls within the scope of AMT. While several previous studies have addressed similar issues, the results presented in this manuscript, particularly those in Figures 3, 7 and 8, provide valuable contributions to the scientific community, enhancing the understanding of this topic.

4. My major concern, as with other reviewers, is the retrieval bias introduced by subpixel-scale horizontal inhomogeneity and three-dimensional radiative transfer effects. These issues should be addressed in a dedicated section. The relevant previous studies have already been sufficiently cited in other reviewers’ comments. Even if the potential

retrieval bias caused by these factors is significant, discussing it should not diminish the value of this study.

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 manuscript to discuss how 3-D radiative effects impact the retrieval of effective radius. We will discuss how sub-pixel inhomogeneity leads to different 3-D radiative effects, such as illumination and shadowing. The works of Zinner et al. (2010), Zhang and Platnick (2011) and Zhang et al. (2012) are crucial to this discussion as they showed the impact of 3-D radiative effects and sub-pixel inhomogeneity on retrievals of droplet size and discussed the implications for discerning cloud vertical structure. Furthermore, these studies provided thresholds on the sub-pixel inhomogeneity index, H_σ that can be used to determine whether 3-D radiative effects need to be considered.

Minor Comments

1. Abstract: The abstract should explicitly state that this study focuses on "non-precipitating warm clouds".

   a. *Authors' Response:* We agree.

   b. *Proposed changes to the manuscript:* The suggested phrase was added to the abstract.

2. L15, "near-infrared": This study utilizes the MODIS 1.6 μm and 2.1 μm channels. While these channels are generally considered part of the near-infrared spectrum, they are often referred to as "shortwave infrared" in research involving MODIS cloud retrievals. Since "MODIS" is mentioned in the title, it would be helpful to clearly specify the wavelength range included in "near-infrared" to avoid potential confusion.

   a. *Authors' Response:* We will change the phrase "near-infrared" to "shortwave infrared" to follow the standard used in the literature.

b. *Proposed changes to the manuscript:* All uses of the phrase “near-infrared” were changed to “shortwave infrared.”

3. L150-152, Sect 2.1: Is aerosol scattering and absorption being ignored, or is it excluded from the retrieval variables but still accounted for in the radiative transfer calculations?

    a. *Authors' Response:* We do not retrieve any aerosol properties, but aerosols are accounted for in the forward model. We made the same assumption as the MODIS collection 6 cloud products forward model, which includes an aerosol optical depth of 0.1for cloudy scenes over ocean (Amarasinghe et al., 2017).

    b. *Proposed changes to the manuscript:* We will add a new paragraph at the end of section 3 describing the assumed aerosol type and optical depth, the Cox-Munk bidirectional reflectance model assumptions used to account for the impact of wind speed and direction on the ocean surface, the assumed effective variance of the droplet distribution, the surface albedo, and the US 1976 standard atmosphere that provides vertical profiles of temperature, molecular oxygen, carbon dioxide, and other trace gases.

4. "adiabatic assumption" for Eqs. (3) and (4), Sect 2.2: My understanding might be incorrect, but in the case of a well-known adiabatic cloud model (e.g., Bennartz, 2007; Merk et al., 2016), all supersaturated water vapor is assumed to condense, meaning the number of free parameters is limited to two. Allowing three degrees of freedom, as in Eqs. (3) and (4), would correspond to a sub-adiabatic model, which assumes that the condensation rate is less than 100%. What is important is not the name, but the cloud microphysical reason why three independent parameters are allowed.

    a. *Authors' Response:* Our model is consistent with the Bennartz adiabatic model. Leveraging observational results, Bennartz (2007) assumed the total droplet number concentration, N_c, was constant with height. Updrafts move droplets toward the cloud top. Along the way, they grow via water vapor deposition, while N_c remains fixed. Therefore, the total liquid water is distributed over the same number of droplets at any height within the cloud (Bennartz, 2007). Liquid water content is linear with respect to the geometric height: $LWC(z) = c_w z$ where c_w is the condensation rate and z is the geometric height within the cloud (Bennartz, 2007). Bennartz (2007) concludes that the volume-averaged cloud droplet radius depends on the total number concentration and the liquid water content rather than the exact shape of the droplet distribution: $r_v(z) = \left(\frac{3\, c_w z}{4\,\pi N_c \rho}\right)^{1/3}$. To show our model is consistent, we start with Eq. (3) from our manuscript and assume the liquid water content at cloud base is 0, therefore eliminating the y-intercept of the linear equation: $LWC(z) = LWC(H)\frac{z}{H}$, where H is the height at cloud top. Using this equation, the effective radius profile (Eq. (4)) is now: $r_e(z) = \left(\frac{3}{4\pi N_c \rho}\; LWC(H)\frac{z}{H}\right)^{1/3}$. The condensation rate, with units of $\frac{g}{m^4}$, depends on temperature and, to a lesser degree, pressure (Rausch et al., 2017). Marine stratus clouds tend to be shallow. Therefore, we can assume temperature is constant over the vertical extent of the cloud and, ignoring the pressure dependence, define the condensation rate as: $c_w = \frac{LWC(H)}{H}$ (Rausch et al., 2017). Making this substitution, our equation for the effective radius becomes: $r_e(z) = \left(\frac{3\, c_w z}{4\pi N_c \rho}\right)^{1/3}$, identical to the equation for the volume-averaged radius in the Bennartz model. The only difference between our two models is that we account for a non-zero liquid water content at cloud base. We do this because we found the in-situ measurements of effective radius vary rapidly while liquid water content (and total number concentration) values are small ($< 0.03\,\frac{g}{m^3}$). This is why we defined the cloud base as the altitude where the liquid water content exceeds $0.03\,\frac{g}{m^3}$ and the total number concentration exceeds 1 m^{-3}.

b. *Proposed changes to the manuscript:* We will mention that our adiabatic model is identical to the Bennartz model but with a non-zero liquid water content value at cloud base. We will also explain why a non-zero liquid water content value is required.

5. L294: Is "the distribution width parameter, α" a parameter of the gamma distribution?"

   a. *Authors' Response:* Yes. We can add 'gamma' to line 294 to avoid confusion. Additionally, the alpha parameter is related to the more commonly used effective variance by: $\alpha = \frac{1}{v_{eff}} - 3$ (Emde et al., 2016) We will include this definition in the paper and report the values used in the more familiar effective variance term.

   b. *Proposed changes to the manuscript:* We will update this sentence to: "For all simulations shown, the gamma distribution width parameter, α, was set to 10 based on analysis of in situ measurements of non-precipitating marine stratocumulus clouds from the VOCALS-REx flight campaign."

6. L296, "Cloud geometric thickness was set to 0.5 km": The setting is acceptable in radiative calculations. However, in the (sub)adiabatic cloud models, the cloud geometric thickness H should be determined uniquely from the set of τ_c, r_{top}, and r_{bot}.

    a. *Authors' Response:* Using the retrievals of τ_c, r_{top}, and r_{bot}, we estimate liquid water path by assuming the total number concentration, N_c, is constant with height. Furthermore, at any height within the cloud, there is a monodispersed distribution represented by $r_e(z)$. Since the effective radius depends on the altitude within cloud, the liquid water path is $LWP = \frac{4}{3}\pi\rho N_c \int r_e^3(z)\, dz$. Assuming $\frac{2\pi r_e}{\lambda} \gg 1$: $\tau_c^\lambda = 2\pi N_c \int r_e^2(z)\, dz$. To estimate liquid water path, we solve for the total number concentration using the equation for optical depth and plug this into the equation for liquid water path: $LWP = \frac{2}{3}\rho\tau_c \frac{\int r_e^3(z)\, dz}{\int r_e^2(z)\, dz}$. Bennartz (2007) assumed an adiabatic cloud with an effective radius and liquid water content of 0 at cloud base to drive an equation for the cloud thickness: $H = \left(\frac{2\, LWP}{c_w C_F}\right)^{1/2}$ where c_w is the condensation rate and C_F is the cloud fraction. We could use our estimate of LWP to estimate the geometric thickness by assuming some cloud temperature to estimate c_w, however, our forward model used to retrieve τ_c, r_{top}, and r_{bot} assumed a cloud geometric thickness of 0.5 km. We expect an estimate of the cloud thickness to be close to our forward model assumption. Furthermore, the geometric thickness is not a radiatively relevant quantity. We found little change to the simulated TOA reflectance when using cloud geometric thicknesses of 0.5 and 1 km.

    b. *Proposed changes to the manuscript:* None.

7. L331, "the first seven spectral channels of MODIS": Are the response functions of these channels taken into account in the forward calculation?

    a. *Authors' Response:* Yes. We will include a sentence clarifying the source of the MODIS spectral response functions used to simulate top-of-atmosphere reflectance.

b. *Proposed changes to the manuscript:* We will add a sentence to section 3 that describes the source of the MODIS spectral response functions used to simulate top-of-atmosphere reflectance.

8. L332, "because they deliberately avoid water vapor absorption, simplifying the forward model": Are water vapor absorption and Rayleigh scattering taken into account in the forward calculation?

    a. *Authors' Response:* Yes, both water vapor absorption and molecular scattering are included within the forward model. The purpose of line 332 was to emphasize that the spectral channels used in our multispectral retrieval were chosen in part because, at those wavelengths, the bulk absorption coefficients for water vapor are negligible.

    b. *Proposed changes to the manuscript:* We will more detail on our forward model assumptions (see response to comment 3).

9. L376: Is it correct that 0.55 μm is being used?

    a. *Authors' Response:* No! Thank you for catching this mistake.

    b. *Proposed changes to the manuscript:* Line 376 has been updated to reflect the correct MODIS visible channel used in the bi-spectral estimate of r_e and τ_c, which was 0.65 μm.

10. Figure 3: To verify horizontal inhomogeneity, it would be preferable to include the corresponding RGB images for these MODIS retrievals. At the very least, the latitude and longitude of the MODIS retrievals should be provided, allowing readers to check the images themselves.

    a. *Authors' Response:* We agree that a discussion on horizontal inhomogeneity is needed. 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. Zhang and Platnick (2011) showed that retrievals of effective radius are biased from 3-D radiative effects such as illumination and shadowing when the cloud under observation has an inhomogeneity index greater than 0.3. This results in a significant difference between retrieved effective radii using 2.1μm and 3.7μm shortwave infrared measurements. 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 include 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

11. Figure 3: I recommend also showing the other effective radius ($r_{e,1.6}$) retrieved using 1.6 μm instead of 2.1 μm ($r_{e,2.1}$), which is included in MOD06, in Figure 3. $r_{e,1.6}$ may be able to sense the cloud particle size in a deeper depth than $r_{e,2.1}$.

a. *Authors' Response:* We agree that for warm, non-precipitating, adiabatic marine stratus clouds, $r_{e,1.6}$ should be smaller than $r_{e,2.1}$ because photons at 1.6 μm have deeper average penetration depths due to a larger single scattering albedo than photons at 2.1 μm (Platnick, 2000). However, we showed $r_{e,2.1}$ along with our multi-spectral retrieval because this value was used for the a priori value of r_{top}, and for estimating the a priori value of r_{bot}.

b. *Proposed changes to the manuscript:* None.

12. L401-405: To investigate why the case in Figure 3b performs worse than the other two, have you considered conducting a remote sensing simulation using the VOCALS-REx in-situ measurements? That is, simulating MODIS reflectance measurements using the droplet size distribution obtained from the VOCALS-REx as input, and then retrieving τ_c, r_{top}, and r_{bot} using your algorithm.

a. *Authors' Response:* We thank the reviewer for this suggestion. We will investigate our solution to the case shown in Figure 3b by using the VOCALS-REx in-situ measurements to simulate MODIS TOA reflectances. However, as Figure 7 shows, the number of possible state vectors that lead to convergence is large when using the first seven MODIS spectral channels. With a large solution space (the area within the isopleth of one), the a priori guess strongly influences the final state vector because the iterative Gauss-Newton technique pushes each state vector along the direction of greatest change. The solution shown in Figure 3.b may suffer from a more inaccurate prior than the other two cases.

b. *Proposed changes to the manuscript:* We will update our manuscript with the findings from this suggestion.

13. Section 4.2: Why are the EMIT specifications and wavelengths used in the simulation instead of CPF?

    a. *Authors' Response:* The EMIT spectral response functions are freely available. Thus, we can simulate TOA reflectance spectra without any guesswork. We used EMIT measurements as a surrogate for CPF measurements because they have a similar spectral range and resolution. However, multiple reviewers asked a similar question, so we reached out to the instrument team that developed HySICS (the HyperSpectral Imager for Climate Science), the spectral instrument on board CPF, and asked if we could obtain the spectral response functions so that we could simulate CPF-sampled TOA reflectance.

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

14. Figure 7: Has it been discussed why this contour pattern appears, particularly why the uncertainties of τ_c and $r_{top} - r_{bot}$ exhibit a negatively correlated pattern?

    a. *Authors' Response:* For this project, we did not investigate the reasons for the particular contour pattern found in Figure 7. In addition, we would argue that the retrieval uncertainty does not exhibit a negative correlation. Our iterative method terminates when the relative ℓ^2-norm difference between the forward modeled reflectances and the MODIS observations is less than one, the inner-most contour in Figure 7. The retrieval uncertainty of optical depth is the width of this contour along the x-axis, and the uncertainty in $r_{top}^{*} - r_{bot}$ is the width along the y-axis. A negative correlation would imply that retrieval uncertainty of τ_c decreases as the uncertainty of $r_{top}^{*} - r_{bot}$ grows, which does not appear to be true. Figure 7 suggests that many values for the radius at cloud bottom will lead to convergence. In addition, we can conclude that the vector normal to the contours of Figure 7, the direction of greatest change, consistently had a larger component along the τ_c axis than the $r_{top}^{*} - r_{bot}$.

b. *Proposed changes to the manuscript:* None.

15. L509: Please list the wavelengths of the 35 spectral channels used. It would be even better if they were presented along with the transmittance of atmospheric gases.

    a. *Authors' Response:* We agree that this would be helpful for readers.

    b. *Proposed changes to the manuscript:* We will include a plot of atmospheric transmittance over the spectral range of the CPF instrument and overlay the 35 spectral channels used in section 4.2 of our analysis.

16. L529-531, Sect. 4.2: Is assuming a radiometric uncertainty of 0.3% still reasonable, even when considering potential uncertainty in forward calculation, including uncertainties in given parameters such as gas absorption, surface albedo, and aerosols? Additionally, is this 0.3% uncertainty fairly defined in comparison to the 2% uncertainty of MODIS L1B?

    a. *Authors' Response:* We acknowledge the lack of discussion on different sources of retrieval uncertainty and agree that they should be discussed. See our response to comment 11 from reviewer 1.

    b. *Proposed changes to the manuscript:* We will update section 3 to include a description on sources of forward model uncertainty, following previous work by Poulsen et al. (2012). In section 4.2, we will adjust the uncertainty added to the simulated TOA reflectance spectra to include both measurement and forward model uncertainty. Instead of explicitly estimating the uncertainty of each source within the forward model, we leverage previous work by Watts et al. (1998) and Platnick et al. (2017) to describe the fraction of the total uncertainty due to forward model uncertainty. We also make it clear that forward model uncertainty can never be reduced entirely. Additionally, we will expand section 4.2 with a comparison of our multi-spectral retrieval uncertainty estimate using simulated CPF TOA reflectances with the MODIS collection 6 cloud products retrieval uncertainty.

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