Authors’ response to comments from Dr. Zhibo Zhang

Andrew J. Buggee & Peter Pilewskie

May 2025

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. The other reviewer has provided an excellent summary of this study. Overall, I find this to be a meaningful contribution that explores the potential of CLARREO Pathfinder (PF) observations for advanced cloud remote sensing. However, in addition to the concerns raised by other reviewers, this study has a critical issue that must be addressed before publication: the failure to consider compounding factors—particularly sub-pixel inhomogeneity and three-dimensional (3D) radiative effects—that can significantly impact the retrieval of cloud effective radius (Re) profiles.

2. As outlined below, the influence of 3D radiative transfer effects and sub-pixel inhomogeneity on bi-spectral retrievals, and their implications for effective radius retrievals at different spectral bands (e.g., Re 2.1 µm vs. Re 3.7 µm), have been extensively studied and documented in the literature. Given these well-established issues, I do not believe the paper should be published unless they are thoroughly addressed.

Reviewer’s Major Concerns: Compounding Factors Affecting Retrievals

The fundamental principle underlying the retrieval algorithm in this study is that different spectral bands are sensitive to different vertical portions of a cloud layer due to their distinct vertical weighting functions, which arise from spectral-dependent absorption. However, spectral differences in retrieved Re values can also be attributed to other factors, such as sub-pixel cloud inhomogeneity and 3D radiative effects, which have not been adequately considered in this paper.

For example, **Zhang and Platnick (2011)** systematically examined the discrepancies in Re retrievals across different spectral bands. A key finding was that Re values retrieved using the 2.1 μm band tend to be significantly larger than those retrieved using the 3.7 μm band. This contradicts expectations based on vertical weighting arguments alone, as the 3.7 μm band, being more absorptive, should produce a larger Re value than the 2.1 μm band. However, actual MODIS retrievals show the opposite pattern. While CLARREO PF does not include the 3.7 μm band, the same biases due to sub-pixel inhomogeneity and 3D effects can still affect retrievals using the 2.1 μm and other bands.

Further, **Zhang et al. (2012, 2016)** demonstrated the impact of sub-pixel inhomogeneity on spectral Re differences (Re 3.7 μm vs. Re 2.1 μm). As shown in **Figure 1 of Zhang et al. (2012)**, the retrieval look-up table (LUT) for Re 3.7 μm is more orthogonal and, therefore, less susceptible to sub-pixel inhomogeneity compared to the Re 2.1 μm retrieval. These findings highlight the need for this study to account for similar effects when evaluating CLARREO PF retrievals.

Reviewer's Recommendations

To strengthen the study, I recommend the following:

1. **Use more realistic cloud fields in radiative transfer simulations.**
    - The study currently focuses only on single vertical profiles of Re without considering horizontal cloud variations within and beyond a given pixel. This approach oversimplifies real-world cloud structures.
    - Ideally, large eddy simulation (LES)-generated cloud fields should be used as input for radiative transfer simulations.
    - At a minimum, simple "toy models," such as step clouds or randomly varying cloud fields, should be employed for sensitivity studies. For example, using a step-cloud case and applying a moving average with a 0.5 km resolution pixel would help emulate CLARREO PF observations and test whether the Re profile retrieval algorithm remains robust under spatially averaged radiances.

        a. *Authors' Response:* We agree with the reviewer that our forward model simplifies real cloud structures, which often exhibit horizontal variation within a single pixel. For our study, we performed single-pixel analysis on real MODIS measurements, which precludes any knowledge of sub-pixel information other than the reflectivity at 855 nm, which is used to compute the sub-pixel inhomogeneity. In the future, we will investigate using more sophisticated, high spatial-resolution cloud models to study the impacts of sub-pixel inhomogeneity and 3-D radiative biases on our retrieval.

Regarding the use of "more realistic cloud fields", we believe our best approach is to cite the reviewer's papers on developing a MODIS retrieval simulator on LES cloud fields to demonstrate the potential for 3-D biases. Applying a similar approach for this study would not produce cloud fields any more *real* than the assumed simple cloud structure since the 3-D in situ data needed to initialize the LES was unavailable. We will discuss the benefits of using an LES model to simulate cloud fields and the results from the reviewer's papers in the Discussion and Conclusion section of our manuscript.

A 'step-function' cloud field is a simple method for testing the impacts of horizontal variability on our droplet profile retrieval. Zhang and Platnick (2011) used this method to test how spatial variations in cloud optical thickness cause 3-D radiative biases and impact effective radius retrievals using different MODIS spectral channels. We will cite this work in our discussion of biases introduced by sub-pixel horizontal inhomogeneity in our Discussions and Conclusions section.

Section 4.1 of our manuscript describes the horizontal variation of effective radius computed from in situ measurements along horizontal legs during the VOCALS-REx field campaign (Wood et al., 2011). At nadir viewing, the MODIS cross-track pixel length is about 1 km, whereas at the maximum scan angle of 55°, it is about 5 km. For these two cross-track pixel length extremes, we found the median horizontal variability of droplet size to be 0.47 μm and 0.57 μm, respectively. These statistics are mentioned because we wish to highlight the relatively small horizontal variations observed in the marine stratocumulus cases used in our analysis.

All pixels used in the development of our algorithm, including the three cases shown in our manuscript, 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.

We should note that Zhang et al. (2012) found horizontal variations in cloud optical thickness were primarily responsible for large differences in retrieved effective radii using different shortwave infrared wavelengths. Due to the flight path characteristics, we are not able to estimate the horizontal variation of optical depth from the VOCALS-REx data at a higher spatial resolution than MODIS.

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.

2. **Include a dedicated section discussing compounding factors that introduce retrieval errors.**
   - A thorough discussion should be added to explicitly address the effects of sub-pixel inhomogeneity and 3D radiative transfer.
   - The paper should explain how these issues could affect retrieval accuracy and describe potential strategies to mitigate them in the proposed retrieval algorithm.

Authors' Response: The authors acknowledge the lack of discussion about 3-D cloud radiative effects and sub-pixel inhomogeneity in our submitted draft. We limited ourselves to cases where these effects would be small, but that does not negate them entirely. We agree that sub-pixel horizontal inhomogeneities likely impact our retrieval and should be discussed. Zhang and Platnick (2011) showed that both cloud vertical structure and 3-D radiative effects can cause differences in effective radii retrieved using shortwave infrared measurements at 2.1 μm and 3.7 μm. They concluded that it may be possible to determine the cloud droplet profile using different shortwave infrared measurements with an inhomogeneity index of less than 0.1 (Zhang and Platnick, 2011). In a follow-up study, Zhang et al. (2012) used Large Eddy Simulations of cloud fields to show that retrievals of droplet size from pixels with high sub-pixel inhomogeneity were affected by small-scale variations in cloud optical thickness (Zhang et al., 2012). The authors concluded that 3-D radiative effects like illumination and shadowing tend to cancel one another out at MODIS-like spatial scales (Zhang et al., 2012). An additional study by Zinner et al. (2010) also used LES-generated cloud fields to investigate the impact of 3-D radiative effects on retrievals of effective radius and found them to be pronounced only for scattered cumulus scenes. In our analysis, we used MODIS observations of marine stratocumulus with a sub-pixel inhomogeneity index of less than 0.1 to limit the 3-D biases on the retrieval of effective radius.

We agree with the reviewer that a discussion of 3-D biases and sub-pixel inhomogeneity is required if our retrieval is to have broader appeal. Zhang et al. (2012) showed that as sub-pixel inhomogeneity increases, so does the retrieval of effective radius using measurements at 2.1 μm. We expect our droplet profile retrieval is susceptible to the same bias when using the first seven MODIS spectral channels or measurements from CPF. Zhang et al. (2016) outlined a mathematical framework that can be used to estimate the retrieval uncertainty of effective radius and optical depth when sub-pixel reflectance variations are large. However, mitigation of 3-D effects on traditional 1-D retrievals is an ongoing field of research. Several have shown that machine-learning techniques trained on LES data are capable of overcoming 3-D biases (Nataraja et al., 2022; Okamura et al., 2017). We will include these results in our discussion.

a. *Proposed changes to the manuscript:* We will expand the Discussion and Conclusion section of our manuscript to 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. **Expand the discussion on key factors influencing even 1D retrievals.**
    - The current study does not sufficiently account for several important factors that impact retrieval accuracy, including:
        - **Sun-viewing geometry**, which affects radiative transfer and retrieval sensitivity.
        - **Errors in ancillary data**, which are necessary for atmospheric corrections.
        - **Surface reflectance effects**, particularly over land and sun-glint regions, which can introduce additional uncertainties.
    - These factors should be explicitly discussed, along with their potential impact on retrieval performance.

    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.

    Platnick (2000) demonstrated the retrieval of effective radius for vertically inhomogeneous clouds depends on the solar-viewing geometry by showing that weighting functions increasingly sample the upper region of the cloud as viewing angle increases. Accordingly, we expect our droplet profile retrieval to estimate larger values at cloud top and bottom as viewing angle increases, if the cloud under observation has a non-homogeneous vertical droplet profile. Furthermore, Grosvenor and Wood (2014) investigated how solar zenith angle affects the MODIS-derived retrieval of effective radius. The authors found that the three effective radius retrievals using the 1.6, 2.1 and 3.7 μm MODIS spectral channels closely agreed with one another for small solar zenith angles (Grosvenor and Wood, 2014). We will include these papers in our discussion of how solar and viewing geometry affects the retrieval of effective radius.

Errors in ancillary data, such as vertical profiles of temperature, water vapor and aerosols, the assumed effective variance of the modeled gamma distribution, and the Cox-Munk ocean surface reflectance model, all contribute to the retrieval uncertainty of our droplet profile. Platnick et al. (2017) estimated the uncertainty of these components in order to estimate the uncertainty of MODIS-derived cloud retrievals. The authors estimated a 20% uncertainty for the amount of precipitable water above cloud, the transmittance through ozone-absorbing regions, and the surface wind speed, which greatly affects ocean surface reflectance (Platnick et al., 2017). Lastly, they estimated the uncertainty due to their assumption on the effective variance of the size distribution, which they claim is equal to the standard deviation of the same distribution. These assumptions are valid for our retrieval as well, and we will discuss each one in our manuscript.

b. *Proposed changes to the manuscript:* We will expand section 3 to include a discussion on sources of forward model uncertainty, such as assumed spectral channel independence, assumed retrieved variable independence, errors in vertical profiles of temperature, water vapor and aerosols, surface reflectance uncertainty, horizontal and vertical cloud structure, and the assumed droplet size distribution. In section 4.2, we will adjust the uncertainty added to the simulated TOA reflectance spectra to include measurement uncertainty and an estimate for the forward model uncertainty. We will leverage previous work by Watts et al. (1998), Poulsen et al. (2012), and Platnick et al. (2017) to estimate the fraction of the total uncertainty due to forward model uncertainty. We will include new analysis in section 4 that shows the impact of solar-viewing geometry on droplet profile retrievals using simulated CPF measurements.

Reviewer's conclusive comment

While this study explores an important topic, its current approach oversimplifies real-world cloud conditions and neglects key retrieval challenges. Addressing sub-pixel inhomogeneity and 3D radiative transfer effects is crucial for ensuring the validity of the retrieval algorithm. Without such considerations, the conclusions drawn from the study may be misleading. I strongly recommend that these issues be thoroughly addressed before the paper is considered for publication.

References

Grosvenor, D. P. and Wood, R.: The effect of solar zenith angle on MODIS cloud optical and microphysical retrievals within marine liquid water clouds, Atmospheric Chem. Phys., 14, 7291–7321, https://doi.org/10.5194/acp-14-7291-2014, 2014.

Li, X.-Y., Wang, H., Chen, J., Endo, S., George, G., Cairns, B., Chellappan, S., Zeng, X., Kirschler, S., Voigt, C., Sorooshian, A., Crosbie, E., Chen, G., Ferrare, R. A., Gustafson, W. I., Hair, J. W., Kleb, M. M., Liu, H., Moore, R., Painemal, D., Robinson, C., Scarino, A. J., Shook, M., Shingler, T. J., Thornhill, K. L., Tornow, F., Xiao, H., Ziemba, L. D., and Zuidema, P.: Large-Eddy Simulations of Marine Boundary Layer Clouds Associated with Cold-Air Outbreaks during the ACTIVATE Campaign. Part I: Case Setup and Sensitivities to Large-Scale Forcings, https://doi.org/10.1175/JAS-D-21-0123.1, 2021.

Nataraja, V., Schmidt, S., Chen, H., Yamaguchi, T., Kazil, J., Feingold, G., Wolf, K., and Iwabuchi, H.: Segmentation-based multi-pixel cloud optical thickness retrieval using a convolutional neural network, Atmospheric Meas. Tech., 15, 5181–5205, https://doi.org/10.5194/amt-15-5181-2022, 2022.

Okamura, R., Iwabuchi, H., and Schmidt, K. S.: Feasibility study of multi-pixel retrieval of optical thickness and droplet effective radius of inhomogeneous clouds using deep learning, Atmospheric Meas. Tech., 10, 4747–4759, https://doi.org/10.5194/amt-10-4747-2017, 2017.

Platnick, S.: Vertical photon transport in cloud remote sensing problems, J. Geophys. Res. Atmospheres, 105, 22919–22935, https://doi.org/10.1029/2000JD900333, 2000.

Platnick, S., Meyer, K. G., King, M. D., Wind, G., Amarasinghe, N., Marchant, B., Arnold, G. T., Zhang, Z., Hubanks, P. A., Holz, R. E., Yang, P., Ridgway, W. L., and Riedi, J.: The MODIS Cloud Optical and Microphysical Products: Collection 6 Updates and Examples from Terra and Aqua, IEEE Trans. Geosci. Remote Sens., 55, 502–525, https://doi.org/10.1109/TGRS.2016.2610522, 2017.

Poulsen, C. A., Siddans, R., Thomas, G. E., Sayer, A. M., Grainger, R. G., Campmany, E., Dean, S. M., Arnold, C., and Watts, P. D.: Cloud retrievals from satellite data using optimal estimation: evaluation and application to ATSR, Atmospheric Meas. Tech., 5, 1889–1910, https://doi.org/10.5194/amt-5-1889-2012, 2012.

Watts, P. D., Mutlow, C. T., Baran, A. J., and Zavody, A. M.: Study on Cloud Properties derived from Meteosat Second Generation Observations, Rutherford Appleton Lab, 1998.

Wood, R., Mechoso, C. R., Bretherton, C. S., Weller, R. A., Huebert, B., Straneo, F., Albrecht, B. A., Coe, H., Allen, G., Vaughan, G., Daum, P., Fairall, C., Chand, D., Gallardo Klenner, L., Garreaud, R., Grados, C., Covert, D. S., Bates, T. S., Krejci, R., Russell, L. M., De Szoeke, S., Brewer, A., Yuter, S. E., Springston, S. R., Chaigneau, A., Toniazzo, T., Minnis, P., Palikonda, R., Abel, S. J., Brown, W. O. J., Williams, S., Fochesatto, J., Brioude, J., and Bower, K. N.: The VAMOS ocean-cloud-atmosphere-land study regional experiment (VOCALS-REx): Goals, platforms, and field operations, Atmospheric Chem. Phys., 11, 627–654, https://doi.org/10.5194/acp-11-627-2011, 2011.

Zhang, Z. and Platnick, S.: An assessment of differences between cloud effective particle radius retrievals for marine water clouds from three MODIS spectral bands, J. Geophys. Res., 116, D20215, https://doi.org/10.1029/2011JD016216, 2011.

Zhang, Z., Ackerman, A. S., Feingold, G., Platnick, S., Pincus, R., and Xue, H.: Effects of cloud horizontal inhomogeneity and drizzle on remote sensing of cloud droplet effective radius: Case studies based on large-eddy simulations, J. Geophys. Res. Atmospheres, 117, 1–18, https://doi.org/10.1029/2012JD017655, 2012.

Zhang, Z., Werner, F., Cho, H.-M., Wind, G., Platnick, S., Ackerman, A. S., Di Girolamo, L., Marshak, A., and Meyer, K.: A framework based on 2-D Taylor expansion for quantifying the impacts of subpixel reflectance variance and covariance on cloud optical thickness and effective radius retrievals based on the bispectral method, J. Geophys. Res. Atmospheres, 121, 7007–7025, https://doi.org/10.1002/2016JD024837, 2016.

Zinner, T., Wind, G., Platnick, S., and Ackerman, A. S.: Testing remote sensing on artificial observations: impact of drizzle and 3-D cloud structure on effective radius retrievals, Atmospheric Chem. Phys., 10, 9535–9549, https://doi.org/10.5194/acp-10-9535-2010, 2010.