# Review of "Characterization of liquid cloud profiles using global collocated active radar and passive polarimetric cloud measurements" by Wang et al.

## Overall Comment:

This study presents a significant methodological advancement in remote sensing of liquid cloud vertical profiles by integrating active (CloudSat radar) and passive (POLDER polarimetric imager) measurements . The work is rigorous and innovative, leveraging global-scale data (12.47M profiles) to classify cloud profile shapes, establish statistical correlations, and develop retrieval models. The paper does several things exceptionally well: 1. Global-scale profile classification is statistically robust, providing a comprehensive understanding of dominant cloud structures (triangle-shaped and monotonically decreasing profiles). 2. Shape simplification using the VM algorithm is clever, effectively reducing noise while preserving key structural features. 3. Correlation analyses (e.g., between TP_CER and CB_CER, LWP) provide valuable physical insights into cloud microphysics. 4. The hybrid ML/physical modeling approach (CPRM reconstruction) is methodologically sound, combining the strengths of data-driven and physics-based methods.

However, passive retrieval limitations and dependence on CloudSat for prior knowledge (especially CB_CER estimation) remain fundamental constraints. Current methods cannot fully resolve vertical uncertainties due to: 1. CloudSat’s 240-m vertical resolution , which restricts layer precision (>2.64 km); 2. POLDER’s coarse spatial resolution (50 km for CER) , which may misrepresent fine-scale cloud variations.

Despite these limitations, this work represents a significant step toward parameterizing cloud processes in climate models , particularly for stratiform/stratocumulus clouds.

Major Comments :

1. The study's heavy reliance on CloudSat-derived empirical relationships for estimating CB_CER represents a critical constraint that significantly impacts the broader applicability of the methodology. While the multivariate regression approach using CT_CER, LWP, and CTH demonstrates reasonable correlation (0.75-0.92), this dependence on active sensor data fundamentally undermines the potential for truly independent passive retrievals. The propagation of errors through this empirical relationship is particularly concerning, with RMSE values reaching up to 1.96 μm for land-based clouds. This limitation is especially problematic because CB_CER serves as a foundational parameter for estimating TP_CER, meaning any errors in the initial cloud-base estimation will cascade through the entire retrieval process. The authors should more thoroughly discuss potential mitigation strategies, such as incorporating ancillary data sources or developing physics-based approaches to reduce this critical dependency on CloudSat for prior knowledge.

2. The observed inconsistencies in POLDER-based TP_CER and TP_NCOT retrievals, particularly evident in Cases 1, 2, and 7 of Figure 9, reveal important limitations in current passive sensing capabilities. These discrepancies likely stem from multiple compounding factors that warrant deeper examination. First, POLDER's relatively coarse spatial resolution (approximately 50 km for CER retrievals) means it cannot resolve fine-scale heterogeneities in cloud microphysical properties that CloudSat can detect along its narrow swath. Second, the visible-band measurements used by POLDER are primarily sensitive to cloud-top properties, making it inherently challenging to accurately characterize vertical microphysical gradients. The study would benefit from a more detailed error

analysis quantifying how these sensor limitations translate to uncertainties in profile reconstruction, perhaps through sensitivity studies or comparison with higher-resolution datasets where available.

3. CloudSat's 240-m vertical resolution, while impressive for spaceborne radar, imposes significant limitations on the study's ability to characterize thin or finely structured cloud layers. This resolution threshold means the CPRM reconstruction cannot resolve features smaller than about 2.64 km in vertical extent, potentially missing important microphysical transitions in shallow cloud systems. The impact is particularly relevant for stratocumulus clouds, which often exhibit thin but meteorologically important structures like sharp inversion layers or thin drizzling layers near cloud base. The authors should expand their discussion of how this resolution limitation affects the physical interpretation of their results, and perhaps suggest how future sensors with finer vertical resolution (like EarthCARE's radar) might overcome this constraint.

4. The coarse resolution of POLDER observations presents multiple challenges that extend beyond the immediate retrieval accuracy issues. At 50 km resolution, individual POLDER pixels often or possiblely integrate across multiple cloud regimes, potentially blending fundamentally different cloud types and obscuring important spatial gradients. This becomes particularly problematic when trying to apply the methodology to broken cloud fields or cloud edges, where sub-pixel variability is high. While the current focus on stratiform clouds is understandable given their relative homogeneity, the paper would benefit from a more thorough discussion of how partial cloudiness and three-dimensional radiative effects might bias the retrievals. The authors might consider adding a sensitivity analysis or at least a more detailed qualitative discussion of these effects in the limitations section.

5. The exclusion of 9.1% of profiles classified as complex-shaped introduces a

subtle but potentially important selection bias in the results. While this filtering improves the clarity of the statistical relationships, it risks creating an overly idealized representation of real-world cloud profiles. Many meteorologically significant situations - such as clouds undergoing strong entrainment, multilayered structures, or precipitating systems - may fall into this excluded category. The authors should more thoroughly justify their exclusion criteria and discuss how this might affect the generalizability of their findings. A sensitivity analysis showing how including some portion of these complex profiles affects the retrieval statistics would significantly strengthen the paper's conclusions.

6. The minimal three-year overlap between CloudSat (2006-2020) and POLDER (2004-2013) operations raises important questions about the dataset's representativeness for global climatological studies. Cloud properties exhibit significant interannual variability influenced by large-scale modes like ENSO, and a three-year period may not adequately capture this natural variability. The authors should discuss whether their training dataset (2013, 2019, and part of 2020) is truly representative of global cloud conditions, and whether the limited temporal sampling might introduce biases in the derived statistical relationships. This is particularly relevant given that some of the training years (like 2019) were characterized by unusual atmospheric conditions in certain regions.

7. The notably weak correlations for TP_NCOT (Figure 5b) reveal fundamental challenges in passively retrieving information about vertical structure inflection points. This poor correlation performance suggests that current passive observables may lack the necessary information content to reliably determine the normalized optical thickness at turning points. The authors should expand their discussion of potential physical reasons for this limitation, such as: The insensitivity of passive measurements to vertical redistribution of cloud water; The degeneracy between different vertical configurations that produce similar top-of-atmosphere signals;

The potential for cloud inhomogeneity effects to obscure the true profile characteristicsA more thorough exploration of these physical limitations would help readers better understand the boundaries of what can realistically be achieved with passive profile retrievals.

8. The substantially higher errors over land (RMSE 1.96 μm vs. ~1.3 μm over ocean) point to important unresolved challenges in land cloud retrievals that deserve more detailed discussion. Several factors likely contribute to this performance gap:

- Greater sub-pixel heterogeneity over land due to surface variability
- Higher and more variable aerosol loading affecting the cloud microphysics
- Stronger surface heating effects on cloud boundary layer dynamics
- Potential artifacts from the underlying terrain elevation and albedo

The paper would benefit from a dedicated discussion of these land-specific challenges and potential strategies to mitigate them, such as incorporating land surface type classifications or aerosol information into the retrieval framework.

Minor Comments:

1. Vertical resolution impact on thin layers:

While CloudSat's 240-m resolution is mentioned (Sec. 2.1), its inability to resolve sub-240 m layers (e.g., thin stratus) should be explicitly discussed.

Terminology consistency:

Line 218: "Stratiform water cloud profiles" → "liquid cloud profiles" for consistency with the rest of the paper.