amt-2022-3

Climatology of estimated LWC and scaling factor for warm clouds using radar – microwave radiometer synergy

04th Jan 2023

Responses to Reviewers

Dear editor,

We want to thank the reviewers for their insightful and constructive comments. We would like to address the reviewer's suggestions here point by point. The reviewers' comments and queries are in black and our responses appear in blue. The line numbers in the response letter refer to the blue coloured mark-up version of the revised manuscript.

Report #1 (Anonymous referee #2)

I did not find Table 2 referenced in the text. I would recommend referring to it at line 132.
We updated the manuscript and added the reference of table 2 at the line 131 in section 2.1.

Report #3 (Anonymous referee #4)

The manuscript presents a methodology to estimate liquid water content (LWC) profiles from synergistic radar - radiometer observations and a statistical analysis that enables the derivation of improved (relative to the existing knowledge) LWC estimates from radar observations only. The main deficiency of the manuscript is that the optimal estimation methodology used for the synergistic radar-radiometer is not really optimal. Mathematically, it has the right ingredients, but, physically, the retrieval framework is characterized by multiple inconsistencies that are likely to affect its optimality. Specifically,

1) First of all, LWP derived from radiometer observations is not an observation. It is an estimate. Mathematically, it may be considered an observation, but LWP is not an independent variable, but one that depends on the state variable vector LWC. The estimation of LWP requires some information about the vertical distribution of LWC, which is assumed independent of the radar observations in the radiometer-only retrievals. I can provide more formal arguments on why the synergistic retrievals are not optimal despite being based on the optimal estimation theory, but I doubt that such arguments are necessary to admit that estimating LWP independently of LWC is suboptimal. A truly optimal methodology would ingest radiometer observations and feature a radiative transfer model instead of LWP=Integral(LWC(r)dr).
Thank you for the comments. We have clearly mentioned that LWP is an estimate/retrieval (line 150), not the measurement from Microwave radiometers. Therefore, we have also considered the uncertainties associated with the LWP retrieval in the error vector. Because one of the primary goals of this algorithm was also to develop a retrieval method without LWP information, this is why the radiative transfer model was not considered. Another essential reason to choose LWP was to constrain LWC to obtain a unique value of scaling factor *lna*. However, the authors agree with the possibility that this synergistic retrieval with LWP in the state vector maybe now suboptimal rather than truly optimal.

2) Uncertainties in the attenuation correction process may be handled better by considering the physical meaning of variations in ln(a). Specifically, Testud et al. (2001) advocated the use of normalized size distributions. Normalized size distributions were first used to describe raindrop spectra but were found applicable to ice cloud particles as well (Delanoe et al. 2014) and are expected to be applicable to cloud particles in general. According to the normalized size distribution formalism, variability in radar – cloud variable relations are explainable by variability in the particle size generalized intercept (usually denoted by Nw) and may be mitigated through the inclusion of the generalized intercept in the relations. Specifically, relations between reflectivity and LWC are much better defined and closer to one to one relations in the form Z/Nw=a' (LWC/Nw)^b than in the form Z=aLWC^b. Consistent attenuation relations have the form A/Nw=alpha (Z/Nw)^beta. If instead of ln(a), ln(Nw) were used as a state variable, the attenuation correction and the LWC estimation process would be consistent irrespective of the final value of ln(a), which may be derived as ln(a' Nw^(1-b)). It may be noted that attenuation may be still linearly related to LWC, in which case the use of ln(Nw) as a state variable would not have any benefit. But it would be useful to explicitly determine that rather than using a collection of potentially inconsistent relationships derived through independent means. Same is true for the entire approach in general. The truly optimal framework may not be significantly more accurate than the approach presented in the manuscript. It would be beneficial though to implement it (or study it) as it would provide insight into the sources of uncertainties in the estimates.

We emphasized that the main idea is to keep the state parameters simple for synergistic retrieval and then use that knowledge to direct the retrieval when synergy is not possible. In order to focus on developing a Climatology of scaling factor, we accounted for attenuation as a function of LWC, which was already available in the literature for W band radar. Normalizing in Z and LWC by the intercept parameter was not considered to stick to the current parameterizations. Note that normalization particularly helps when you have Mie effects by reducing the scatter for a better fitting but then requires to provide Nw. The team is familiar with the normalization technique, but it wasn't essential in that case. However, we foresee a comparative study of this method and the normalized approach to obtain the possible reason for uncertainties.

3) Another thing to consider when deciding on the state variables to be included in optimal estimation framework is that the mass weighted diameter Dm and the generalized intercept Nw tend to be inversely related. Dm is analytically related to LWC and Nw (Testud et al. 2001) and joint distribution of Nw, Dm may be derived from field observations (e.g. Wood et al. 2011). Therefore, considering a more physical retrieval framework would benefit from existing information that otherwise would be not ingestible in the retrieval framework.
The derivation of information about ln(a) that can be used in radar-only retrievals is the strong point of this paper. But, as mentioned, results may be placed into a broader perspective by considering (or at least discussing) a more general (and truly optimal) synergistic retrieval framework.

As stated in the article, to focus LWC parameter, we wanted a relatively simple retrieval that can be used in LWC=f(Z) framework without other instrument inputs. Note that LWC, N0*, and Dm are obviously linked as N0*=A LWC/Dm^4, with A constant. We initially considered implementing the N0* and Dm framework, but we also needed an apriori of N0* and Dm beforehand. This is why we contemplated employing LWC. The team also used the normalization approach for its radar-lidar-radiometer retrieval technique. We use the normalized technique and optimal estimation even for our radar-lidar liquid retrieval.