Microphysical Properties of Clouds with Low Liquid Water Paths: An Update from Clouds with Low Optical (Water) Depth

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Introduction

Clouds play a critical role in the modulation of the radiative transfer in the atmosphere, and how clouds interact with radiation is one of the primary uncertainties in global climate models (GCMs). To reduce this uncertainty, the U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) program collects an immense amount of data from its Climate Research Facilities (CRFs); these data include observations of radiative fluxes, cloud properties from active and passive remote sensors, upper atmospheric soundings, and other observations. The program's goal is to use these coincident, long-term observations to improve the parameterization of radiative transfer in clear and cloudy atmospheres in GCMs.

Within ARM, and the broader community as well, the primary workhorse to measure the liquid water path (LWP) is the 2-channel (23.8 and 31.4 GHz) microwave radiometer (MWR), and ARM has deployed MWRs at all of its CRFs. Recent analyses have demonstrated that the uncertainty of the MWR's LWP is between 20-30 g/m^2 (Liljegren and Lesht 1996, Westwater et al. 2001, Marchand et al. 2003). However, Marchand et al. (2003) demonstrated that over 50% of the warm liquid water clouds (i.e., clouds that have base temperatures of 5°C or warmer) over the Southern Great Plains (SGP) CRF have LWPs < 100 g/m^2. In similar analyses, Shupe and Intrieri (2004) have shown that nearly 80% of the clouds observed during Surface Heat Budget of the Arctic Ocean (SHEBA) that contain liquid water (as determined by a polarization-sensitive lidar) have LWPs < 100 g/m^2, and McFarlane and Evans (2004) have demonstrated that nearly 90% of the non-precipitating liquid clouds over the CRF site at Nauru had LWPs < 100 g/m^2. This results in a large uncertainty in the LWP observations for a large fraction of the clouds above all of the ARM CRF sites.

This presents an important problem for ARM for two reasons. First, both the longwave and shortwave computed radiative fluxes are extremely sensitive to small changes in the LWP when the LWP is low (e.g., O'Hirok et al. 2004, Sengupta et al. 2003), and therefore large uncertainties in the retrieved cloud properties for low LWP clouds makes the radiative parameterization of these conditions fraught with uncertainty. Secondly, the understanding of many physical processes of clouds, such as the indirect effect of aerosols or the evolution of mixed-phase clouds, requires accurate retrievals of cloud microphysical properties.

To address the need for more accurate microphysical properties in these clouds, ARM created in late 2003 a cross-cutting focus group called Clouds with Low Optical (Water) Depth (CLOWD, pronounced "klode"). The main objective of this group is to compare and evaluate the different techniques to determine the microphysical properties of clouds with low LWP and recommend/develop techniques that can be automated within ARM to provide these microphysical properties routinely with the required accuracy, as well as determine the required accuracies needed for different sky cover conditions.

The first action of this group was to organize an intercomparison of microphysical properties retrieved from the range of algorithms that were currently available. A small set of 5 case study periods from March 2000 at the SGP site were selected that encompassed the range of different conditions that fall under the auspices of CLOWD (Table 1). An open invitation was then broadcast to the ARM science team in January 2004, and results from 15 different algorithms were submitted for these cases. These participants and some details on their retrieval algorithms are given in Table 2. The purpose of this

Table 1. Initial CLOWD intercomparison cases.

Date	Time (hours UTC)	Comments
14 Mar 2000[†]	20:20 – 21:50	Single-layer overcast warm cloud
15 Mar 2000	17:30 – 22:30	Single-layer cumulus
11 Mar 2000	16:30 – 22:00	Single-layer cumulus (very tenuous)
12 Mar 2000	16:30 – 22:00	Single-layer mid-level mixed-phase cloud
13 Mar 2000	18:45 – 20:15	Mid-level water cloud below thick cirrus

[†] Listed in approximate order of difficulty (i.e., the first case is assumed to be easier to retrieve cloud properties and evaluate then subsequent cases).

Table 2. Algorithms and participants in the CLOWD intercomparison exercise.

Key Name	Contributor	Comments and [*Reference*]
ARM Stat	N/A	MWR LWP, standard ARM product, uses monthly retrieval coefficients determined from Liebe and Layton 1987 and Grant et al. 1957 absorption model [*Liljegren and Lesht 1996*]
Clough Phys	Clough and Turner	MWR LWP, physical-iterative method using optimal estimation, forward model is monoRTM [*Marchand et al. 2003, Turner et al. 2004*]
Lilj Stat2	Liljegren and Turner	MWR LWP, "variable coefficient" method where retrieval coefficients are predicted from surface met observations, absorption model is Rosenkranz 1998 [*Liljegren et al. 2001, Turner et al. 2004*]
Lin Stat3	Lin	MWR LWP, "variable coefficient" method, absorption model uses Liebe and Layton 1987 and Ray 1972. [*Lin et al. 2001*]
Microbase	Miller and Johnson	MMCR LWC and r_e, using the Liao and Sassen 1994 parameterization of Z-LWC and scaling the LWC to match the MWR's LWP [*Miller et al. 2003*]
MFRSR	Min	MFRSR-derived τ, and when MWR LWP is included, r_e is also retrieved and more accurate retrievals of τ are realized. [*Min and Harrison 1996*]
MIXCRA v2	Turner	AERI-derived τ and r_e, and hence LWP, using radiance observations from 8-13 um [*Turner 2005*]
MIXCRA v3	Turner	AERI-derived τ and r_e, and hence LWP, using radiance observations from 8-13 um and 3-5 um [*Turner and Holz 2005*]
Lidar-Radar	McFarlane	Lidar-radar retrievals of τ and r_e, for cloud elements seen by both the lidar (MPL) and the radar simultaneously [*Donovan and van Lammeren 2001*]
NFOV	Marshak and Chiu	Retrievals of τ from the narrow-field-of-view zenith radiometer (870 nm) [approach similar to *Marshak et al. 2004*]
VISST	Minnis, Khaiyer, and Heck	GOES8 Visible Infrared Solar Split-window Technique applied to 10-km diameter footprint centered at SGP CF, providing τ, r_e, and LWP [*Minnis et al. 1995*]
Not shown[†]	Minnis	Terra-MODIS retrieved cloud properties [*Minnis et al. 1995*]
Not shown[†]	Long	Broadband shortwave retrievals of τ using an empirical relationship derived from Min and Harrison 1996. Effective radius is assume to be 10 um [*Barnard and Long 2004*]
Not shown[†]	Wang	Raman lidar retrievals of τ
Not shown[†]	Flynn	MPL retrievals of τ

[†] These datasets were not shown in this manuscript in order to maintain some clarity in Figure 3.

exercise was to gain some insight as to the performance of the different algorithms/techniques compared to each other, identify pressing needs required to improve these retrievals, and use this knowledge to design a more robust statistical intercomparison exercise.

Results: Overcast Stratiform Case

A single-layer overcast stratiform cloud existed over the Southern Great Plains (SGP) on 14 March (Figure 1). A low pressure center in central Mexico directed warm, moist air from the Gulf of Mexico over the SGP region; however, a weak fast-moving system propagated into northern Nebraska during the afternoon of the 14th which brought drier air into the area and led to the eventual dissipation of the cloud layer. This case is an ideal starting point for the intercomparison, as overcast conditions reduce much of the 3D influence on the retrieval algorithms and mitigate the sampling issues. Furthermore, a few of the techniques which rely on diffuse radiative fields are only valid in overcast cases. This cloud is also a warm cloud, with temperatures above 5°C; thus there is no ice present in the cloud to complicate the analysis. Therefore, this is perhaps the easiest case to understand in the initial CLOWD ensemble.
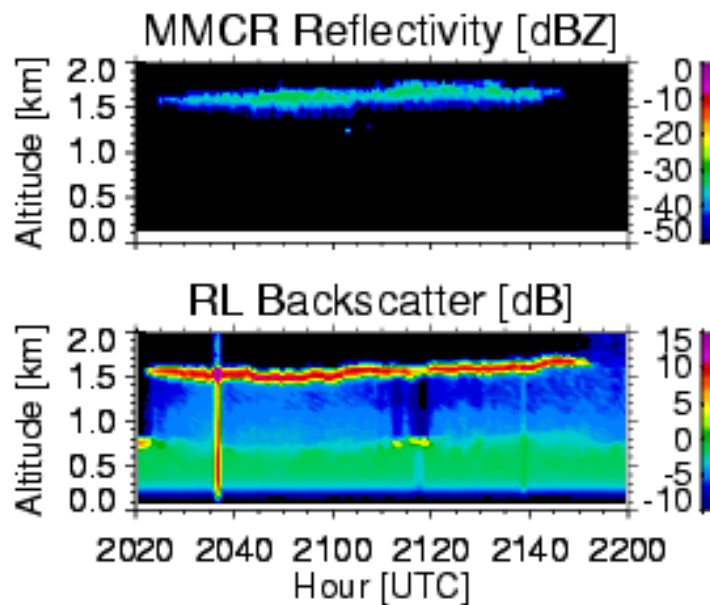

Figure 1. Time-height cross-sections of radar reflectivity from the millimeter-wave cloud radar and elastic backscatter from the Raman lidar for the stratiform cloud case on 14 March 2000. Note the very weak low-level cloud return seen in the lidar data at 21:15-21:20 at 700 m.

As indicated above, the main tool used by ARM currently to determine the LWP is the MWR. However, the retrieved LWP is sensitive to the absorption model as well as the retrieval technique used in the retrieval. This is clearly depicted in Figure 2, where 4 different absorption models were used along with three different techniques to retrieve LWP from the same observed MWR brightness
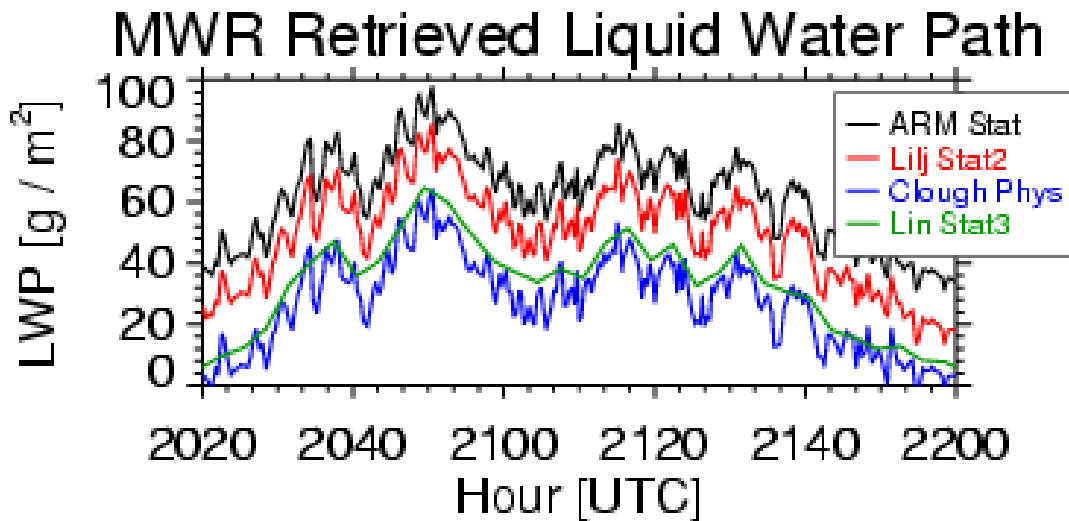
Figure 2. LWP retrieved from the MWR at the SGP site for the stratiform cloud on 14 March 2000 using 4 different retrieval algorithms / absorption models. The spread in the retrieved LWPs, all which are derived from the same brightness temperature observations, exceeds 40 g/m^2.

temperatures. The resulting spread between the different LWP values is as large as 40 g/m^2. Work is ongoing to separate the influence of retrieval technique from absorption model and to evaluate the different components relative to each other (e.g., Turner et al. 2004).

The retrieved results from many of the algorithms for this cloud are given in panels A-C of Figure 3. These panels show that there is substantial disagreement in the retrieved cloud properties from the different algorithms. For example, Figure 3A demonstrates that differences in the retrieved LWP approach 60 g/m^2. However, both the muti-filter rotating shadowband radiometer (MFRSR) and the Microbase results are actually estimates of LWP derived from the MWR, where the MFRSR value is really the "ARM Stat" dataset and the Microbase results use an earlier version of the "Lilj Stat2" data. The MWR LWP trace on this panel (Figure 3A) is the "Lilj Stat2" product. The techniques that utilize infrared observations (visible infrared solar-infrared split-window technique [VISST] and MIXCRA) retrieve significantly lower LWPs, which are in fair agreement with the "Clough Phys" MWR product.

Figure 3B shows the various retrieved values of effective radius. The lidar-radar method, which only provides observations up to the limit of lidar signal attenuation, has a range for the effective radii ranging from 3 to 6 μm. The MIXCRA v3 results, which retrieve cloud properties using radiance observations in both the 8-13 μm and 3-5 μm band, show similar effective radii, and the Microbase values are slightly larger. However, the MIXCRA v2 (which uses only observations in the 8-13 μm band), MFRSR, and VISST retrievals produced significantly larger effective radii.

The retrieved optical depth data are shown in Fig3C. The VISST and MIXCRA v2 retrievals are in fair agreement with each other but are significantly smaller then the other algorithms. There is fair agreement between the Microbase, MFRSR, and narrow field of view retrievals, and the MIXCRA v3 results are between.

This intercomparison shows significant differences in LWP, effective radius, and optical depth among the different retrieval algorithms. A high priority for the CLOWD group is to determine a measure to evaluate the accuracy of each algorithm retrieval, and gain insight into means for improving them. Therefore, we've conducted two "closure experiments" where the retrieved microphysical properties were used to compute both the downwelling shortwave diffuse flux (Figure 3D) and the mean radar reflectivity of the cloud (Figure 3E) which were then compared to the observations. Both of these variables are sensitive to particle size and LWP; however, the radar reflectivity is more sensitive to the particle size than the LWP, while the opposite is true for the diffuse flux. Therefore, these two closure experiments provide two bounds at which to evaluate the adequacy of the different retrievals.

There are many conclusions that can be drawn for this example in Figure 3. First, the VISST and MIXCRA v2 algorithms, both of which retrieved relatively low optical depths and large particle sizes, do not close well in either diffuse flux or radar reflectivity, although the reasons are different for the two algorithms. However, the MFRSR method, which also retrieved a relatively large particle size, does close well in diffuse flux (which was expected since it retrieves the cloud properties from the diffuse flux at 415 nm) but does not close well in radar reflectivity. This suggests that the retrieved particle size is too large. However, if the input LWP used in the MFRSR algorithm was smaller (for example, if the MWR Clough Phys retrieval was used), then the MFRSR-retrieved results would have closed in both diffuse flux and radar reflectivity for this case (not shown). This highlights the importance of having accurate LWP data to input into the MFRSR algorithm.

The MIXCRA v3 results have a similar level of agreement in diffuse flux as the MFRSR, and show better closure (albeit not perfect) in radar reflectivity. The inclusion of the 3-5 μm data in the v3 algorithm extends the maximum optical depth that can be retrieved to approximately 20 (the upper limit depends on solar zenith angle), while the v2 algorithm was limited to approximately 6. Both algorithms have similar sensitivity to the LWP (Figure 3A), but the inability of the v2 algorithm to retrieve optical depths above 6 results in a positive (negative) bias in the retrieved particle size (optical depth) when the true optical depth is above this threshold.

The diffuse flux calculated using the Microbase retrieved properties slightly underestimates that measured by the shaded PSP and, relative to the other methods, overestimates the particle size. In Microbase, the radar reflectivity is used only in the relative sense to vertically partition the LWP from the MWR to obtain LWC(z) based on the normalized distribution of dBz with height. The effective radius is retrieved from LWC(z) assuming a fixed number density distribution, which is independent of LWC(z). So, similar to other methods presented here, radar closure is not achieved because of the uncertainty in the MWR LWP, and the retrieved effective radius. Radar closure would be achieved by the Frisch et al (1995) approach, wherein the number density was retrieved from a combination of the radar reflectivity and MWR LWP. However, the Frisch method is not valid for drizzling clouds and, while it might work better for this CLOWD case, it would completely fail for a large fraction of liquid water clouds over the SGP that have some drizzle associated with them. The current Microbase method was chosen so to optimize the retrieval stability and accuracy over the wide range of cloud conditions found at the SGP.
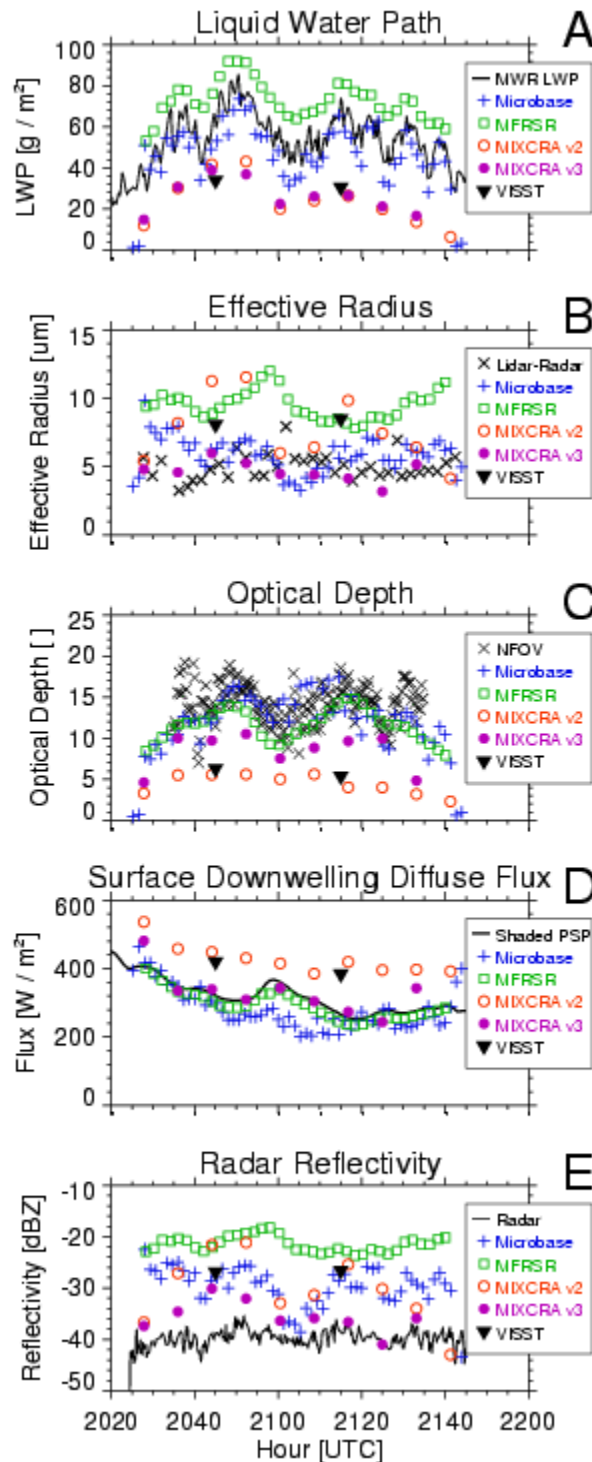
Figure 3. Retrieved LWP, effective radius, and cloud optical depth from the various algorithms on 14 March 2000 in panels A, B, and C, respectively. These retrieved properties were used to compute downwelling diffuse flux (D) and radar reflectivity (E), which were then compared with the observed flux and mean observed radar reflectivity, to evaluate the adequacy of each retrieval. See text for more details.

Conclusions

This paper demonstrates that large differences exist in the retrieved LWP, effective radius, and optical depth for a stratiform cloud case among well-established algorithms that have been published in the literature, with some of the algorithms achieving better closure in diffuse flux and radar reflectivity than others. However, we urge caution extending these results more generally; this is but a single case and a more statistical intercomparisons (which will be undertaken as part of CLOWD) may demonstrate different results. More importantly, this case, and this effort in general, should serve as a rallying cry to the retrieval community to examine the accuracy of their retrieval algorithms for low LWP clouds. We have focused on a stratiform overcast warm cloud here, as it greatly reduces the complexity of the retrieval algorithms and in the closure exercise. However, the adequacy of these (and other) retrieval algorithms for broken cloud cases and mixed-phase clouds must also be assessed. These conditions will not only challenge the retrieval algorithms, but will also require careful, well-constructed closure exercises to evaluate the results. For example, closure in diffuse flux may not be a viable approach for evaluating retrieved microphysical properties in a cumulus scene, as uncertainty in the cloud fraction will dominate the shortwave flux uncertainty. In the end, the ideal technique to provide these microphysical properties for all low LWP clouds may not lie in a single algorithm that has already published or an established instrument, but perhaps a conjoined algorithm may need to be developed or a new instrument may need to be fielded to address this need.

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