Evaluation of Cloud Water Retrieval Using Radar Measurements in Stratocumulus Clouds

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Introduction

A universal relation between radar reflectivity factor, Z, and liquid water content (LWC), W, would be a useful tool in retrieving W from readily available reflectivity measurements. Several studies attempted to find the functional relation in the form:

$$Z = aW^b \tag{1}$$

One of the fundamental difficulties in verification of retrieval algorithms is the problem of obtaining the ground truth because of a usually small overlap between radar and aircraft sampling. In this study, performance of various radar-based cloud water retrieval algorithms is evaluated using numerically simulated three-dimensional (3-D) stratocumulus cloud fields. A large-eddy simulation (LES) model provides spectral microphysical data for calculations of cloud properties and radar characteristics to which retrieval algorithms are applied. Retrieved cloud water profiles are compared with those calculated directly from cloud drop spectra. We consider only the retrieval of cloud fraction (i.e., nondrizzling part) of LWC assuming that drizzle is absent or its effect has been removed from both Z and W.

ASTEX Case

In-situ data used in this study are obtained from marine stratiform clouds during the Atlantic Stratocumulus Transition Experiment (ASTEX) in the Azores in 1992. The Cooperative Institute of Mesoscale Meteorological Studies (CIMMS) LES model is initialized with observations and provides the spectral microphysical data for calculating cloud parameters including radar reflectivity. The drizzle part in reflectivity and in LWC has been removed in these calculations.

Simulated horizontally averaged profiles of thermodynamic and microphysical characteristics were shown to match closely the observations (Khairoutdinov and Kogan 1999). Figure 1 shows simulated vertical profiles of total droplet concentration, N, and relative dispersion, σ_r/r_{avr}, which is a good approximation to the logarithmic width (σ_{lnr}) in often used lognormal approximation of the droplet size distribution. The profiles show that common assumptions of N and σ_{lnr} being constant with height are violated in this case.

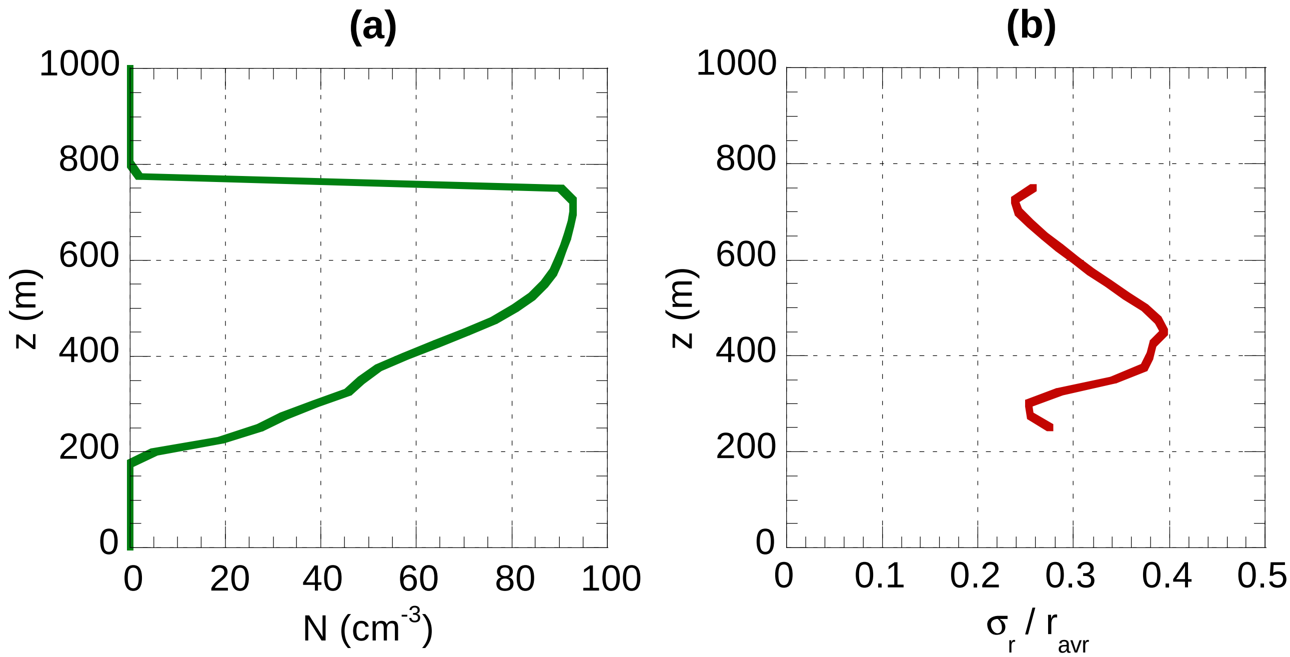

Figure 1. Vertical profiles of horizontally averaged (a) total droplet concentration, N, and (b) relative dispersion, σ_r/r_{avr}.

Z Versus W for Observed and Simulated Spectra

A scatter plot of reflectivity versus LWC calculated from cloud droplet spectra measured by the forward scattering spectrometer probe (FSSP) is shown in Figure 2a. An analogous Z-W plot using model spectra is shown in Figure 2b. To be consistent with the observations, the simulated spectra are truncated at the maximum size measured by the FSSP (~45 μm). Any possible drizzle effect therefore is removed in both cases. The scatter in both figures is rather large and LWC variation by a factor of two is common for any particular value of Z. Both data sets exhibit similar tendencies with power curves fitted to data having a slope between one and two. The slope is measured by a factor b in Eq. (1).

Z-W Relation for Individual Profiles

Three-dimensional simulated fields allow us to look at the Z-W correlation within individual vertical profiles. Nine such randomly selected profiles are shown in Figure 3. Primarily monotonic Z-W dependence reflects the fact that in nondrizzling stratocumulus clouds both variables generally increase with height with possible exceptions very near cloud boundaries (upper right and bottom left corners of the plot). An important feature of the figure is that the slope varies widely not only between the shown profiles but within each profile as well. Therefore, it is not possible to use a single formulation (Eq. [1]) to retrieve individual vertical profile of cloud LWC from reflectivity measurements.

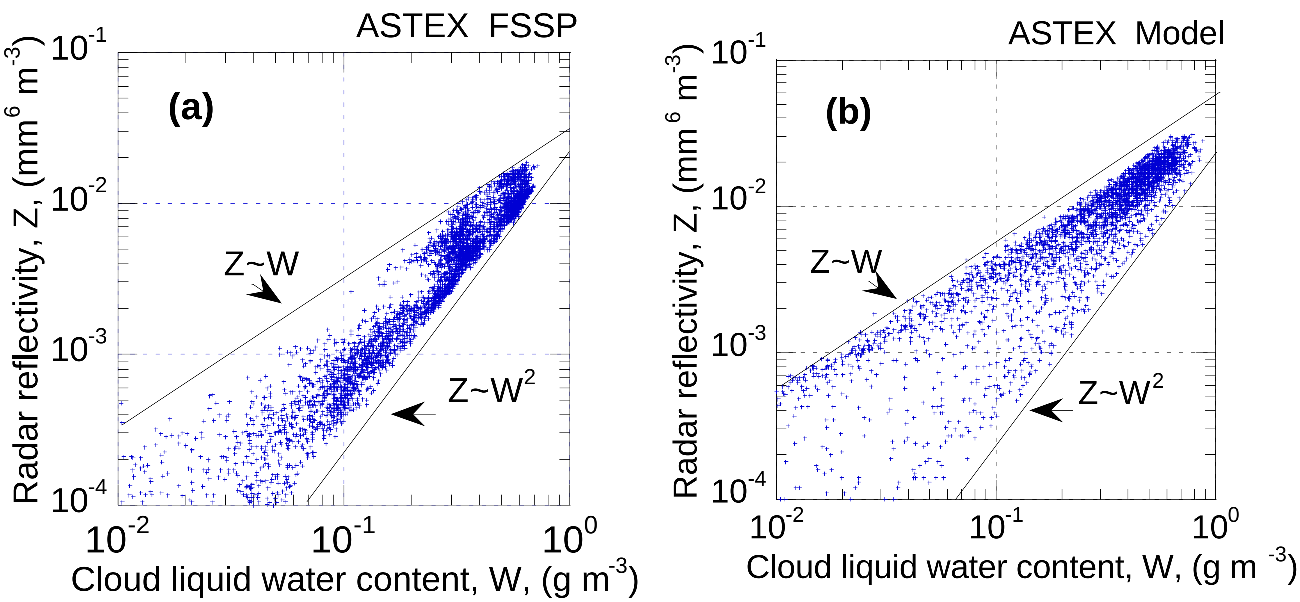

Figure 2. Scatter plots of radar reflectivity, Z, versus cloud liquid water content, W, for measured (a) and simulated (b) spectra.

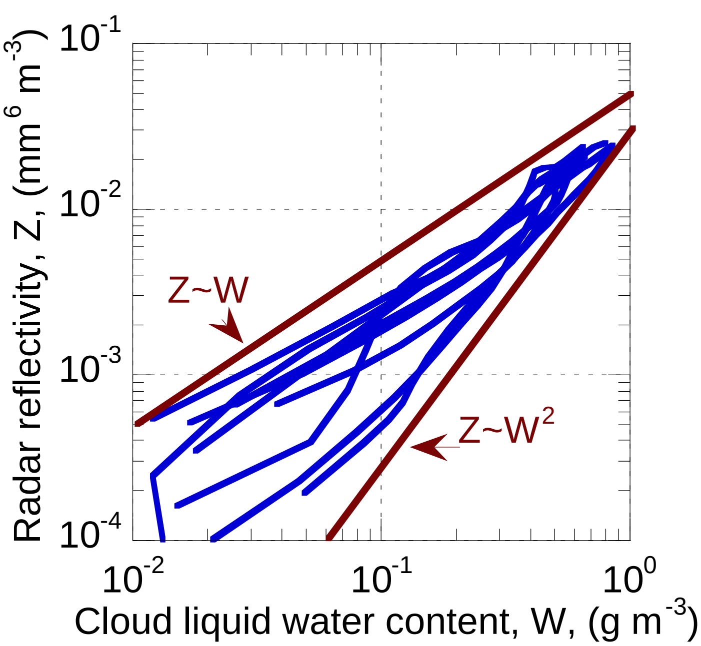

Figure 3. Z-W relations for nine randomly selected vertical profiles.

Radar Algorithms

Empirical Z-W relationships are found by fitting a power curve to reflectivities and LWC calculated from measured cloud droplet spectra as shown in Figure 2a. A theoretical Z-W relationship can be derived by assuming a specific shape of the cloud particle spectrum such as lognormal distribution. A summary of tested algorithms is given in Table 1.

Table 1. The one-parameter retrieval algorithms assessed using the LES model data.

Symbol	Reference	Formula	Assumptions	Cloud Types
At	Atlas (1954)	$W = 4.56 \cdot Z^{0.5}$	Empirical	All
SO	Sauvageot and Omar (1987)	$W = 5.32 \cdot Z^{0.55}$	Empirical	Nonprecipitating Cu and Sc
FI	Fox and Illingworth (1997)	$W = 9.24 \cdot Z^{0.64}$	Empirical	Sc
Ln	Frisch et al. (1995)	$W = 3.0 \cdot Z^{0.5}$	Lognormal spectrum of cloud droplets; σ_{lnr}=0.35; N=100 cm^{-3}	Sc
Lr		$W = 21.6 \cdot Z$	Lognormal spectrum of cloud droplets; σ_{lnr}=0.35; r_V=10 μm	Sc

The performance of the algorithms from Table 1 in retrieving a horizontally averaged vertical profile of the cloud LWC is illustrated in Figure 4. The averaging is performed on 1600 profiles corresponding to the 40 × 40 horizontal grid cells in the model.

None of the considered algorithms based on radar reflectivity alone is able to reproduce the average liquid water profile exactly. The discrepancy between the maximum LWC at the top of the cloud is on the order of 10% to 30 %. At cloud base, the relative errors are even larger although absolute errors are smaller. The SO algorithm delivers the best overall performance in this case by catching the general shape of the vertical profile and overestimating cloud LWC by 0.05 to 0.1 g m^{-3} at all heights. However, sensitivity studies have shown that this is largely a coincidence that does not indicate a superiority of this particular algorithm.

Integrated Measurements

Considering natural variability of cloud droplet spectra, it is not surprising that we don't find a universal Z-W relationship. It is expected that the accuracy of cloud water profile retrieval can be improved by combining radar reflectivity with another independently measured parameter of the cloud droplet spectra such as total concentration, N, or vertically integrated liquid water path, P. These algorithms are summarized in Table 2 and their performance is illustrated in Figure 5.

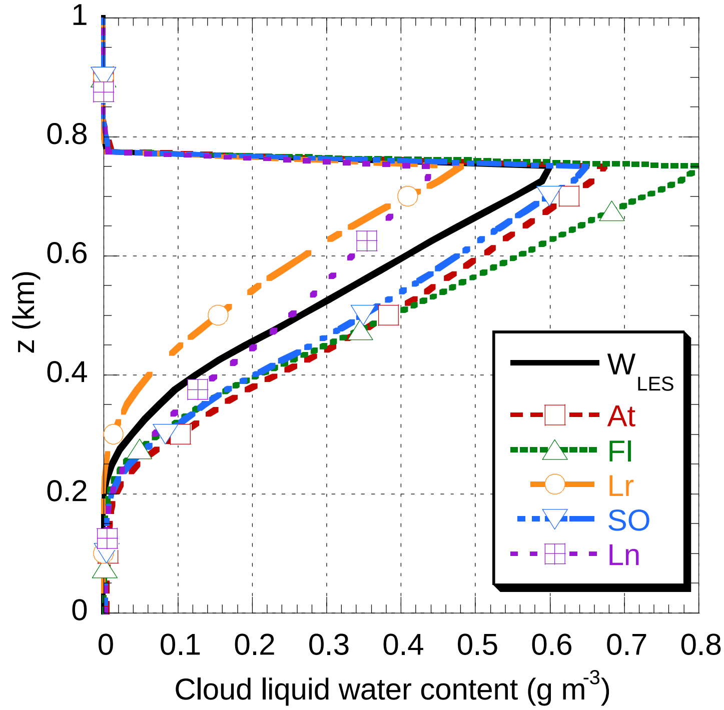

Figure 4. Cloud LWC profiles retrieved using one-parameter algorithms listed in Table 1.

Table 2. The two-parameter retrieval algorithms assessed using the LES model data.

Symbol	Reference	Formula	Assumptions	Cloud Types
N_real	Frisch et al. (1995)	$W = 0.30\rho_w N^{0.5} Z^{0.5}$	Lognormal spectrum of cloud droplets; σ_{lnr}=0.35; N is known(a)	Sc
P_0.5	Frisch et al. (1995)	$W(x,y,z) = \frac{P(x,y)}{\int [Z(x,y,h)]^{0.5} dh} [Z(x,y,z)]^{0.5}$	$W \propto Z^{0.5}$ P is known(a)	Sc
P_0.7	This study	$W(x,y,z) = \frac{P(x,y)}{\int [Z(x,y,h)]^{0.7} dh} [Z(x,y,z)]^{0.7}$	$W \propto Z^{0.7}$ P is known(a)	Sc
Pa_0.7	This study	$W(x,y,z) = \frac{P_{avr}}{\int [Z(x,y,h)]^{0.7} dh} [Z(x,y,z)]^{0.7}$	$W \propto Z^{0.7}$ P_{avr} is known(a)	Sc

(a) In this study, this parameter is calculated directly from the LES data. An estimate of this parameter can be obtained from independent measurements. The effect of possible inaccuracy of such an estimate is not considered in this study.

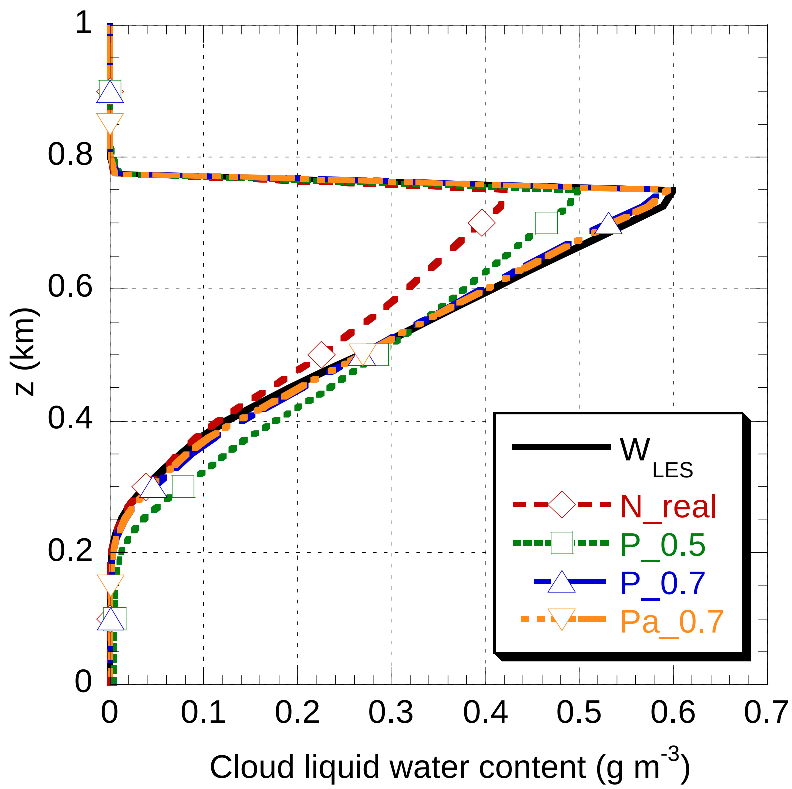

Figure 5. Cloud LWC profiles retrieved using two-parameter algorithms listed in Table 2.

Note that the N_real algorithm fails to reproduce the cloud LWC profile despite using real cloud drop concentrations. In fact, the error in this retrieval is similar to those of simpler algorithms (Figure 4). The other three algorithms preserve the integrated liquid water path and produce better results. The best agreement is achieved when the exponent b in Eq. (1) is around 1.4 (or, 1/ b =0.7).

Conclusions

Performance of various radar-based cloud water retrieval algorithms is evaluated using numerically simulated three-dimensional stratocumulus cloud fields. It is shown that:

- Methods based on radar reflectivity alone do not provide a reliable estimate of the cloud liquid water profile.

- Knowledge of the exact cloud droplet concentration does not necessarily improve the retrieval if the assumption of constant spectral width is retained.

- Combination of radar reflectivity with liquid water path from microwave radiometer can significantly increase the accuracy and the robustness of the retrieval.

- The best accuracy of the retrieved cloud water profile is achieved when the exponent in a power law Z-W relationship (Eq. [1]) is around 1.4 (or, 1/ b =0.7).

Acknowledgment

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