A Diagnostic Study on Retrieving Bulk Microphysical Properties of Low-Level Stratiform Clouds and Its Implication on Climate Research

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Introduction

The importance of low-level stratiform clouds to the planetary radiation balance is due to their persistence and coverage, and their effect on the planetary albedo. The vertical distribution of liquid water in these clouds is pertinent to many applications in atmospheric research. As a result, some cloud retrieval techniques have been developed with the assumptions, such as an adiabatic condition, no loss of liquid water via drizzle and/or a large liquid water path (LWP) (Liao and Sassen 1994; Frisch et al. 1995; Han and Westwater 1995, referred to as HW in this study).

Airborne measurements of these clouds over the marine oceans and the islands (e.g., Albrecht et al. 1985; Nicholls and Leighton 1986; Rogers and Telford 1986; Ishizaka et al. 1995) indicate that the vertical distributions of liquid water content (LWC) ratio profiles generally fall into two distinct categories (Figure 1): one decreases slowly near the cloud base and rapidly near the cloud top (e.g., the ones to the right; referred to as the Type-I in this study), and the other shows an opposite variation (e.g., the ones to the left; Type-II). These in situ observations further show that both types of LWC ratio profiles can exhibit substantial sub-adiabatic character.

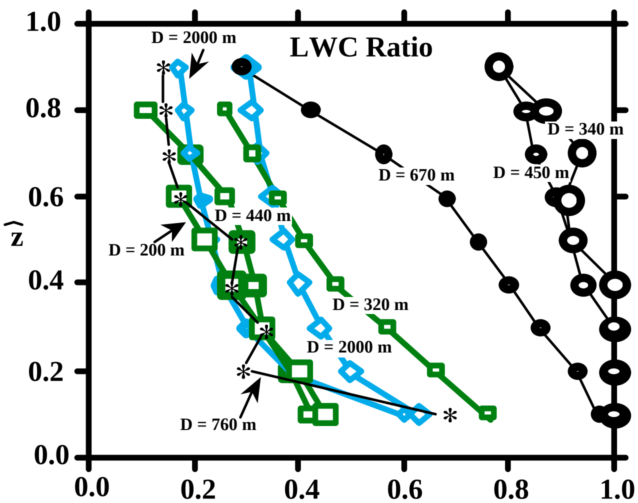

Figure 1. Ratio of LWC profiles from airborne measurements to their adiabatic values. The vertical coordinate is the scaled height between the cloud base and top. The lines in circles sampled from marine stratus (Nicholls and Leighton 1986); squares, marine stratocumulus (Albrecht et al. 1985); asterisk, stratus over the island (Ishizaka et al. 1995); diamonds, small cumulus (Cotton 1975). D on each profile stands for the cloud depth. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/chin-98.pdf*.)

A similar feature was also reported for midlatitude continental low-level stratiform clouds (Politovich et al. 1995); the low-level clouds with strong sub-adiabatic character (e.g., the ratio of integrated LWC to its adiabatic value is less than 50%) account for about 65% of the cloud population (including 36 cloud systems). Another noticeable feature of these cloud samples is that these low-level clouds with the depth factor (df; the ratio of the actual cloud depth to the one derived from the adiabatic assumption) greater than two occupy about 50% of the whole samples. Therefore, the earlier cloud retrieval technique with the adiabatic assumption can significantly underestimate the cloud depth and overestimate the maximum LWC for the low-level clouds with substantial sub-adiabatic character. As a result, the retrieved LWC profile and its associated effective radius of cloud droplets would have substantial impact on the heating profile and cloud albedo, and thereby influence the cloud mixing processes and longevity, and radiation transfer.

Using the intensive measurements from the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Program at the Southern Great Plains (SGP) site, we propose and evaluate a modified cloud retrieval technique to strengthen the applications of ground-based remote sensors to the retrieved microphysical and optical properties of low-level stratiform clouds.

The main objective of this study is to examine the macroscopic microphysical properties of these clouds, that have substantial sub-adiabatic character. Along with the development of an improved cloud retrieval technique, we can also study the sensitivity of retrieved cloud structures to the cloud optical properties and radiation budgets. Another objective is to evaluate the feasibility of incorporating the radiosonde data with the ground-based remote sensor measurements to the retrieved microphysical properties.

Modified Retrieval Scheme

As shown in observations, the measured LWC in marine and continental low-level stratiform clouds exhibits substantial sub-adiabatic character. Therefore, the retrieved LWC profile can be represented by the product of a weighting function (i.e., the LWC ratio profile) and an adiabatic LWC profile. As seen in Figure 1, two distinct types of LWC ratio profiles exist. The weighting function representing both types of LWC ratio profiles can be expressed in the same form given by $f(\hat{z}) = e^{-\alpha \cdot \hat{z}^{\beta}}$; $\hat{z}$ is the scaled height within the cloud deck, and α and β are two positive constants to represent the departure of LWC from its adiabatic value and the curvature of the weighting function, respectively.

Figure 2 shows the vertical variation of the weighting function for the given parameters of α and β. This figure indicates that the general character of LWC ratio profiles is determined by the parameter β. When β is greater than 1, it is referred to as the Type-I weighting function (affected by the cloud-top entrainment mixing only). On the other hand, the weighting function with $\beta < 1$ corresponds to the Type-II LWC ratio profile (affected by both the drizzle effect and the cloud-top entrainment mixing). Since β is relatively insensitive to the type of the weighting function, it can be treated as a constant. In this study, the parameter β is set to 4 and 0.5 for the Type-I and Type-II weighting functions, respectively.

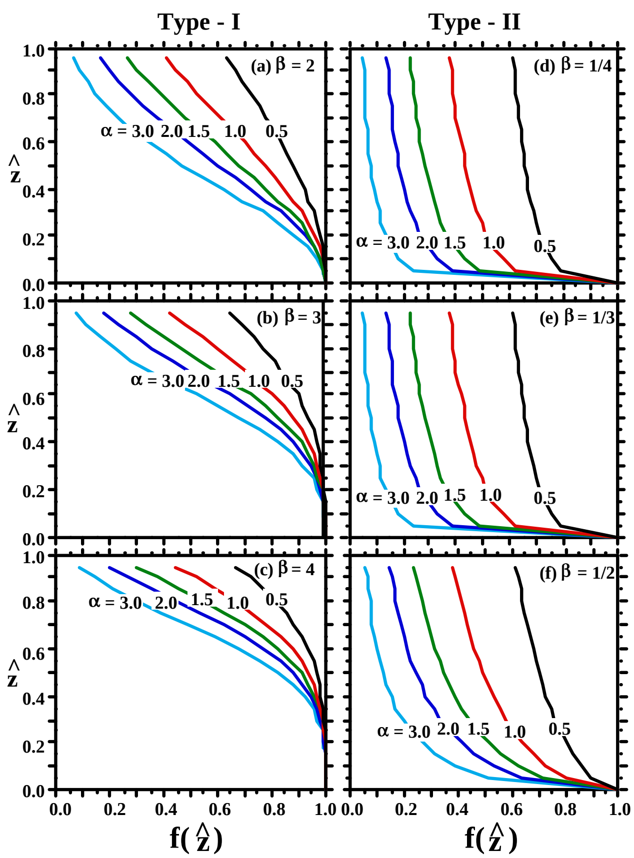

Figure 2. Vertical profiles of the weighting functions for varied parameters of α and β. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/chin-98.pdf*.)

Along with the fairly justified assumptions of zero and unity LWC ratio at the cloud top and base by in situ measurements, respectively, the weighting function for each type of LWC ratio profiles is thus uniquely determined by computing α in the iteration process via adding the cloud-top information into the HW scheme (see Figure 3). Note

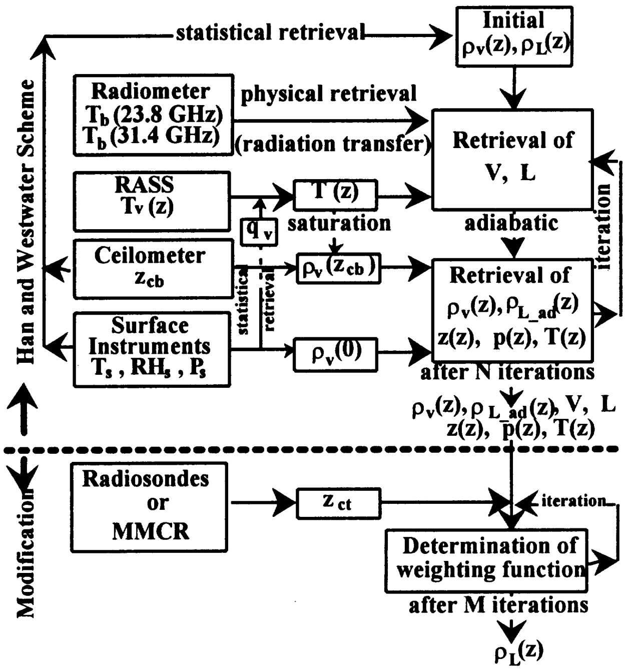

Figure 3. A schematic diagram of the system to retrieve profiles of temperature T(z), water vapor $\rho_v(z)$ and cloud liquid water $\rho_L(z)$, adiabatic cloud liquid water $\rho_{L\_ad}(z)$, integrated water vapor V, and integrated cloud water L from measurements of microwave brightness temperatures T_b at 23.8 and 31.4 GHz, virtual temperature profile $T_v(z)$, cloud-base height z_{cb}, cloud-top height z_{ct}, and surface temperature T_s, relative humidity RH_s, and pressure P_s; $\rho_v(0)$ and $\rho_v(z_{ch})$ are water vapor density at the surface and cloud-base height.

that the tolerance of the cloud-top height difference between retrieved and observed ones is set to 5 meters in the iteration process. As in the HW scheme, the application of the modified scheme is limited to a single layer cloud with the cloud temperature warmer than -20° C. However, this limitation is fairly justified for the low-level clouds under investigation.

To determine the optical properties of low-level stratiform clouds, it is also necessary to know the effective radius of cloud droplets (R_e). Following Martin and Johnson (1992) for continental clouds, R_e is defined as

$$Re = 1.15 \cdot \left(0.75 \cdot \frac{LWC}{\pi \cdot \rho \cdot N}\right)^{1/3}, \quad N = N_0 \cdot [\sin(\pi \cdot \hat{z})]^{1/2},$$

where ρ is the liquid water density and N is the droplet number concentration. The squared root distribution of N is used to account for the decrease of number concentrations near the cloud boundaries and nearly constant N within the most part of the cloud deck. To focus on the dependence of R_e on the retrieved LWC in this study, N_0 is given from the observations.

Observations And Validations

Three stratus cloud systems observed during ARM intensive observation periods (IOPs) at the SGP site are used in this study: Case-A on 94/4/30, Case-B on 97/4/9, and Case-C on 97/4/12. Case-A and Case-C occurred in a well mixed boundary layer. The former is in a warmer and more moist regime and the latter is in a colder and drier environment. Case-B is associated with a decoupled boundary layer caused by a surge of cold and dry low-level air.

Measurements needed for the HW scheme include two microwave brightness temperatures, virtual temperature, cloud-base height, and surface temperature, pressure and humidity. The cloud-top height for determining the weighting function can be obtained from radiosonde or millimeter wave cloud radar (MMCR) data. Both in situ measurements and MMCR reflectivity data are used to validate our modified cloud retrieval scheme.

Results

Using different prescribed cloud-top heights, the general solutions of this modified cloud retrieval algorithm for the given LWP and the cloud base height from the Case-A can be summarized in terms of the df as shown in Figure 4. Results indicate that the df is a useful parameter to classify the sub-adiabatic character of low-level stratiform clouds. This figure clearly indicates that both types of LWC profiles exist in the low df regime (i.e., df ≤ 1.25). These two types of LWC profiles have been observed in marine clouds with small dfs (Slingo et al. 1982).

The vertical structure of retrieved LWC is very different in both types of LWC profiles; the Type-II profile exhibits a monotonous increase of LWC with height above the cloud base and then rapidly drops near the cloud top while the Type-I profile shows a skew-parabolic distribution of LWC within the cloud deck. In addition, the altitude of maximum LWC in the Type-II profile is elevated as the df increases while its counterpart in the Type-I LWC profile shows an opposite change.

As the df is larger than the threshold value (i.e., df > 1.25), the solution for the Type-I LWC profiles no longer exists and the general pattern of the Type-II LWC profile is also changed noticeably. For the very large df case (say, df ε 2.5), the retrieved Type-II LWC profile tends to evenly

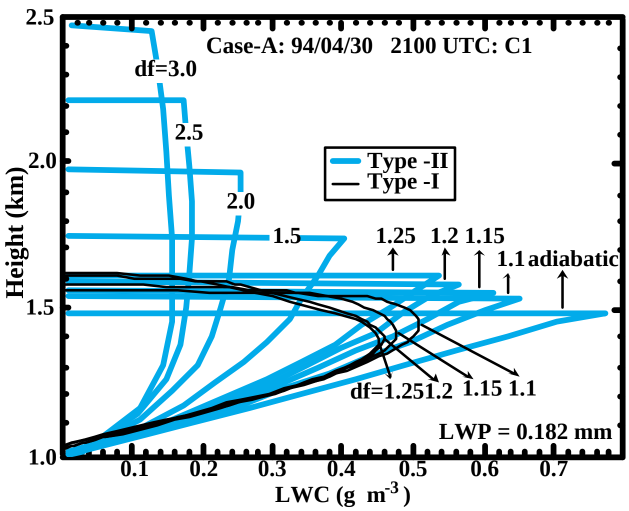

Figure 4. Vertical profiles of retrieved LWCs based on the data at the central facility of the SGP site from the radiosonde and remote sensors at 2100 UTC, April 30, 1994, and specified cloud-top heights (represented by different dfs) under the given LWP. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/chin-98.pdf*.)

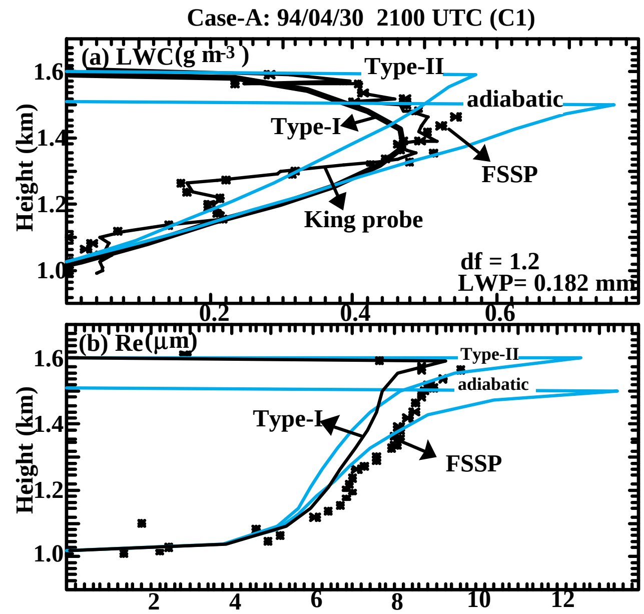

Figure 5. Vertical profiles of retrieved and in situ measured microphysical properties for Case-A. (a) LWC. (b) effective radius (Re) of liquid water. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/chin-98.pdf*.)

distribute over the most part of the cloud deck. This type of LWC profile was also observed in the marine stratiform cloud sheet, which had substantial sub-adiabatic character throughout the cloud deck (Nicholls and Leighton 1986).

The validation of retrieved cloud structures for cases of A, B, and C are conducted using airborne measurements and/or MMCR reflectivity data according to their availability in each case. Results indicate that in situ measurements support the Type-I LWC and Re profiles in Case-A (Figure 5), and the Type-II LWC profile of Case-B (Figure 6a) is consistent with MMCR data, that show heavy drizzle (not shown). Besides, both airborne and MMCR data (light drizzle; not shown) support a Type-II LWC profile in Case-C (Figure 6b).

Summary and Discussion

The use of MMCR data enables the modified cloud retrieval scheme to become well posed in determining appropriate types of microphysical properties in the low df regime. Results indicate that the sub-adiabatic character of low-level stratiform clouds can have substantial impacts on LWC and associated effective radius profiles, and thus it can affect radiation budgets [particularly in shortwave (SW)] and cloud longevity (Figure 7). As shown in the earlier studies (e.g., Stephens 1984), water clouds with sufficient LWP

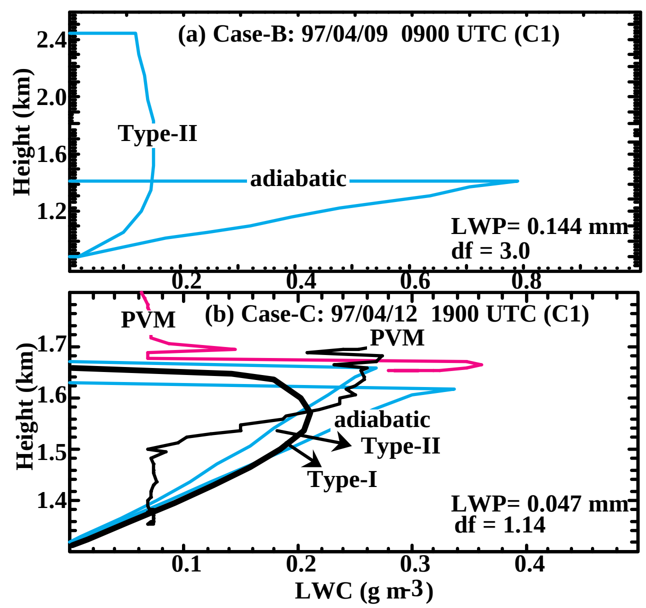

Figure 6. Vertical profiles of retrieved LWCs. (a) Case-B. (b) Case-C. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/chin-98.pdf*.)

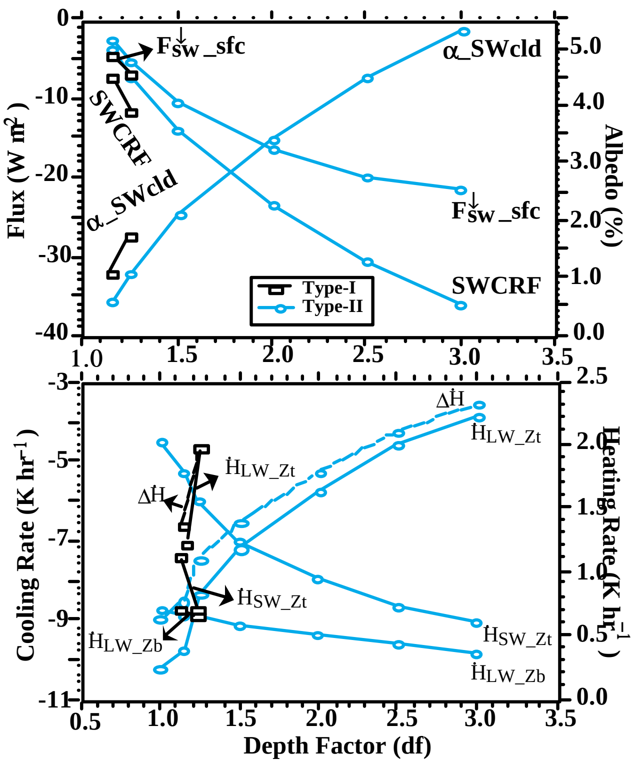

Figure 7. As in Figure 4, except for (a) SW cloud radiative forcing (SWCRF), SW cloud albedo (α_SWcld), and net surface downward SW flux ($F^{\downarrow}_{Sw\_sfc}$), and (b) the temperature change rate of maximum SW heating and LW cooling at the cloud top ($\dot{H}_{SW\_Zt}$ and $\dot{H}_{LW\_Zt}$), LW heating at the cloud base ($\dot{H}_{LW\_Zb}$), and cooling/heating rate contrast (($\Delta\dot{H}$).) between the cloud top and base. Results are calculated using the surface albedo of 0.2 and the zenith angle of 60°, and shown by the deviations to their adiabatic counterparts in (a). (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/chin-98.pdf*.)

(> 0.05 mm) behave as blackbodies so that the sub-adiabatic impact on longwave (LW) radiation fluxes are generally much less than their SW counterparts.

In terms of SW cloud radiative forcing (SWCRF) at the top of the atmosphere (estimated by a global annual mean coverage of 25%; Hartmann et al. 1992), the difference caused by the adiabatic and sub-adiabatic distributions of LWC and associated Re profiles can be -1.13 W m^{-2} in a low df case (Case-A). This sub-adiabatic impact on SW forcing difference is even larger than the direct effect of anthropogenic sulfate aerosols (-0.2 to -0.9 W m^{-2}) on climate (Chuang et al. 1997). This impact caused by different types of retrieved microphysical properties in the low df regime is not negligibly small. The sub-adiabatic impact also acts to stabilize the cloud deck by reducing the in-cloud radiative cooling/heating contrast (ΔH; Figure 7b). These sub-adiabatic impacts strengthen as the df increases. Therefore, appropriate and reasonable distributions of retrieved bulk microphysical properties of low-level stratiform clouds are of importance for climate research due to their strong cloud-radiation interaction.

Acknowledgments

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