A Novel Approach to Retrieve Cloud Liquid Water Content using Two Collocated Cloud Radars

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INTRODUCTION

Clouds play a vital role in the Earth's climate and weather, but currently, there are no means to accurately attain extensive details of cloud properties. This limits our ability to predict climate changes through computerized models.

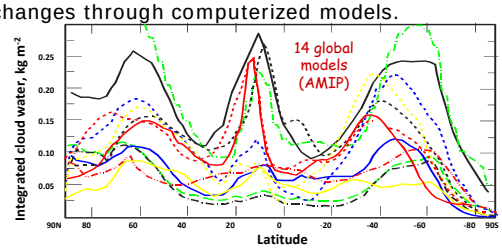

Fig. 1 The LWC calculated by 14 global climate models. The magnitudes differ by one order.

Using a dual-radar approach, we can derive vertical profiles of cloud Liquid Water Content (LWC) from the differential attenuation between the two radars.

METHODOLOGY

We used remote sensing technique via two radars operated by the Department of Energy Atmospheric Radiation Measurement Program: the Millimeter Wavelength Cloud Radar (MMCR) and the W-Band ARM Cloud Radar (WACR) stationed in the Southern Great Plains region. By the light scattering theory, the differential attenuation in reflectivity between these two radars is directly proportional to cloud LWC. Thus we can directly retrieve vertical profiles of cloud LWC (Hogan's approach), which are necessary to investigate the role of cloud in the climate system.

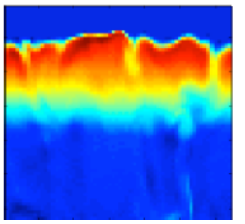

Fig. 2 Cloud liquid water content, in gm^{-3}

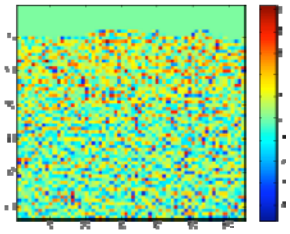

Fig. 3 Cloud LWC field obtained by the direct approach

Unfortunately, the radars are prone to random noise during measurement, and this direct approach in LWC profile retrieval is highly sensitive to this noise, leading to ambiguous results. Fig. 2 shows the true LWC of a cloud, while Fig. 3 is an LWC profile retrieved by Hogan's direct approach; the image is inadequate image because it is highly sensitive to noise.

In this study, we employed a mathematical technique, total variation regularization, to minimize the variation in the data, and thus reduce the impact of noise. We use the constrained inversion algorithm to minimize the variation in LWC measurements.

$$\min \int \|\nabla \mathbf{x}\|_1 \quad \text{subject to:} \quad \|\mathbf{Ax}-\mathbf{b}\|_2 \le \varepsilon \text{ and } \mathbf{x} \ge 0$$

Fig. 4 These are the constraints by which we regularize our data, where Ax-b is equal to the modeling error, ε is the measurement error inherent to the sensor, and ∇ X is the variation in LWC measurements

This partially conforms the noisy measurements to theoretical values. From these regularized measurements, we can apply the light scattering theory, using differential attenuation, to retrieve a better cloud profile.

RESULTS

Our approach was validated in three ways: through the Microwave Radiometer (MWR) measurements, cloud physics, and through Lidar measurements. The retrieved cloud LWC (Fig.5b) increases linearly with height, which is consistent with adiabatic cloud models. The cloud base heights from the Lidar provides further validation for our technique. The Lidar independently measures cloud boundaries, and when we overlayed the Lidar cloud base heights to our retrieved cloud profile, the cloud bases matched properly. Most cloud LWC in the retrieval (Fig. 5b) is above the Lidar cloud base. The MWR, which independently measures vertically-integrated cloud LWC, liquid water path (LWP), served as a final validation for our retrieval method. As shown in Fig. 5d, the LWP measured by the MWR mostly agrees with that calculated from our retrieved LWC. The average difference in calculated LWP versus the LWP measured by the MWR is 70 g/m^2 through our approach, and 150 g/m^2 through the direct approach. Our approach generates a more physically plausible cloud profiles than that retrieved by the direct approach, and this is especially clear during precipitation, as evident through UTC 12-17 in figures 5a-5c.

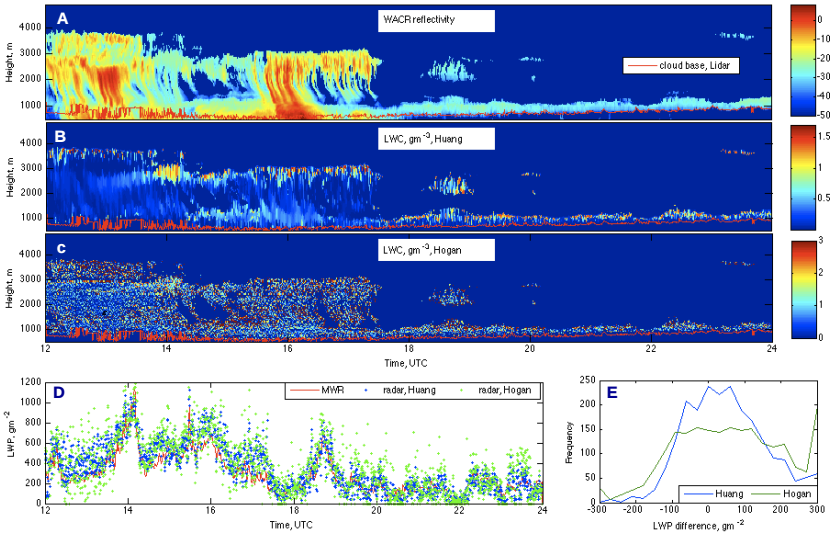

Fig. 5 Three methods of validation. (a): the cloud reflectivity measured by the WACR radar; (b): the LWC profile retrieved through our approach; (c) the LWC retrieved through the direct process; (d): the comparison of LWPs; and (e): the histograms of the retrieval error through the two approaches.

DISCUSSION

The dual-radar method was suggested decades ago, but has not been explored due to the problems that arise from radar noise. Directly converting the difference in radar attenuation to cloud LWC generates poor profiles. By using the constrained inversion algorithm to regularize the data, we can produce a much more accurate profile of cloud LWC. One observation is that the LWP calculated from our retrievals overestimated the LWP measured by the MWR during the precipitating period (UTC 12-17). This is due to the Mie scattering effect of precipitation. Normally, the difference in cloud reflectivity is solely caused by radar attenuation. However, during precipitation, the difference can be attributed to both radar attenuation and the Mie effect. This then creates a systematic error in the calculated MWP levels, but the error can be corrected by employing further calculations. Now that the accuracy of our retrieval approach has been verified, we can use our profiles to evaluate the performance of other climate models.

REFERENCES

Hogan, R., N. Gaussiat and A. Illingworth (2005): Stratocumulus liquid water content from dual-wavelength radar. *J. Atmos. Oceanic Technol.*, 22, 1207-1218.

ACKNOWLEDGEMENTS

I would like to thank Brookhaven National Laboratory, the Science Undergraduate Laboratory Internship program, and the Department of Energy for giving me this wonderful opportunity to work among scientists who are so passionate in their fields of interest.