FINAL REPORT
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Operational Retrieval of Cloud Microphysical Properties
Using Combined Measurements by Diverse Instruments

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The objectives of the research activities of this project are to develop and improve retrievals of cloud microphysical properties that utilize measurements from multiple ARM instruments, to evaluate the resulting retrievals in various ways, and to provide a foundation for further improvements that will contribute to operational retrievals of cloud properties.

Activities during the final segment of this project have focused on improving both ice and liquid microphysical retrievals by allowing all distribution parameters to vary through the cloud column, testing the performance of the improved retrievals through flux comparisons, and adding liquid water path data from the microwave radiometer to the liquid cloud retrievals. These exploratory studies follow on from activities during the first two years of the project in which prior retrieval approaches were investigated by similar methods and effects of variations in a priori data were examined. These recent developments are further described in the following sections.

1. Improvement of ice and liquid retrievals

The liquid and ice cloud microphysical retrieval algorithms used in this effort model the distribution of particle sizes in each cloud column using three-parameter size distribution functions. Former versions of these retrievals were constrained to have two of the three distribution parameters constant with altitude in a given cloud column. This was done initially to reduce the number of unknowns to be retrieved, but this assumption had its disadvantages. The retrieval algorithm often has difficulty finding a solution in the case of cloud columns having radar reflectivity values that vary over a wide dynamic range because only one parameter of the size distribution is allowed to vary with height. Because the other two parameters must take on compromise values that serve through the cloud column, agreement between the modeled and actual measurements may suffer for portions of the column at the high or low extremes of the measurement range.

The improved retrievals allow all three distribution parameters to vary with height. While these parameters may still be primarily determined by a priori data (depending on the number of measurements), the additional degrees of freedom allow better fits to the measurement data and allow a priori data to vary through the cloud column according to temperature or other criteria. The removal of the constant parameter constraint should also facilitate more sophisticated future retrievals in which multiple particle species are considered simultaneously.

A sample RVOD (radar + visible optical depth) ice cloud retrieval in which all distribution parameters are allowed to vary through the column is shown in Figure 1.

Figure 1. Sample RVOD ice cloud retrieval in which all distribution parameters vary with height.

2. Flux Comparisons

As in previous retrieval comparisons in this project, flux comparisons were used to give insight into the performance of the retrieval algorithms. Retrievals were performed on a collection of ice and liquid cloud cases from 2000-2001 at the ARM SGP site using both radar-only (RO) and radar-visible optical depth (RVOD) retrievals with different a priori data and uncertainties. The various sets of retrieved cloud properties were then used as inputs to a radiative transfer model (BUGSRAD) to calculate fluxes for comparisons against direct observations. A schematic of the flux comparison process is shown in Figure 2.

Figure 2. Flux comparison procedure for RO, RVOD, and RVODMWR retrievals.

Results of the comparison (Figure 3) show the effects on fluxes of changing the assumptions regarding the vertically varying distribution parameters and regarding the uncertainties in the cloud optical depth. For ice cloud cases, flux bias and rms differences improved significantly when vertically varying distribution parameters were used. For liquid cloud cases, the biases and rms differences for the fluxes typically increased slightly when vertically varying distribution parameters were used, but in some cases, these increases were offset when high-accuracy optical depths were used with the RVOD retrieval.

In the case of ice clouds, for downwelling flux at the surface, allowing the distribution parameters to vary vertically reduced the bias and rms differences for the shortwave flux by 25% and 20% respectively. For upwelling flux at top-of-atmosphere, the biases for both the shortwave and longwave fluxes were reduced. The shortwave bias was reduced by 50% and the longwave bias was reduced by almost 100% compared to the original RO and RVOD retrievals. The rms differences were essentially unchanged for the shortwave flux and reduced by 10% for the longwave flux. These results were largely insensitive to changes in the assumptions regarding the uncertainties in the cloud optical depth.

For liquid cloud cases, the downwelling longwave flux at the surface was essentially unaffected by these changes in the retrieval assumptions. For the downwelling shortwave flux at the surface, biases and rms differences generally increased with the use of vertically varying distribution parameters. For the RVOD retrieval, though, these increases in biases and rms differences were reduced when high-accuracy optical depth observations were used. At the top-of-atmosphere, the use of vertically varying distribution parameters led to modest increases in the biases and rms differences (approximately 10% and 5% respectively for the RVOD retrieval) for the upwelling shortwave flux. Similarly for the upwelling longwave fluxes, biases and rms differences increased modestly, with the biases increasing in magnitude from 2 to 7 W m⁻² and rms differences increasing from 8 to 10 W m⁻².

Figure 3. Comparison of observed and modeled flux for liquid and ice cases using various retrieval methods and assumptions.

3. Addition of MWR Liquid Water Path

Initial tests of a liquid cloud retrieval incorporating brightness temperature data from the microwave radiometer (MWR) (a three-data-stream retrieval algorithm: radar reflectivity, visible optical depth, and microwave brightness temperature) performed during the second phase of the project were somewhat inconclusive. While further investigations of that technique are certainly warranted, a different approach was investigated during the final project period. In an approach analogous to the RVOD retrieval, which used retrieved visible optical depth values rather than raw radiance data from the MFRSR, a retrieval was constructed using retrieved values of liquid water path (LWP) from the ARM MWR product `sgpmwr1os`. Sample outputs from a March 2000 case are shown in Figure 4.

Figure 4. Sample three-instrument retrieval using MMCR, visible optical depth (MFRSR), and liquid water path (MWR) data. Optical depth and LWP plots (rows 2 and 7) show input data in red, modeled data in black.

Initial results from this technique appear promising. As shown in Figure 5, the addition of LWP information improved the agreement between modeled and measured shortwave flux both at the surface and at the top of the atmosphere compared to either the RO or RVOD retrievals. While agreement in the longwave flux was not improved and sometimes slightly degraded, the differences are much smaller in magnitude than in the shortwave case.

Figure 5. Flux comparison of RO, RVOD, and RVODMWR retrievals using 8 cases from March and June 2000.

4. Highlight result

The highlight result for this report is the improvement in agreement in shortwave flux (both at the surface and top-of-atmosphere) obtained by using liquid water path information from the MWR in addition to the radar and visible optical depth information (RVODMWR retrieval), as compared with both the RO and RVOD solutions, as shown in Figure 5.

5. Publications

Turner, D. D., A. M. Vogelmann, R. T. Austin, et al., 2007: Thin Liquid Water Clouds: Their Importance and Our Challenge, *Bull. Amer. Meteorol. Soc.*, **88**, 177-190.

Austin, R. and G. Stephens, 2008: Improved retrieval of stratus cloud microphysical parameters using millimeter-wave radar and visible optical depth: I. Algorithm and synthetic analysis, submitted to *J. Geophys. Res.*

Austin, R., S. Miller, Q. Min, and G. Stephens and N. Wood, 2008: Improved retrieval of stratus cloud microphysical parameters using millimeter-wave radar and visible optical depth: II. Application and Evaluation, submitted to *J. Geophys. Res.*

Austin, R., A. Heymsfield and G. Stephens, 2008: Retrievals of ice cloud microphysical parameters using the CloudSat millimeter-wave radar and temperature, submitted to *J. Geophys. Res.*

Wood, N. B., R. T. Austin, and G. L. Stephens, 2008: Assessment of two-stream radiative fluxes derived from optimal estimation cloud properties, in revision for *J. Appl. Meteor. Clim.*