Extended Validation of an Optimal Estimation Cloud Property Retrieval Algorithm

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Introduction

The activities described here have the aim of providing a foundation for long-term operational retrieval of cloud microphysical properties using measurements from multiple Atmospheric Radiation Measurement (ARM) program instruments. These activities have focused on development of a retrieval that currently uses MMCR and cloud visible optical depth (VOD) observations, but which is extensible to incorporate observations from additional instruments (e.g., microwave radiometer). Validation of the retrieval involves using retrieval results to model radiative fluxes and comparing those fluxes with observations, using observations from the Southern Great Plains (SGP) site between March 2000 and February 2001.

Results are presented which illustrate the evaluation of the retrieval using in situ data collected during the March 2000 Cloud Intensive Observation Period (IOP) and the incorporation of these observations into the retrieval algorithm. The observations are used to modify the a priori estimates of cloud properties used in the retrieval, and the influence of the modified a priori data are evaluated for a number of liquid cloud cases. The retrieval algorithm is further evaluated using observations over the yearlong period following the Cloud IOP. Finally, the extensibility of the retrieval algorithm is illustrated by incorporating microwave radiometer (MWR) observations to augment the MMCR and VOD inputs. Two cases are examined to evaluate the influence of the liquid water path constraints from the MWR on the retrieval results.

Performance of the retrieval algorithm is evaluated in terms of bias and scatter of modeled radiative fluxes versus observations. The inclusion of VOD reduces scatter in all the modeled radiative fluxes in comparison to those obtained using only MMCR observations. The reductions range from 5% to over 50%. For shortwave fluxes, the inclusion of cloud optical depth information reduces both the top-of-atmosphere flux bias and the surface flux bias, while effects on the longwave biases are slight. Overall, the results suggest that the retrievals that include cloud optical depth information provide improved cloud microphysical properties in comparison with radar-only retrievals.

Retrieval Method and Radiative Transfer Model

The cloud property retrieval algorithm is a more advanced form of an earlier algorithm (Austin and Stephens 2001) using optimal estimation methods (Rodgers 2000) and derives from the corresponding algorithm used for the CloudSat mission (Stephens et al. 2002). The algorithm uses 35-GHz radar reflectivity from the vertically pointing MMCR and, optionally, visible optical depth as inputs. The 35-GHz reflectivities, taken from ARM's Active Remotely Sensed Clouds Locations (ARSCL) data product (Clothiaux et al. 2000), are sampled at 45 m vertically and 10 s temporally. Cloud optical depths are provided by analyses of multifilter rotating shadowband radiometer observations (Min and Harrison 1996) made coincident to the radar observations. Cloud droplet distributions are assumed lognormal. For each radar profile, the retrieval provides a column value for cloud droplet number concentration and distribution width parameter. Values of geometric mean radius are provided for each radar range gate occupied by cloud.

Radiative fluxes are calculated using BUGSrad, a two-stream parameterization developed for use in general circulation models and as a single-column model (Stephens et al. 2001, Stephens et al. 2004). For this work, the single-column version is used. In addition to cloud properties, BUGSrad requires vertical profiles of temperature and humidity. These are obtained from measurements by the Balloon-Borne Sounding System at the time nearest the radar observations. Ozone is also required and is set to values from a standard midlatitude summer atmosphere (McClatchey et al. 1972) scaled to match the daily average column ozone amount determined by the Total Ozone Mapping Spectrometer (McPeters et al. 1998) over the SGP site. For use in the radiative transfer calculations, the retrieved cloud properties are temporally averaged, typically using a 20-minute averaging window, but the window may vary in the case of comparisons versus in-situ observations. In addition, the input profiles are rebinned to a lower vertical resolution more similar to that of a cloud resolving model.

Incorporating In-Situ Observations from March 2000 Cloud IOP: Limited Evaluation of Revised a *Priori* Values for Liquid Clouds

During the March 2000 Cloud IOP at the ARM SGP site, extensive in situ observations of cloud particle size distributions were made. Liquid clouds were observed using both a Particle Measuring Systems Forward Scattering Spectrometer Probe (FSSP-100) and a King probe. The FSSP datasets provide the droplet size distribution sampled into fifteen bins at 4 Hz frequency and liquid water content (LWC) sampled at 1 Hz (Dong et al. 2002). The King probe provided LWC at 4 Hz.

Cases were prepared by selecting data from time periods during which the aircraft was located primarily in the vicinity of the MMCR and for which the aircraft appeared to sample nearly the full depth of the cloudy layers. This produced a total of five cases, ranging in sample size from about 8 minutes to 40 minutes. Both radar-only (RO) and radar plus visible optical depth (RVOD) retrievals were performed over the same time periods. Aircraft data and retrieved cloud properties were averaged over the time window and rebinned vertically as described above. In addition to the RO and RVOD profiles, two additional profiles were formed by substituting the in-situ data into the RVOD profiles (at altitudes for which in situ measurements were available), using the FSSP size data and the LWC from either the FSSP or from the King probe (e.g., Figure 1). Radiative fluxes were then computed for each profile and compared versus observations averaged over the corresponding time window (Figure 2).

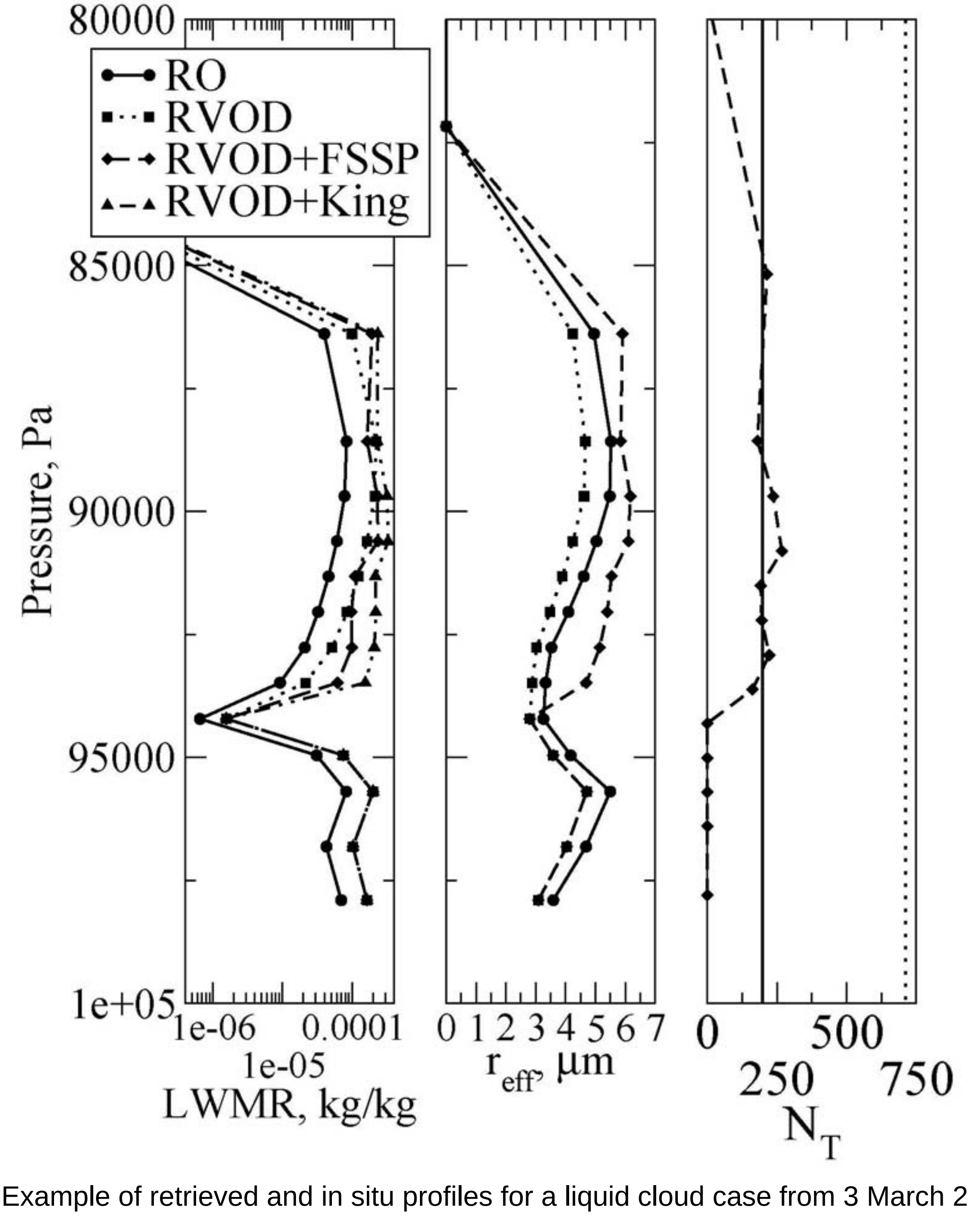

Figure 1. Example of retrieved and in situ profiles for a liquid cloud case from 3 March 2000.

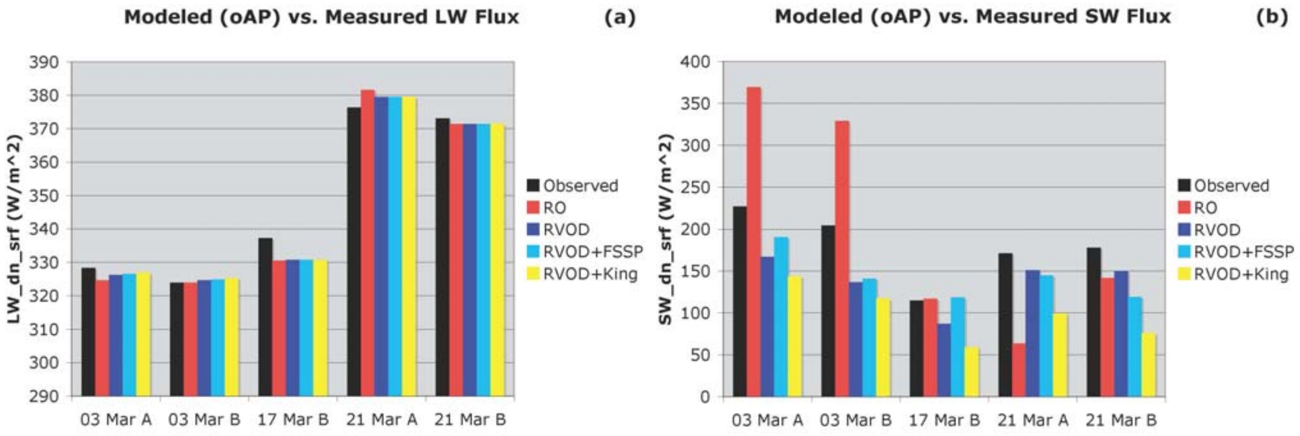

Figure 2. Comparison of measured and modeled radiative fluxes for retrieval-only (RO and RVOD) and for retrieval+in situ (RVOD+FSSP and RVOD+King) profiles.

Comparisons showed that the averaged droplet size distribution parameters from the in-situ data differed significantly from the original *a priori* estimates (Table 1) and that there was significant variation in the parameters between the in situ cases. As a result, a number of modified *a priori* (mAP) retrieval trials were performed in which the *a priori* estimates used in the retrieval were modified to more closely match the in situ data (Table 2). A comparison of modeled downwelling shortwave and longwave fluxes versus observations showed the longwave fluxes were only slightly sensitive to the choice of *a priori* values. The shortwave fluxes were somewhat more sensitive (Figure 3) with trial ra2-t20 providing a better match to the observed fluxes. Based on these comparisons, the RA2 *a priori* values were used as the modified *a priori* (mAP) values for the remainder of the liquid cloud evaluations described here.

Table 1. Estimates of droplet number concentrations, geometric mean radii and distribution width parameters obtained from in situ observations.

Case	N_T (cm^{-3})	r_g (μm)	σ_{log}
03_Mar, A	225.9	5.83	0.209
17_Mar, B	62.9	7.4	0.235
21_Mar, A	27.3	6.5	0.292
21_Mar, B	67.6	6.6	0.230

Table 2. Modified *a priori* values for size distribution parameters used in the retrieval algorithm, shown as "value +/- uncertainty".

Trial	N_T (cm^{-3})	r_g (μm)	σ_{log}
mn	231.0 ± 219.0	3.60 ± 1.88	0.39 ± 0.087
fs-t20	225.9 ± 69.3	5.83 ± 3.00	0.2088 ± 0.087
ra-t20	225.9 ± 225.9	6.6 ± 3.0	0.25 ± 0.1
ra2-t20	175.0 ± 70.0	6.6 ± 3.0	0.25 ± 0.1
ra3-t20	175.0 ± 70.0	6.6 ± 2.0	0.22 ± 0.08

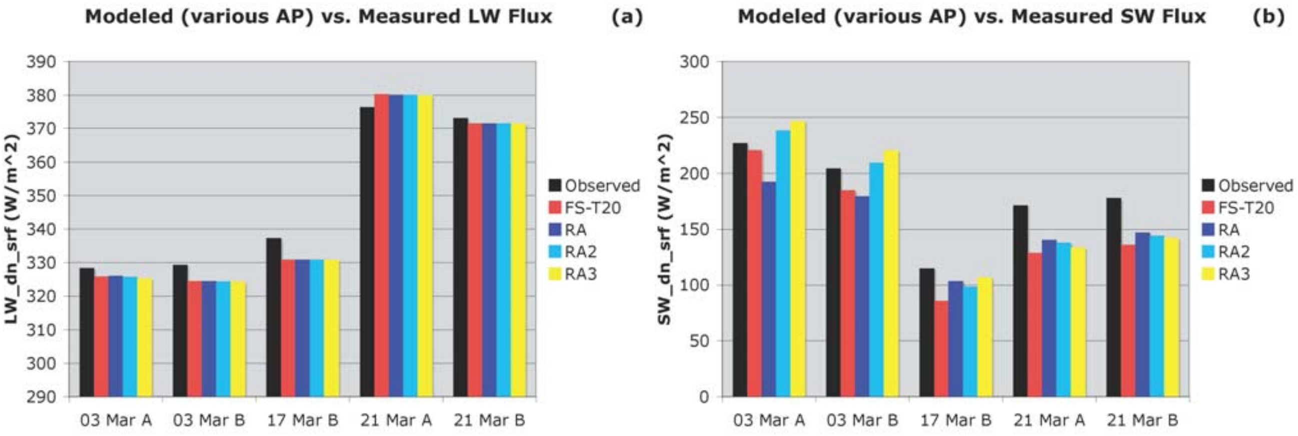

Figure 3. Comparison of measured and modeled radiative fluxes for RVOD retrievals with modified a priori values.

Evaluating the performance of the cloud property retrieval using radiative fluxes is complicated by the possibility of inhomogeneities (fractional cloudiness and horizontal variability) in the cloud field. The use of a plane-parallel radiative transfer model requires that these variations be eliminated (usually by horizontal averaging) in the profile used by BUGSrad. This averaging, coupled with the fact that the radar is viewing a limited sample of the full three-dimensional cloud field, contributes to errors in the calculated fluxes.

To reduce the potential for such “3D” errors to influence the results, and so to focus more clearly on the performance of the cloud property retrieval, a set of four additional cases which appear to be strongly plane-parallel were selected for further evaluation (Figure 4). Along with plane-parallel radiative flux calculations using temporally averaged cloud properties based on the ra2-t20 *a priori* values, calculations were also performed using the independent column approximation (ICA), producing fluxes for each retrieved cloud profile that were then averaged across the time window for each case (Figure 5). The error bars on the surface observations and the ICA results indicate the corresponding standard deviations and give indications of the influence of temporal variations on the fluxes. In general the ICA results agree well with the observations, except for the surface SW flux on 29 March, and are not particularly better than the plane-parallel RO and RVOD results. The high variability in both the observations and the ICA results for surface SW on 29 March suggest that the cloud field does not meet plane-parallel conditions very well.

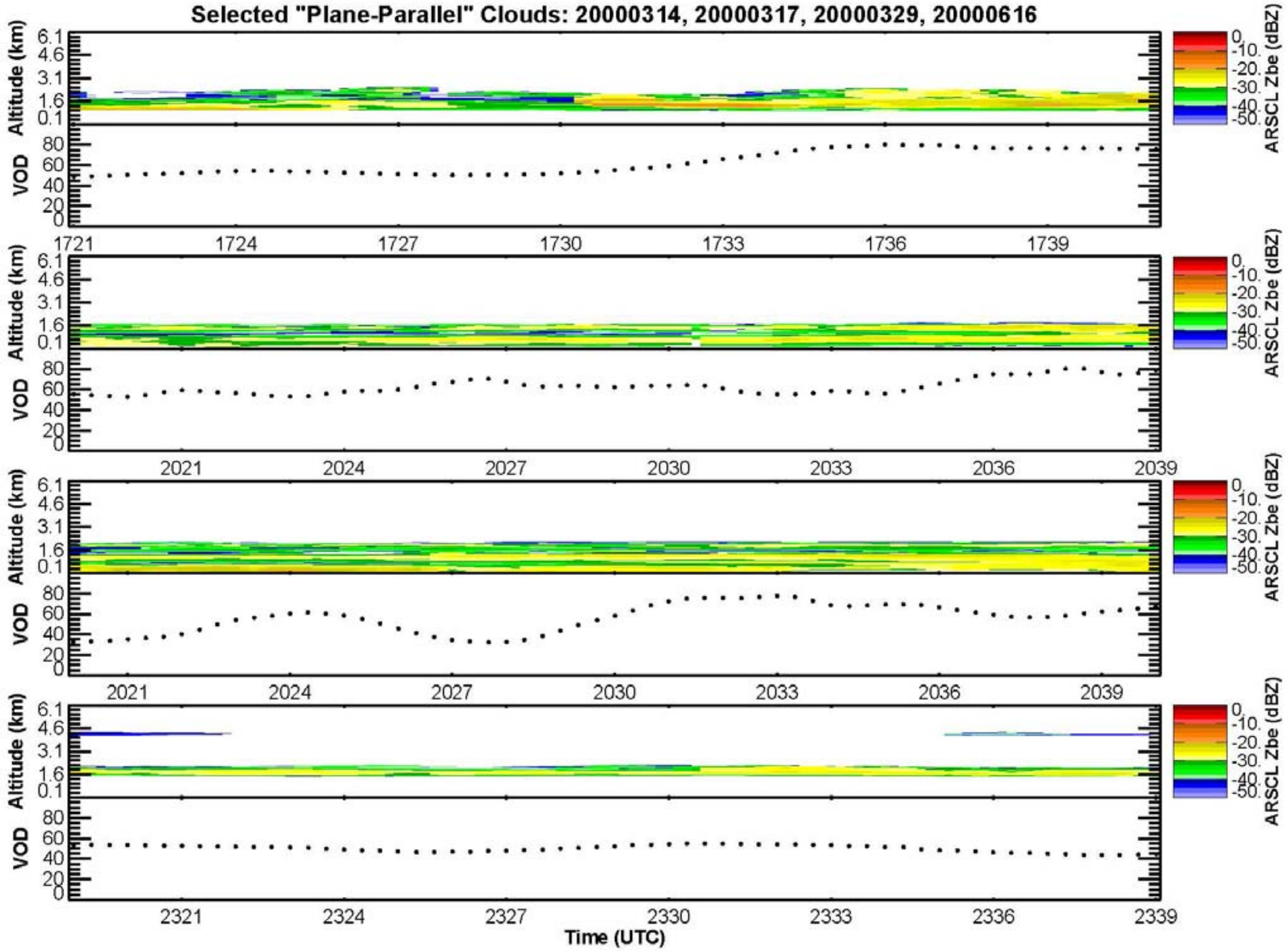

Figure 4. Radar reflectivities and visible optical depths for four “nearly plane-parallel” cases used for testing the retrieval algorithm.

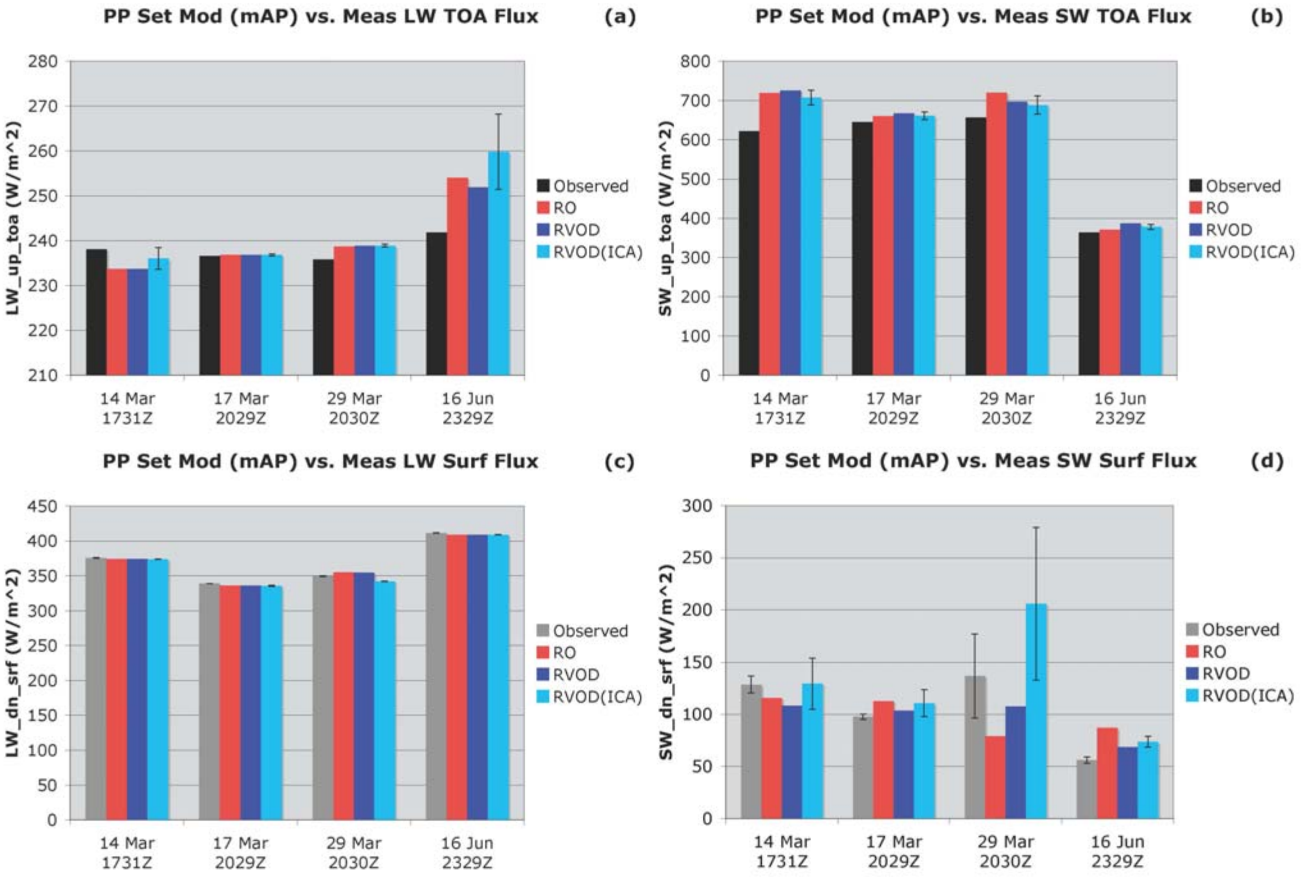

Figure 5. Comparison of measured and modeled radiative fluxes for four “nearly plane-parallel” cases, including RVOD with the independent column approximation.

Extended Evaluation: Liquid Cloud

Broadband heating rate profile (BBHRP) datasets have been produced for the entire year following the March 2000 Cloud IOP at the SGP site. These datasets allow an extended evaluation of the retrieval and radiative transfer algorithm. Using the BBHRP Pi version 1.2.2 results, thirteen liquid cloud cases were selected from the time period between March 2000 and February 2001. The cases were required to consist principally of liquid, single-layer clouds. Retrievals were performed both with the original *a priori* (oAP) values and the modified values (mAP) using both the RO and RVOD techniques. Fluxes were computed using BUGSrad and compared versus observations. Scatter plots of modeled versus measured fluxes are shown in Figure 6. The red ovals on the scatter plots highlight several extreme outliers in the comparisons. In panels (a) and (b), the upwelling shortwave and longwave fluxes at the top of the atmosphere for the outlier case are grossly overestimated and underestimated, respectively, by BUGSrad. The small figure to the left of panel (a) is the time series of ARSCL data for the highlighted cases and shows a short interval of high-level cloud overlying the low level cloud. Two factors may have contributed to the errors in the modeled fluxes. First, the retrieval treated this upper-level cloud as a liquid water cloud and so the retrieved size distribution parameters would have been incorrect. Second, the conversion to a plane-parallel profile for use by BUGSrad extended this cloud over the whole domain. Although the water contents are reduced appropriately, this sort of conversion generally produces scenes that are too reflective in the shortwave and that emit at too-cold temperatures in the longwave. Both of these errors are consistent with the highlighted data.

Similarly, in panels (c) and (d) the red ovals highlight outlying data and, as before, the small figure to the left of panel (c) shows the ARSCL time series associated with these data points. In this case, a data gap occurred in the ARSCL data. The radiative transfer model treated this as a case of fractional cloudiness and, in the conversion to a plane-parallel profile, converted the cloud to an overcast scene. The result was that the shortwave and longwave fluxes to the surface were underestimated and overestimated, respectively, by the model. For an optically thick cloud, these errors are not consistent with the conversion of the actual cloud to a plane-parallel representation with lower water content. However, the errors would be consistent if the actual 3D cloud field viewed by the radiation instruments was broken rather than overcast. Bias and scatter relative to the observations (excluding these outliers) are given in Table 3. Overall, the RVOD method gives smaller bias and scatter than does the RO method. The use of original or modified *a priori* values has little impact on the bias and scatter. This suggests that the retrieval results are being driven primarily by the observations rather than by the *a priori* values in these cases, which is desirable.

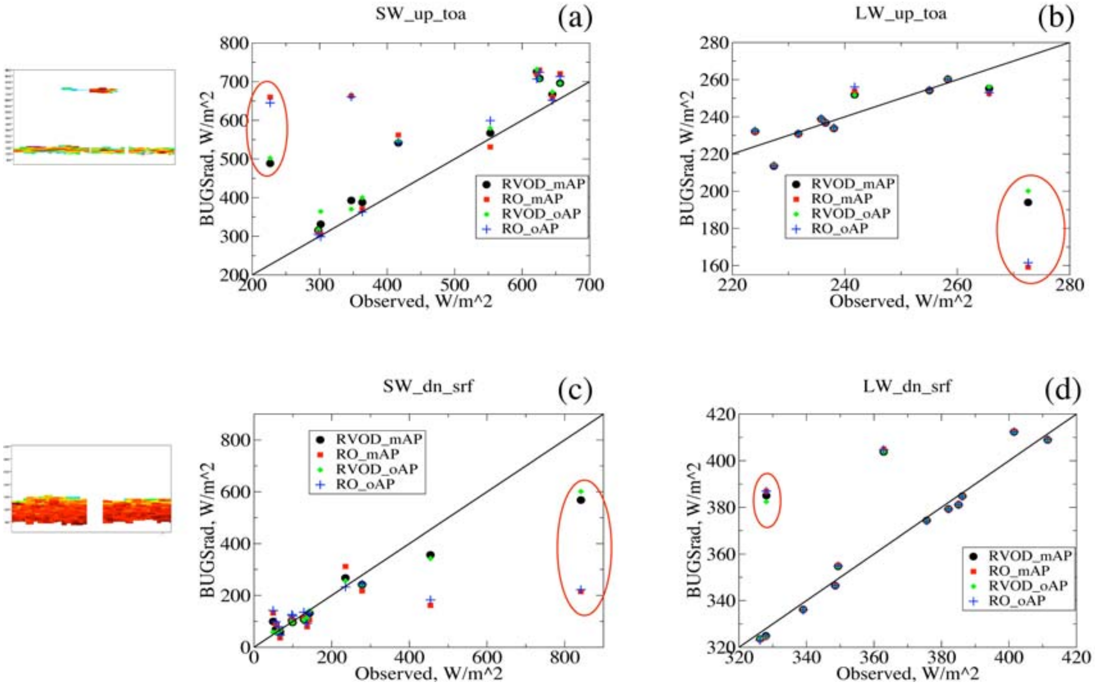

Figure 6. Scatter plots showing modeled versus observed radiative fluxes for 13 extended comparison liquid water cloud cases. The outliers circled in the upper plots (a and b) correspond to the radar reflectivity image to the left of plot (a). Similarly, the outliers circled in the lower plots (c and d) correspond to the radar reflectivity image to the left of plot (c).

Table 3. Comparison of bias (model - measurement) and scatter (in parentheses) for radiative fluxes computed for RO and RVOD retrievals performed on extended comparison liquid water cloud cases with either original (oAP) or modified (mAP) *a priori* values.

	Modeled Fluxes, Bias and Scatter vs. Observations			
	RO_oAP	**RO_mAP**	**RVOD_oAP**	**RVOD_mAP**
SW_dn_srf	-61.4 (190.9)	-69.9 (196.5)	-32.0 (75.2)	-29.2 (83.6)
LW_dn_srf	7.2 (20.4)	7.3 (20.5)	6.8 (19.2)	7.0 (19.9)
SW_up_toa	105.1 (168.5)	107.3 (174.3)	75.7 (104.7)	69.7 (99.1)
LW_up_toa	-10.4 (34.4)	-11.0 (35.0)	-6.9 (22.8)	-7.8 (24.7)

Extended evaluation: Ice cloud

Similar to the extended evaluation for liquid cloud, a corresponding evaluation was performed for ice cloud cases. Nine ice cloud cases were selected from the BBHRP datasets for the time period between March 2000 and February 2001. The primary criterion was that the cases consist predominantly of single-layer ice cloud. Retrievals were performed using both RO and RVOD techniques, fluxes were calculated using BUGSrad and compared versus observations. Scatter plots of fluxes are shown in Figure 7. The bias and scatter statistics (Table 4) suggest that while the RVOD technique somewhat improves the results in comparison to the RO technique for the upwelling top of the atmosphere fluxes, it has little influence on the downwelling fluxes at the surface. This issue remains to be explored further.

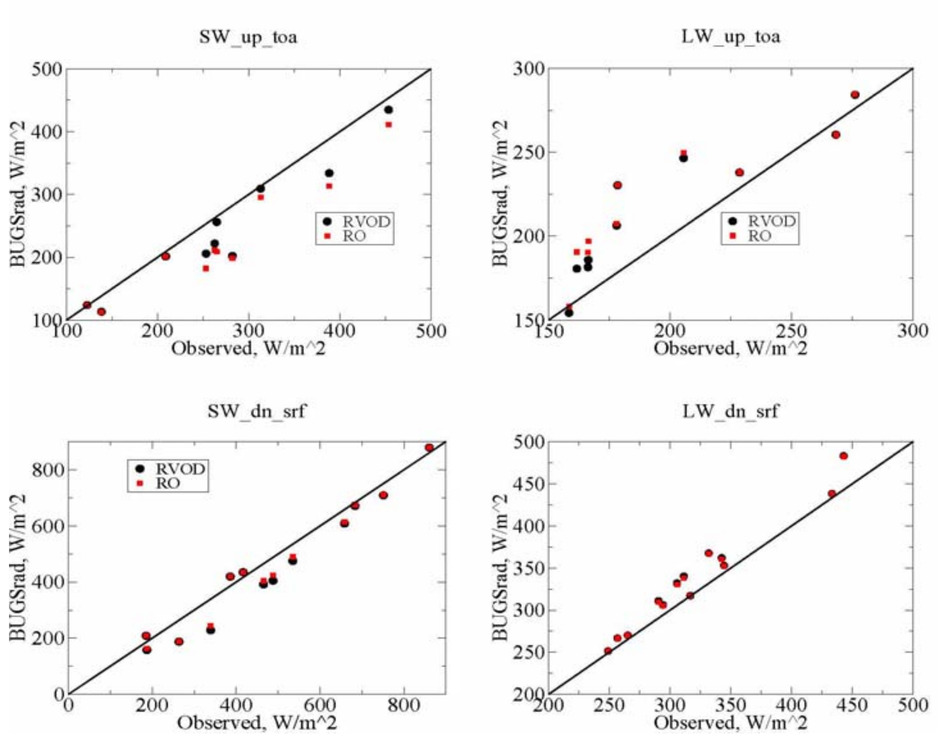

Figure 7. Scatter plots showing modeled versus observed radiative fluxes for 9 extended comparison ice water cloud cases.

Table 4. Comparison of bias (model - measurement) and scatter (in parentheses) for radiative fluxes computed for RO and RVOD retrievals performed on extended comparison ice water cloud cases.

Modeled Fluxes, Bias and Scatter vs. Obs.		
	RO	**RVOD**
SW_dn_srf	-31.58 (50.4)	-38.5 (58.5)
LW_dn_srf	16.9 (20.7)	17.7 (21.6)
SW_up_toa	-47.6 (53.8)	-31.8 (40.0)
LW_up_toa	25.2 (29.9)	20.9 (26.5)

Adding MWR Brightness Temperatures to Retrieval Inputs

The optimal estimation retrieval method lends itself well to the inclusion of additional datastreams. In this part, microwave brightness temperatures from the MWR are added to the RVOD algorithm. This modification requires the addition of the 23.8 GHz and 31.4 GHz brightness temperatures to the state vector and a forward model to simulate the brightness temperatures as a function of the vertical profile of liquid water contents. As an example, Figure 8 shows the radar reflectivity, along with time series of visible optical depth and microwave brightness temperatures for a one-hour period on 16 June 2000. The corresponding retrieved liquid water path (Figure 9) is moderately sensitive to assumptions regarding uncertainties in both the brightness temperatures and the radar reflectivity. A comparison of modeled versus measured shortwave and longwave fluxes downwelling at the surface (Figure 10) for two cases suggests that the inclusion of MWR brightness temperatures in the retrieval may provide improved performance.

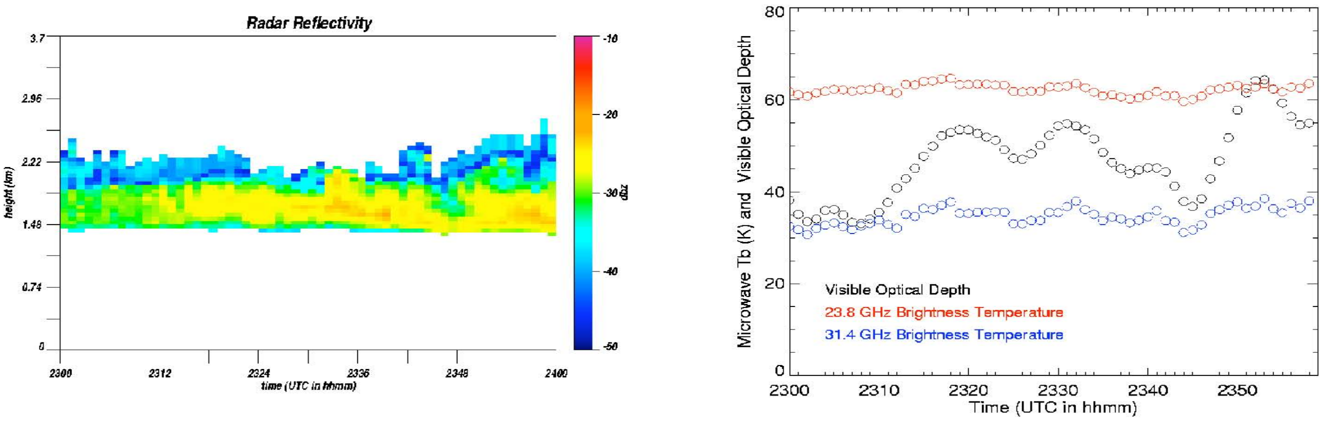

Figure 8. Example of time series of radar reflectivities, visible optical depth and microwave brightness temperatures from 16 June 2000.

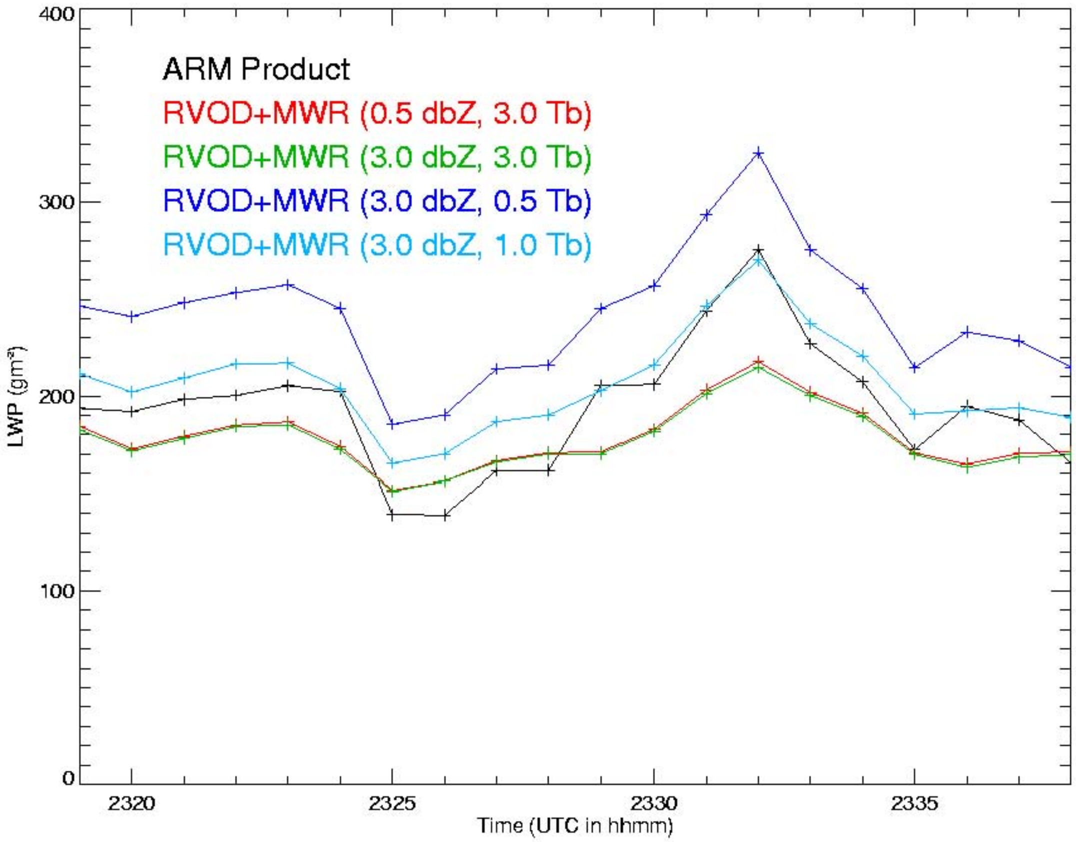

Figure 9. Comparison of time series of liquid water path from the RVOD retrieval augmented with microwave brightness temperatures. The legend shows the values (in parentheses) used for uncertainties in the MMCR reflectivities and microwave brightness temperatures).

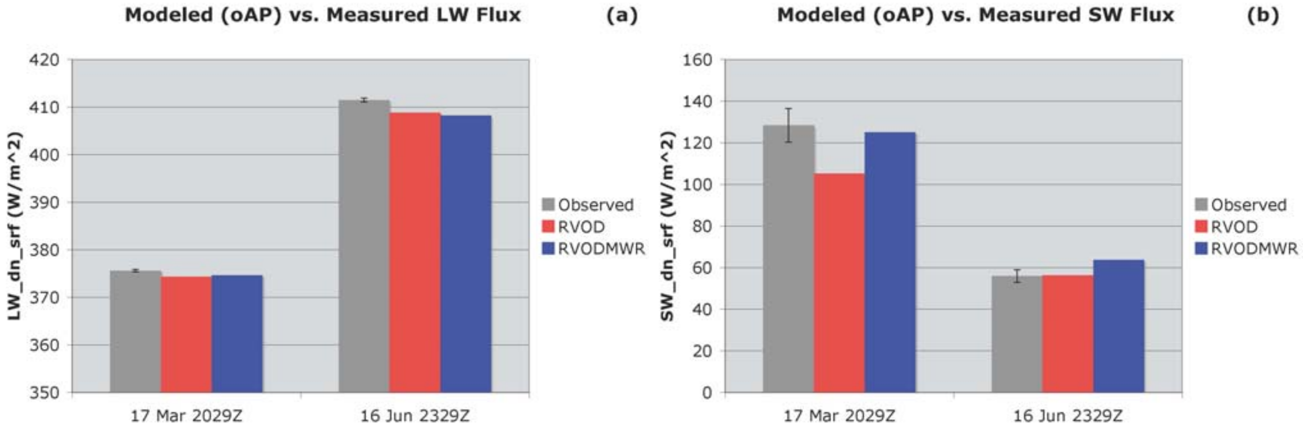

Figure 10. Comparison of measured and modeled radiative fluxes obtained using both the original RVOD retrieval and the RVOD retrieval augmented with microwave brightness temperatures.

Summary and Conclusions

In situ observations of cloud properties taken during the March 2000 Cloud IOP allowed the *a priori* assumptions used in the retrieval algorithms to be examined. Differences between the observed and assumed values were apparent. Retrievals using both the oAP and mAP values were performed and, for these cases, the differences do not appear to have a significant influence on radiative fluxes calculated using the retrieval results. This suggests that the results are well-constrained by the observations for these cases. Other cases, less well-constrained by the observations, might benefit from better *a priori* values.

In an extended evaluation of thirteen liquid cloud cases, the RVOD technique appears to produce improved results in comparison to the RO technique. Bias and scatter of modeled radiative fluxes relative to observations was smaller for the RVOD technique than for the RO technique. For nine ice cloud cases similarly evaluated, the RVOD technique produced smaller bias and scatter in upwelling fluxes than did the RO technique. A similar improvement was not noted in the downwelling fluxes. This result requires further examination of the performance of the retrieval and the radiative transfer algorithm for ice cloud cases.

Finally, a modification of the retrieval algorithm is tested in which MWR brightness temperatures are added to the observations used by the algorithm. The retrieval results are sensitive to assumptions about the uncertainties in the MMCR radar reflectivities and the MWR brightness temperatures. The modified algorithm is tested in the same manner as the original algorithm, by modeling radiative fluxes and comparing those fluxes with observations. For a pair of test cases, including the MWR brightness temperatures improved the flux comparisons in one case, and had little effect in the other. More extensive evaluation of the usefulness of the MWR brightness temperatures to the retrieval should be performed.

Acknowledgements

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