Cloud Products and the Evaluation of a Radiation Parameterization Scheme in Support of Broadband Heating Rate Profile

N. Wood, R. Austin, and G. Stephens
Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

Introduction

A fundamental measure of the successful retrieval of cloud microphysical properties lies in the application of those properties to reproduce observed radiative fluxes and heating rates, as seen in the recent broadband heating rate profile (BBHRP) value-added product (VAP) (Mlawer et al. 2004). By comparing measured values of surface and top-of-atmosphere radiative fluxes against values calculated using retrieved cloud microphysical profiles, the accuracy of the radiative transfer scheme and the microphysical retrievals can be determined.

For this work, we examine a series of clear-sky and cloudy domains structured to match those used by the BBHRP "instantaneous" product. Each domain consists of a 20-minute interval centered on a sonde launch time. The work proceeds with the following three domain types:

1. Clear sky
2. Cloudy, with BBHRP (MicroBase) microphysics
3. Cloudy, with CloudSat-derived microphysics

For each domain, radiative fluxes are calculated and the results are compared with those from BBHRP and observations. For (1) and (2), radiative transfer calculations are performed using an alternate radiative transfer scheme (BUGSrad), allowing this scheme to be compared with the rapid radiative transfer model (RRTM) employed by BBHRP. For (3), cloud microphysical properties are obtained from an alternate microphysical retrieval scheme (derived from algorithms being developed for CloudSat). BUGSrad is applied to these CloudSat-derived microphysics, and the results are compared with the BBHRP results obtained from MicroBase and RRTM.

Methods

Radiative Fluxes

Radiative transfer calculations are performed using BUGSrad (Stephens et al. 2001), a two-stream radiative transfer model that incorporates a correlated-k treatment for gaseous absorption, treats cloud optics via anomalous diffraction theory (including longwave scattering), and handles cloud overlap using the Overcast Random Method (ORM). The ORM used by BUGSrad conserves total cloud amount and can use information derivable from cloud radar observations regarding the vertical decorrelation lengths between cloudy layers (Stephens et al. 2004). For this work, BUGSrad was also modified to use aerosol optical properties and spectral surface albedos consistent with those used by RRTM.

Microphysical Retrievals

The cloud microphysical retrievals are performed using a set of algorithms (Austin and Stephens 2001) being developed for the CloudSat mission, modified to apply to ground-based cloud radar observations. The algorithms are based on an optimal estimation technique (Rodgers 2000) that uses both observations and a priori data to develop profiles of cloud properties and estimates of uncertainties in those properties.

The algorithms use cloud visible optical depth estimates and input profiles of cloud radar reflectivities from the Atmospheric Radiation Measurement (ARM) Atmospheric Remotely-Sensed Clouds Locations (ARSCL) VAP. The optical depths are obtained using a separate retrieval algorithm applied to multi-filter rotating shadowband radiometers (MFRSR) observations (Min et al. 2003). At nighttime, and when the cloud optical depth is not available, the cloud microphysical retrieval proceeds using only the cloud radar profiles.

The algorithms produce estimates of cloud water content and effective radius, along with estimates of the uncertainties in these quantities. Although not employed here, these uncertainty estimates will be used in future work to examine radiative flux closure.

Results

Clear Sky Domains

Approximately 45 clear sky domains were evaluated (Figure 1). RRTM and BUGSrad showed similar biases versus observations except for downwelling shortwave, for which BUGSrad exhibited larger biases than RRTM (Table 1). BUGSrad’s bias in downwelling shortwave appears related to direct beam aerosol scattering (Figure 2). Removing the delta-M scaling used by BUGSrad removes a significant part of the bias in the direct beam (Figure 3).

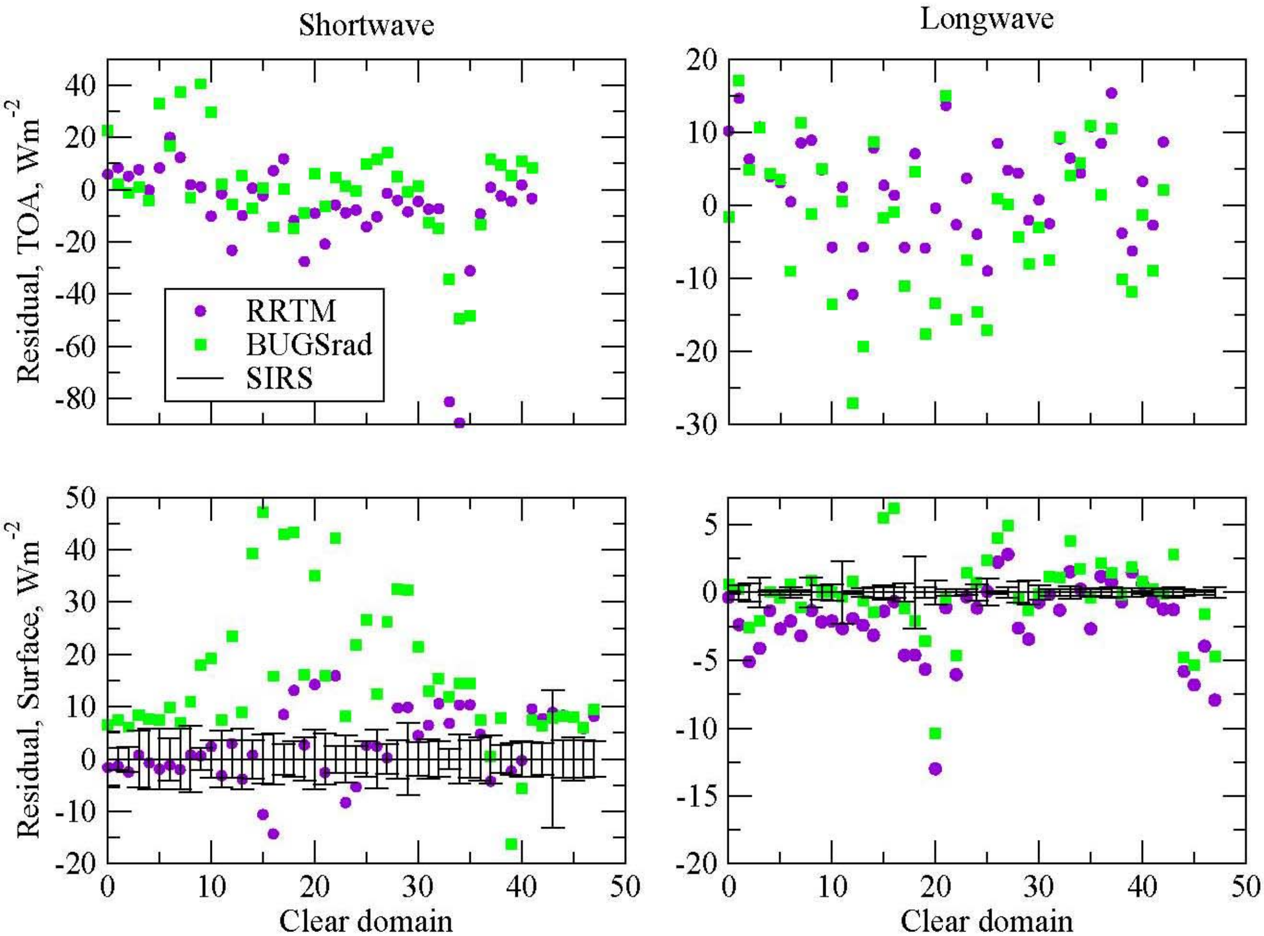

Figure 1. Residuals (RRTM, BUGSrad - observations) for clear-sky longwave and shortwave radiative fluxes at TOA and surface. Error bars for surface plots indicate standard deviations of surface measurements.

Table 1. Bias (rms) differences versus observations for clear-sky domains

		Shortwave	Longwave
TOA	RRTM	-7.76 (20.4)	2.95 (6.63)
	BUGSrad	1.18 (18.43)	-2.22 (10.2)
Surface	RRTM	2.90 (6.52)	-2.17 (2.85)
	BUGSrad	15.49 (13.2)	-0.09 (2.92)

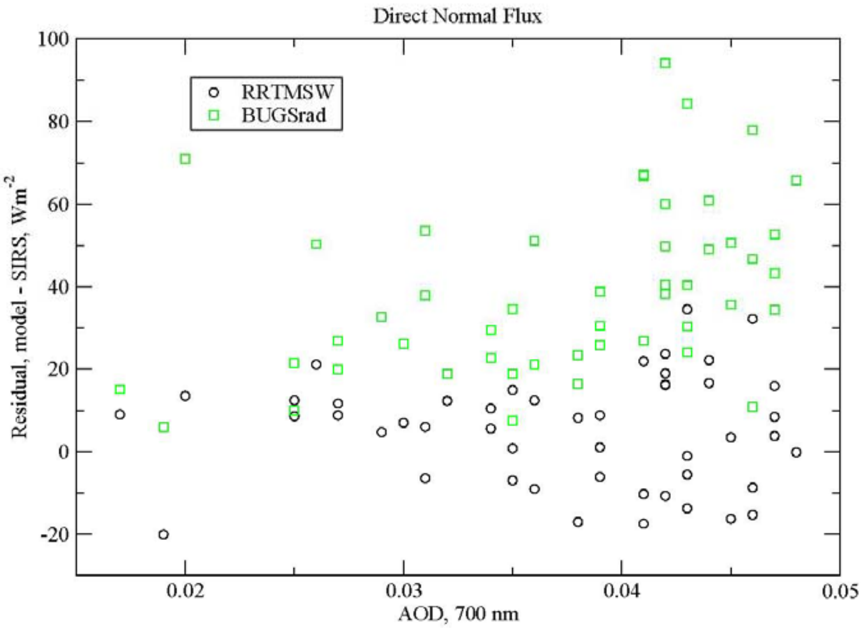

Figure 2. Residuals for clear-sky shortwave direct normal flux at the surface as a function of aerosol optical depth.

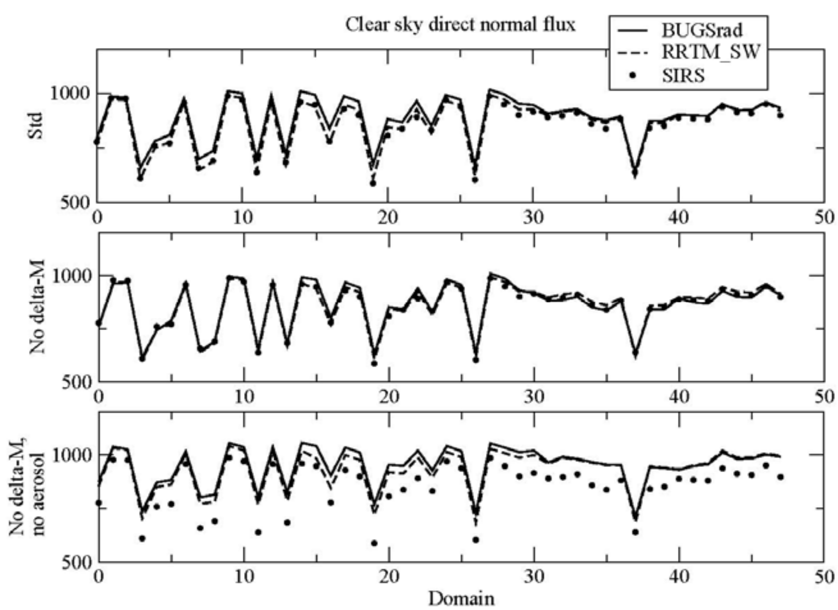

Figure 3. Clear-sky direct normal fluxes as observed (SIRS) and calculated by BUGSrad and RRTM_SW with (upper panel) standard delta-M scaling, (middle panel) no delta-M scaling, and (lower panel) no delta-M scaling and no aerosol.

Cloudy Domains, MicroBase Microphysics

Approximately 80 shortwave and 240 longwave domains were examined (Figure 4). BUGSrad and RRTM exhibit similar bias and scatter relative to observations (Table 2).

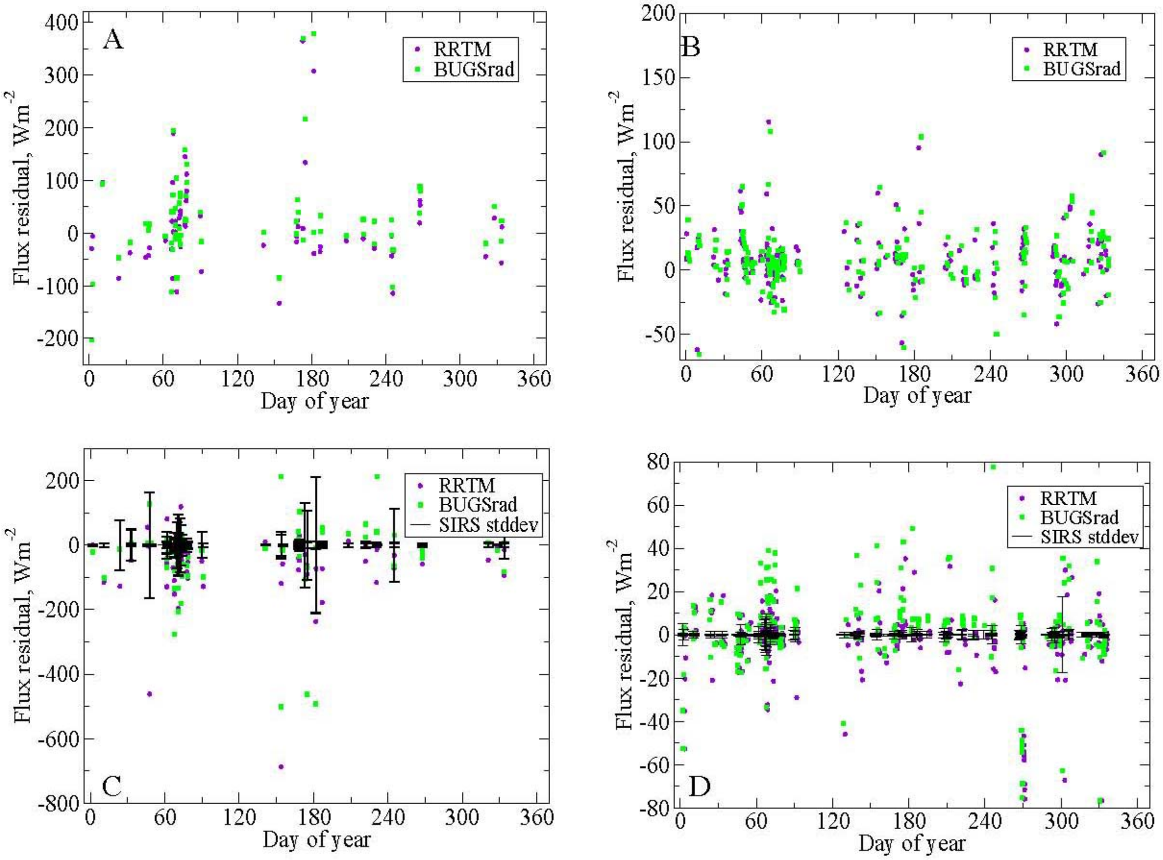

Figure 4. Radiative flux residuals for cloudy cases for RRTM and BUGSrad. (A) shortwave TOA, (B) longwave TOA, (C) shortwave surface, and (D) longwave surface.

Table 2. Bias (rms) differences versus observations for cloudy domains with MicroBase cloud properties.

		Shortwave	Longwave
TOA	RRTM	19.62 (98.96)	11.27 (20.85)
	BUGSrad	37.58 (107.0)	8.88 (22.42)
Surface	RRTM	-28.8 (144.6)	-4.97 (16.00)
	BUGSrad	-5.04 (158.9)	1.82 (18.42)

Cloudy Domains, CloudSat Microphysics

The CloudSat retrieval algorithms were applied to a set of selected domains, with selections focused on single-layer, low-level clouds. CloudSat liquid and ice water retrievals were applied with a simple temperature test for ice versus water. Comparisons versus MicroBase for BBHRP P_i v 1.2 were made for 25 domains with liquid water clouds. Cloud droplet effective radii were generally larger with the CloudSat microphysics versus MicroBase (Figure 5). Several anomalous domains require further analysis. In domains 168D and E, the CloudSat retrieval produced very large droplets in a low-level cloud with strong echos, probably indicative of drizzle rather than cloud. In domains 268A through 268H, the CloudSat algorithm identified low-level clouds with some deeper convective columns (Figure 6). MicroBase identified zero cloud fraction for these domains, probably classifying them as drizzle, while no sort of drizzle screening was applied to the CloudSat results.

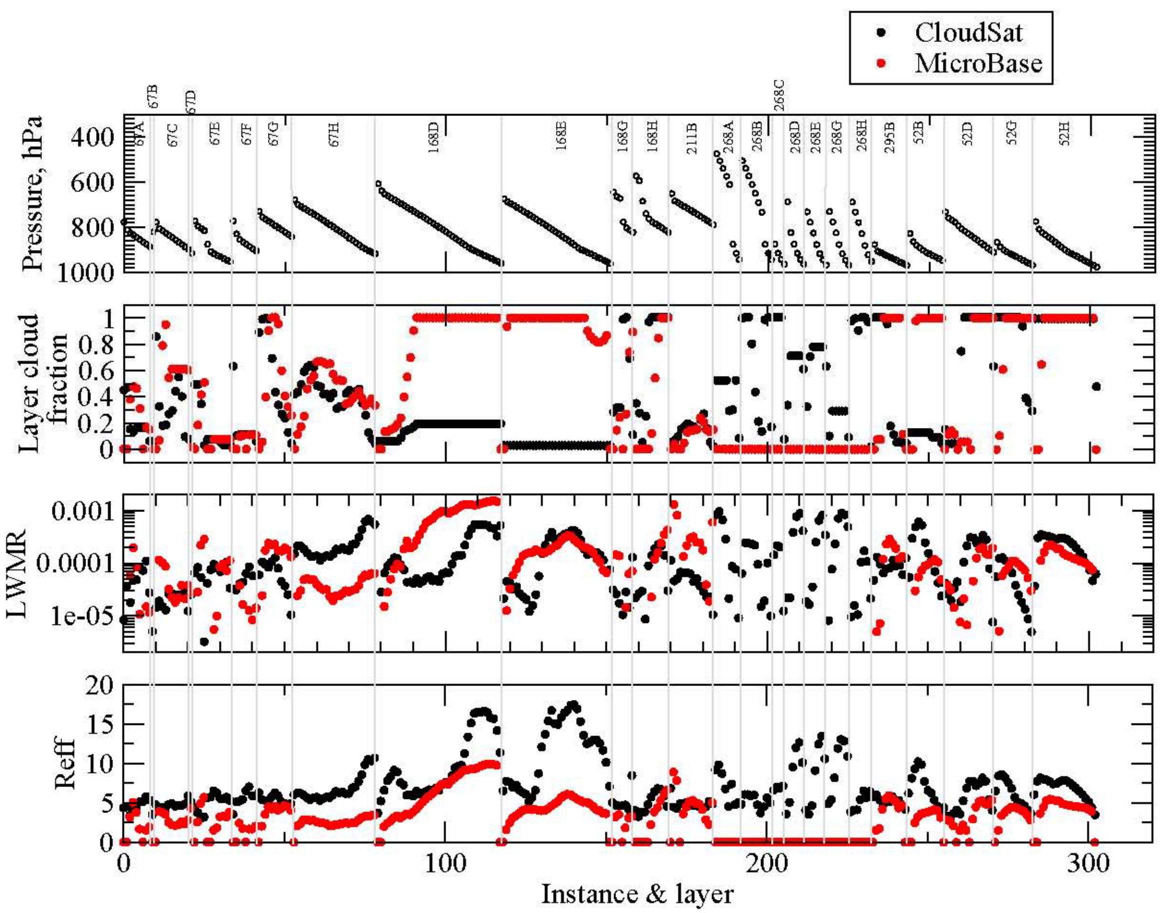

Figure 5. Liquid water cloud microphysical properties as retrieved by CloudSat and MicroBase. Vertical light-gray lines separate cloudy domains, and the individual points within each domain represent layer properties.

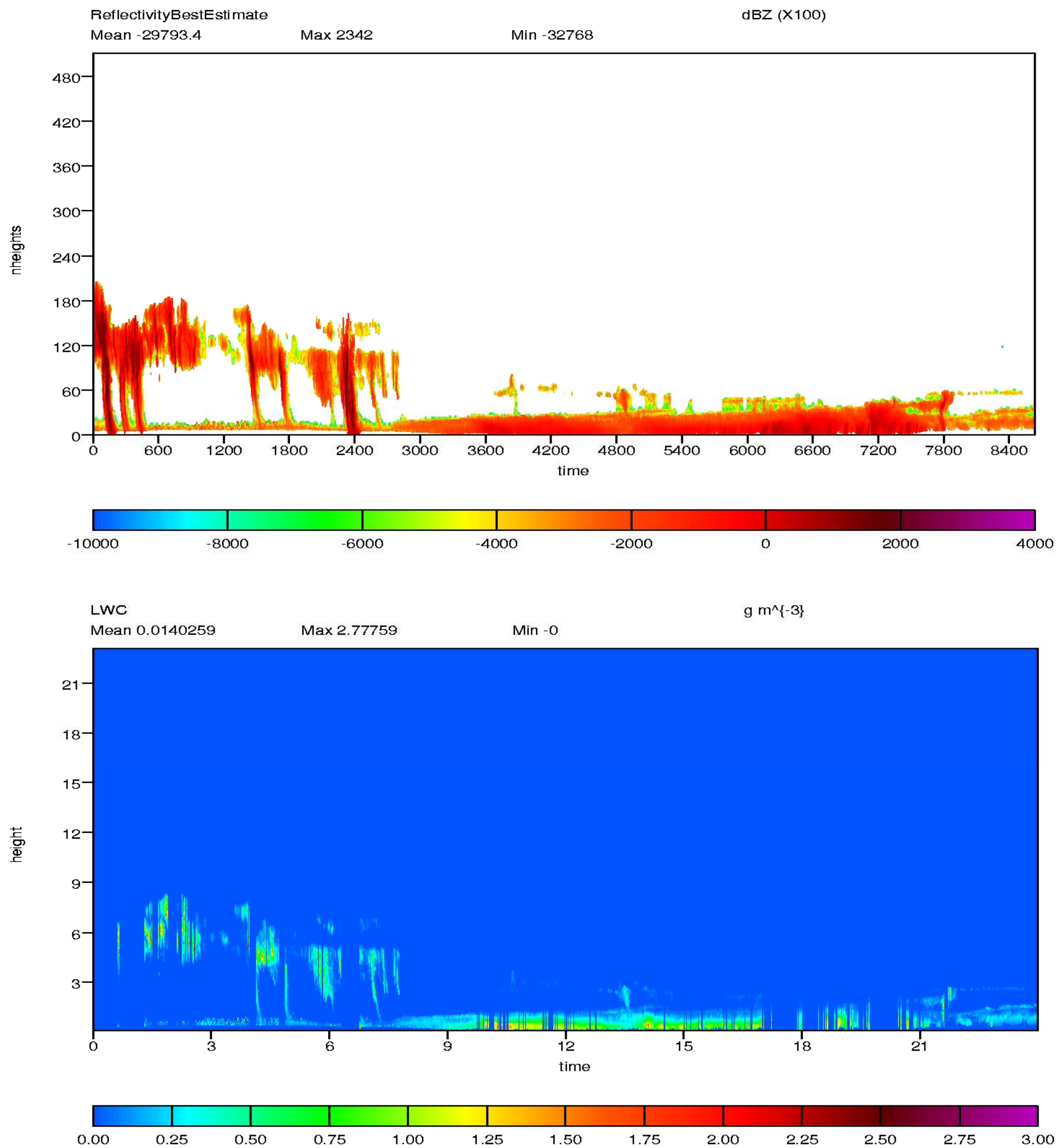

Figure 6. ARSCL reflectivity (upper panel) and CloudSat-retrieved liquid water contents (lower panel) for domain 268.

For ice clouds, 9 domains were evaluated. The CloudSat algorithm appears to retrieve higher ice water mixing ratios in the upper portions of clouds than MicroBase (Figure 7). The CloudSat retrievals for domains 67F and 52G showed extremely high ice water mixing ratios and effective radii, which should be examined further. For domain 52B, a midlevel cloud with strong radar echos occurred. The CloudSat algorithm produced reasonable ice water mixing ratios and effective radii, but cloud fraction was grossly underestimated.

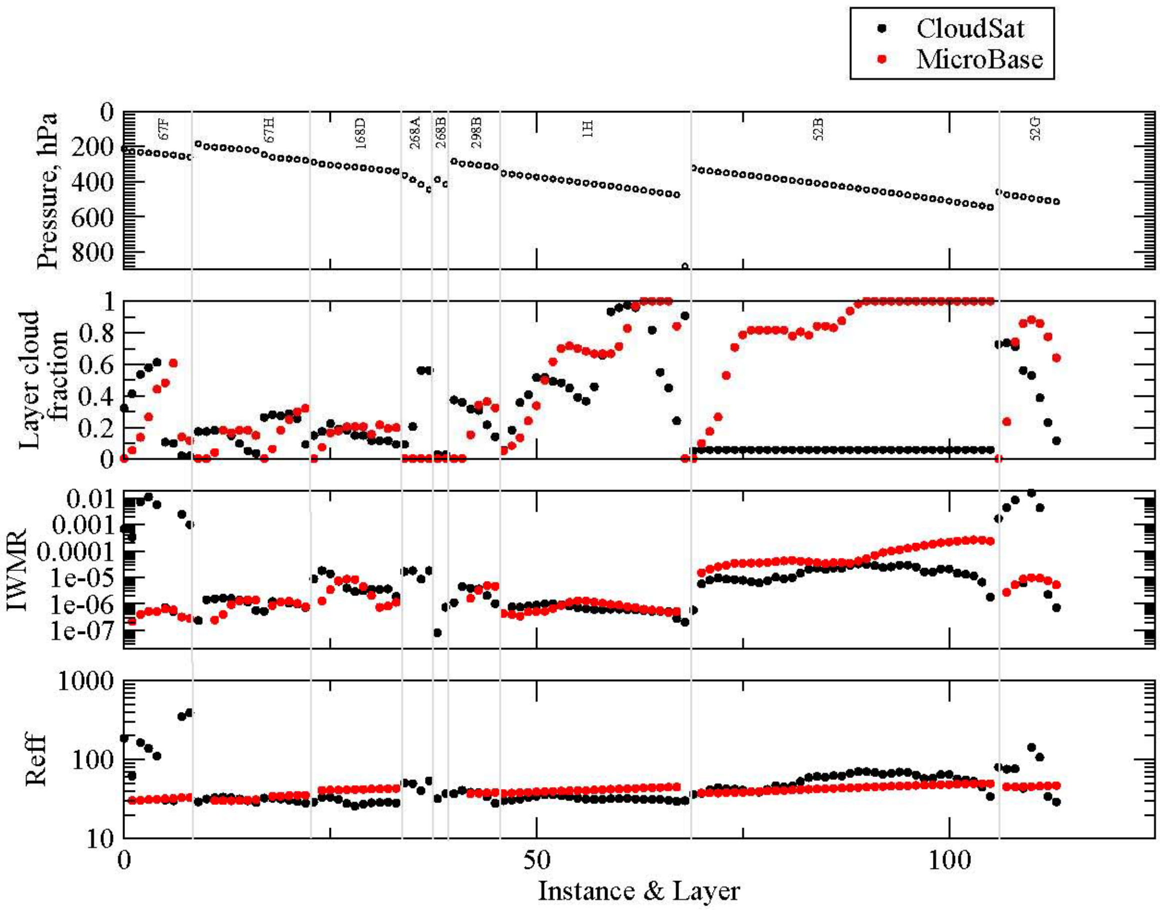

Figure 7. Ice water cloud microphysical properties, as retrieved by CloudSat and MicroBase. The arrangements of domains and layer properties are the same as in Figure 5.

Discussion

Two basic pieces of information are provided by the cloud retrievals: (1) the presence or absence of cloud in a particular radar range gate, and, if present, (2) the microphysical properties. In several of the anomalous cases described above, failure to retrieve microphysical properties resulted in severe underestimates of layer cloud fraction, which led to significant errors in the calculated radiative fluxes for liquid water (Table 3) and ice water clouds (Table 4).

Table 3. Comparison of RRTM and BUGSrad residuals versus observations for domains with water clouds.

		dF Surface, W/m^2				dF TOA, W/m^2			
Instance	**MB Class**	**Shortwave**		**Longwave**		**Shortwave**		**Longwave**	
		RR	BR	RR	BR	RR	BR	RR	BR
67A	W	-	-	-7.97	10.22	-	-	8.47	0.9
67B	W	-	-	-0.99	2.33	-	-	-	-
67C	W	-	-	7.48	1.9	-	-	8.55	4.47
67D	W	-	-	1.27	7.12	-	-	2.53	3.88
67E	W	-71.93	-63.49	-14.88	13.54	-85.84	-51.13	12	3.04
67G	W	-152.01	-8.97	9.82	10.15	190.02	103.33	3.99	-3.74
67H	M	-13.71	-17.5	16.07	37.44	2.4	55.87	120.32	100.97
168H	M	-6.59	46.94	-4.8	-2.54	12.24	15.98	25.85	13.25
211B	W	-	-	5.22	24.23	-	-	10.92	-2.28
295B	M	-	-	2.7	0.15	-	-	2.21	-2.4
1H	O	-	-	-36.41	-35.03	-	-	31.18	39.54
52D	M	-	-	-12.79	-11.41	-	-	8.69	0.57
52H	M			3.64	5.81	-	-	11	8.54

Table 4. Comparison of RRTM and BUGSrad residuals versus observations for cloudy domains with ice clouds

		dF Surface, W/m^2				dF TOA, W/m^2			
Instance	**MB Class**	**Shortwave**		**Longwave**		**Shortwave**		**Longwave**	
		RR	**BR**	**RR**	**BR**	**RR**	**BR**	**RR**	**BR**
67F	M	-109.74	-382.8	-1.88	33.97	96.52	307.63	-5.88	-156.56
168D	M	-	-	-8.06	-6.8	-	-	54.67	51.01
168E	W	-47.43	523.43	3.18	-14.19	23.7	-364.89	10.02	15.52
268A	O	-	-	-48.11	6.62	-	-	28.6	-19.34
268B	O	-	-	-52.3	-2.6	-	-	-	-
268C	O	-	-	-55.38	-4.34	-	-	16.9	13.71
268D	O	-	-	-57.38	-7	-	-	16.44	10.06
268E	O	-	-	-59.11	-1.64	-	-	-	-
268F	O	-	-	-72.82	-69.44	-	-	23.97	24
268G	O	-	-	-77.13	0.79	-	-	35.31	22.2
268H	O	-	-	-70.13	-2.18	-	-	23.89	7.31
52B	M	-	-	-3.32	-5.35	-	-	8.86	68.13
52G	M			-3.56	-0.3	-	-	0.09	-52.3
MB Class = MicroBase Classification (Water, Mixed, Outlier)									
RR = RRTM residual									
BR = BUGSrad residual									

A more meaningful comparison of the retrievals can be made in those cases where the cloud fractions are in better agreement. For this limited sample, the CloudSat algorithm results in less scatter (Table 5). Given similar performance from the radiative transfer schemes (e.g., 3.2 above), this suggests that using cloud optical depth information with cloud radar reflectivity profiles in an optimal estimation technique provides improved estimates of cloud microphysical properties when compared to MicroBase retrieval methods.

Table 5. Bias (rms) differences versus observations for cloudy domains with similar CloudSat and MicroBase cloud fractions.

		Shortwave	Longwave
TOA	RRTM	29.70 (115.6)	20.5 (32.6)
	BUGSrad	31.0 (65.4)	13.9 (29.8)
Surface	RRTM	-61.1 (67.3)	-2.43 (13.48)
	BUGSrad	-10.76 (45.3)	4.96 (17.13)

Conclusions

- Clear-sky comparisons revealed a bias in the BUGSrad direct beam calculation that appears to be related in part to aerosol optical depth.

- Under cloudy conditions, BUGSrad and RRTM exhibited similar error characteristics

- Estimates of shortwave fluxes were improved by the use of a CloudSat-like optimal estimation retrieval which integrates radar and cloud optical depth observations. The limited number of domains examined here are being expanded

- Accurate cloud fraction estimates are of paramount importance if accurate flux and heating rate profiles are to be obtained. This suggests that the determination of cloud presence (for the purpose of calculating cloud fraction) may need to be treated separately from the cloud microphysical retrieval.

- Future work will also incorporate the uncertainties in the cloud microphysical properties provided by the CloudSat algorithms.

Acknowledgements

The work described here was supported under the Department of Energy, Office of Science, Biological and Environmental Sciences Division under grant DE-FG03-94ER61748 of the Atmospheric Radiation Measurement Program. We appreciate the assistance of Eli Mlawer, Mark Miller, and Tim Shippert in making available the BBHRP and MicroBase results.

Corresponding Author

Norman Wood, nbwood@lamar.colostate.edu, phone: 970-491-8480.

Publications Derived from this Research

Barker HW, GL Stephens, PT Partain, JW Bergman, B Bonnel, K Campana, EE Clothiaux, S Clough, S Cusack, J Delamere, J Edwards, KF Evans, Y Fouquart, S Freidenreich, V Galin, Y Hou, S Kato, J Li, E Mlawer, JJ Morcrette, W O'Hirok, P Raisanen, V Ramaswamy, B Ritter, E Rozanov, M Schlesinger, K Shibata, P Sporyshev, Z Sun, M Wendisch, N Wood, F Yang. 2003. "Assessing 1D atmospheric solar radiative transfer models: Interpretation and handling of unresolved clouds." *Journal of Climate* 16(16), 2676-2699.

Luo, Z, and GL Stephens. 2005. "Characterization of the upper tropospheric temperature, moisture and cloud biases of a climate model using satellite observations." *Journal of Climate* submitted

Stephens, GL, NB Wood, and P Gabriel. 2004. "An assessment of the parameterization of sub-grid scale cloud effects on radiative transfer, I: Vertical overlap." *Journal of Atmospheric Science* 61, 715-732.

Stephens, GL and NB Wood. 2005. "Properties of tropical convection observed by millimeter-radar systems." *Journal of Atmospheric Science* in preparation.

Wood, NB, P Gabriel, and GL Stephens. 2005. "An assessment of the parameterization of sub-grid scale cloud effects on radiative transfer, II: Horizontal inhomogeneity." *Journal of Atmospheric Science* accepted.

Wood, NB, GL Stephens, and R Austin. 2005. "Evaluation of a radiation parameterization scheme using ARM data." *Journal of Atmospheric Science* in preparation.

Related Publications

Stephens, GL. 2004. "Cloud feedback in the climate system: A critical review." *Journal of Climate* 18, 237-273.

Stephens, G.L, PL Webster, RH Johnson, R Engelen, and TS L'Ecuyer. 2004. "Observational evidence for the mutual regulation of the tropical hydrological cycle and tropical sea surface temperatures." *Journal of Climate* 17, 2213-2224.

References

Austin, RT and GL Stephens. 2001. "Retrieval of stratus cloud microphysical parameters using millimetric radar and visible optical depth in preparation for CloudSat, Part I: Algorithm formulation." *Journal of Geophysical Research* 106, 28233-28242.

Mlawer, EJ, TR Shippert, CN Long, MA Miller, KL Johnson, DT Troyan, GG Mace, SA Clough, MH Zhang, SC Xie, RT Cederwall, JJ Yio, DR Doelling, DA Rutan, DD Turner, R Ferrare, JA Ogren, AP Trishchenko, Y Luo, Z Li, JJ Michalsky, RG Ellingson, EE Takara, and JS Delamere. 2004. "Status of the Broadband Heating Rate Profile (BBHRP) VAP." In *Proceedings, Fourteenth ARM Science Team Meeting*, Albuquerque, New Mexico, March 22-26.

Min, Q-L, M Duan, and R Marchand. 2003. "Validation of surface retrieved cloud optical properties with in situ measurements at the Atmospheric Radiation Measurement Program (ARM) South Great Plains site." *Journal of Geophysical Research* 108, 4547.

Rodgers, CD, 2000. "Inverse methods for atmospheric sounding." World Scientific Publishing Company Pte. Ltd., Singapore. 238 pp.

Rodgers, CD, 2000. *Inverse Methods for Atmospheric Sounding: Theory and Practice*. Vol. 2, *Series on Atmospheric, Oceanic and Planetary Physics*. World Scientific Publishing Company Private. Ltd.: Singapore. 238 pp.

Stephens, GL, PM Gabriel, and PT Partain. 2001. "Parameterization of atmospheric radiation transfer, Part I: Validity of simple models." *Journal of Atmospheric Science* 58, 3391-3409.

Stephens, GL, NB Wood, and PM Gabriel. 2004. "An assessment of the parameterization of sub-grid scale cloud effects on radiative transfer, Part I: Vertical overlap. *Journal of Atmospheric Science* 61, 715-732.