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An evaluation of operational GOES-derived single-layer cloud top heights with ARSCL data over the ARM Southern Great Plains Site

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[1] Cloud top heights retrieved from Geostationary Operational Environmental Satellite (GOES) data are evaluated using comparisons to 5 years of surface-based cloud radar and lidar data taken at the Atmospheric Radiation Measurement (ARM) program's site near Lamont, Oklahoma. Separate daytime and nighttime algorithms developed at NASA Langley Research Center (LaRC) applied to GOES imager data and an operational CO_2-slicing technique applied to GOES sounder data are tested. Comparisons between the daytime, nighttime and CO_2-slicing cloud top heights and the surface retrievals yield mean differences of -0.84 ± 1.48 km, -0.56 ± 1.31 km, and -1.30 ± 2.30 km, respectively, for all clouds. The errors generally increase with increasing cloud altitude and decreasing optical thickness. These results, which highlight some of the challenges associated with passive satellite cloud height retrievals, are being used to guide development of a blended LaRC/CO_2-slicing cloud top height product with accuracies suitable for assimilation into weather forecast models. **Citation:** Smith, W. L., Jr., P. Minnis, H. Finney, R. Palikonda, and M. M. Khaiyer (2008), An evaluation of operational GOES-derived single-layer cloud top heights with ARSCL data over the ARM Southern Great Plains Site, *Geophys. Res. Lett.*, *35*, L13820, doi:10.1029/2008GL034275.

1. Introduction

[2] Clouds are a significant element in the Earth-atmosphere system and constitute one of the largest sources of uncertainty in predicting climate change [*Wielicki et al.*, 1995; *Intergovernmental Panel on Climate Change*, 2001]. Because they play a critical role in the Earth's heat balance and affect weather, an accurate characterization of cloud boundaries is needed to specify their radiative impact and determine the distribution of condensed water in the atmosphere. Cloud top height information derived from GOES is routinely assimilated into Numerical Weather Prediction (NWP) analyses [*Baylor et al.*, 2000; *Benjamin et al.*, 2004] and is particularly valuable for the transportation industry, including aviation, because it provides improved analyses and forecasts of the locations of low clouds, fog, icing conditions and thunderstorms, for example. For these and other reasons, there is a high priority placed on accurately monitoring the horizontal and vertical distribution of clouds from satellites.

[3] The purpose of this paper is to evaluate cloud top height estimates made from a set of algorithms developed at LaRC. The algorithms, described by *Minnis et al.* [1995], were developed for application to Moderate Resolution Imaging Spectroradiometer (MODIS) data to provide critical information on cloud properties for the Clouds and the Earth's Radiant Energy System (CERES) experiment. The methods have been adapted for application to GOES and other satellites to produce long-term records of cloud and radiation parameters at high spatial and temporal resolution across the globe for the Atmospheric Radiation Measurement (ARM) [*Ackerman and Stokes*, 2003] and other programs [*Minnis et al.*, 2004]. In addition, the LaRC nighttime algorithm, described briefly in the next section, has been adopted as the baseline algorithm for the next GOES-R series satellite program. Nearly 5 years of cloud top height retrievals from GOES over the ARM Southern Great Plains (SGP) site provide the basis for this study. Cloud top height estimates from surface-based radar and lidar at the ARM SGP Central Facility (CF) near Lamont, Oklahoma serve as ground truth. Operational CO_2-slicing estimates from the GOES sounder are also compared to examine the relative strengths and weaknesses of each technique and to guide the future development of a blended LaRC/CO2 slicing cloud top height product for data assimilation.

2. Data and Methodology

2.1. Satellite Data

[4] Cloud top heights deduced from GOES are determined using several techniques. The 4-channel VISST (Visible Infrared Solar-infrared Split-window Technique), an updated version of the 3-channel algorithm described by *Minnis et al.* [1995] is employed during the daytime. At night, the SIST (Solar-infrared Infrared Split-window Technique) is used [*Minnis et al.*, 1995; *Smith et al.*, 1996]. Both VISST and SIST match theoretically computed radiances with the satellite radiance observations to retrieve cloud parameters, including effective particle size, optical depth (τ), emissivity (ε), and effective cloud temperature (T_e). For optically thick clouds ($\tau > 6$), T_e is equivalent to the atmosphere-corrected 11-μm brightness temperature (T_{11}) and assumed to represent the cloud top temperature (T_t). Hereafter, these cases are denoted as IRONLY since T_t is based solely on the 11-μm temperature. For optically thin clouds, T_e is less than T_{11} and expected to lie between the true cloud base and top temperatures since the cloud transparency is taken into account based on ε. Empirical formulae [*Minnis et al.*, 1990a] are applied to T_e to account

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for the effective emission depth and estimate T_t for thin clouds. To date, no such correction is employed for optically thick clouds. For middle and high level ice clouds, cloud effective height (Z_e) and top height (Z_t) are computed from T_e, and T_t using a local temperature profile obtained from a corresponding Rapid Update Cycle (RUC) model analysis [*Benjamin et al.*, 2004]. For low-level water clouds, a simple lapse rate derived from aircraft data, −7.1 K/km [*Minnis et al.*, 1992] is anchored to the RUC surface temperature to determine Z_e and Z_t from T_e. The lapse rate method substitutes for the RUC sounding since the true inversion temperature is often poorly characterized in radiosonde and model sounding data. *Dong et al.* [2008] discuss the rationale for this technique in some detail and show that typical cloud-top height overestimates of ~1 km or more found using model soundings for temperature to height conversion, are significantly reduced with the lapse rate technique.

[5] Radiances taken at 0.63, 3.9, 10.8 and 12.0 μm from the GOES-8 and GOES-10 imagers at 4-km resolution were analyzed with VISST and SIST in a 25-km radius region centered at the ARM CF every 30 minutes from January 2000 through December 2004. GOES-8 at 75°W was replaced by GOES-10 at 135°W in this analysis beginning 1 April 2003. GOES-12 data were not used due to the absence of the 12.0-μm channel needed for SIST.

[6] The LaRC cloud top height estimates are evaluated relative to the common CO_2-slicing technique [e.g., *Chahine*, 1974; *Smith et al.*, 1974] by utilizing results from an operational single field of view (FOV) CO_2-slicing dataset similar to that described by *Hawkinson et al.* [2005] (hereinafter referred to as HFA), for the period March 2000 to April 2002. *Schreiner et al.* [2001] and *Bedka et al.* [2007] demonstrated that CO_2-slicing applied to the GOES sounder yields cloud-top height underestimates of ~1.5 km on average. In practice, a CO_2-slicing retrieval is not performed for low clouds due to signal-to-noise considerations [*Schreiner et al.*, 2001]. In those cases, the height is determined with the IRONLY method and a local temperature profile from a NWP analysis.

2.2. Surface Data

[7] To evaluate satellite-derived cloud top heights over the ARM SGP, the satellite estimates are compared to the active remotely sensed cloud (ARSCL) product [*Clothiaux et al.*, 2000]. The ARSCL cloud boundaries (top and base for up to 10-levels) are objectively determined at vertical and temporal resolutions of 45 m and 10 s, respectively, using a combination of ARM CF Micro-Pulse Lidar (MPL) and Millimeter Cloud Radar (MMCR) data. The study by *Clothiaux et al.* [2000] and subsequent studies by *Intrieri et al.* [2002], *Gultepe et al.* [2004], and others have shown that the integration of lidar and radar datasets is critical to obtaining accurate cloud boundary estimates from active sensors since the two instruments have different but complementary sensitivities to the cloud particle size distribution. The ARSCL product is assumed to provide the most accurate remotely sensed vertical characterization of cloud boundaries from surface sensors to date, although errors are known to exist due to beam attenuation, rain, non-hydrometeor clutter such as insects, and instrument failure [*Clothiaux et al.*, 2000]. Data quality flags help reduce the impact of some of these uncertainties on the current comparisons. Here, the ARSCL product is assumed to be the 'ground truth' in the comparisons. It is recognized that the ARSCL cloud top heights represent a lower bound on the true cloud top heights.

2.3. Matching Procedure

[8] The data were carefully screened and averaged in time and space to maximize the likelihood that the surface and satellite systems viewed the same cloud volume. Therefore, only single-layer, overcast cloud scenes with uniform top heights are considered. The matching procedure adopted here is similar to that reported by HFA. The 10-s ARSCL data are averaged over a 10-minute period centered at the times when the GOES scans across the ARM CF. We consider only the cases when (1) both the MPL and MMCR are operational, (2) the ARSCL cloud-top height is determined from the MMCR, (3) the ARSCL-retrieved clouds observed during the 10-minute averaging period consisted only of single-layer clouds, (4) the cloud fraction in the 25-km radius GOES averaging area exceeds 0.95, and (5) at least 66% of the MMCR-determined cloud top heights were within 500 m of each other (the uniformity check).

3. Results and Discussion

[9] Figure 1 depicts the time series of radar reflectivity with an overlay of VISST, SIST and CO_2-slicing cloud height retrievals at the CF on January 10, 2002. Of the points shown, 75% satisfied the matching criteria described above and are included in the bulk statistics shown later. This example shows a cloud system that is primarily single layer and persists for nearly 24 h. At night (0–12 UTC), the mean optical depth determined from SIST is 2.6 with a standard deviation of 2.0. The SIST cloud-top height retrievals yield a mean difference of -0.63 ± 0.69 km. For this case, the CO_2-slicing algorithm does not perform as well as the SIST and yields a mean difference of -1.99 ± 2.05 km. During the daytime, the cloud system thickens; the mean VISST optical depth is 9.4 ± 4.8. The CO_2-slicing and VISST cloud top height errors are comparable, -1.69 ± 2.10 km and -1.72 ± 1.91 km, respectively. These large biases for an optically thick single layer cloud system illustrate one shortcoming of passive satellite cloud top height retrievals. Since the advent of the cloud radar and lidar, it has become clear that even deep convective clouds with large optical depths often radiate at effective temperatures significantly warmer than the cloud top temperature, yielding cloud top height underestimates of 1–2 km [*Sherwood et al.*, 2004]. One partial explanation is that the ice water content in the tops of these clouds, like those in thinner cirrus clouds, may decrease with decreasing temperature [e.g., *Heymsfield and Platt*, 1984] resulting in lower extinction [e.g., *Minnis et al.*, 1990b]. The condensed water content in liquid clouds is typically much greater than the ice water content in ice clouds and, therefore, their extinction is much larger. Thus, in most cases, the IRONLY technique will only yield accurate cloud top temperatures for optically thick liquid water clouds since they radiate effectively at or near the temperature of the physical cloud top.

[10] Figure 2 shows the scatter plot and linear regression line for 2,813 matched cloud-top heights from the LaRC

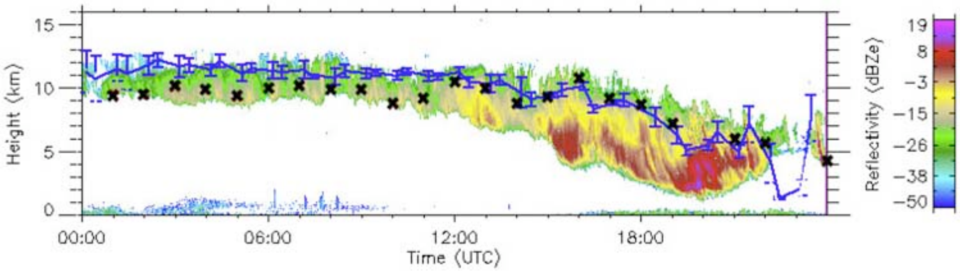

Figure 1. GOES-derived cloud top heights for the LaRC algorithms (blue) and operational CO_2-slicing algorithms (black) superimposed over Radar reflectivity images at the ARM SGP on January 10, 2002. Sunrise at 13:40 UTC. Radar image courtesy of G. Mace at the University of Utah.

GOES and ARSCL datasets between April 2000 and September 2004. Overall, there is reasonable agreement with a mean difference of -0.78 ± 1.53 km. The correlation coefficient is 0.94 and the standard deviation of the fit is 1.29 km. Similar statistics are computed for the single FOV CO_2-slicing retrievals published by HFA but screened with the filtering procedure described above (scatter plot not shown for brevity). This procedure appears to be more conservative than that used by HFA since 942 of the 1,511 points analyzed by HFA were removed. The mean difference between the 569 CO_2-slicing and ARSCL cloud top heights is -1.30 ± 2.30 km. The standard deviation of the fit is 1.67 km and the correlation coefficient is 0.864. With the exception of the larger RMS found here, these results are similar to those reported by HFA. For consistency, the LaRC retrievals were also analyzed for the same 2-year period as by HFA but the cloud top height errors were found to be nearly identical (within ~150 m) to those found for the five year period shown in Figure 1. Table 1 summarizes those statistics along with those shown in Figures 1 and 2. Similar statistics were computed for Z_e to examine the impact of the empirical corrections applied in the LaRC algorithms to obtain Z_t but are not shown in Table 1. The mean $Z_e - Z_{ARSCL}$ difference for the 2000–2002 time period is -1.38 ± 2.05 km, which is comparable to the CO_2-slicing results but about 0.5 km worse on average than the LaRC Z_t results. Considering only optically thin clouds, the empirical corrections make about a 1.0 km improvement.

[11] Cloud top height errors for VISST, SIST and CO_2-slicing, stratified by cloud-top level (low: 0–3 km, mid: 3–7 km, and high: 7+ km) are shown in Table 2. The biases generally increase with increasing altitude for all three algorithms. The LaRC nighttime algorithm (SIST) is the best performer overall, especially for high clouds. For low clouds, the lapse-rate method applied in VISST and SIST, yields biases of -0.10 km and -0.21 km, respectively, smaller than the positive bias of 0.49 km found for the CO_2-slicing method. This is expected since CO_2-slicing uses a local sounding for cloud temperature-to-height conversion resulting in an overestimate of cloud-top height whereas VISST and SIST use the lapse rate technique [*Dong et al.*, 2008]. Although the -7.1 K/km lapse rate is based on observations of marine Stratocumulus and yields a nearly unbiased result in this study over the ARM SGP, it's likely that this value is not globally applicable for all low clouds, which may account for some of the scatter shown in Figure 2. In the future, new global data from space-borne lidar (i.e. GLAS and CALIPSO) will help refine this approach. For mid-level clouds, the cloud top height biases are -0.77, -1.13 and -0.66 for VISST, SIST and CO_2-slicing, respectively. For SIST, the largest errors are for mid-level clouds. High clouds yield the largest errors for VISST and CO_2-slicing. The high-level cloud top height biases shown in Table 2 are -1.14, -0.48, and -2.04 for VISST, SIST, and CO_2-slicing, respectively.

[12] Table 3 lists the height errors for three ranges of high-cloud optical depth. The statistics are computed from the VISST and SIST results for (1) thin clouds with $\tau < 3.0$, (2) thin clouds with $3.0 \leq \tau < 6.0$ and (3) thick clouds with $\tau \geq 6.0$. Although there is no optical depth determined by the CO_2-slicing method, the effective cloud amount (A_{cld}), which is the product of the cloud fraction (f_{cld}) and emissivity (ε), is retrieved. Because the matching procedure requires that the 10-minute ARSCL period contains all single-layer clouds, it is assumed that the corresponding GOES sounder FOV is overcast ($f_{cld} = 1$, thus $A_{cld} = \varepsilon$) so that $A_{cld} = 0.95$ represents optically thin semi-transparent

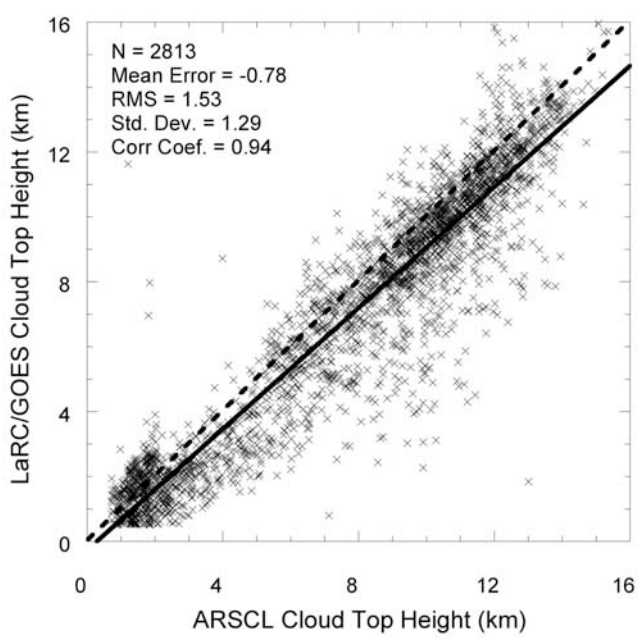

Figure 2. Comparison of LaRC GOES-derived cloud top heights with ARSCL (all points) at the ARM SGP site between April 2000 and September 2004. Line of perfect agreement (dashed) and linear fit (solid) also shown.

Table 1. GOES-Derived Cloud Top Height Comparison ($Z_{satellite}$ minus Z_{arscl}) for All Clouds With ARSCL for the LaRC and CO_2-Slicing Techniques

Algorithm	Bias (km)	StdDev (km)	RMS (km)	R	Npts
LaRC (2000–2002)	−0.88	1.29	1.60	0.94	1059
CO_2-Slicing (this Study)	−1.30	1.67	2.30	0.86	569
CO_2-Slicing (HFA Study)	−1.59	1.48	1.68	0.87	1511
LaRC (2000–2004)	−0.78	1.29	1.53	0.94	2813

Table 3. Cloud Top Height Differences ($Z_{satellite}$ Minus Z_{arscl}) for VISST and SIST Compared With CO_2-Slicing Using ARSCL As Ground Truth for High Level Clouds (7+ km)[a]

	Bias (km)			RMS (km)			Npts		
High Cloud	VISST	SIST	CO2	VISST	SIST	CO2	VISST	SIST	CO2
$\tau < 3$	−1.93	−0.15	−2.93	2.57	1.24	3.57	173	301	169
$3 \le \tau < 6$	−1.32	−0.97	−1.32	1.67	1.46	1.73	129	264	113
$\tau \ge 6$	−1.10	−0.37	−0.63	1.57	0.83	1.08	410	320	53

[a]The VISST and SIST retrievals are stratified by optical depth, while CO2 slicing is stratified by the corresponding cloud emissivity assuming overcast scenes.

clouds corresponding to $\tau \sim 3.0$, and A_{cld} = 1.0 represents optically thick clouds with $\tau \ge 6.0$. The results shown in Table 3 indicate that cloud-top height errors increase with decreasing optical depth for VISST and CO_2-slicing. For τ < 3.0, the mean differences are −1.93 ± 2.57 km, −0.15 ± 1.24 km, and −2.93 ± 3.57 km for VISST, SIST and CO_2-slicing, respectively. For clouds with τ between 3 and 6, the errors are more comparable between the three algorithms: −1.32 ± 1.67 km, −0.97 ± 1.46 km, and −1.32 ± 1.73 km, respectively. For thick clouds, the SIST and CO_2-slicing biases are comparable at −0.37 ± 0.83 km and −0.63 ± 1.08 km, respectively. The VISST errors are about a factor of 2 larger and found to be −1.10 ± 1.57 km. One possible explanation for the thick-cloud differences may be the diurnal cycle of deep convection over land. That is, high thick clouds could be more opaque near their tops during the nighttime convective peak than during the daytime when convective minima are typically found in the late morning [e.g., *Minnis and Harrison*, 1984]. This might explain the difference between the VISST (daytime) and SIST (nighttime) bias. The idea is reinforced by the brightness temperature differences (BTD) found between the GOES 11 and 12-μm channels. At night, the mean BTD for optically thick clouds with T_{11} < 230 K is 0.78 K compared to 1.01 K during the daytime. This difference should increase as the IR extinction decreases in the upper part of the cloud resulting in a larger T_e. The CO_2-slicing technique probably yields a lower bias than VISST due to the fact that ice clouds absorb radiation more effectively in the CO_2 absorption bands between 13 and 15 μm than at 11 μm. Thus, the cloud radiating temperature in the CO_2 bands is expected to be slightly colder than that at 11 μm for optically thick clouds.

4. Concluding Remarks

[13] This study provides a validation of operational single-layer cloud-top height estimates from passive satellite data determined using two imager-based methods (VISST and SIST) with respect to the traditional CO_2-slicing technique applied to the GOES sounder. The ARSCL cloud boundary dataset serves as ground truth and provides a lower limit on the error assessment. For all clouds, comparisons between VISST, SIST and CO_2-slicing cloud top heights and those derived from the surface data yield mean differences of −0.84 ± 1.48 km, −0.56 ± 1.31 km, and −1.30 ± 2.30 km, respectively. The errors were found to increase with increasing cloud altitude and decreasing cloud optical depth. Empirical corrections applied to the effective radiating cloud altitude determined in the VISST and SIST algorithms significantly improve the estimate of high, optically thin cloud top heights and account for much of the difference found in the comparisons with the CO_2-slicing estimates. A lapse rate method employed in VISST and SIST is found to improve the determination of low cloud top heights. The nighttime SIST is the best performer overall, with cloud top height errors found to be similar for both thin clouds with τ < 3 and thick clouds with τ > 6. For clouds with τ between 3 and 6, all three algorithms are comparable. For optically thick clouds, CO_2-slicing is found to be comparable to SIST and yields smaller errors than the daytime VISST. New empirical corrections [e.g., *Minnis et al.*, 2008] could significantly improve optically thick ice cloud-top height estimates from passive satellite data by accounting for the emission depth and possibly other factors that contribute to the large errors found even for deep convective clouds. The largest errors found in this study, close to 2 km, occur for optically thin high clouds with τ < 3 when retrieved with the VISST and CO_2-slicing methods. Achieving more accurate heights for those techniques may require improvements in the characterization of ice cloud scattering and emission. The results shown here are only for single-layer clouds over one area. Future validation efforts should utilize data from active sensor satellites for a more accurate, global assessment of passive satellite cloud-top altitude estimates for all cloud types and in multi-layer situations. In the meantime, these results indicate that for purposes of assimilation into NWP analyses, the LaRC cloud heights can be used as reliably as those from the operational CO_2-slicing method.

Table 2. Cloud Top Height Differences ($Z_{satellite}$ minus Z_{arscl}) for VISST, SIST and CO_2-Slicing Using ARSCL As Ground Truth for All, Low (0–3 km), Mid (3–7 km), and Hi (7+ km) Level Clouds

	Bias (km)			RMS (km)			Npts		
	VISST	SIST	CO2	VISST	SIST	CO2	VISST	SIST	CO2
All	−0.84	−0.56	−1.30	1.48	1.31	2.30	1412	1201	569
Low	−0.10	−0.21	0.49	0.73	1.49	1.48	458	108	86
Mid	−0.77	−1.13	−0.66	1.21	1.67	1.28	242	207	147
Hi	−1.14	−0.48	−2.04	1.88	1.18	2.76	712	886	336

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