P1.24 USE OF ACTIVE REMOTE SENSORS TO IMPROVE THE ACCURACY OF CLOUD TOP HEIGHTS DERIVED FROM THERMAL SATELLITE OBSERVATIONS

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1. INTRODUCTION

Spectral bands in the infrared (IR) atmospheric window (10-12 μm) are routinely used to estimate cloud top heights from passive satellite sensors (Minnis et al., 1995). Radiation in this spectral range is relatively transparent to the atmosphere above the cloud, and the brightness temperatures (T_B) can be matched to local temperature soundings to find the cloud height. It is commonly assumed that clouds, particularly deep convective clouds, have sharp boundaries and optically thick edges. They are treated as blackbodies for most purposes, and so the observed 11-μm brightness temperature T_{11} is assumed to be equivalent to the true temperature of the cloud top plus a small correction for atmospheric absorption, if any correction is made at all. Recent research suggests however, that even deep convective clouds do not have such sharply defined boundaries in the IR spectrum (Sherwood et al., 2004b). Sherwood et al. (2004a) found that cloud tops derived from the eighth Geostationary Operational Environmental Satellite (GOES-8) were 1-2 km below the tops given by lidar data collected during the Cirrus Regional Study of Tropical Anvils and Florida Area Cirrus Experiment (CRYSTAL-FACE). Thus it seems that optically thick clouds do not have boundaries as sharp and distinct as previously thought.*

Until recently, active remote sensing of the atmosphere suffered from major limitations. Ground-based radars and lidars profile the atmosphere continuously, but observe only one location. Active sensors aboard aircraft sample a larger area during field campaigns but collect data for only a few days over the duration of the experiment. The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite flies behind the Aqua satellite in the Afternoon Constellation, providing global measurements which are coincident and nearly simultaneous with measurements taken by instruments on Aqua. Because the CALIPSO orbit is slightly inclined to that of Aqua, Aqua frequently views the CALIPSO ground track at a slightly off-nadir viewing angle (Winker et al., 2007). The main instrument on CALIPSO is the Cloud Aerosol Lidar with Orthogonal Polarization (CALIOP) which has 532- and 1064-nm channels for profiling cloud and aerosol layers (Winker et al., 2006). The CALIOP footprints nominally fall on the CALIPSO ground track with a diameter of 70 m. This instrument allows researchers to study vertical cloud structure all over the globe with vertical resolution as high as 30 m.

2. CLOUD TOP HEIGHT CORRECTION

The National Aeronautics and Space Administration's (NASA) Langley Research Center (LaRC) routinely derives cloud physical, optical, and microphysical properties from radiances observed by various satellite instruments. LaRC uses the Visible Infrared Solar-Infrared Split Window Technique (VISST) (Minnis et al., 1998) to derive cloud temperature, height, thermodynamic phase, optical depth, and other cloud properties from radiances collected by sensors such as GOES and the Moderate-Resolution Imaging Spectroradiometer (Barnes et al., 1998) which is aboard the Aqua and Terra satellites. Since the actual vertical profiles of temperature and particle density within a cloud are unknown, the VISST first characterizes a cloud in terms of an effective radiating temperature T_{eff} which corresponds to a height somewhere within the cloud z_{eff} (Min et al., 2004; Minnis et al., 1990). The value of z_{eff} is determined by matching T_{eff} to a local atmospheric temperature sounding and taking the corresponding height to be z_{eff}. It is assumed that deep convective clouds and other optically thick clouds have sharp, optically thick boundaries and therefore most of the infrared radiation reaching the satellite sensor is emitted by the uppermost layers of the cloud. Under

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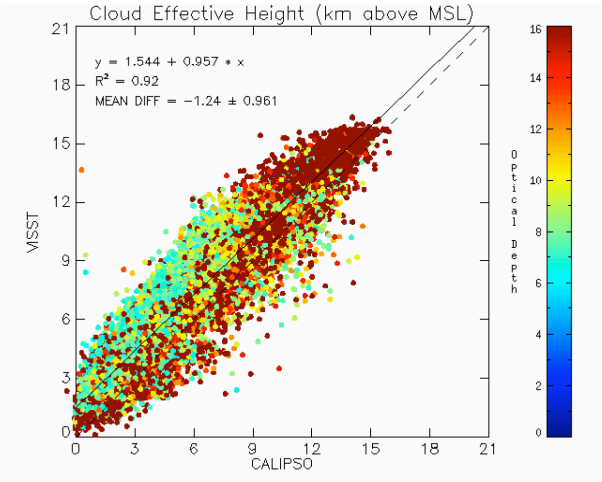

Figure 1. Scatter plot of the height of complete lidar beam attenuation and the effective cloud height from VISST

this assumption, T_{eff} is equivalent to the temperature at the cloud top T_{top} and $z_{top} = z_{eff}$.

Since the advent of CALIPSO, a product is generated at LaRC in which the cloud properties observed by the Aqua MODIS are collocated with the field of view (FOV) of CALIPSO to give an estimate of the cloud properties within the CALIPSO FOV. We analyzed matched VISST and CALIPSO data from April 2007 and compared cloud heights of optically thick ice clouds. In our analysis, the cloud effective emittance had to be greater than 0.98 to be considered optically thick, and we excluded polar clouds from the analysis to avoid problems with mischaracterizing clouds over sea ice and snow. Interestingly, z_{eff} from VISST corresponds fairly well to the level at which the CALIOP lidar signal is totally attenuated as shown in Figure 1 and Min et al. (2004) showed similar results with radar reflectivity profiles. However, Figure 2 reveals that the assumption $z_{top} = z_{eff}$ for thick ice clouds tends to cause underestimation of cloud top heights. On average, the VISST cloud tops were 1.3 km below the tops observed by CALIOP. The VISST assumes that the tops of optically thick clouds are dense and nearly opaque to IR radiation, and therefore the cloud top is placed at or near the same level as the effective radiating height. Figure 2 suggests that sharp, dense cloud edges are not very common and that IR radiation from lower, warmer layers in the cloud does indeed contribute to the total radiance observed by the satellite sensor. By assuming $T_{top} = T_{eff}$, T_{top} is overestimated. T_{top} is then matched to a warmer level in the temperature sounding, causing an underestimation of z_{top}.

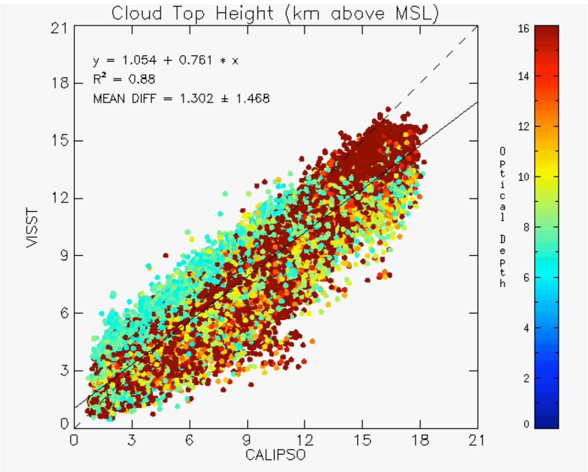

Figure 2. Scatter plot of cloud top heights from CALIPSO and VISST

Although the current method of determining z_{top} tends to underestimate the true cloud top height, there appears to be a strong linear relationship between the two quantities, and the squared correlation coefficient of 0.88 provides evidence of this. To correct z_{top}, we derived a least-squares linear fit for the entire month of April 2007, which included over 40000 data points, using z_{eff} as the regressor. Since Aqua's viewing zenith angle (VZA) of the CALIPSO FOV never exceeded 20° we assume that any VZA dependence is negligible in this case. In the next section, we demonstrate the effectiveness of this fit to other datasets and discuss a correction for large VZAs.

3. VALIDATION

In order to test the validity and applicability of the cloud top height correction previously described, we applied the linear fit to other datasets and compared to other active remote sensors. CRYSTAL-FACE and the Tropical Composition Cloud and Climate Coupling (TC4) missions provided excellent opportunities for validation. The NASA ER-2 high altitude aircraft flew during both of these field campaigns carrying the Goddard Cloud Physics Lidar (CPL), designed specifically for providing multiwavelength measurements of cirrus, subvisual cirrus, and aerosols (McGill et al., 2002). Satellite data during CRYSTAL-FACE was available from the GOES-8 and Aqua satellites and from GOES-12 and Terra during the TC4 campaign. Cloud heights were derived with the VISST from the coincident GOES and MODIS scans and compared to the CPL cloud heights. Scatter plots of the uncorrected VISST cloud top heights against the CPL heights are shown in Figure 3. The VISST cloud top heights from both GOES and MODIS were underestimated compared to the CPL, although the difference was smaller with the MODIS data. The VZAs from Aqua and Terra were larger than from the GOES satellites, and this could explain the difference. As VZA increases, the satellite senses more radiation from the cold upper layers of the cloud. Therefore z_{eff} is physically closer to the actual cloud top thus reducing the error associated with assuming $T_{top} = T_{eff}$.

We applied the linear fit derived from the CALIPSO data to the GOES and MODIS data from CRYSTAL-FACE and TC4, and because our original cloud top correction was derived for near-nadir conditions we reduced our correction by an amount Δz given by

$$\Delta z = (z_{fit} - z_{eff})(1 - \mu), \qquad (1)$$

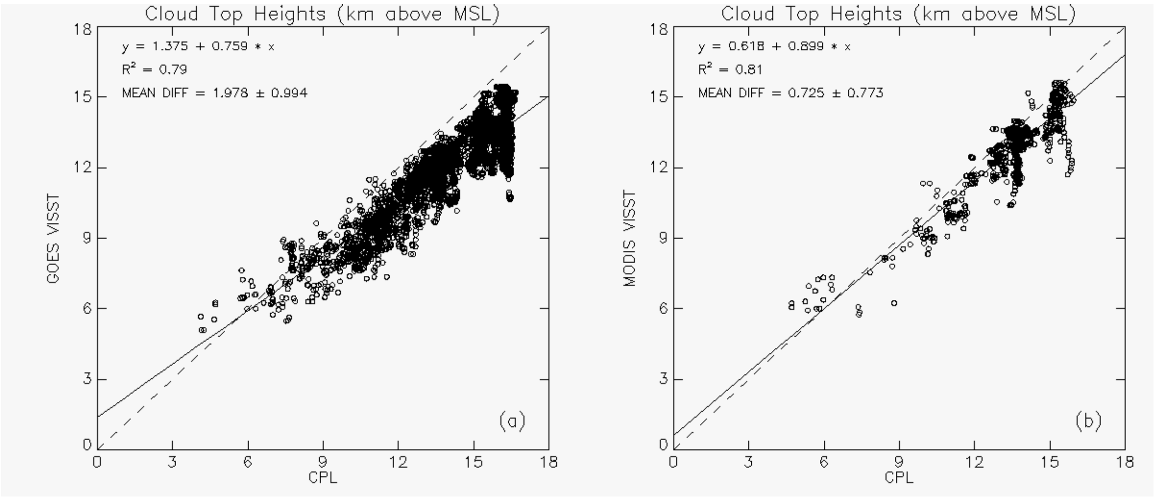

Figure 3. Comparison of CPL cloud top heights to (a) GOES- and (b) MODIS-derived cloud tops

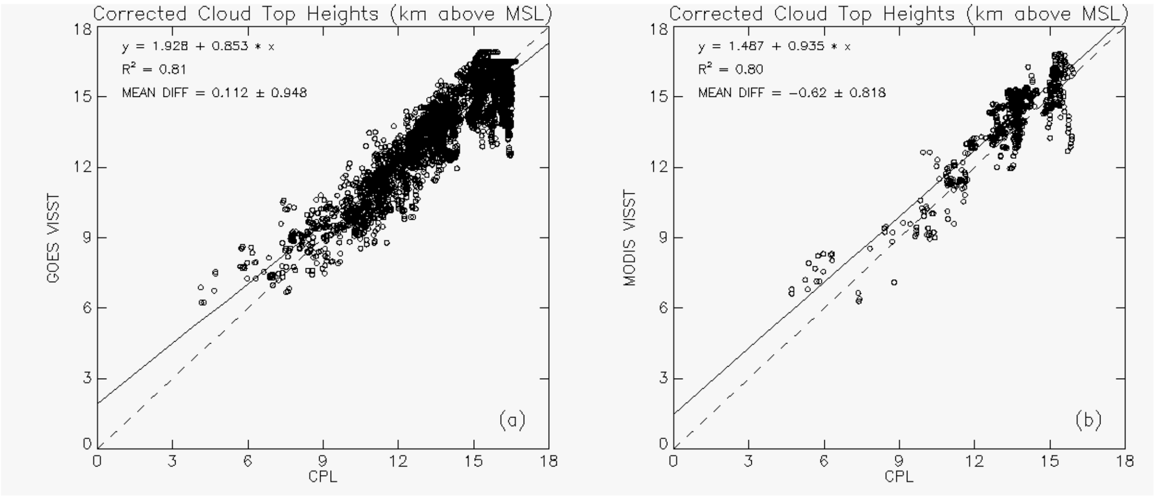

Figure 4. Comparison of CPL cloud top heights to corrected (a) GOES- and (b) MODIS-derived cloud tops

Table 1. Mean difference between CPL and VISST cloud top heights ($z_{top,\ CPL} - z_{top,\ VISST}$) during CRYSTAL-FACE and TC4

Campaign & Date	Satellite	Mean Difference (no correction), km	Mean Difference (corrected), km
CRYSTAL-FACE 29 Jul, 2002	GOES-8	1.31	-0.40
	Aqua	0.58	-0.99
TC4 22 Jul, 2007	GOES-12	1.95	0.27
	Terra	1.13	-0.21
TC4 24 Jul, 2007	GOES-12	1.69	-0.34
	Terra	0.69	-0.36
TC4 31 Jul, 2007	GOES-12	2.78	0.78

where z_{fit} is the height obtained from the linear fit and μ is the cosine of the viewing angle. The final corrected cloud top height z_{corr} is then

$$z_{corr} = z_{fit} - \Delta z. \tag{2}$$

The results of this correction are shown in Figure 4. The mean difference between the CPL and GOES cloud tops decreased significantly from 2.0 to 0.1 km. Our correction actually overcorrected the MODIS cloud heights, but still the absolute value of the mean difference decreased by 0.1 km. The results for each individual flight are summarized in Table 1. The mean difference between the CPL and VISST cloud tops decreased in each case except the Aqua cloud tops during CRYSTAL-FACE. These cloud tops needed little correction anyway, and since our correction is statistical, it is not expected to perform better in every instance. Clouds that do not conform to the plane-parallel assumption can also introduce errors. When matching the VISST cloud products to the flight track of the ER-2, GOES products receive a parallax correction while VISST products from MODIS receive no such correction. This can potentially cause slight mismatches between what the satellite views and what the plane's sensors view. In this case, a cloud top correction may not help and could potentially be less accurate. Looking at all the case studies however, we do see a marked improvement over the uncorrected cloud tops.

4. DISCUSSION

We compared ice-phase cloud top heights from CALIOP and the CPL to heights derived by VISST from GOES and MODIS radiances. VISST assumes the tops of optically thick ice clouds are opaque to upwelling IR radiation from within the cloud so that the observed T_{11} is very nearly equal to the true cloud top temperature. However VISST cloud top heights were consistently underestimated by at least 1 km compared to cloud tops sensed by CALIPSO and the CPL so the assumption of sharp, dense cloud boundaries seems inappropriate even for deep convective clouds. MODIS cloud tops were more accurate than GOES, presumably because larger viewing angles cause the sensor to view the tops of clouds at oblique angles, thus reducing the contributions of lower warmer layers to the total observed radiance. Additionally, it was found that the effective cloud height z_{eff} from VISST corresponds fairly well to the height at which the lidar signal is totally attenuated. Assuming CALIOP can detect the true cloud top, we derived a linear fit to estimate z_{top} based on the VISST effective cloud height z_{eff} and the cosine of the viewing angle μ of the satellite sensor. We applied this correction to GOES and MODIS cloud heights during the CRYSTAL-FACE and TC4 field experiments and compared the corrected VISST cloud tops to those determined by the CPL which flew on the ER-2 aircraft during both experiments. The absolute mean difference between the CPL and corrected VISST cloud tops was reduced by 1.9 km for GOES and 0.11 km for MODIS cloud tops, respectively, compared to the uncorrected cloud tops. It was expected that GOES cloud tops needed a larger correction because the viewing angles were smaller than the MODIS viewing angles during both field experiments and the results reflect this. Clouds with much spatial variation can potentially cause problems, especially for high viewing angles, and continued validation is necessary, but overall we see much better agreement between the corrected cloud tops and the tops observed by active remote sensors.

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