Evaluations of the CALIPSO Cloud Optical Depth Algorithm Through Comparisons with a GOES Derived Cloud Analysis

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ABSTRACT

CALIPSO (Cloud-Aerosol Lidar and Infared Pathfinder Satellite Observations) combines an active lidar instrument with passive infared and visible imagers to probe the vertical structure and properties of thin clouds and aerosols over the globe. The geometry of the sun-synchronous orbit is such that the ground track is repeated every 16 days, with optical depth measurements reported at 5 km resolution. The CMG (Cloud-Mask Generator) ingests GOES multi-spectral imagery (at 4 km, 15 minute resolution) and applies a series of single- and multi-spectral tests to detect clouds. CMG gives a cloud/no cloud decision for each GOES pixel; no estimation of cloud optical depth is made. In our analysis, we compared CMG pixels (cloud/no cloud) that pass within 7.5 minutes of the 5 km CALIPSO footprint for various locations in CONUS. While some disagreement is expected due to differences in temporal resolutions, preliminary results show that CALIPSO is finding many thin clouds that the CMG does not detect. Further investigations into disagreements between CALIPSO and CMG will be conducted and reported on.

1. Introduction

Remote sensing of clouds from geostationary satellites has been performed since the 1960's. Data sets such as the International Satellite Cloud Climatology Project (ISCCP) (Schiffer and Rossow (1983)), Wylie and Menzel (1989), and Min et al. (2004) all produced cloud data sets based on GOES imagery or sounder data. Many of the cloud optical depth retrievals, however, have been difficult to validate. Typically, the user would compare the remote sensed optical depths to surface based lidar measurements. However, this would be typically limited to field campaigns and for limited locations. With the launch of CALIPSO (Cloud-Aerosol Lidar and Infared Pathfinder Satellite Observations), cloud optical depth retrievals are routine albeit from a nadir point of view. This makes it now possible to estimate the limit of detection of GOES based cloud climatologies such as the data sets discussed above. In this paper, we discuss the Cloud Mask Generator (CMG), a custom cloud/no cloud retrieval algorithm used for optical communication studies and how it compares to optical depth retrievals from a space based lidar.

a. Motivation for analysis

The CMG cloud mask is a GOES derived product that gives a cloud/no cloud decision for each 4 km by 4 km pixel. From previous work, the detection limit of the CMG is estimated to be between 0.23 and 0.35 optical depth. CALIPSO contains a lidar that detects optically thin clouds. Due to CALIPSO's sensitivity to optically thin clouds, comparing the CMG to CALIPSO will help us to refine our estimate on the limit of detection.

b. CALIPSO

1) CALIOP

CALIPSO contains CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization), an active lidar that measures in two wavelengths (532 and 1064 nm). CALIOP is sensitive to small particles in the atmosphere (ice crystal clouds and aerosols, for example) and particles with small optical depths will, therefore, be easily detected by CALIPSO. The signal from CALIOP will be attenuated if thick clouds are present, but optically thick clouds will not be examined in this analysis.

2) Temporal/Horizontal Resolution

CALIPSO is part of the A-train formation, flying in a sun-synchronous orbit. Due to the narrow footprint of CALIPSO's nadir pointing beam (1/3 km), the same location on Earth is passed over once every 16 days. CALIPSO takes a measurement every 1/3 km, but for the optical depth parameter, the measurements are averaged together every 5km. The vertical resolution of the lidar varies with altitude. Below 8.2 km, the vertical resolution of the lidar is 30 meters. From 8.2 km to 20.2 km, the vertical resolution is 60 meters. Above 20.2 km, resolution increases to 180 meters.

3) Data Products

For this analysis, the CALIPSO Lidar Level Two 5 km Cloud Layer data product was used. This product has column properties and layer properties. Column properties are the same for the entire column (time, latitude, longitude), while layer properties are different for each cloud found in the column. CALIPSO can find up to 10 clouds in each column measurement. The layer parameters included in this release include integrated attenuated backscatter, column reflectance, lidar depolarization ratio, cloud base height, cloud top height, and cloud optical depth. CALIPSO also detects aerosols, but this analysis will focus only on the cloud optical depth.

4) CALIPSO Opacity

For each cloud layer retrieved, an opacity flag is assigned. This flag does not quantify the opacity of the actual cloud; rather it indicates whether the lidar signal was completely attenuated as it passed through that layer. In most cases, the opacity flag is set to transparent because either the ground or another cloud layer was found below it. When the cloud layer is set to opaque (which occurs 20% of the time), that is the last layer to be detected before the lidar signal became totally attenuated. An optical depth is still reported for this layer, but the reported optical depth refers only to the layer where there is measurable lidar signal. Also, any clouds below this layer are not detected, and the optical depth measurement may be underestimated. This underestimation of optical depth should not affect our results, since our focus is on the optically thin clouds.

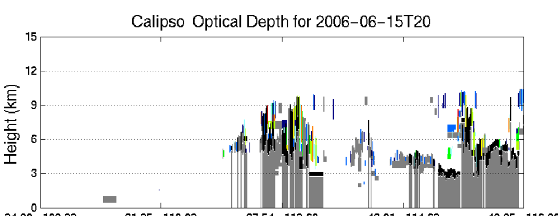

Fig. 1. The graph of CALIPSO's optical depth as it passes over CONUS on June 15th, 2006, 20 UTC. Black bands indicate that the lidar signal becomes attenuated.

c. CALIPSO example

Two different CALIPSO passes over CONUS are presented here as visual examples. Figures 1 and 2 show the optical depth of CALIPSO plotted by altitude (y-axis) and lat/lon (x-axis). Each figure shows CALIPSO's journey across CONUS. The range of optical depths is from 0 (white) through 5 optical depth (red). Black clouds indicate the cloud layer is classified as opaque (signal is lost within the layer), so everything below this cloud is classified as unknown.

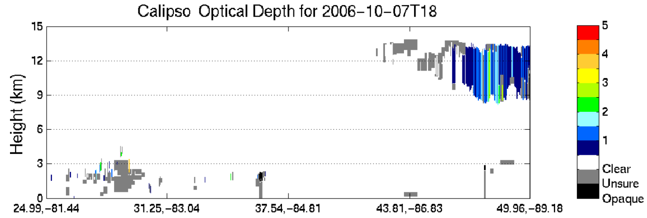

Fig. 2. A second example of the optical depth of CALIPSO for one pass over CONUS on October 7th, 2006, 18 UTC. There is a large optically thin and physically thick cloud at the end of the CALIPSO pass.

d. CMG

1) Temporal/Horizontal Resolution

The CMG (Cloud-Mask Generator) ingests GOES multispectral imagery (at 4 km, 15 minute resolution) and applies a series of single- and multi-spectral tests to detect clouds (Alliss et al. (2000)). The GOES imager has 5 bands: visible (0.6 μm), shortwave infared (3.9 μm) (SWIR), water vapor (6.7 μm), longwave infared (10.7 μm) (LWIR), and split window (11.2 μm). The water vapor channel is not used for cloud detection and is replaced by a fog product at night and a shortwave reflectivity product during the day.

2) CMG Cloud Algorithm

The CMG generates a cloud mask consisting of cloud/no cloud decisions. For each 4 km pixel, the difference between the LWIR temperature, visible albedo, derived products, and the dynamically computed clear sky background (CSB) is calculated. The classification of a pixel as clear or cloudy is based on where the calculated difference falls with respect to the threshold confidence range. Threshold confidence ranges for each test are spatially and temporally defined. From previous studies, it's been estimated that the limit of the CMG cloud detection is between 0.23 and 0.35 optical depth (Alliss et al. (2000)).

2. Analysis

For each 5 km column measurement, CALIPSO may identify up to ten cloud layers. NASA runs the cloud optical depth algorithm three times, each time using more measurements. The first pass is at 5 km resolution (15 1/3 km measurements), the second pass at 20 km (60 1/3 km measurements), and finally the last pass at 80 km (240 1/3 km measurements). This is done to boost the signal to noise ratio in order to find more subtle cloud layers. The different horizontal averages within one column makes it difficult to determine the total cloud optical depth. Often clouds of one horizontal average are contained within clouds of another horizontal average, so adding the two together will "double count" the optical depth in the overlapped region. For that reason, a different approach is needed to determine the total column optical depth (Vaughn (2007)).

The CALIPSO total cloud optical depth parameter used in this analysis was calculated using code provided to us by Mark Vaughn, an algorithm developer from NASA-Langley Research Center. This code sums the different cloud layers in each column, without double-counting any overlapping layers. The code is a Matlab version of the C code that will be used to calculate the total cloud optical depth data product (set to be released Spring, 2009) (Vaughn (2007)).

TABLE 1. Agreement between the CMG and CALIPSO. The threshold for CALIPSO cloud is 0.35 optical depth. Both the CMG pixel (middle column) and CMG 3x3 (right column) are compared to CALIPSO. Overall agreement decreases when moving from pixel to 3x3.

Area	*PixelAgree(%)*	*3X3Agree(%)*
CONUS	84.9	84.7
AZ	86.2	81.2
CA	85.8	81.0
FL	82.1	78.2
NE	86.8	83.3
SC	84.9	80.2
TX	83.6	80.4

Our analysis was conducted over CONUS and 6 areas within CONUS: AZ, CA, FL, NE, TX, SC. Each location is a 6 degree longitude by 2 degree latitude box centered on the area of interest. Due to differences in proximity of each location to the CALIPSO ground track, the amount of points per location varies. The number of points per site ranges from 4,800 for SC to 11,338 for AZ (June 2006 - October 2008).

3. Results

a. *CALIPSO threshold for clouds*

Our goal is to compare the CMG with CALIPSO at the nearest matching time and location. The CMG provides a cloud/no-cloud decision, while CALIPSO provides an optical depth. We want to find times when CALIPSO and the CMG agree, so we first must determine the CALIPSO optical depth at which we can say a cloud exists. We used eight different CALIPSO cloud thresholds, from 0.023 to 1.16 optical depth. We added up the percent of the time they agreed with each other (CMGCld/CalCld and CMGClr/CalClr) to give us an overall agreement. From this analysis, the CALIPSO cloud threshold that gives us the highest overall agreement is 0.35 optical depth, a threshold we will use in the rest of our analysis.

TABLE 2. Breakdown of how the CMG pixel compares with CALIPSO. Columns 2 and 5 show when they agree (sum of these is our overall agreement from Table 1); column 3 shows when CMG pixel is cloudy but CALIPSO does not measure an optical depth above the threshold; column 4 shows when CMG reports no cloud but CALIPSO measures an optical depth above the threshold.

Area	*CMGCld CalCld*	*CMGCld CalClr*	*CMGClr CalCld*	*CMGClr CalClr*
CONUS	42.8	6.5	8.6	42.1
AZ	13.7	10.6	3.2	72.4
CA	11.4	9.9	4.3	74.4
FL	18.6	8.4	9.5	63.5
NE	21.5	8.1	5.1	65.3
SC	17.5	8.3	6.8	67.4
TX	20.7	9.0	7.4	62.9

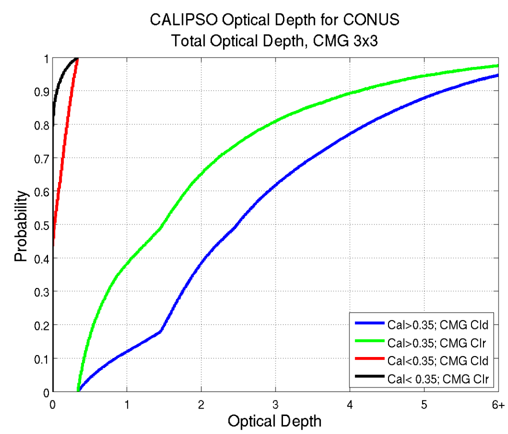

FIG. 3. For each quadrant of our contingency table (see Table 3), a CDF of CALIPSO optical depth for CONUS.

b. *Agreement between CMG Pixel and CALIPSO*

The overall agreement between CALIPSO and the CMG pixel ranges from 82.1% to 86.8%, depending on location (Table 1). We created a 2x2 contingency table for each location, the results of which are summarized in Table 2.

TABLE 3. Breakdown of how the CMG 3x3 compares with CALIPSO. Columns 2 and 5 show when they agree (sum of these is our overall agreement from Table 1); column 3 shows when the 3x3 CMG is cloudy but CALIPSO does not measure an optical depth above the threshold; column 4 shows when the entire 3x3 CMG reports no cloud but CALIPSO measures an optical depth above the threshold.

Area	*CMGCld CalCld*	*CMGCld CalClr*	*CMGClr CalCld*	*CMGClr CalClr*
CONUS	47.6	11.5	3.8	37.1
AZ	16.0	17.3	1.5	65.2
CA	12.7	15.9	3.1	68.3
FL	24.7	17.2	4.6	53.5
NE	24.8	14.3	2.4	58.5
SC	21.6	16.9	2.9	58.6
TX	25.8	16.7	2.9	54.6

Columns 2 and 5 show when the CMG pixel and CALIPSO agree (their sum is the total agreement value in Table 1), column 3 shows when the CMG pixel is cloudy but CALIPSO is clear (below the optical depth threshold of 0.35), and column 4 is the reverse, when the CMG pixel is clear but CALIPSO is cloudy. We are particularly interested in CMG under detection of optically thin clouds, i.e. CALIPSO reports a cloud but the CMG does not. Depending on location, between 3.2-9.5% of the time this occurs.

c. Agreement between CMG 3x3 and CALIPSO

Due to the possible large differences in time between the CMG measurement and the CALIPSO measurement (as much as 7.5 minutes), we decided to compare a 3x3 CMG pixel area (12 x 12 km) to CALIPSO. For the 3x3, if one of the nine pixels is cloudy, then the entire area is deemed cloudy. This would diminish the probability of having a "near miss", a time when CALIPSO says it is cloudy and the CMG pixel says it is clear, but an adjoining CMG pixel is cloudy. The same analysis was repeated, only using the CMG 3x3 in place of the CMG pixel. From Table 1, the right column shows that going from pixel to 3x3 decreases agreement between CMG and CALIPSO. When this agreement is broken down into Table 3, we see that the times when CALIPSO sees a cloud and the CMG 3x3 does not decreases (1.2-4.9% decrease, depending on location). The reason that the overall disagreement increases is because the percent of the time when the CMG 3x3 sees a cloud but CALIPSO does not increases, off-setting the better agreement between CMG clear, CALIPSO cloudy.

We then wanted to get more insight into what the distributions of optical depth was for CALIPSO, especially for when CALIPSO measured a cloud and the CMG 3x3 did not. For each of the four cases (each column in Table 3), the CDF of CALIPSO optical depth is graphed (see Figures 3-9). The red line is when CALIPSO is clear but the CMG 3x3 is cloudy, blue is when CALIPSO and the CMG 3x3 are both cloudy, green is when CALIPSO is cloudy and the CMG 3x3 is clear, and black is when they are both clear.

Figures 3-9 show us several things. First, when the CMG 3x3 is clear and CALIPSO is below 0.35 optical depth, CALIPSO measures a non-zero optical depth 10-20% of the time, depending on location (AZ and CA show a higher occurence of being totally clear, as we would expect). These thin clouds might be too thin to be detected by the CMG. Looking at the times when CALIPSO measures a cloud (green and blue lines in Figures 3-9), the

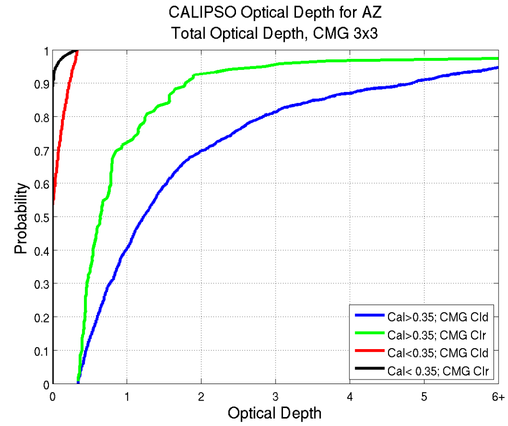

FIG. 4. For each quadrant of our contingency table (see Table 3), a CDF of CALIPSO optical depth for AZ.

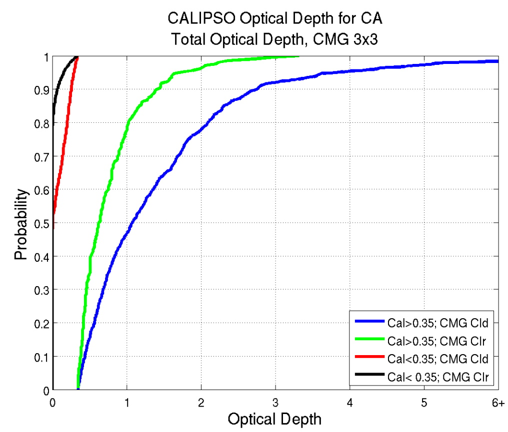

FIG. 5. For each quadrant of our contingency table (see Table 3), a CDF of CALIPSO optical depth for CA.

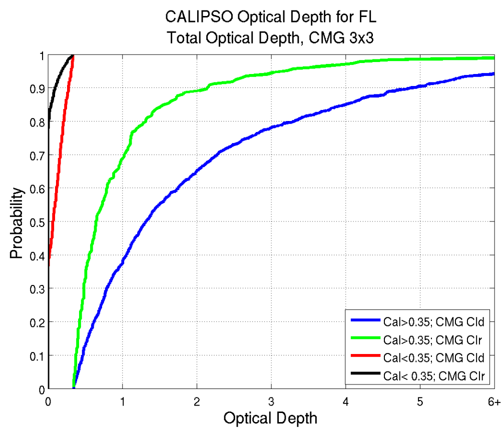

FIG. 6. For each quadrant of our contingency table (see Table 3), a CDF of CALIPSO optical depth for FL.

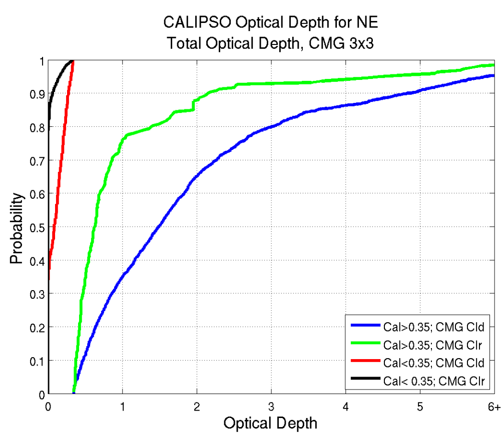

FIG. 7. For each quadrant of our contingency table (see Table 3), a CDF of CALIPSO optical depth for NE.

cloud is more likely to be thick if the CMG agrees that it is cloudy. For example, for all of CONUS, when the CMG says it is clear, 40% of the clouds CALIPSO finds are less than one optical depth. When the CMG and CALIPSO agree that it is cloudy, only approximately 10% of the clouds are one optical depth or less.

4. Conclusions

Overall agreement between the CMG and CALIPSO is excellent (above 80% for all locations). For a small amount of cases, CALIPSO is finding thin clouds that the CMG is missing. While previous studies have shown that the CMG can detect optical depths between 0.23 and 0.35, it appears that the CMG is missing some clouds with an optical depth above 0.35. Some of the discrepancy can be explained by differences in temporal resolution, but some of it is due

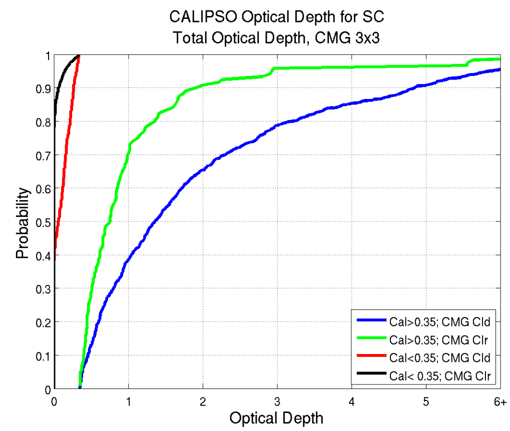

FIG. 8. For each quadrant of our contingency table (see Table 3), a CDF of CALIPSO optical depth for SC.

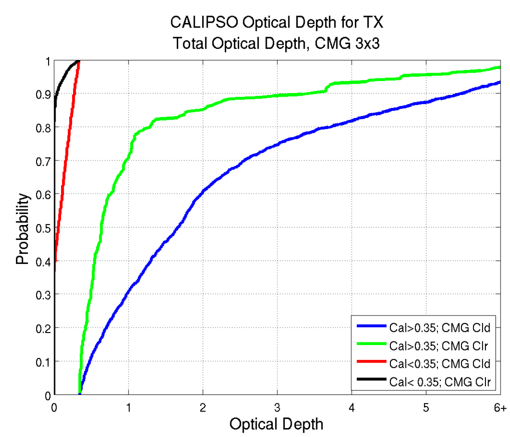

FIG. 9. For each quadrant of our contingency table (see Table 3), a CDF of CALIPSO optical depth for TX.

to the CMG being unable to detect optically thin clouds. Future analysis should include restricting our temporal differences to a smaller window to guarantee that the CMG and CALIPSO are looking at the time place at the same time.

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