

Analysis of co-located MODIS and CALIPSO observations near clouds

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Popular summary

The purpose of this paper is to help researchers combine data from different satellites and thus gain new insights into two critical yet poorly understood aspects of anthropogenic climate change, aerosol-cloud interactions and aerosol radiative effects. For this, the paper explores whether cloud information from the Aqua satellite's MODIS instrument can help characterize systematic aerosol changes near clouds by refining earlier perceptions of these changes that were based on the CALIPSO satellite's CALIOP instrument.

Similar to a radar but using visible and near-infrared light, CALIOP sends out laser pulses and provides aerosol and cloud information along a single line that tracks the satellite orbit by measuring the reflection of its pulses. In contrast, MODIS takes images of reflected sunlight and emitted infrared radiation at several wavelengths, and covers wide areas around the satellite track.

This paper analyzes a yearlong global dataset covering all ice-free oceans, and finds that MODIS can greatly help the interpretation of CALIOP observations, especially by detecting clouds that lie outside the line observed by CALIPSO. The paper also finds that complications such as differences in view direction or clouds drifting in the 72 seconds that elapse between MODIS and CALIOP observations have only a minor impact. The study also finds that MODIS data helps refine but does not qualitatively alter perceptions of the systematic aerosol changes that were detected in earlier studies using

only CALIOP data. It then proposes a statistical approach to account for clouds lying outside the CALIOP track even when MODIS cannot as reliably detect low clouds, for example at night or over ice.

Finally, the paper finds that, because of variations in cloud amount and type, the typical distance to clouds in maritime clear areas varies with season and location. The overall median distance to clouds in maritime clear areas around 4-5 km. The fact that half of all clear areas is closer than 5 km to clouds implies that pronounced near-cloud changes in aerosol properties have significant implications for overall clear-sky characteristics, including the radiative impact of aerosols.

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Abstract

This paper aims at helping synergistic studies in combining data from different satellites for gaining new insights into two critical yet poorly understood aspects of anthropogenic climate change, aerosol-cloud interactions and aerosol radiative effects. In particular, the paper examines the way cloud information from the MODIS imager can refine our perceptions based on CALIOP lidar measurements about the systematic aerosol changes that occur near clouds.

The statistical analysis of a yearlong dataset of co-located global maritime observations from the Aqua and CALIPSO satellites reveals that MODIS's multispectral imaging ability can greatly help the interpretation of CALIOP observations. The results show that imagers on Aqua and CALIPSO yield very similar pictures, and that the discrepancies—due mainly to wind drift and differences in view angle—don't significantly hinder aerosol measurements near clouds. By detecting clouds outside the CALIOP track, MODIS reveals that clouds are usually closer to clear areas than CALIOP data alone would suggest. The paper finds statistical relationships between the distances to clouds in MODIS and CALIOP data, and proposes a rescaling approach to statistically account for the impact of clouds outside the CALIOP track even when MODIS cannot reliably detect low clouds, for example at night or over sea ice. Finally, the results show that the typical distance to clouds depends on both cloud coverage and cloud type, and accordingly varies

1 with location and season. The global median distance to clouds in maritime clear-sky
2 areas is in the 4-5 km range.

3 4 **1 Introduction**

5 Aerosol measurements near clouds play an important role in studying two critical yet
6 poorly understood aspects of anthropogenic climate change, aerosol-cloud interactions
7 and aerosol radiative effects (e.g., Loeb and Schuster, 2008). Such measurements indicate
8 that clouds are surrounded by a wide transition zone, in which aerosol optical properties
9 and size change systematically (e.g., Koren et al. 2007; Su et al. 2008; Chiu et al. 2009;
10 Redemann et al. 2009; Twohy et al. 2009; Várnai and Marshak, 2011). Several factors
11 can alter particle populations in the vicinity of clouds, for example aerosols swelling in
12 the humid air surrounding clouds, aerosol particles merging after cloud droplets merge
13 through coagulation and then evaporate, a few large particles lingering around after a
14 cloud dissipates, and even a few droplets appearing before stable clouds could form
15 (Koren et al., 2009; Tackett and Di Girolamo 2009).

16 While satellites offer excellent opportunities for aerosol studies, satellite measurements
17 of aerosols are particularly challenging near clouds. For example, even the separation of
18 cloudy and cloud-free areas is often ambiguous, as very thin or small clouds can appear
19 similar to thick aerosols in satellite data (e.g., Charlson et al., 2007; Koren et al. 2008;
20 Redemann et al. 2009), and both aerosol and cloud particles can be present in the
21 atmospheric column or volume we observe (Liu et al. 2009). This leads to bigger
22 uncertainties in remote sensing retrievals.

23 The combination of remote sensing uncertainties and systematic aerosol changes near
24 clouds creates a dilemma for researchers (Várnai and Marshak, 2011): On one hand,
25 excluding the transition zone in order to avoid its remote sensing uncertainties can create
26 a bias toward low aerosol optical depths thus weaker radiative effects calculated from
27 these optical depths. On the other hand, including the transition zone despite the remote
28 sensing uncertainties can create a bias toward too high aerosol optical depths and stronger
29 radiative effects. Improving our ability to measure aerosols near clouds and to better

1 understand the impact of remote sensing uncertainties can help resolve this dilemma, and
2 yield more precise information on aerosol-cloud interactions and aerosol radiative effects.

3 This paper explores issues related to combining data from two different satellites with the
4 goal of obtaining more detailed information on aerosols near clouds. Combining data
5 from various instruments allows one to take advantage of the active and passive
6 instruments' capabilities and limitations complementing each other (e.g., vertical
7 information but larger noise for a lidar, and spectral and cross-track information but
8 complications due to 3D radiative processes for passive imagers). Specifically, the paper
9 examines various possibilities and concerns in combining data from the CALIOP (Cloud-
10 Aerosol Lidar with Orthogonal Polarization) lidar on the CALIPSO (Cloud-Aerosol Lidar
11 and Infrared Pathfinder Satellite Observation) satellite with data from the MODIS
12 (Moderate Resolution Imaging Spectroradiometer) imager on the Aqua satellite. Data
13 from the WFC (Wide Field Camera) imager on the CALIPSO satellite is also used in
14 exploring the combination of MODIS and CALIOP data.

15 The outline of this paper is simple: Section 2 describes the dataset used in the study,
16 Section 3 discusses the results, and Section 4 provides a brief summary.

18 **2 Data**

19 This study analyzes a yearlong (November 2006-October 2007) global dataset of daytime
20 satellite data over all oceans free of sea ice.

21 The study uses the operational 1 km-resolution CALIOP cloud mask and cloud top
22 altitude products (Vaughan et al., 2009; Winker et al.; 2009), and also attenuated lidar
23 backscatter profiles at both 532 nm and 1064 nm wavelengths, degraded from 333 m to 1
24 km resolution. It also uses 61 km wide swaths of 1 km-resolution WFC images of
25 0.65 μm solar reflectance. These images are registered to the lidar measurements such
26 that they extend 30 km away on each side of the single line that is observed by the lidar
27 along the satellite orbit.

28 In order to reduce data volume, we obtained MODIS data for 201 km wide swaths from
29 NASA's A-train data depot at <http://disc.sci.gsfc.nasa.gov/atdd/data-holdings>. MODIS

products were registered to WFC images by identifying the MODIS pixel with the closest geographical coordinates to each WFC pixel. The study uses the MODIS cloud mask (Ackerman et al., 1998; Frey et al., 2008) and 0.65 μm solar reflectances provided at 1km resolution, and also cloud top pressures provided at 5 km resolution (Menzel et al., 2008).

3 Results

While combining data from different satellites offers new possibilities, it also poses new challenges. One such challenge is that since CALIPSO flies slightly behind Aqua, CALIOP sees the same scene 72 seconds later than MODIS. This implies that even if MODIS encounters a cloud at a given spot, the cloud drifting with the wind may move away by the time CALIOP arrives, and so solar reflectances for the cloud may be combined with lidar returns from a clear sky column. Naturally, this could cause data interpretation errors, for example overestimations of clear-sky MODIS solar reflectances near clouds when using a CALIOP cloud mask.

This problem of drifting clouds can be examined with the help of the WFC imager on the CALIPSO satellite, since comparisons of 0.65 μm images by WFC and MODIS can reveal cloud movements between the two satellite overpasses (Figure 1). We estimate the impact on near-cloud reflectances by dividing the center portion of WFC imagery to 51 km by 51 km segments, and then testing what shifting of the geographically co-registered images can maximize the covariance of WFC and MODIS pixel values. (Using 51 km by 51 km segments that extend 25 km away on each side of the CALIOP track allows us to detect displacements up to 5 km in any direction within the 61 km wide available dataset.) The results indicate that while clouds can certainly drift large distances when the wind is strong, this occurs mostly for high clouds such as those in Figure 1. In contrast, we found that the drift exceeds 1 km for less than 10 % of scenes containing only clouds below 3 km. In such scenes median MODIS reflectances plotted against the distance to the nearest cloud detected by CALIOP are very similar regardless whether or not MODIS images are shifted to maximize their covariance with WFC images. Similarly, median CALIOP backscatters plotted as a function of distance to clouds detected by MODIS are

1 almost identical with or without wind shift correction. (Wind shift makes significant
2 differences only for the first distance bin, clear areas 1 km away from clouds.)

3 Though wind shifts and cloud development during the 72 s between the CALIPSO and
4 Aqua overpasses can cause random differences between WFC and MODIS images, WFC
5 and MODIS reflectances can be expected to be very similar statistically. To test this,
6 Figure 2 compares WFC and MODIS reflectances at the first, second, third, ..., 99th
7 percentiles of the WFC and MODIS reflectance histograms, respectively. The figure
8 shows that WFC and MODIS reflectances tend to be very similar, although the inset
9 reveals that dark pixel reflectances are slightly higher for WFC than for MODIS, whereas
10 bright pixel reflectances are slightly lower for WFC than for MODIS. These differences
11 likely come from two main factors. First, while WFC sees the lidar footprint at nadir,
12 MODIS sees it at a viewing zenith angle ranging from 5° to 20°, as Aqua flies slightly off
13 to the side and not exactly in front of CALIPSO. Such view angle differences can create
14 systematic reflectance differences for anisotropic reflectors such as clear oceans. Second,
15 WFC calibration uncertainties can also play a role in WFC-MODIS reflectance
16 differences. We note that while mean reflectances are similar for WFC and MODIS, local
17 standard deviations of 9 reflectance values within 3 km by 3 km areas is roughly 20%
18 smaller for WFC than for MODIS images. Because the MODIS observational noise is
19 much less than 20%, this difference likely comes from a smoothing effect that can arise if
20 WFC has a wider instantaneous field-of-view (or point spread function) than MODIS.
21 This hypothesis is also consistent with the result that 0.65 μm reflectances exhibit larger
22 increases near clouds in WFC than in MODIS images (not shown).

23 One key benefit from adding MODIS data to CALIOP observations is that while
24 CALIOP can detect clouds along a single line tracking the satellite orbit, MODIS can
25 also detect clouds that lie off to the side from this line. Therefore it is important to
26 examine how near-cloud behaviors change if, instead of using the CALIOP cloud mask
27 as earlier CALIOP studies did (Tackett and Di Girolamo, 2009; Várnai and Marshak,
28 2011; Yang et al., 2011), we use the MODIS cloud mask. Figure 3 compares CALIOP
29 lidar backscatter enhancements in the vicinity of clouds for three cloud masks: CALIOP
30 mask searching for clouds along a single (1D) line, MODIS mask searching for clouds

1 along the same (1D) line, and MODIS mask searching for clouds throughout the (2D)
2 MODIS images.

3 Because most near-cloud enhancements of CALIOP backscatter occur at low altitudes
4 (Várnai and Marshak, 2011), the figure shows CALIOP backscatters integrated from 30
5 m to 3 km altitude. Since low clouds are likely to impact this altitude range the most,
6 distance to nearby clouds in this and subsequent figures means distance to clouds below
7 3km when using CALIOP, and distance to clouds with cloud top pressure exceeding 700
8 hPa when using MODIS data (e.g., for clouds outside the CALIOP lidar track).

9 The figure shows that, at least for the first 5 km, the MODIS 1D mask yields higher
10 backscatter near clouds than the CALIOP cloud mask does. This likely comes from two
11 reasons associated with the MODIS cloud mask being less sensitive and missing some of
12 the thin clouds identified by CALIOP (Eguchi and Yokota, 2008). First, borderline cases
13 with relatively high particle concentrations (and hence lidar backscatter) may be included
14 into the clear-sky population only when using the MODIS cloud mask, since the more
15 conservative CALIOP mask may classify these cases as clouds. For example, as MODIS
16 and CALIOP define clouds differently, the more conservative CALIOP cloud mask may
17 classify as cloud even some of the harder-to-detect cloudy cases mentioned in Koren et
18 al. (2009), such as a few large particles lingering around even after the bulk of a cloud
19 dissipates. Second, missing the thinnest clouds means that clear areas appearing next to
20 clouds in the MODIS mask are next to relatively thick clouds, and these thicker clouds
21 may have a stronger impact on their surroundings than the thin clouds identified only by
22 CALIOP.

23 The figure also shows that the backscatter curve moves to the left (and hence lower) if we
24 use the 2D MODIS cloud mask instead of the 1D one. This occurs because whenever the
25 closest cloud lies outside the CALIOP track, 1D searches need to go farther to find a
26 cloud than 2D searches do. For example, Figure 3 shows that median backscatter reaches
27 0.0042 sr^{-1} at a distance of $d_{2D} = 4.5 \text{ km}$ for the 2D mask, but only at $d_{1D} = 9 \text{ km}$ for the
28 1D MODIS cloud mask. The 2D curve being below the 1D curve even at 20 km is likely
29 a sign that backscatter keeps dropping in the increasingly dry air even past 20 km away
30 from clouds (as in Koren et al., 2007), since pixels that are 20 km away from clouds in

1 the 2D mask are often even farther from the clouds found by the 1D MODIS cloud mask
2 that searches only along the CALIPSO track.

3 Finally, let us mention that the MODIS curves in Figure 3 are based only on clear pixels
4 labeled “confident clear” by the MODIS cloud mask, and that including “probably clear”
5 pixels as well makes near-cloud enhancements stronger (not shown). Overall, Figure 3
6 shows that while the details of near-cloud enhancements depend on the cloud mask used,
7 their basic behavior does not change by considering off-track clouds. As a result, the
8 transition zone surrounding clouds is likely at least as wide and pronounced as it was
9 discussed in earlier papers considering CALIOP data only (Tackett and Di Girolamo,
10 2009; Várnai and Marshak, 2011; Yang et al., 2011).

11 The main reason for the difference between the 1D and 2D MODIS curves in Figure 3—
12 that is, the relationship between clear areas’ distance to the nearest cloud using 1D and
13 2D cloud masks—is explored quantitatively in Figure 4a. This figure was created by
14 selecting various color ratio values in a plot similar to Figure 3 that displays near-cloud
15 enhancements in color ratio rather than backscatter, and then comparing the d_{1D} and d_{2D}
16 distances at which these color ratio values are attained. (The color ratio, the ratio of lidar
17 backscatters at 1064 nm and 532 nm, is closely related to particle size and increases near
18 clouds much like 532 nm backscatter does (Tackett and Di Girolamo, 2009; Várnai and
19 Marshak, 2011).) The horizontal and vertical positions of each dot in Figure 4a are
20 determined by the d_{1D} and d_{2D} distances for each selected color ratio value. The red and
21 blue dots use d_{1D} values from the MODIS and CALIOP cloud masks, respectively (d_{2D} is
22 always obtained from MODIS). We note that while Figure 4a is constructed by
23 examining at which d_{1D} and d_{2D} distances we reach certain color ratio values, using
24 backscatter values or even examining the histograms of d_{1D} and d_{2D} directly for the red
25 curve yield nearly identical results, with the slope of linear fits being 0.584 and 0.591
26 instead of 0.577.

27 The slope of the red line in Figure 4a is determined by the spatial scaling in clouds, which
28 is closely related to the spatial autocorrelation of cloud fields. At one extreme,
29 calculations for artificial broken cloud fields generated by a 2D stochastic cloud model
30 based on fractional Brownian motion (e.g., Barker and Davies, 1992; Davis et al., 1996)

1 indicate that the slope (s) peaks close to 1 for white noise fields because, lacking any
 2 spatial correlations, d_{2D} is largely independent from d_{1D} (the only connection being $d_{2D} \leq$
 3 d_{1D}), and hence the difference between d_{1D} and d_{2D} is dominated by d_{1D} itself. At the
 4 other extreme, for cloud fields with variability only at the very largest scales, the slope is
 5 just under 1/3. This limit may be conceptually understood by considering that if large-
 6 scale variability dominates, the nearest cloud can be assumed to have a straight boundary.
 7 Therefore $d_{2D} = d_{1D} \cos \phi$, where ϕ is the angle between the CALIOP track and the line
 8 to the cloud's closest point. Simple geometry then says that the slope s of the linear fit
 9 relating $d_{1D} - d_{2D}$ to d_{1D} can be approximated as

$$10 \quad s = \frac{d_{1D} - d_{2D}}{d_{1D}} = 1 - \frac{d_{2D}}{d_{1D}} = 1 - \cos \phi, \quad (1)$$

11 which is close to 0.3 for $\phi = 45^\circ$.

12 The impact of scaling is illustrated in Figure 4b, which compares the slopes for the two
 13 sample areas highlighted in Figure 4c. In particular, Panel b shows that the slope is
 14 significantly steeper (0.87 vs. 0.60) for the right side area dominated by small-scale
 15 variability, than for the left side area featuring strong large scale variability. Finally, we
 16 note that the slope in Figure 4a is different for the blue line than for the red one because
 17 the blue data is also affected by the different sensitivities of MODIS and CALIOP cloud
 18 masks.

19 Figure 5 shows that one can use the blue linear fit in Figure 4a to estimate d_{2D} from d_{1D} ,
 20 and then to rescale color ratio curves based on 1D CALIOP cloud masks in order to
 21 obtain curves similar to the ones based on 2D MODIS cloud masks. This can be
 22 especially helpful for considering the impact of clouds lying outside the lidar track when
 23 the MODIS cloud mask has large uncertainties in detecting low clouds, for example at
 24 night or over bright surfaces such as snow and ice. In essence, Figure 5 shows that we
 25 can rescale results based on the 1D CALIOP cloud mask to statistically account for
 26 clouds lying off the CALIOP track.

27 Regardless of which cloud mask one uses, the typical distance to the nearest cloud can
 28 also be of interest because it can help putting into context the importance of near-cloud

1 particle changes. For example, larger (smaller) typical distances would imply that near-
2 cloud changes have weaker (stronger) impacts on overall clear-sky characteristics. Figure
3 6a shows that this distance varies significantly with location. The variations are caused by
4 two main factors. First, the distance tends to decrease as cloud coverage increases and
5 clouds “grow closer”. A comparison of Figures 6a and 6b can indeed reveal strong anti-
6 correlations between cloud coverage and distance to clouds, for example the large median
7 distance to clouds over the Mediterranean can be attributed to the small cloud coverage.
8 Second, the typical distance to clouds also depends on cloud type, for example it is lower
9 in the small gaps in cumulus fields than in the vast areas separating large stratiform cloud
10 decks. The effect of cloud type can be illustrated through the two sample areas in Figure
11 4c: Although cloud coverage is similar in the two areas (0.54 and 0.53, respectively),
12 typical distances to cloud are much smaller in the area on the right (median distance to
13 clouds is 2.2 km and 1 km in the left and right side areas, respectively). The dominance
14 of marine stratus and stratocumulus can explain, for example, the large median distance
15 to clouds off the coast of California in Figure 6a.

16 The typical distance often also varies with season and tends to be greater in summer than
17 in winter. Table 1 shows that at Northern Hemisphere mid-latitudes, the distance being
18 smaller in winter than summer coincides with cloud coverage being larger in winter than
19 summer—a trend consistent with the distance decreasing as clouds “grow nearer”.
20 However, Table 1 also shows that at Southern Hemisphere mid-latitudes, the distance
21 being smaller in winter than summer coincides with cloud fractions also being smaller in
22 winter than summer—which further illustrates that in addition to cloud fraction, cloud
23 type also greatly impacts the typical distance to clouds. Overall, the annual median
24 distance to clouds over all oceans is around 4.3 km using the 2D MODIS cloud mask and
25 5 km using the 1D CALIOP cloud mask. In other words, roughly 50% of all clear pixels
26 are closer than 5 km to low clouds. Therefore it seems attractive for future studies to
27 characterize near-cloud enhancements by comparing the roughly two halves of clear
28 pixels that are closer or farther than ~5 km to the nearest cloud, respectively.

4 Summary

The purpose of this paper is to help synergistic studies to use data from different satellites for gaining new insights into two critical yet poorly understood aspects of anthropogenic climate change, aerosol-cloud interactions and aerosol radiative effects. For this, the paper examines the way cloud information from the MODIS imager can refine our CALIOP lidar-based perceptions of systematic aerosol changes near clouds.

The paper explores this topic by analyzing a yearlong global dataset that covers all ice-free oceans, and includes co-located data by the Aqua satellite's MODIS imager and by the CALIPSO satellite's CALIOP lidar and WFC imager. A statistical analysis of this dataset reveals that, despite some challenges, MODIS's multispectral imaging ability can greatly help the interpretation of CALIOP observations, especially by detecting clouds outside the single line that is observed by the CALIOP lidar along the satellite orbit. Specifically, the main findings are as follows.

Generally, MODIS and WFC reflectances are very similar, with WFC being slightly brighter in dark areas and slightly darker in bright areas. The discrepancies likely come from MODIS viewing obliquely the areas that CALIPSO observes vertically, although calibration issues may also play a role. Matching the spatial patterns of MODIS and WFC images reveals that although clouds certainly drift with the wind during the 72 seconds between Aqua and CALIPSO overpasses, ignoring this typically modest drift doesn't significantly alter the observed systematic aerosol changes near low clouds.

By detecting clouds outside the CALIOP track, MODIS reveals that clouds are usually closer to clear areas than CALIOP data would suggest. While this does not change qualitatively our perceptions of aerosol behaviors near clouds, it does impact quantitative features such as median backscatter values at given distances from clouds. The paper finds simple statistical relationships between the distances to cloud in MODIS and CALIOP data, and shows that this relationship is determined predominantly by cloud spatial autocorrelations. Based on this finding the paper proposes a rescaling approach that statistically accounts for the impact of clouds outside the CALIOP track even when MODIS cannot reliably detect low clouds, for example at night or over ice.

1 Finally, the paper examines clear areas' typical distance to clouds, as this can help putting
2 into context the importance of near-cloud changes. The results show that the this distance
3 depends on both cloud coverage and cloud type and, as a result, varies both with
4 geographical location and season. Globally, the median distance to clouds in maritime
5 clear areas is in the 4-5 km range, indicating that the pronounced near-cloud changes
6 have significant implications for overall clear-sky characteristics.

7 In conclusion, the results presented here can help future satellite studies of aerosols near
8 clouds. We plan to report on a such follow-up study—examining relationships between
9 near-cloud changes in MODIS solar reflectances, CALIOP lidar returns, and aerosol and
10 cloud properties retrieved by MODIS and CALIOP—in a future article.

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Tables

Table 1. Mid-latitude summer and winter median distances to clouds and, in parentheses, cloud fractions for low clouds based on the MODIS cloud mask.

	Summer	Winter
30°-60° North	7.7 km (0.39)	3.3 km (0.52)
30°-60° South	4.8 km (0.61)	2.2 km (0.55)

Figures

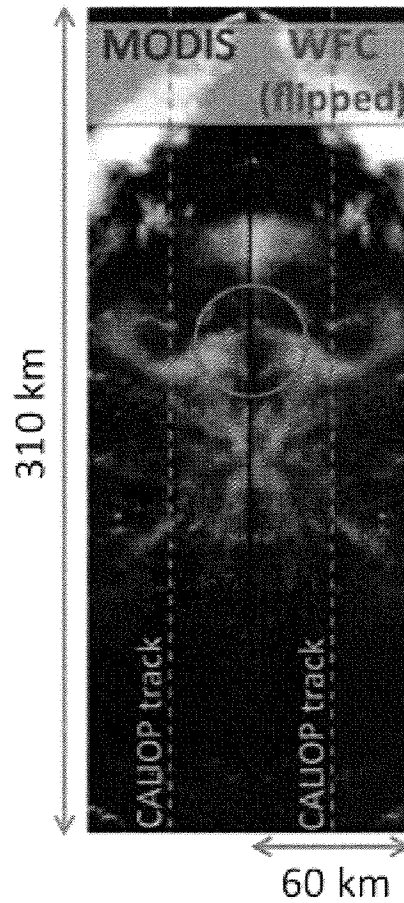


Figure 1. A sample scene of MODIS and WFC 0.65 μm reflectances. As the WFC image is flipped, the full image should be symmetric if clouds didn't change between the CALIPSO and Aqua overpasses. The asymmetry highlighted by a circle illustrates clouds drifting with the wind.

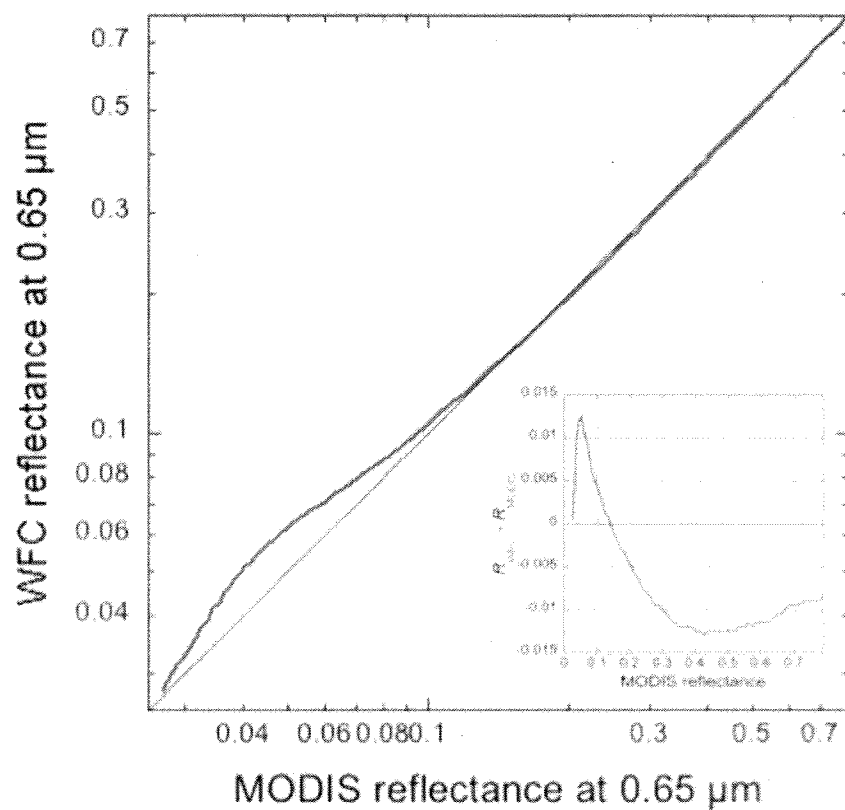


Figure 2. Comparison of WFC and MODIS reflectances at the first, second, third,... 99th percentiles of the overall WFC and MODIS reflectance histograms. Inset: Difference between WFC and MODIS reflectances at each percentile bin, plotted on a linear scale.

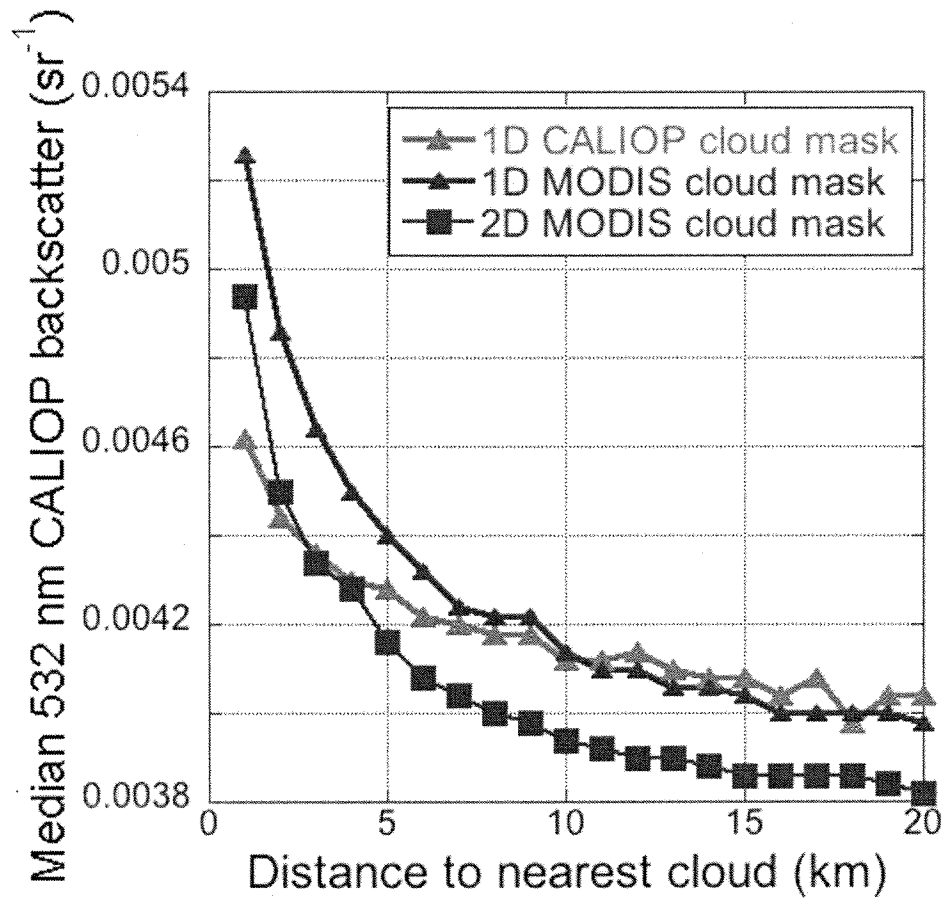


Figure 3. Median of CALIOP 532 nm backscatters integrated up to 3 km altitude near clouds whose top is below 3 km, for three different cloud masks (CM): CALIOP CM (red triangles), MODIS CM along a single line (blue triangles), and MODIS CM (blue squares). Plot is for winter (December 2006-February 2007) in the 30°-60° North latitude band.

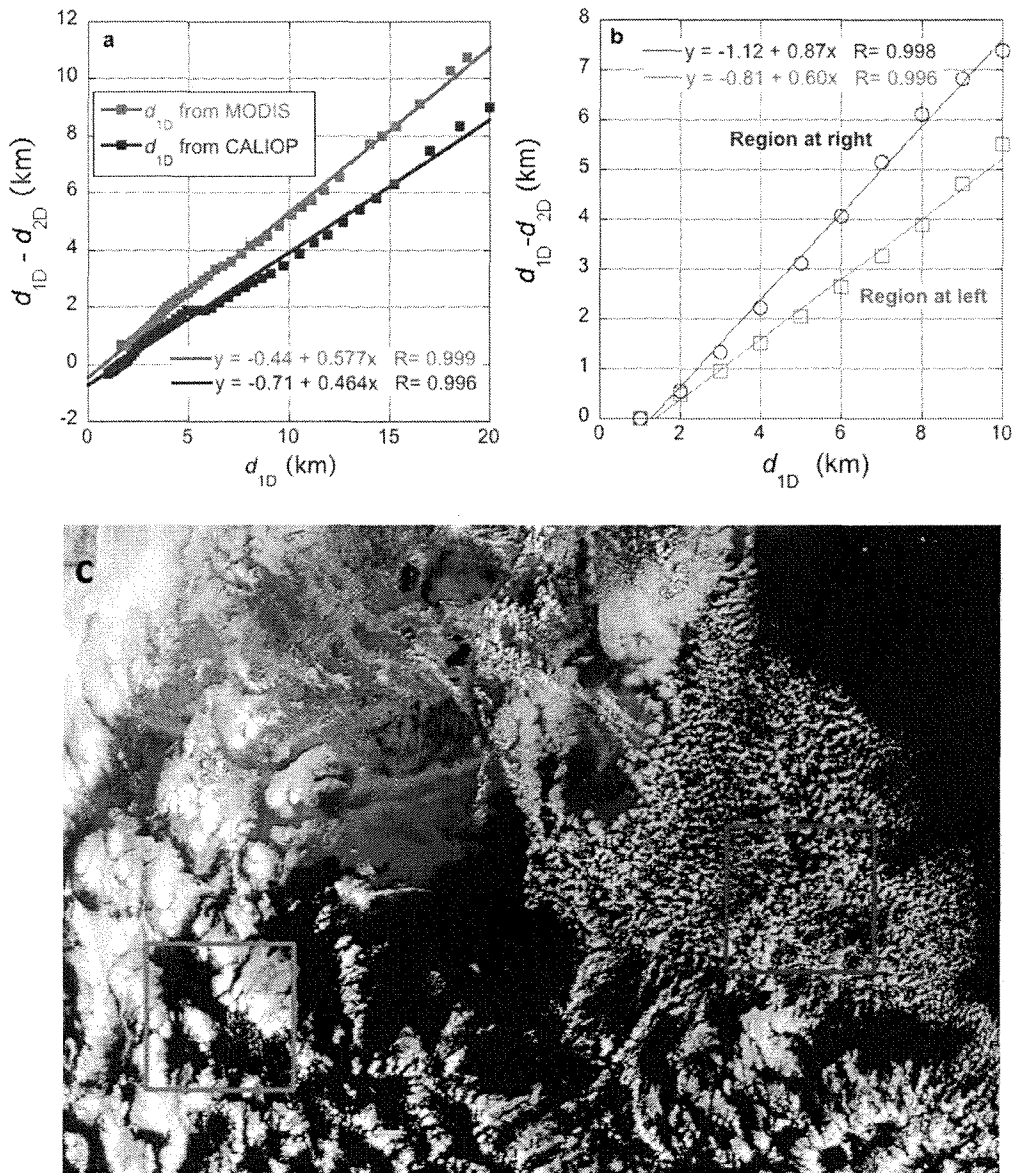


Figure 4. (a) Relationship between clear areas' distance to the nearest clouds in 1D and 2D searches for clouds. (b) Same relationship for the two sample areas in Panel c, with the difference that d_{1D} and d_{2D} are obtained directly from the 2D MODIS cloud mask (without considering lidar color ratios as in Panel a). For each d_{1D} bin, median values of $d_{1D} - d_{2D}$ are plotted. (c) MODIS image of the Mississippi delta, with the two 100 km X 100 km size sample areas highlighted.

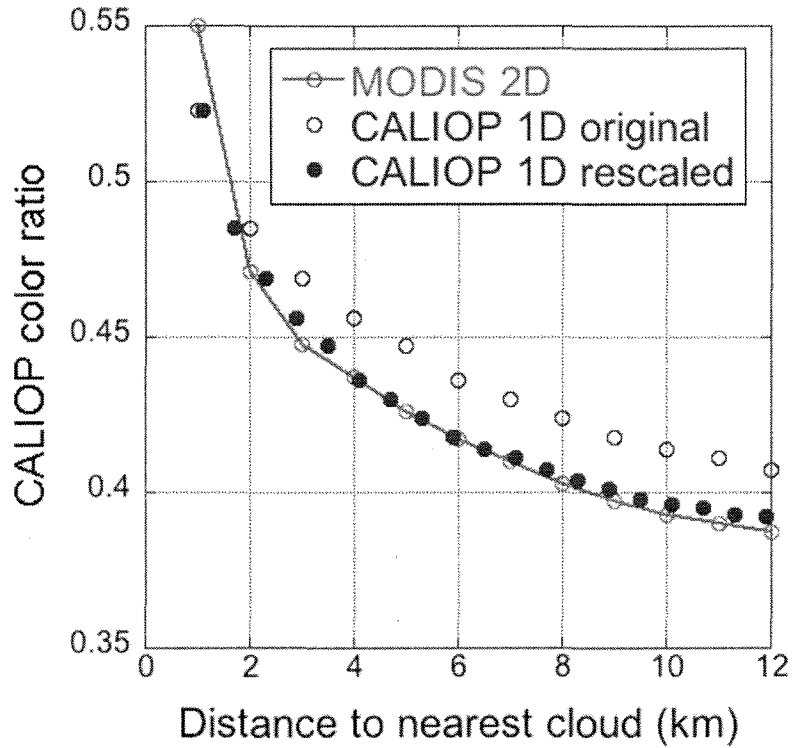
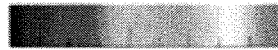
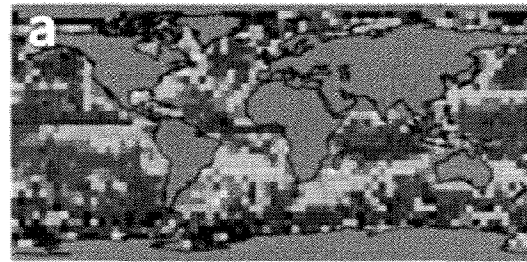
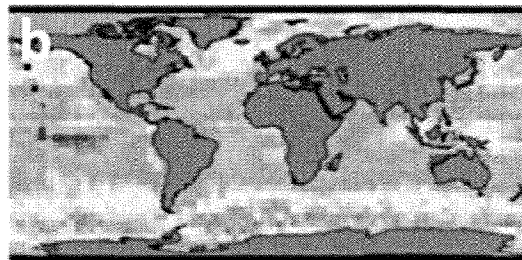


Figure 5. Median CALIOP backscatter (integrated up to 3 km altitude) near clouds detected by the 2D MODIS cloud mask (red circles), by the 1D CALIOP cloud mask (blue empty circles) and if the distance to clouds detected by the 1D CALIOP mask are rescaled to estimate the effect of clouds outside the lidar track (blue full circles). The plot extends to 12 km, the 2D distance that corresponds to a 1D distance of 20 km for the blue line in Figure 4a.



1 5 10

Annual median distance to clouds (km)



0 0.2 0.4 0.6 0.8 1

Annual mean cloud fraction

1

2

3

4

5

6

7

Figure 6. (a) Annual median distance to low clouds. (b) The cloud fraction of low clouds based on the 2D MODIS cloud mask.