Cloud features detected by MODIS but not by CloudSat and CALIOP

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[1] The ability to characterize the global cloud cover from space has been greatly enhanced by the availability of MODIS, CloudSat, and CALIOP data. The three sensors provide good complementary information about clouds. In this study, we investigated unexpected observations of certain types of clouds apparent in the MODIS data but not detected by CloudSat and CALIOP. Several examples are presented and generally these undetected clouds are geometrically thin, low-level clouds. In particular, they are located in the Arctic region and have optical thicknesses of less than 14, top height altitudes of below 2.5 km, and layer thickness of less than 1 km. CloudSat may miss such low-level clouds because of its coarse vertical resolution of about 500 m and it has limited sensitivity near the surface. Unexpectedly, CALIOP with a much higher vertical resolution of 30 m also misses these clouds and this is due to the cloud’s geometrically thin nature and surface proximity. Citation: Chan, M. A., and J. C. Comiso (2011), Cloud features detected by MODIS but not by CloudSat and CALIOP, Geophys. Res. Lett., 38, L24813, doi:10.1029/2011GL050063.

1. Introduction

[2] Clouds are a major component of the Earth’s climate system. They reflect shortwave radiation from the sun and emit longwave radiation thereby controlling the Earth’s radiation budget. They drive the Earth’s hydrological cycle through the vertical exchange of water between the surface and the atmosphere. Also, they are a major element of the surface weather system and are associated with the most damaging storms, severe winds, tornadoes, hail and lightning [Curry and Webster, 1999]. A major challenge in climate change studies is the accurate characterization of clouds that cover about half of the surface area of the Earth. Satellite remote sensing systems have provided good spatial and temporal coverage of global cloud cover but proper interpretation of the data, especially at high latitudes, has not been trivial [Comiso, 2010]. Among the most useful systems available is the Moderate Resolution Imaging Spectroradiometer (MODIS) [Stephens et al., 2002], a passive sensor on board EOS Terra and Aqua satellites that provides complete coverage of the Earth every two days. However, analysis of the data is difficult and sometimes ambiguous, especially in the Polar Regions where clouds and snow covered surfaces have very similar radiative signatures.

[3] The launch of new sensors in recent years that are dedicated for cloud cover studies provided some potential in resolving some of the ambiguities in the interpretation of MODIS cloud data. To explore this possibility, we analyzed data from the afternoon constellation of satellites called the “A-Train” [Stephens et al., 2002], which is a formation of satellites flying in close proximity providing an almost simultaneous measurement of the Earth’s atmospheric and surface characteristics. In addition to Aqua/MODIS, the key cloud sensors in the A-train are the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) onboard CALIPSO, and Cloud Profiling Radar (CPR) onboard CloudSat [Stephens et al., 2002]. It turned out that CALIOP and CPR are good complementary sensors that are very useful for detecting and characterizing clouds. However, we unexpectedly found out that these sensors are not able to detect some types of cloud features that are apparently present, as observed in the MODIS visible channel data. Such inability of two cloud sensors to detect some cloud cover types needs to be investigated because of the important role of these sensors in cloud cover studies [Menzel et al., 2008]. The focus of this paper is to gain insight into this phenomenon and improve our understanding why CALIOP and CPR are not able to detect these types of clouds.

2. Satellite Observations

[4] There are slight temporal sampling differences between the satellites, as CloudSat and CALIPSO trail the Aqua orbit by approximately 60 and 77.5 seconds, respectively. The uncertainties resulting from temporal sampling differences are minimal as cloud sizes observed are tens to hundreds of km wide and the cloud features cannot possibly disappear during this time interval. Both CPR and CALIOP are near-nadir-pointing sensors and they pass through the near-nadir field-of-view of MODIS. This configuration allows a better spatial comparison and collocation, as parallax effect from MODIS is negligible. The following sections briefly describe MODIS, CPR, and CALIOP instruments and their cloud detection algorithms. In addition, MODIS cloud product used to characterize these undetected clouds is also presented.

2.1. Moderate Resolution Imaging Spectroradiometer (MODIS)

[5] MODIS measures radiances at 36 wavelengths with center wavelengths ranging from the visible to long wavelength infrared (0.413 μm to 14.235 μm) with spatial resolution of 250 m to 1 km. Having a scan angle of ±55 degrees at an orbit of 705 km it achieves a swath dimensions of 2,330 km (cross-track) by 10 km (along-track at nadir) for every scan. The level 1 product contains both geolocation...
(level 1a) and measured radiances (level 1b), along with reflectance for the visible channels. Every product granule contains five minutes of data that has about 203 scans, which is equivalent to 2030 km (along-track). MODIS cloud mask product (MYD35 collection 5) \cite{Frey et al., 2008} uses a threshold approach coupled with a fuzzy logic system to discriminate whether a scene is confident cloudy, probably cloudy, probably clear, or confident clear. Thresholds for brightness temperature, brightness temperature difference, reflectance, and reflectance ratio for various cloud detection tests are established. These are derived from heritage algorithms, manual inspection, and statistics from collocated CALIOP products and MODIS radiance data, and statistics from quality controlled MODIS radiances data and MYD35 cloud mask results. Derived MODIS cloud characteristics (MYD06 collection 5.1) are also used, which provide information on the particle phase, effective cloud-particle radius, and cloud optical thickness, as well as cloud top temperature and height, surface effective emissivity, phase, and cloud fraction.

2.2. Cloud Profiling Radar (CPR)

\cite{Marchand et al., 2008} The CPR is a 94 GHz near-nadir-looking radar which measures the return power backscattered by clouds as a function of distance from the radar. It operates at a much shorter wavelength than typical weather radars to detect clouds rather than rain. Its sampling frequency is at 625 kHz (i.e. 0.16 sec/sample) and a sample defines a profile. A single profile has a footprint of approximately 1.3 km across-track and 1.7 km along-track with a vertical resolution of 500 m, and with 60 vertical data bins this creates a 30 km data window. The CPR cloud detection algorithm \cite{Marchand et al., 2008} differentiates radar return power that is due to scattering by clouds from those that contain only noise. The algorithm output is stored in the CloudSat operational geometric profile (2B-GEOPROF release R04) data product. Cloud mask values from 0 to 40 are assigned for each vertical bin. Masked values of 20, 30, and 40 indicate sufficient echo and high confidence of cloud presence with low false detection rates of only 5%, 4.3%, and 0.6%, respectively. On the other hand, very weak echo with masked values from 6 to 10 indicate probable cloud presence using along-track averaging. The false detection rate of masked values from 6 to 10 is high at 44% \cite{Marchand et al., 2008}, and these values are therefore considered in this study as clear sky signals.

2.3. Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP)

\cite{Liu et al., 2009} CALIOP is a near-nadir-viewing, polarization-sensitive elastic backscatter lidar which uses a pumped Nd:YAG laser transmitting at wavelengths of 1063 nm and 532 nm \cite{Liu et al., 2009}. Two polarization-sensitive 532 nm receivers observe the degree of linear depolarization of the return signal, which has perpendicular and parallel components of the polarization vector of the linearly polarized output of the laser transmitter. Measurements of the total backscatter radiation at 1063 nm and degree of linear depolarization at 532 nm are used to discriminate between clouds and aerosols. This is achieved using a multi-dimensional probability density function based approach. Also, the vertical distribution of cloud and aerosols along with their microphysical and optical properties are determined. The spatial resolution of CALIOP is degraded with increasing altitude above mean sea level. At an altitude between −0.5 km and 8.2 km (a negative altitude means below mean sea level), it has a maximum resolution of 30 meters vertical resolution and 333 meters horizontal resolution (for both along-track and cross-track). At a higher elevation between 8.2 km and 20.2 km, the vertical and horizontal resolutions are 60 meters and 1000 meters, respectively. The CALIOP level 2 Vertical Feature Mask (VFM version 3.01) data product provides feature classification within a vertical profile. There are six VFM features identified and these are: clear air, cloud, aerosols, stratospheric feature, surface, and sub-surface.

2.4. Methodology

\cite{Marchand et al., 2008} The strategy is to analyze a few examples in which cloud cover is observed in the MODIS data but not by CPR or CALIOP. We then evaluate the characteristics of the cloud using cloud parameters derived from the MODIS data. The results are presented in the following section using sets of images and plots arranged in a logical manner, starting with an Aqua MODIS 1 km (MYD021KM collection 5) image that is derived from 0.659 \(\mu m\), 0.555 \(\mu m\), and 0.470 \(\mu m\) reflectance, representing red, green, and blue, respectively. Undetected clouds are labeled in the MODIS image and also in the other panels as well. CALIOP and CloudSat tracks are overlaid onto the MODIS image as shown by the black and red lines, respectively, the latitude of the first and last coincident MODIS and CALIOP/CloudSat data points are indicated and their tracks will pass at least one undetected cloud for all cases. This is followed by a cloud mask result (MYD35 collection 5) of the scene. Various scenes are color-coded with gray, white, red, dark green, and spring green which correspond to not determined, cloudy, uncertain, probably clear, and clear, respectively. VFM (version 3.01) and GEOPROF (release 4) profiles starting from the first and last MODIS and CALIOP/ CPR coincident data points are presented. The cloud mask from CPR 2B-GEOPROF is color-coded with white, green, sky blue and blue violet signifies clear air, weak echo, good echo, and strong echo, respectively. Also, features from the VFM are designated with white, sky blue, orange, yellow, green, gray, and black to indicate clear air, cloud, aerosol, stratospheric feature, surface, subsurface, and fully attenuated or no signal, respectively. Cloud optical thickness and top height from MODIS cloud product (MYD06 collection 5.1) are shown to provide insight into the characteristics of these undetected clouds. Cloud top heights are translated from cloud top pressures by using a pressure to geopotential height conversion \cite{Kalnay et al., 1996}. The cloud top height and optical thickness that lies closest to the CloudSat track are used. Finally, reflectance values from 0.659 \(\mu m\), 0.555 \(\mu m\), 0.470 \(\mu m\) bands are plotted to assess cloud presence that might be associated with abrupt increase in top of the atmosphere (TOA) reflectance. This is accompanied by a bar indicating MODIS cloud mask results (top) and the scene background (bottom) along the CloudSat track. Bilinear interpolation was used to determine reflectance values on a CloudSat footprint.

3. Results

\cite{Marchand et al., 2008} Figure 1a shows a 1 km MODIS granule image over Baffin Bay, Labrador Sea, and Greenland on June 30, 2009. This particular scene is very cloudy and has a complex cloud formation. The Cloudsat/CALIPSO track started from
50° N and ended at about 67.4° N and passing through different cloud types over water as shown in Figures 1h and 1i. The mask results in Figures 1b clearly show that the entire Cloudsat/CALIPSO track is cloudy all throughout with some small area of probably clear scenes. The vertical profiles of CPR and CALIOP along their track are shown in Figures 1c and 1d, respectively. The CPR did not detect any clouds with the exception of the geometrically thick clouds between 60° N and 64° N and around 67° N. This is not consistent with MODIS observation. The CALIOP data also show cloud free regions but not as extensive as that observed by CPR. CALIOP produces a multifaceted view, detecting high clouds at an altitude of 10–11 km from 50° N to 53° N, and underneath, it detects thin low-level clouds with a top height.
below 1 km between 50° N to 55.7° N. Furthermore, another multi-layered cloud is detected between 57° N to 64° N.

Although CPR and CALIOP miss some cloud types, it is important to note that when they are able to detect clouds they provide useful and complementary cloud cover characterization. For example, CALIOP is able to detect thin clouds as well as multilayered clouds, but for geometrically very thick clouds the signal gets fully attenuated thus the full profile will be incomplete and the bottom height is undetected. On the other hand, CPR provides full profile of thick clouds as well as information on its bottom height. It is evident that CPR does not detect geometrically thin clouds (detected by CALIOP in Figure 1d) at different altitudes. The synergy of these two active sensors could potentially provide detection of a whole variety of cloud types. Looking at both Figure 1c and Figure 1d, it is evident that there is a cloudless portion between 56° N and 57° N labeled ‘A’, which otherwise, is cloudy as seen from Figures 1a and 1b, and indicated from the sharp rise in the values of TOA reflectance as shown in Figure 1g. To examine the characteristics of these undetected clouds, cloud optical thickness and top height from MODIS are plotted, as shown in Figures 1e and 1f. In this particular case, when the clouds have an optical thickness of less than 11, both CPR and CALIOP are not able to detect them. When the optical thickness is above 11, CALIOP is able to detect the clouds but CPR may miss it except when it is geometrically thick, such as those above 67° N. An optical thickness of 11 appears to be a lower limit wherein CALIOP does not detect these specific clouds. The clouds that are not detected are low clouds with a cloud top height of about 1.9 km as indicated by the MODIS cloud product. There is an obvious difference in the top height values between MODIS and CALIOP, especially for low clouds. From 53° N to 55.7° N, the low cloud detected by CALIOP has a top height near the sea surface at 0.8 km whereas for MODIS it is at 1.9 km, despite the difference, MODIS still reveals that the low cloud is continuous from 53° N up to 57° N, which includes the undetected cloud. However, the uncertainty in the height measurements for low clouds as determined using MODIS data is relatively high. MODIS overestimates marine stratus clouds (bias > 1 km) especially during low-level temperature inversions [Holz et al., 2008; Hagihara et al., 2010]. The cloud not detected by CPR is part of a continuous low cloud starting from 53° N to 55.7° N. A portion of this was not detected by CALIOP because the optical thickness declined from values between 11–15 to optically thinner values of 5–11, as shown in Figure 1e. It does appear that optical thickness provides key information that helps determine whether CALIOP is able to detect a cloud feature. It is also apparent that these undetected clouds could have a layer thickness of less than 1 km and top height of below 1 km, as can be inferred from the characteristics of the low clouds detected by CALIOP. It is also noted that the TOA reflectance over the scene with undetected clouds ranges from about 25% to 35%.

A similar case though not as extensive in cloud cover is presented in Figure 2. In this case, there are two undetected clouds labeled ‘A’ and ‘B’ shown in Figures 2a and 2b. Since the clouds are isolated it is easier to distinguish them from the background scene, which is water. Also, the abrupt increase in the TOA reflectance values (from 3%–7% over water to 12–14% and 25–27%, for undetected clouds ‘B’ and ‘A’ over water, respectively) as the scene changes from surface water to clouds facilitates the identification of clouds ‘A’ and ‘B’, as shown in Figures 2g, 2h, and 2i. The Cloudsat/CALIPSO track went through the Greenland ice sheet and unto Baffin Bay where the two undetected clouds are located. In this case the cloud cover characterization by CPR and CALIOP are very similar as shown in Figures 2c and 2d. It can be seen that it is very cloudy over the Greenland ice sheet. It showcases sorts of cloud types, low and thick marine clouds from 59° N to 60° N, and multilayered cloud over the ice sheet and coast. Again, clouds ‘A’ (74.3° N–75.5° N) and ‘B’ (72° N–72.7° N) are undetected by both CPR and CALIOP. Their cloud properties shown in Figures 2e and 2f are very similar to the previous case, having a maximum cloud optical thickness of 4.1 (for cloud ‘B’) and 10.7 (for cloud ‘A’) and cloud top height of 1.9 km and 2.1 km, respectively. These undetected clouds are again low-level clouds (top height below 2.5 km).

To demonstrate that the phenomenon occurs in other parts of the Arctic region and for a different time period, two other examples are provided in Figures 3 and 4. Figures 3a and 3b show a MODIS image and cloud cover image, respectively, over Norwegian and North Sea on 6 July 2007 with a transect line indicating the Cloudsat/CALIPSO track. The Cloudsat/CALIPSO track started from 52.5° N to 69.8° N passing through two significant cloud features, one below 64°N and the other above 66° N. The cloud features are quite evident in the MODIS image and are classified as cloudy as shown in Figure 3h and 3i, and further confirmed in Figure 3g which shows an abrupt increase in the TOA reflectance over the cloud-covered region. Again, neither CPR nor CALIOP is able to detect the significant cloud feature above 66° N, labeled ‘A’. The MODIS derived cloud properties of this undetected cloud is presented in Figure 3e and 3f. It indicates that the cloud top height is at 1.9 km and the maximum cloud optical thickness is 11.5. Thus it can be classified as a low-level marine stratus. The inability of CPR to detect such low level clouds has been studied previously and attributed to the inherent difficulty of the sensor to detect low clouds due to surface clutter [Marchand et al., 2008]. On the other hand, it is totally unexpected that CALIOP is not able to detect such a pronounced feature with an optical thickness well above its minimum sensitivity of about 0.01 [Hagihara et al., 2010].

The final example for clouds undetected by CPR and CALIOP but detected by MODIS is shown in Figure 4. This time, the phenomenon occurred at Chuckchi Sea on 10 July 2007 where a significant cloud feature is present from 66° N to 74° N, as shown in Figures 4a and 4b. The Cloudsat/CALIPSO track passed through almost the entire length of this cloud feature, labeled as ‘A’. Figures 4c and 4d again indicate that this feature is not detected by either CALIOP or CPR. Its cloud top height is 1.6 km and maximum cloud optical thickness is 13 from Figures 4e and 4f. As in the previous cases, the retrieved MODIS cloud parameters suggest that the feature is a near surface cloud feature. As shown in Figure 4g, the TOA reflectance went from 10% up to 35% as the MODIS field of view moved from clear sky over land to cloud cover over water (see Figures 4h and 4i).
possibly because of the cloud’s geometrically thin nature (1 km layer thickness is equivalent to 2 CPR pixels only) and the signal may be lost during spatial filtering. The inability of CALIOP to detect the cloud feature is again a surprise because it has a much higher vertical resolution of 30 m (at altitudes below 8 km) and is sensitive to most clouds with cloud optical thickness as low as 0.01. It is expected that these clouds with relatively high optical thickness will cause a discernible backscatter return detectable by CALIOP as a cloud feature. It is possible that CALIOP misidentifies the low-level cloud as a surface feature. This is suggested by Figure 3d in which a slight increase in sea surface elevation (in green) over the location of the undetected clouds is indicated by the CALIOP VFM. The presence of these undetected low-level clouds could be partially the reason why MODIS detects more low clouds.

**Figure 2.** (a) MODIS image, (b) MODIS mask results, (c) CPR and (d) CALIOP vertical profiles, (e) optical thickness and (f) top height of undetected clouds, (g) TOA reflectance, (h) MODIS mask on CloudSat track, and (i) surface type. Data are from 1540 UTC 21 June 2010.
compared to that of combined CPR-CALIOP as reported by Hagihara et al. [2010].

4. Conclusion

[15] The three sensors that have been used successfully for studying global cloud cover have been the MODIS, CPR and CALIOP. These sensors provide good complementary information about clouds. In our study, we investigated unexpected observations of certain types of clouds that are apparent in the MODIS data but not detected by either CPR or CALIOP. In general, we found that these undetected clouds are geometrically thin, low-level clouds. In particular, they have optical thickness of less than 14, top height altitude of below 2.5 km (from MODIS) and layer thickness of less than 1 km. CPR may miss such cloud type because its vertical resolution is about 500 m and it has low sensitivity near the surface. Unexpectedly, CALIOP, with a very high

Figure 3. (a) MODIS image, (b) MODIS mask results, (c) CPR and (d) CALIOP vertical profiles, (e) optical thickness and (f) top height of undetected clouds, (g) TOA reflectance, (h) MODIS mask on CloudSat track, and (i) surface type. Data are from 1225 UTC 6 July 2007.
vertical resolution of 30 m, also misses this cloud type due to
the cloud’s geometrically thin and near-surface character-
istics that could have caused them to be misinterpreted as
surface features instead.

[16] The accuracy of Earth’s surface parameter retrieval
and energy budget highly depends on the proper identification
of cloud cover. Since CPR and CALIOP have been used to
validate cloud detection algorithms for MODIS data, it is
useful to know that the former have some limitations that
have to be taken into consideration. The results are also
needed for accurate characterization of the global cloud
cover. Because of the strong impact of a changing cloud
cover on the Earth climate system, future studies should
include a more comprehensive sampling and statistical

Figure 4. (a) MODIS image, (b) MODIS mask results, (c) CPR and (d) CALIOP vertical profiles, (e) optical thickness and
(f) top height of undetected clouds, (g) TOA reflectance, (h) MODIS mask on CloudSat track, and (i) surface type. Data are
from 2335 UTC 10 July 2007.
analysis of the frequency of occurrence of the cloud type undetected by CPR and CALIOP.

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**References**

Comiso, J. C. (2010), *Polar Oceans from Space*, Atmos. Oceanogr. Sci. Libr., vol. 41, Springer, New York.
Curry, J. A., and P. J. Webster (1999), *Thermodynamics of Atmospheres and Oceans*, Int. Geophys. Ser., vol. 65, Academic, London, U. K.
Frey, R. A., et al. (2008), Cloud detection with MODIS. Part I: Improvements in the MODIS cloud mask for collection 5, *J. Atmos. Oceanic Technol.*, 25, 1057–1072, doi:10.1175/2008JTECHA1052.1.
Hagihara, Y., H. Okamoto, and R. Yoshida (2010), Development of a combined CloudSat-CALIOP cloud mask to show global cloud distribution, *J. Geophys. Res.*, 115, D00H33, doi:10.1029/2009JD012344.
Holz, R. E., S. A. Ackerman, F. W. Nagle, R. Frey, S. Dutcher, R. E. Kuehn, M. A. Vaughan, and B. Baum (2008), Global Moderate Resolution Imaging Spectroradiometer (MODIS) cloud detection and height evaluation using CALIOP, *J. Geophys. Res.*, 113, D00A19, doi:10.1029/2008JD009837.
Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, 77, 437–471, doi:10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.
Liu, Z., et al. (2009), The CALIPSO lidar cloud and aerosol discrimination: Version 2 algorithm and initial assessment of performance, *J. Atmos. Oceanic Technol.*, 26, 1198–1213, doi:10.1175/2009JTECHA1229.1.
Mace, G. G., R. Marchand, Q. Zhang, and G. Stephens (2007), Global hydrometeor occurrence as observed by Cloudsat: Initial observations from summer 2006, *Geophys. Res. Lett.*, 34, L09808, doi:10.1029/2006GL029017.
Marchand, R., G. G. Mace, T. Ackerman, and G. Stephens (2008), Hydrometeor detection using Cloudsat—An Earth-orbiting 94-GHz cloud radar, *J. Atmos. Oceanic Technol.*, 25, 519–533, doi:10.1175/2007JTECHA1006.1.
Menzel, W. P., et al. (2008), MODIS global cloud-top pressure and amount estimation: Algorithm description and results, *J. Appl. Meteorol. Climatol.*, 47, 1175–1198, doi:10.1175/2007JAMC1705.1.
Stephens, G. L., et al. (2002), The CloudSat mission and the A-Train: A new dimension of space-based observations of clouds and precipitation, *Bull. Am. Meteorol. Soc.*, 83, 1771–1790, doi:10.1175/BAMS-83-12-1771.

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