Comparison of cloud top heights derived from MISR stereo and MODIS CO_2-slicing

Catherine Naud and Jan-Peter Muller

University College London

Eugene E. Clothiaux

The Pennsylvania State University

Abstract. The EOS-TERRA MODIS and MISR instruments provide radiances for independent spectral and stereo retrievals of cloud top height (CTH), respectively. Collocated and coincident CTH retrievals were compared against each other and with coincident millimeter-wave radar (MMCR) retrievals over the British Isles and the ARM SGP site. This inter-comparison suggests close agreement between MMCRR, MODIS and MISR when they detect the same CTHs. When MISR detected high clouds, MISR stereo CTH was generally higher than MODIS CO2-slicing CTH. However, for large areas in most of the 27 scenes studied here, high clouds were detected by MODIS but not by MISR. These high clouds occurred during periods of multi-layered clouds. Inspection of all off-nadir MISR radiances during these periods indicated that MISR has sufficient sensitivity to detect these clouds, but not with the innermost 3 MISR cameras used for stereo CTH retrieval.

Introduction

The TERRA satellite was launched on December 18th 1999, and hosts, amongst other instruments, the MODerate resolution Imaging Spectrometer [MODIS; Ardanuy et al., 1991] and the Multi-angle Imaging SpectroRadiometer [MISR; Diner et al., 1998]. Both instruments are used to retrieve cloud properties, including cloud top heights (CTHs), on a global scale. The CTHs from MODIS are derived using four channels in the CO2 absorption band at 15 μm using the CO2-slicing method [; King et al., 1992], while MISR CTHs are derived from multi-angle red channel radiances and a stereo photogrammetric technique [Diner et al., 1999; Moroney et al., 2002; Muller et al., 2002; Zong et al., 2002].

This study presents the first assessment of the similarities and differences between CTHs retrieved from MODIS and MISR. We first examined MODIS and MISR CTH differences over a large area covering the British Isles for 7 cases between August 2000 and November 2000 and 20 cases between March 2001 and October 2001. We then compared both MODIS and MISR CTHs with millimeter-wave radar CTH retrievals at the UK Radar Facility in Chilbolton and the Atmospheric Radiation Measurements (ARM) Program Southern Great Plains (SGP) site over the period from March 2001 through August 2001.

MODIS and MISR product descriptions

The MODIS cloud properties are archived in the MOD06 product [King et al., 1992], which includes cloud top pressure. We transformed these pressures into heights using ECMWF Operational Analysis (OA) profiles [ECMWF 1995. The description of the ECMWF/WCRP Level III-A Global Atmospheric Data Archive]. On 25 August 2000, 07 September 2000 and 13 April 2001 we tested the difference between the cloud top temperature given in the MOD06 product and the cloud top temperature derived from the cloud top pressure using the ECMWF OA profiles. The percentage difference per pixel was on average less than 1% with no systematic bias and a maximum difference under 3.5%. A 1% temperature error linearly translates into a height error of 100 m for a cloud at 10 km, while a temperature difference of 4% leads to an error of 500 m for a cloud at 12 km.

The CO2-slicing technique is not accurate below 3km due to low signal-to-noise ratio of the sounding spectral bands near the surface. For low clouds, cloud top pressures are operationally retrieved using the MODIS brightness temperatures at 11 μm (TB,11). The MODIS cloud top heights retrieved from TB,11 and the CO2-slicing techniques were separated into two distinctdata pools, both considered in the comparisons. The MISR cloud top heights were derived using a stereo technique that used operationally the nadir view and either one of the two cameras closest to nadir with wind corrections derived from a triplet of off-nadir cameras [Diner et al., 1999; Moroney et al., 2002; Muller et al., 2002; Zong et al., 2002].

The current resolution of the MOD06 product is 5 km (derived from radiances averaged to 5 km), whereas the MISR cloud top heights are given at a resolution of 1.1 km (derived from radiances at 275m). In order to compare the two on a pixel-by-pixel basis the MISR data were re-projected onto the MODIS latitude-longitude grid using weighted averages. While we did not systematically assess the interpolation method, it did appear to be more accurate than just selecting the central MISR pixel or performing an average over the relevant group of MISR pixels. We obtained similar results irrespective of whether we projected MODIS pixels into MISR space or vice-versa as we did for this study.

In addition to cloud top pressure the MOD06 product contains a variety of other cloud properties, including cloud effective emissivity, fraction, phase, particle effective radius and optical depth [King et al., 1992]. We attempted to use these products as explanatory variables for the differences in CTH retrieved from the two instruments.

Comparisons over the British Isles

To compare CTHs we selected a MODIS granule location that covered most of the British Isles and MISR blocks 43-51 of EOS-TERRA paths 201-207 since they significantly overlapped with the MODIS granule. We then averaged CTHs over that part of each scene where both instrument swaths overlapped and compared the results. These CTH averages and pixel-by-pixel comparisons included all cloud top heights from low (above 3 km) to high-level clouds. Overall, the average CTHs were higher for MODIS than for MISR, with only 2 of the 27 case study periods having a higher MISR average CTH. The MODIS minus MISR average CTH differences were less than 1 km in 10 cases, between 1 km and 2 km in 12 cases and greater than 2 km in 5 cases (Figure 1). The standard deviations of the MODIS and MISR CTHs about each of their corresponding scene averaged CTH varied between 1.2 km and 3.77 km. In 14 cases the standard deviations were less than 2 km, while in 22 cases they were less than 2.5 km.

Selecting those pixels for each scene where MISR CTH was above MODIS CTH and averaging these CTHs for both MODIS and MISR, we found that the MISR average CTH was 0.63 km higher than the corresponding MODIS value across all 27 case study periods, with a slight increase in the difference as the MISR average CTH increased (Figure 1). For these scene averaged CTHs, the correlation coefficient was 0.92, indicating a consistent relationship from one date to the next. Selecting those pixels for each scene where MODIS CTH was above MISR CTH and averaging them, we found that the resulting MISR CTHs did not vary much, as for a majority of cases they fell between 2 km and 4 km (Figure 1).

To ascertain why MISR sometimes failed to detect high clouds, we selected 15 scenes containing pixels with a MODIS-retrieved optical depth less than 0.5 and compared the corresponding averaged MISR and MODIS CTHs (Figure 2). Even for the minimum optical depth of 0.1, we found that MISR detected these clouds and produced CTHs comparable to the MODIS values. Consequently, thin clouds not detected by MISR would require an optical depth less than 0.1, which is the lower limit on cloud optical depth retrieved by MODIS. Nevertheless, we did not exclude the possibility that clouds with an optical depth less than 0.1 were detected by MODIS and not by MISR.

We then examined the five scenes that occurred on 10 October 2001, 1 May 2001, 17 April 2001, 30 March 2001 and 13 April 2001 when MISR average CTHs were 2 km or more below the MODIS values. Stereo color anaglyphs of each individual scene, produced by the two most off-nadir MISR cameras at 60° and 70°, revealed that areas where MISR CTHs were lower than MODIS CTHs were actually covered by high thin clouds. The anaglyphs also demonstrated that thin clouds not detected by MISR using the narrower angles (±26° and 0°) were in regions covered by low clouds as well. Although MISR can detect high thin clouds with the most off-nadir cameras, the use of the innermost 3 cameras for stereo processing led to results where thin clouds over lower-level clouds were not detected by the current MISR CTH retrieval scheme. Lack of contrast in thin clouds for the innermost MISR cameras is the most probable cause of this result. To summarize, MODIS tended to retrieve average CTHs slightly higher than MISR. Inspecting five case study periods when the average difference between the two instruments was greater than 2.5 km, the CTH differences arose from areas where MODIS detected high clouds (above 5 km) and MISR detected low clouds (around 2 km). Stereo anaglyphs of these areas using the two most off-nadir MISR cameras showed high clouds above lower-level cloud decks. Finally, for scene averages of those pixels where MISR CTHs were above the MODIS values the correlation coefficient between the MISR and MODIS scene averaged CTHs was 0.92, suggesting that, when MISR did detect the tops of the highest clouds, the MODIS top heights were consistently biased 0.63 km too low. To explore these findings we used ground-based radar profiles from the Chilbolton and ARM SGP sites to investigate MODIS and MISR CTHs in more detail.

Comparison over Chilbolton and ARM SGP sites

The Chilbolton site

The Chilbolton Radar Facility (CRF), situated at 51.15°N and 1.43°W, has a zenith-pointing, 94-GHz cloud profiling radar, called Galileo. We visually estimated cloud top heights from reflectivity plots of Galileo data (courtesy of Robin Hogan, University of Reading) since no processed data were yet available from Galileo. To compensate for difficulties 94-GHz radars have in detecting small particles at high altitudes we took Galileo retrieved CTH to be the maximum CTH detected by the radar over the analysis interval for each scene. The MODIS and MISR CTHs for each scene were averaged over a ±0.1° latitude-longitude box centered on Chilbolton. The MISR CTHs were kept in their original 1.1 km resolution to avoid any inaccuracies introduced by the reprojection into the MODIS 5km grid. Pixels with MODIS CTHs derived from the IR channel were kept in this study since we were limited to small regions centered on the CRF site. Inclusion of these pixels did not affect the outcome of the comparisons, as the differences examined here mainly concerned high clouds for which CTH is derived principally using the CO2-slicing technique.

All three instruments observed clouds simultaneously on 8 dates, MISR and Galileo had simultaneous observations on 9 dates, MODIS and Galileo had 8 such cases and MODIS and MISR had 13 overlap periods (Figure 3). Relative to Galileo MODIS tended to overestimate slightly low cloud CTHs and underestimate high cloud CTHs. On one occasion (2001-10-10) MODIS detected a high cloud while the radar detected a broken cloud prior to and after but not during the MODIS overpass..

When comparing MISR CTHs with those from radar, we found reasonable agreement between the retrievals up to 4 km, but for Galileo CTHs above 4 km either the MISR CTHs were too low or the MISR retrieval did not detect the highest cloud layer. For the four cases where MISR failed to detect the highest cloud layer, the radar reflectivity plots showed multiple cloud layers (Table 1). For two of these four cases the clouds were scattered, while for three of the four cases the MISR stereo-derived CTHs referred to the lowest layer.

The MISR and MODIS CTHs agreed fairly well for values less than 4 km, but MISR underestimated CTHs above 4 km relative to MODIS. In four case study periods MISR failed to detect high thin clouds identified by the MODIS retrievals. Overall, MISR stereo CTHs exhibited more variability than MODIS CTHs over the same region (as seen from the one standard deviation error bars in Figure 3), which is likely to be the result of the higher resolution of the MISR pixels or the naturally higher variability in CTH retrievals using the stereo techniques. Stereo-matching blunders, which did not occur for more than 1% of the matched pixels, can also lead to unrealistic altitudes that can significantly enhance variability in CTHs.

The ARM SGP site

We performed a similar study at the ARM SGP site in Oklahoma (36.62°N, 97.50°W). Clothiaux et al. [2000] processed data from the ARM MMCR at the site to produce time-height profiles of radar returns from hydrometeors. We used these data to estimate the median CTH over the analysis interval for each scene. From March 2001 through August 2001 there were 6 cloudy case study periods with coincident MMCR, MODIS and MISR data. During this same period, there were 4 additional periods of coincident MMCR and MODIS data and 4 additional periods of coincident MMCR and MISR data (Figure 4).

The MODIS CTHs were lower than the MMCR CTHs for 8 out of the 10 case study periods. On most days the height differences were within 2 km, except for 22 March 2001 when MODIS CTHs were about 4 km lower than the MMCR CTHs. On this particular day, both the MODIS and MISR CTH distributions exhibited a fairly clear scene with scattered and sparse high clouds. From 10:00-20:00 UT the radar returns showed a cloud layer with a top around 11 km and a lower cloud layer with a top at about 5 km, which was the cloud layer detected by MODIS. In this case MODIS may have failed to detect the upper cloud because of its small (i.e., less than 0.1) optical thickness. For the 2 days when the MODIS CTHs were higher than the MMCR CTHs, they differed by no more than 2 km.

The MISR CTHs were in reasonable (i.e., 1 km) agreement with the MMCR CTHs below 7 km, which happened on four occasions. For the remaining six periods the MISR CTHs were too low relative to the MMCR retrievals. In two cases MISR CTHs were within 3 km of the MMCR CTH and in the other four cases MISR did not detect the highest cloud layer detected by the MMCR. The four significant failures in the MISR CTH retrievals resulted both from blunders in the MISR stereo-matching procedure and from the MISR retrievals failing to detect the highest cloud layer and reporting the heights of lower cloud layers (Table 2).

Comparing MISR and MODIS average CTHs, we found excellent agreement in two cases. For two other cases MISR average CTHs were higher by about 2 km, while for the last two cases (i.e. 15 and 22 March 2001) MISR failed to detect consistently mid-level clouds identified by MODIS. The two cases of higher MISR CTHs most likely result from inclusion of IR channel CTH estimates, as MISR CTHs tend to be higher than those derived with this technique.. On 22 March 2001, the clouds were broken and MISR failed to detect the highest layer. Moreover, the maximum MISR CTH for this scene was 17 km, which is unrealistic and indicative of a stereo-matcher blunder. For the scene on 15 March 2001 the MISR maximum CTH was fairly close to the MODIS average CTH. Both instruments detected the same cloud, but the MISR average CTH was too low because either the clouds were scattered or the retrieval failed on part of the mid-level cloud.

Conclusions

A comparison of MISR and MODIS CTHs over the British Isles showed that the two sets of averaged CTHs were generally within 2 km of each other, with MODIS CTHs being slightly higher overall. When the MISR retrieval did detect high clouds, MISR CTHs were generally higher than the MODIS values. There were large areas within many scenes where MODIS detected high clouds while MISR detected clouds at lower altitudes. High cloud layers not detected by the MISR retrieval were generally above lower cloud decks, as revealed by anaglyphs of these areas and by a comparison against radar-retrieved CTHs at the Chilbolton and ARM SGP sites. The failure of MISR to detect high clouds appears to result from the use of the innermost 3 cameras in the stereo matching and not from any lack of sensitivity of this instrument at the most oblique camera views.

Radar and MODIS CTHs were most often within 1-2 km of each other with a tendency for MODIS to underestimate CTH relative to the radar, especially at the ARM SGP site. As the ARM SGP site radar is more sensitive than the Chilbolton radar, this result was not surprising. Radar and MISR CTHs were in reasonable agreement for low altitude radar CTHs at both the Chilbolton and ARM SGP sites. However, at both sites MISR CTHs were biased low in comparisons with high altitude clouds detected by the radars. In most of these high altitude cloud cases lower-level clouds were also present, which the MISR retrieval did detect.

A consistent finding across all of the comparisons was the failure of the MISR CTH retrieval to detect high thin clouds. The MISR cameras closest to nadir did not exhibit features with strong contrast in high thin clouds when these clouds were located over lower-level clouds. The first objective of the stereo CTH retrieval is to characterize the height of the Reflecting Level Reference Altitude (RLRA), and in these cases successfully attributes it to more opaque lower-level clouds. However, for thin high clouds, the two outermost cameras displayed large contrasts with the nadir view, suggesting that their use could significantly improve MISR stereo CTH accuracy during periods of thin clouds over lower-level clouds insofar as the altitudes of both cloud layers might be retrieved. Large displacements of high clouds between the two most off-nadir cameras due to strong high altitude winds (about 20km for a 50m/s wind) would be accounted for in a fashion similar to the current MISR approach (e.g. Zong et al., 2002). The possibility does remain that the filamentary structure of some of these clouds, or their scattered spatial distribution, may cause problems for the current stereo matcher between the different views. To understand better the differences between the MODIS and MISR CTH retrievals some specific scenes will be analyzed again using different stereo matching techniques and different views.

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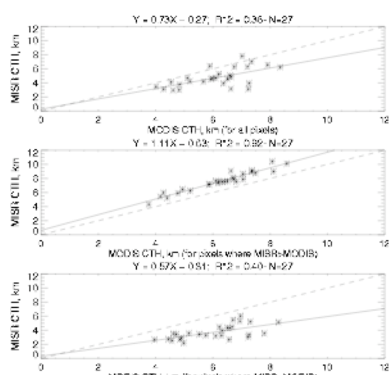

Figure 1. Top panel shows MISR averaged CTH against MODIS averaged CTH for 27 scenes. The average includes all pixels in the scene. Middle panel shows the same but with only the pixels where MISR CTH is greater than MODIS CTH. Lower panel shows the same as the top panel but keeping only the pixels where MODIS CTH is greater than MISR CTH. The solid lines show the linear fit and the dashed ones the 1-1 line.

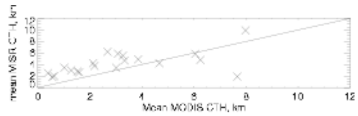

Figure 2. Average per date of all pixels where MODIS retrieved optical depth is less than 0.5 of MISR CTH as a function of MODIS CTH averaged in the same way.

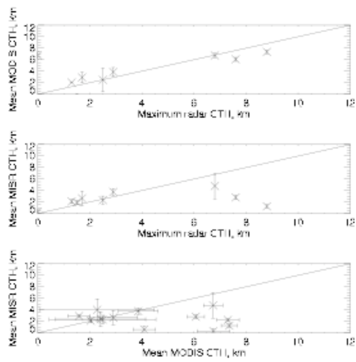

Figure 3. Chilbolton: MODIS mean CTH against radar maximum CTH (top panel), MISR mean CTH against radar maximum CTH (middle panel) and MISR mean CTH against MODIS mean CTH. The mean MODIS and MISR CTH are calculated in a latitude-longitude box of ±0.1° centered at Chilbolton. The error-bars correspond to one standard deviation from the mean.

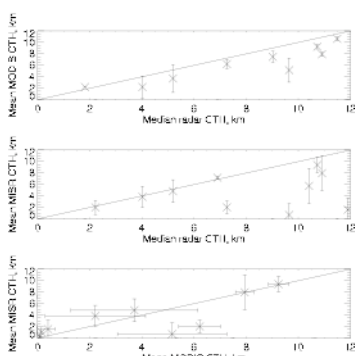

Figure 4. SGP ARM site: MODIS mean CTH against radar median CTH (top panel), MISR mean CTH against radar median CTH (middle panel) and MISR mean CTH against MODIS mean CTH. The mean MODIS and MISR CTH are calculated in a latitude-longitude box of ±0.1° centered at the SGP ARM site. The error-bars correspond to one standard deviation from the mean.

Table 1. Chilbolton: details on the cloud distribution when MISR CTH does not detect the highest cloud detected by the radar.

Date	Cloud distribution	Problem
2001-04-01	Multiple layers	MISR CTH refers to the lowermost layer
2001-06-06	Multiple layers	MISR CTH refers to the lowermost layer
2001-09-26	Multiple and broken layers	MISR detects parts of the uppermost layer but average gives lower CTH. High variability within lat-long box.
2001-10-10	Multiple and broken layers	MISR CTH refers to the lowermost layer

Table 2. SGP: details on the cloud distribution when MISR CTH does not detect the highest cloud detected by the radar.

Date	Cloud distribution	Problem
2001-03-15	Multiple layers	MISR CTH refers to the lowermost layer, few pixels show a CTH close to the highest layer
2001-03-22	Multiple and broken layers	MISR CTH does not detect highest cloud layer, blunder problem.
2001-07-05	Multiple layers	MISR CTH refers to lowermost layer
2001-08-22	Multiple and broken layers	MISR CTH does not detect highest cloud layer and may refer to lowermost layer, and blunder problem