On the use of ICESAT-GLAS measurements for MODIS and SEVIRI cloud-top height accuracy assessment

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Abstract. This study reports on the first attempt to use cloud boundary and optical depth retrievals from the GLAS lidar to assess the accuracy of cloud-top heights obtained with MODIS (onboard NASA-TERRA and AQUA) and SEVIRI (onboard METEOSAT-8). Over the period from 25 September to 18 November 2003, MODIS-GLAS coincidences were only found in the Polar Regions, whilst SEVIRI-GLAS coincidences were available for a larger range of latitudes. For both passive instruments, cloud-top heights were overestimated by about 300-400m when clouds were low and opaque. For high and thin clouds, MODIS and SEVIRI cloud-top heights were underestimated, and the bias increased with decreasing optical depth. For optical depths below 0.3, the number of misdetections increased significantly and the bias in cloud-top height increased from 1 to 2km. The bias was found to be larger when lower cloud layers were present.

1. Introduction

Passive instruments have been used for around 30 years but there has never been an opportunity before to assess the cloud optical depth limits that such instruments can sample. This is crucial in understanding the role of thin cirrus clouds in a warming climate. A better characterization is also necessary for building a long-term global climatology of cloud properties. Here we considered the Moderate resolution Imaging Spectroradiometer instrument (MODIS, onboard NASA TERRA and AQUA) for its collection 4 datasets (Platnick et al., 2003). In addition, the Spinning Enhanced Visible and InfraRed Imager data (SEVIRI, onboard the Meteosat Second Generation geostationary satellite, recently renamed METEOSAT-8) were processed at the Satellite Application Facility on Support to Nowcasting and very short range forecasting (SAFNWC) Meteo-France in Lannion (Le Gléau and Derrien, 2003) and provided for this study. Both instruments use state-of-the-art algorithms to retrieve cloud properties with infrared channels. They are scheduled for launch on successive missions (MODIS follow-on is VIIRS for the National Polar-Orbiting Operational Environmental Satellite System), and will then provide a continuous time series over at least a further 10 years.

The first active polar-orbiting instrument was launched on 12 January 2003, as part of the Ice, Cloud and Land Elevation satellite (ICESat) mission: the Geoscience Laser Altimeter System (GLAS) instrument (Zwally et al., 2002). GLAS has the great advantage of providing a high-resolution vertical profile of the distribution of cloud and aerosol layers of optical depth less than 2. Its depolarization capability also provides the optical depth of these layers (the minimum optical depth detected was 0.001). The observation of extremely tenuous cloud layers is unique to lidars and very helpful in assessing the performance and limiting optical depth of passive instrument algorithms.

Coincident GLAS retrievals were used to study the limit in cloud optical depth for understanding the accuracy of cloud-top heights from MODIS and SEVIRI. Assessment of MODIS cloud-top height retrievals was performed previously against ground-based lidar (Naud et al., 2004) and ground-based radar (Mace et al., 2005). However, beam attenuation in the first instance and the lack of optical depth retrieval in the second prevented an estimate of a limit in cloud optical depth. SEVIRI cloud-top heights were also assessed against MODIS and ground based radar measurements (de Valk et al, 2004), but again precise information on cloud optical depth was lacking. Errors for both instruments are expected in the case of optically thin clouds, multilayer clouds, clouds over bright surfaces, scattered clouds or clouds with complex three-dimensional structures and varying emissivity. The algorithms are optimized for thick, uniform, single-layered and overcast clouds and GLAS measurements were used to assess the consequences of such assumptions on cloud layer height assignment.

The datasets and method of comparison are discussed in sections 2 and 3 respectively. The results of the inter-comparison of cloud top heights obtained from GLAS, MODIS and SEVIRI as a function of GLAS optical depths can be found in section 4. Section 5 presents the conclusions of this study.

2. Data

The GLAS lidar transmits 4ns short pulses of infrared (1064 nm) and visible green light (532 nm). The altimeter uses a 1-m diameter telescope, the beam's footprint is 65 m and the separation between two consecutive measurements is 170 m. The first GLAS laser failed after three months and to avoid further problems, the second laser is only used every 3 months. Data retrieved with laser 2a from 25 September to 18 November 2003 have been processed with the latest algorithm (version 19) and publicly released. This algorithm has a better ability to distinguish between cloud and aerosol layers and better layer detection than the previous versions. The GLA-11 product (Zwally et al., 2003) provides the optical depth and boundary locations for up to 10 cloud layers from the top of the atmosphere to the level of complete laser attenuation or surface depending on which comes first. Clouds of optical depth up to 2 can be fully observed by the laser but higher optical depths cause total attenuation and no information below the attenuation level can be obtained. The great advantage of observing clouds with GLAS from space, compared to ground-based observations, is that it can still provide cloud-top heights of the highest clouds with a precision of 76.8 m. The instrumental issues have no impact on the performance of retrievals (S. Palm, 2005, private communication).

MODIS TERRA and AQUA were launched in December 1999 and March 2002 respectively. Operational cloud-top pressures (from the MOD06 product, Menzel et al., 2002) were converted to cloud-top heights using ECMWF operational analysis profiles. For clouds that emit sufficient signal in the channels close to the 15μm CO_2 absorption band, the CO_2-slicing method (e.g. Baum and Wielicki, 1994) is used to retrieve cloud-top pressure, whilst clouds below 3-5 km have to be retrieved using the 11μm brightness temperature. The initial 1km MODIS radiances are averaged to give a product at 5x5 km resolution.

SEVIRI is a 12 channel imager mounted on the geostationary METEOSAT-8 (launched in August 2002) centered on (0°N,-3.4°E) and rectified to (0°N,0°E). SEVIRI cloud-top heights are automatically generated by the SAFNWC Meteo-France and only available at 11:00UT. They are obtained using the 10.8μm brightness temperatures when clouds are opaque, no matter what altitude. When clouds are optically thin, another three sounding channels at 6.2μm, 7.3μm and 13.4μm are used with the 10.8μm channel and either the H_2O-IRW intercept method (Schmetz et al., 1993) or the radiance ratioing method (Menzel et al., 1983) are used. The pixel size increases as the view angle departs from nadir, and is about 5x3 km at (50°W,0°N) to 5x5 km at (50°W,50°N).

3. Method

Spatio-temporal coincidences between ICESAT and the two orbiters (TERRA and AQUA) were first isolated. We constrained the observations to be less than 5-minutes and 150km apart. The coincidences were found with a search engine provided by the Global Hydrology Resource Center. Over the laser 2a operation period, GLAS-MODIS coincidences occurred 15 times for TERRA and 16 times for AQUA, although always in the polar regions north or south of ±70° and for solar zenith angles greater than 60°. Therefore, the assessments are solely on how well the MODIS retrievals perform over night-time Polar Regions. Mahesh et al (2004) showed that, when compared with earlier GLAS data, the MODIS collection 4 cloud mask tended to show large discrepancies over Polar Regions, in particular at night. We found that the MODIS cloud mask tends to detect clouds in otherwise clear areas over ice for around 15% of all point measurements examined here. So we ignored any measurement where GLAS did not detect a cloud even if the MODIS cloud mask did. For each coincident timeslot, we selected a MODIS 5-minute granule and the corresponding GLAS data. Then comparisons on a pixel by pixel basis were performed selecting the nearest MODIS pixels for each GLAS measurement performed every 4 seconds. We chose a maximum inter-point distance in degrees of latitude and longitude of 1°. Smaller distances reduced the number of points available for the comparison without leading to different results. A total of 2,285 pixels was found.

The coincidences between SEVIRI and ICESAT involved looking for ICESAT orbits that crossed the earth disk observed by SEVIRI, not too close to the edge of the field of view. However, only the 11:00UT SEVIRI data were available and only 6 days remained. GLAS pixels were first selected for the time period corresponding to SEVIRI data acquisition (approximately 12 minutes). Then for each GLAS pixel during this time period, we matched SEVIRI pixels by selecting the nearest neighbor in terms of latitude, longitude and observation time. About two thirds of all cloudy pixels (427 in total) were found within ±30° latitude and the rest was found between 40°N and 60°N. The longitudes were confined between 45°W and 60°W. False positive detections were marginal with SEVIRI (4.5% of all 750 coincident pixels).

For the comparison of cloud-top heights, we decided to combine all coincidences together to obtain a larger dataset and more significant statistics. All coincident pixels were separated into two distinct pools: those with a GLAS optical depth retrieval of the highest cloud layer ("thin clouds" pool) and those without (optical depth greater than 2, "opaque clouds" pool). In the thin clouds pool, we also eliminated all cloud pixels where GLAS detected more than one cloud layer (about two thirds of all thin cloud cases).

4. Results

We first looked at the limit in cloud detectability of the MODIS cloud mask at night in Polar Regions. Cloudy pixels that were detected as clear by MODIS had on average a smaller GLAS optical depth than those for which both instruments agreed. Furthermore, we found that the fraction of pixels without a MODIS retrieval increased from about one third for optical depth less than 1.0 to two thirds for optical depth less than 0.05. When comparing MODIS and GLAS cloud-top heights for opaque clouds (1029 pixels), we found an average difference between GLAS and MODIS of -0.3±1.5 km. The bias is negative indicating that MODIS overestimated cloud-top heights for optical depths larger than 2. However, Figure 1a indicates that most of these clouds were found below 5 km where the 11μm brightness temperature is mainly used. It has already been observed that this retrieval method tends to overestimate cloud-top height of thick clouds, possibly because of contributions from water vapor above the cloud-top (Del Genio and Wolf, 2000) or poorly resolved temperature inversions in reanalysis profiles. Here the difference is of the order of 300 m. When thick clouds were found above 5 km then the MODIS cloud-top heights were underestimated when compared to the GLAS product. However, no additional information is available for these clouds to draw any firm conclusion. Analyzing the thin cloud pool (418 single-level cloudy pixels), we find an average difference of 1.1±2.2 km, indicating that MODIS underestimates cloud-top heights of thin clouds. Figure 1b shows that these clouds are mostly found above 3km so the retrieval technique should be the CO_2-slicing method. The differences increased as cloud-top heights increased, and this does not appear to be related to cloud optical depth. In fact, for an equal optical depth we found that a cloud of 2 km vertical extent will display a larger difference in cloud-top height than a shallower cloud. When GLAS cloud-top heights were greater than 5km and the cloud vertical extent was greater than 2 km, the difference between GLAS and MODIS cloud-top height increased more or less linearly with cloud vertical extent (not shown here). This suggests that the radiatively active part of the cloud tended to be closer to cloud base than cloud top, causing the differences in cloud-top height to increase as cloud tops are found at higher altitudes. The relationship between the difference in cloud top height and the ratio of GLAS optical depth and GLAS cloud vertical extent (equivalent to an effective extinction coefficient) showed that differences in cloud-top height became greater than 1 km for an effective extinction coefficient of 0.5 km^{-1}. The difference in cloud top height was also found to increase with decreasing GLAS optical depth and is usually less than 1km when cloud optical depths are greater than 0.3 for single level clouds (Figure 1c). Finally, when considering multilayer cloud situations, we found that the difference in cloud-top height further increased for optical depths of the highest layer smaller than 1, as the effective radiative center of the cloud moves down in the atmosphere when more than one cloud is present in the cloudy column (Figure 1c, solid line).

The fraction of pixels with no SEVIRI retrieval over the number of pixels with an optical depth less than 1 was about a quarter, whilst for optical depths less than 0.3, although the number of pixels was too small to get an accurate fraction, there was a clear increase in misdetection for optical depths down to 0.05. The better performance of the SEVIRI cloud mask is not surprising given that all scenes were non-polar and in daylight. In addition, SEVIRI observes most scenes with a slanted view. This increases the optical path and therefore the cloud effective optical depth, giving this instrument a greater chance to detect sub-visual cloud layers. Opaque clouds (125 pixels) gave a difference between GLAS and SEVIRI cloud top heights of -0.4±2.1 km and thin single clouds (138 pixels) of 0.9±1.4 km. Compared with MODIS, the bias for thick clouds was very similar with a slightly larger standard deviation, maybe caused by a tendency for SEVIRI retrievals to show a greater overestimate as cloud-top heights reach 4 km compared to lower altitudes (Figure 2a). In general these clouds are found in the lower levels of the atmosphere. This confirms again that the 11μm brightness temperature technique overestimates cloud-top heights for opaque clouds, in this case by 400 m. For thin clouds (Figure 2b), SEVIRI cloud-top heights gave a similar bias compared to MODIS, on the order of 1 km, with a smaller standard deviation. The smaller standard deviation can be attributed to the smaller number of pixels available (10%) in the inter-comparison. Also, MODIS measurements were performed in the more difficult situation of the Polar Regions. The relationship between the difference in cloud-top heights and the GLAS cloud-top height is not linear as for MODIS, with the difference being confined around 1km for most cloud-top heights, probably because the comparison is not restricted to Polar Regions, and the highest clouds in the pool are probably thick tropical or mid-latitude clouds. Indeed, Figure 2b shows that most of these clouds are found above 10 km, up to a height of 15 km. Figure 2c shows how the differences increased with decreasing optical depth, with differences within 1km for optical depths greater than 0.3 and within 2 km for smaller optical depth. The effective cloud extinction coefficient was evaluated and the cloud-top height differences were also found to increase with decreasing extinction with a limit of 0.4 km^{-1} beyond which differences reached 2 km. We found that in multilayer situations the differences were larger for an equal optical depth of the highest layer, confirming that the SEVIRI algorithm is also optimized towards the radiative center of the cloudy column (Figure 2c).

5. Conclusions

We used the first polar-orbiting lidar cloud retrievals from GLAS in order to assess the accuracy of two passive instruments (MODIS and SEVIRI) for their cloud detection lower limits and cloud-top height retrievals. We found that when the optical depth was greater than 0.3 both algorithms could detect more than two thirds of the thin clouds and the cloud-top heights obtained with MODIS and SEVIRI were found within 1 km, on average, of GLAS cloud-top heights, albeit with a systematic underestimate in agreement with Mace et al. (2005). However, we also found that if the clouds were not single layer with other clouds present below the highest layer, then the bias was larger, suggesting that high altitude thin clouds have less chance of being detected if lower clouds are present. For optical depths less than 0.05, misdetections became prevalent for the dataset available here. Opaque clouds, i.e. an optical depth greater than 2, were found to have a tendency for both MODIS and SEVIRI cloud-top heights to be overestimated when clouds were below 5 km and underestimated when clouds were above 5 km. Clouds below up to 5 km were mainly retrieved with the 11μm brightness temperature technique which tends to overestimate cloud-top heights of optically thick clouds and in this case, the bias was of the order of 300-400 m.

Passive instruments were found to be reliable as far as detection is concerned, with some limitations over Polar Regions. Errors in cloud-top heights can affect cloud typing such as the one used for cloud classification in the ISCCP dataset (Rossow and Schiffer, 1991). It should be noted that the occurrence and coverage of thin and tenuous cirrus clouds may be significantly underestimated in present cloud climatologies. This appears to be a particular problem when lower and opaque clouds are present. It will be necessary to have a longer lidar dataset in order to estimate the impact of this missing information on the evaluation of cloud forcing or feedback in a changing climate.

References

Baum B. A. and B. A. Wielicki (1994), Cirrus cloud retrieval using infrared sounding data: multilevel cloud errors, *J. Appl. Meteorol. 33*, 107-117.

Del Genio A. D. and A. B. Wolf (2000), The temperature dependence of the liquid water path of low clouds in the Southern Great Plains, *J. Climate*, *13*, 3465-3486.

Le Gléau H. and M. Derrien (2003), SAFNWC/MSG SEVIRI cloud products, *Proc. Of the 2003 EUMETSAT Meteorological satellite conference*, Weimar, Germany, 29 sept.-3 oct., 191-198.

Mahesh A., M. A. Gray, S. P. Palm, W. D. Hart and J. D. Spinhirne (2004), Passive and active detection of clouds: comparisons between MODIS and GLAS observations, *Geophys. Res. Lett*. *31*, L04108.

Mace G. G., Y. Zhang, S. Platnick, M. D. King, P. Minnis and P. Yang (2005), Evaluation of cirrus cloud properties derived from MODIS data using Cloud properties derived from ground-based observations collected at the ARM SGP site, *J. Appl. Meteorol*., *44*, 221-240.

Menzel W. P., W. L. Smith and T. R. Stewart (1983), Improved cloud motion wind vector and height assignment using VAS, *J. Clim. Appl. Meteorol*. *22*, 377-384.

Menzel P., B. Baum, K. Strabala and R. Frey (2002), Cloud top properties and cloud phase algorithm theoretical basis document, ATBD_MOD_04, NASA Goddard Space flight center.

Naud C., J. P. Muller, M. Haeffelin, Y. Morille, and A. Delaval (2004), Assessment of MISR and MODIS cloud top heights through inter-comparison with a back-scattering lidar at SIRTA, *Geophys. Res. Lett*., *31*, L04114. Doi 10.1029/2003GL018976.

Platnick S, King MD, Ackerman, SA, Menzel WP, Baum BA, Riédi JC, Frey RA (2003), The MODIS cloud products: algorithms and examples from Terra, *IEEE Trans. Geosci. Remote Sens. 41*, 459-473.

Rossow W. B. and R. A. Schiffer (1991), ISCCP cloud data products, *Bull. Amer. Meteor. Soc*., *71*, 2-20.

Schmetz J., Hollmund K., Hoffman J. and B.Strauss (1993), Operational cloud motion winds from Meteosat infrared images, *J.Appl.Meteor*, *32*, 1207-1225.

Valk de J.P.J.M.M., C. Naud, M. Derrien, H. LeGleau, T. Smyth, C. L. Wrench and E. C. Slack (2004), MSG validation: an ongoing process, *Proc. The 2004 EUMETSAT Meteorological satellite Conference*, Prague, Czech Republic, 31 May-4 June, 85-93.

Zwally, H.J., B. Schutz, W. Abdalati, J. Abshire, C. Bentley, A. Brenner, J. Bufton, J. Dezio, D. Hancock, D. Harding, T. Heering, B. Minster, K. Quinn, S. Palm, J. Spinhirne and R. Thomas (2002), ICESat's laser measurements of polar ice, atmosphere, ocean, and land, *Journal of Geodynamics 34*, 405-445.

Zwally, H.J., R. Schutz, S. Palm, W. Hart, S. Hlavka, J. Spinhirne, and E. Welton (2003), updated current year, *GLAS/ICESat L2 Global Thin Cloud/Aerosol Optical Depths Data V018*, 15 October to 18 November 2003. Boulder, CO: National Snow and Ice Data Center. Digital media.

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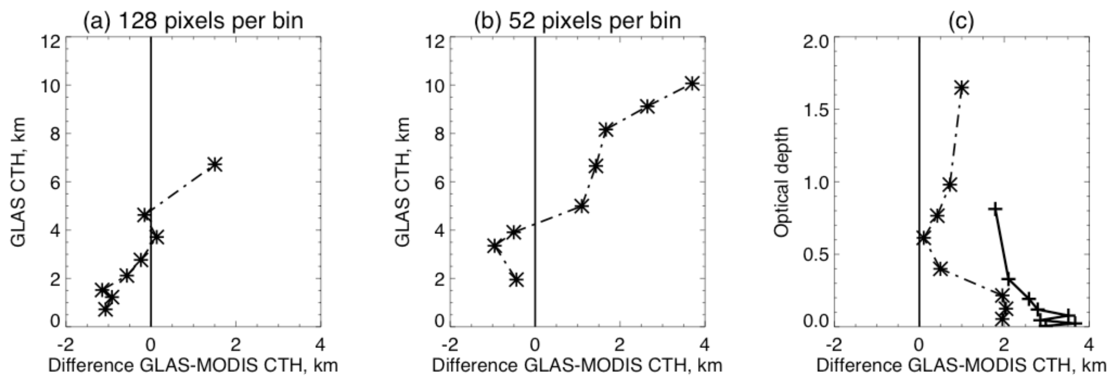

Figure 1: GLAS – MODIS cloud-top height difference against GLAS cloud top height for opaque clouds (a) and single level thin clouds (b), with pixels arranged according to GLAS cloud-top height (CTH) in 8 bins and against GLAS optical depth (c) with pixels arranged according to GLAS optical depth in 8 bins (stars for single clouds and + for multilayer clouds).

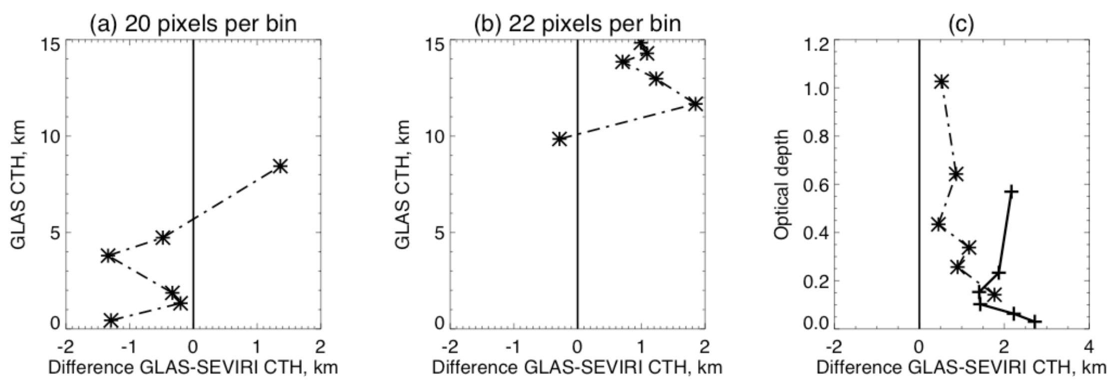

Figure 2: GLAS – SEVIRI cloud-top height difference against GLAS cloud top height for opaque clouds (a) and single level thin clouds (b), with pixels arranged according to GLAS CTH in 6 bins and against GLAS optical depth (c) with pixels arranged according to GLAS optical depth in 6 bins (stars for single clouds and + for multilayer clouds).