Inter-comparison of ground-based radar and satellite cloud-top height retrievals for overcast single-layered cloud fields

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Abstract

The objective of this study is to assess the accuracy of the SACURA algorithm that retrieves cloud top heights using hyperspectral Scanning Imaging Absorption Spectrometer for Atmospheric CHartographY (SCIAMACHY) onboard ENVISAT measurements for overcast single-layer cloud fields. Intercomparison with ground-based 35 GHz millimeter wave cloud radar cloud-top heights were performed for 14 dates during 2003-2007 at the USA Atmospheric Radiation Measurement (ARM) program Southern Great Plains site (36.6°N, 97.5°W). In addition, for some of these dates, ESA Medium Resolution Imaging Spectrometer (MERIS) and the NASA-TERRA Moderate Resolution Imaging Spectroradiometer (MODIS) cloud top pressure retrievals were also collected, transformed into cloud top heights using nearby ARM radiosonde profiles and compared with the SACURA SCIAMACHY and radar retrievals. The accuracy of the SACURA-SCIAMACHY cloud top height retrievals is better than 0.34 km for low-level clouds and 2.22 km for high-level clouds with an underestimate in cloud-top height on average for all clouds. The average bias in SCIAMACHY cloud top heights was about 0.07 km for low clouds and about 0.5 km for high-level clouds. Both MODIS and MERIS slightly overestimated the cloud-top heights of low-level clouds by 300 m, with an uncertainty better than 1 km. However, although MODIS accuracy for high-level clouds is close to SCIAMACHY, MERIS cloud-top heights were significantly underestimated for these fairly optically thick cases.

Key words: clouds, remote sensing, radiative transfer

1. Introduction

The cloud top altitude is an important parameter to characterize cloud properties in global climate modeling. It is influenced by atmospheric dynamics and thermodynamics. Also the anthropogenic influence on cloud top altitudes can not be ignored (Devasthale et al., 2005). Therefore, a number of satellite remote sensing techniques have been developed for the determination of the cloud top altitudes (for a review, see Rozanov and Kokhanovsky, 2004). They include, in particular, infrared (IR) measurements (11 and 12 μm cloud brightness temperature measurements, CO_2 slicing technique), measurements in the oxygen A-band, stereoscopic methods, and also active measurements from space lidars and radars. The most accurate results are derived using active satellite remote sensing methods. However, those are limited with respect to the spatial and temporal coverage. Moreover, the cloud top height (CTH) information is needed in processing schemes of various satellite instruments aimed at studies of atmospheric trace gases such as, for example, SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric CHartographY) and GOME (Global Ozone Monitoring Experiment). Therefore, it is desirable to develop simultaneous cloud top height and trace gas vertical column retrieval techniques using a single optical instrument (Rozanov and Kokhanovsky, 2008). One of such operational algorithms named SACURA has been developed at Bremen University (www.iup.physik.uni-bremen.de/sacura). The algorithm determines cloud top heights using oxygen A-band measurements. It is based on the approximate asymptotic solutions of the radiative transfer equation in the gaseous absorption band (Kokhanovsky and Rozanov, 2004). SACURA CTH retrievals are valid for optically thick single-layered clouds. In particular, altitudes of thin cirrus clouds over low-level level or middle-level thick clouds can not be retrieved using this technique. Preliminary studies of the algorithm accuracy have been reported by Rozanov et al. (2006) and Kokhanovsky et al. (2007). These studies were based mostly on the comparison of SACURA CTH retrievals with other satellite techniques such as CO_2-slicing and 12 μm cloud brightness temperature measurements using data from the Moderate Resolution Imaging Spectroradiometer (MODIS) and Along Track Scanning Radiometer 2 (ATSR-2), respectively. The results showed that SACURA gives results close to the CTHs derived using IR channels (the average differences are smaller than 1km). However, different passive instruments have different limitations and there is a need for comparison with observations as precise as possible in all situations. Indeed active instruments such as lidars and radars have been found to give the most accurate measurements available at present (Clothiaux et al., 1999) and have been used to assess the accuracy of passive observations (Kokhanovsky et al., 2004; Naud et al, 2005).

The objective of this paper is to study the accuracy of the SACURA algorithm applied to SCIAMACHY data using ground-based radar measurements as well as retrievals from NASA-Terra MODIS and ESA-Envisat MEdium Resolution Imaging Spectrometer (MERIS) standard operational processing algorithms. MODIS retrievals are based on the CO_2 slicing technique (Menzel et al., 2008) and ESA MERIS algorithm is based on a neural network technique applied to measurements in the oxygen A-band (Fischer et al., 2000; Lindstrot, 2006). MERIS and SCIAMACHY are on the same satellite platform (ENVISAT) and observe the same cloud field simultaneously. Terra (10:30 equator crossing time) lags ENVISAT by about 30 min. Therefore, the CTHs derived from MODIS and SCIAMACHY measurements may not always observe the same scene. However, overcast and slow changing cloud fields, which are the primary targets of this study, will cause little differences. In addition, this type of scenes will help contravene the issue of different spatial resolutions.

The different instruments and corresponding measurements are presented in section 2, section 3 presents the result of the comparisons between ground-based and satellite cloud-top height retrievals and section 4 contains our conclusions.

2. Measurements

2.1. SCIAMACHY

SCIAMACHY is a passive imaging spectrometer, comprising a mirror system, a telescope, a spectrometer, and thermal and electronic subsystems (Gottwald et al., 2006). It measures the spectral top-of-atmosphere (TOA) reflectance in 8 overlapping channels spanning the spectral range 0.24-2.4 μm. The SACURA algorithm was designed to retrieve cloud-top heights, cloud base heights and cloud optical thickness from measurements in the oxygen A-band, where the spectral resolution is 0.48 nm and the spatial resolution is 60 km x 30 km. A fit of the measured TOA spectral reflectance is iteratively performed for each SCIAMACHY cloudy pixel by changing the CTH in the radiative transfer model (Rozanov and Kokhanovsky, 2004, 2008). The cloud optical thickness needed for the CTH retrieval is determined just outside the oxygen A-band (at 758 nm). The example of several calculated spectra in the O_2 A-band is given in Fig.1. The calculations were done for an overhead sun and an observation angle of 60^o. The upper cloud is assumed to be composed of ice crystals (see, Mishchenko et al., 1999, for the model of the phase function of fractal ice crystals) and the lower cloud was assumed to contain water droplets only (Cloud C1 model of Deirmendjian, 1969).

The best fit of the measurement spectrum to the model radiative transfer calculations for a single-layered cloudiness provides the output CTH value. The cloud fraction (CF) is estimated using SCIAMACHY polarization measurement devices (PMDs). The spatial resolution of PMDs is approximately 8 km x 30 km. Therefore, they enable the observation of the cloud distribution inside the SCIAMACHY granule (Rozanov et al., 2006). For this study, only measurements with CF=1 have been selected.

The SCIAMACHY pixels that fall within 0.5 degrees from the Atmospheric Radiation Measurement (ARM) program South Great Plain (SGP) site were used for the comparisons. Since SCIAMACHY pixel has a spatial resolution of 60 km across by 30 km along track at nadir, we have used measurements over 0.5*0.5 degrees area at this geographical position. The comparison of the radar and satellite measurements is meaningful only if the both satellite and radar CTHs do not vary significantly in space and time domains. Therefore, only cases with the standard deviation (STDV) of SACURA-derived CTHs smaller than 3% were taken in the consideration for low-level clouds. For the high-level clouds, we used a STDV threshold of 30% to increase the number of analyzed cases. The variability of CTH for high-level clouds is much more pronounced than for low-level clouds (see Fig.2).

2.2. MODIS

The Moderate Resolution Imaging Spectroradiometer (Salomonson et al., 1989) measures radiances in 36 spectral bands from 0.4 to 14.2 μm with a nadir spatial resolution from 250 m to 1 km. MODIS is onboard two platforms, NASA Terra and Aqua, but here only Terra MODIS collection 5 cloud products (Platnick et al., 2003) are used, the time lag between AQUA and ENVISAT being too large for this type of comparison.

MODIS cloud top pressures are obtained using the CO_2-slicing method, applied to three channels (13.64, 13.94 and 14.24 µm), close to the $15\,\mu m$ CO_2 absorption band (Menzel et al. 2008). Due to signal-to-noise issues, CO_2-slicing cloud-top pressures are generally limited to the range from approximately 700 hPa (i.e., about 3 km above sea level) up to the tropopause. Consequently, when low-level clouds are present, the MODIS CTH algorithm defers to the infrared window technique where cloud-top pressure and temperature are determined through comparison of model-calculated and observed 11µm radiances. A full description of the algorithm is available in Menzel et al. (2008) along with a description of the latest improvements implemented in collection 5.

Cloud top pressures are obtained at 5-km resolution using averaged 1-km radiances. Here, they are transformed into cloud-top heights using coincident radiosonde profiles collected within the hour at the Southern Great Plain site. Using Terra-MODIS cloud-top pressures from the previous Collection 4, Naud et al. (2005) found an accuracy in MODIS cloud top heights of 1 km for high-level and mid-level clouds but degraded to nearly 3 km for low-level clouds. However, improvements in the algorithm for collection 5 should increase the accuracy for low-level clouds (Menzel et al., 2008).

MODIS cloud-top heights are collected in a ± 0.5° latitude-longitude area centered on the SGP site. The mean cloud top height and cloud fraction are then calculated for all the selected 5 km^2 pixels. The standard MODIS product contains cloud top pressures that were converted into CTH using radiosonde profiles .

2.3. MERIS

The MERIS operational cloud-top heights were provided by ESA. It is based on a neural network retrieval technique developed at the Free University of Berlin (Fischer et al., 2000). The physical principle of these retrievals is similar to that of SACURA. In particular, the O_2 A-band absorption band is also used, although, with SCIAMACHY's 0.48 nm high spectral resolution, about 50 different measurements are available in this band rather than one for MERIS. The MERIS channel 11 (the central wavelength 760.625 nm with a bandwidth of 3.75 nm) in combination with retrievals of the cloud optical thickness just outside of the oxygen A-band (753.75nm with a bandwidth 7.5nm) is used for the cloud top pressure retrievals (Fischer et al., 2000). The product was validated in a number of studies mostly focused on low level clouds, where a high accuracy of retrievals was found (Lindsrot et al., 2006). For this work, we have selected the closest MERIS pixel to the radar site. MERIS CTHs were not averaged in a latitude-longitude box around the site as for overcast clouds, because we found that the difference in CTH between the box average and the central pixel is negligible. The standard ESA product contains cloud top pressure and not CTH. The conversion was performed in the same way as with the MODIS data.

An example of a MERIS browse image is given in Fig.3, where an overcast cloud field is present around the SGP site as observed by the radar measurement shown in Fig.2 for the same day.

2.4. Radar

The Atmospheric Radiation Measurement program (Ackerman and Stokes, 2003) operates a collection of ground-based sites in various locations deemed representative of the Earth climatic regions. Here we focus on the mid-latitude site near Oklahoma City, Southern Great Plain (36.6N; 97.5W). The Active Remotely Sensed Cloud Locations dataset (ARSCL; Clothiaux et al., 2000) provides a cloud-mask at 10 s and 45 m resolution based on the reflectivities measured by a 35-GHz Millimeter wave Cloud Radar (MMCR; Moran et al., 1998). This cloud mask indicates if each pixel contains clear air, hydrometeors, clutter (e.g. vegetation debris or insects) or a mixture of hydrometeors and clutter. Clutter can hide the presence of hydrometeors near the surface. It is mainly a problem in summer months and can be present up to 5 km latitude. At each time step, we extract the highest cloud top height and calculate the median CTH for a 25-minute period centered on the time of the ENVISAT overpass. The duration of the period is the time it takes for a cloud to travel the along-track length of a SCIAMACHY granule (30km) at 20 m/s. Along with the median cloud-top height, we calculate the cloud fraction over the 25-minute time interval, the standard deviation of the CTH and we derive the vertical distribution of ice fraction at 45 m resolution over the 25-min period (this distribution is used to determine if there are more than one cloud layer in the atmospheric column). An example of the radar cloud mask time series for November 22nd, 2004 is shown in Fig.2, when both a high-level cloud and a broken low level cloud field were present over the site.

3. Results

For the comparisons only the cases with comparatively low SACURA – retrieved CTH coefficients of variance (CV=standard deviation/average) were taken ($CV \leq 3\%$ for low-level (below 3km) clouds and $CV \leq 30\%$ for high-level (above 6km) clouds were allowed). The variability of CTHs for high-level clouds is much larger. Therefore, we were not able to take smaller thresholds values for the CV of high-level clouds. In addition, because radar measurements only cover one point in space that is compared with satellite pixels of a much larger coverage, temporal and spatial averages respectively have to be used. Therefore, cases with large temporal and spatial variations in CTH must be discarded (see discussion in Naud et al., 2006). This will insure that only overcast clouds with relatively homogeneous cloud top altitudes enter the analysis. For the entire period of 2003-2007 only 15 dates could be kept, once all the dates with no direct overpass (SCIAMACHY alternates observations between nadir and limb view, which significantly reduces the number of radar/SCIAMACHY observation coincidence points), no clouds, the radar not functioning and broken cloud fields were removed. MERIS retrievals were available also for all these dates but one, while only 7 of these dates included Terra-MODIS retrievals.

The results of inter-comparisons for the selected dates are shown in Tables 1 and 2 for low-level and high-level clouds separately. One date was found to include an overcast mid-level cloud situation, with a radar CTH= $5.46 \pm 1.19 km$ and SCIAMACHY-SACURA CTH= 5.76 ± 1.36km. Figure 4 shows the comparison for all 15 dates between the radar and the three satellite based measurements.

The seven low-level cloud cases are listed in Table 1. The average difference for the seven cases between satellite based and radar CTHs being -0.07±0.34 km for SCIAMACHY, 0.29±0.62 km for MODIS (only 3 cases), and 0.34±0.75 km for MERIS. SCIAMACHY retrievals have the lowest bias, and the smallest uncertainty, while MODIS and MERIS are comparable with a slight overestimate and an uncertainty less than 1 km. Therefore, we conclude that the oxygen A-band spectrometry based technique performs well for low-level clouds, with a negligible bias and an uncertainty around 300 m, which is similar to the performance of the Multiangle imaging spectroradiometer stereoscopic retrievals (Naud et al., 2005).

For high-level clouds (7 cases listed in Table 2), both SCIAMACHY and MODIS retrievals have similar accuracies with an average difference between the satellite based and radar CTHs of -0.57±2.22 km for SCIAMACHY and -1.34±0.36 km for MODIS (see Table 3). For comparison between MODIS and SCIAMACHY, we also calculate the average difference between SCIAMACHY and the radar CTH for the four dates where MODIS is available and find: -1.45±1.25 km. The absolute bias is similar to MODIS but the uncertainty is larger. The low optical depth of these clouds probably explain the underestimate in cloud top heights for both MODIS and SCIAMACHY. The larger uncertainty for the latter instrument probably stems from its lower resolution. It is also possible that despite our precautions to remove them, some of these cases have non-overcast high-level clouds. The CTHs retrieved using the SACURA algorithm as applied to SCIAMACHY are close to the physical upper cloud boundary as shown in Figs. 5 and 6 for low-level and high-level clouds respectively.

For this study, scenes with single-layered clouds were selected. As it was found by Rozanov et al. (2004) and Rozanov and Kokhanovsky (2008), the oxygen spectrometry is characterized by large errors of the retrieved CTH in case of multi-layered cloud systems, if single layer clouds are assumed in the retrieval procedure. This also illustrated in Fig.1, where we show TOA spectral reflectances in the O_2 A-band for a number of different situations, including the case of a low-level cloud and the case of a two – layered cloud system that have the same total cloud optical thickness. In particular, a low-level cloud case positioned between 0.5 and 1.4 km is considered. Line 1 corresponds to calculations for just this one cloud and line 3 corresponds to calculations when this cloud is accompanied by a thin cloud in the 10-11 km height interval (with the cloud optical thickness of 1 for the upper cloud and 59 for the lower cloud). Both spectra (lines 1 and 3 in Fig.1) are very close. Therefore, if a two-layered cloud system is present during the measurements, SACURA will underestimate the cloud top heights. Because it is difficult to know a-priori if a scene is multilayered, IR measurements (e.g. CO_2-slicing), which are less sensitive to multilayer cloud situations (e.g. Naud et al., 2007) should be preferably used for high-level clouds. The combined O_2 A-band and IR measurements may prove to be useful for the detection of multi-layer cloud cases. For instance, large positive differences between IR and O_2 A-band CTH retrievals give a clear indication of the multi-layered clouds.

4. Conclusions

We have compared the cloud top altitudes derived using a ground-based radar and SCIAMACHY onboard ENVISAT. In addition, MERIS and MODIS retrievals were compared to the same radar measurements. It was found that all satellite instruments retrieve CTHs close to those derived from radar measurements for low-level clouds. In the case of high-level (single-layered) clouds the errors of retrievals are generally larger with the underestimation of radar CTHs by MODIS (on average -1.34km). SCIAMACHY also retrieves lower clouds as compared to radar on average(average bias is about -0.46km). MERIS CTH retrievals are accurate for low-level clouds and biases are smaller than +0.34 km on average, which is close to +0.23 km bias found in study of Lindstrot (2006) using airborne lidar observations for low-level clouds over northern Germany. We found that MERIS CTH retrievals fail for high-level clouds, which can be related to the limitation of the information content of MERIS measurements (just one spectral point in the oxygen A-band available for the analysis) as compared for about 50 points for SCIAMACHY. On the other hand the operational cloud retrievals with SACURA as applied to SCIAMACHY miss optically thin high-level clouds and retrieve CTHs of thick clouds present closer to the surface. This is a clear drawback of the oxygen A-band spectrometry as applied to the determination of the positions of high-level clouds. On the other hand, combined use of IR and O_2 A-band measurements brings an additional information on the cloud multi-layered structure. It is advisable for future missions to have both IR sounders and oxygen A-band spectrometers for the characterization of cloud heights.

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Table 1. Cloud top heights (in km) of low-level clouds derived from radar and satellite data

Date(d/m/year)	Radar	SCIA	MERIS	MODIS
10/03/2003	**1.73**	1.46	2.21	1.37
28/03/2003	**2.04**	1.45	2.01	2.91
22/05/2003	**1.73**	1.45	2.50	2.09
06/11/2003	**1.32**	1.44	1.71	-
16/11/2003	**1.37**	1.45	0.73	-
10/06/2004	**1.86**	2.30	1.61	-
26/ 04/2007	**1.46**	1.45	3.12	-

Table 2. Cloud top heights (in km) of high-level clouds derived from radar and satellite data

Date(d/m/year)	Radar	SCIA	MERIS	MODIS
17/04/2003	**11.66**	14.54	5.31	-
15/05/2003	**11.54**	9.35	5.20	10.39
04/06/2003	**10.60**	12.31	5.10	-
31/10/2003	**13.20**	11.87	6.61	11.32
12/11/2003	**9.56**	9.82	6.92	8.35
13/11/2003	**10.64**	8.09	6.91	9.51
22/11/2004	**11.04**	8.27	6.64	-

Table 3. Average cloud top heights (in km) for all dates analyzed. Average biases are given brackets.

Instrument	Radar	SCIAMACHY	MERIS	MODIS
Low-level clouds	1.64	1.57(-0.07)	1.98(0.34)	2.12(0.29)
High-level clouds	10.46	10.0(-0.46)	6.10(-5.08)	9.89(-1.34)

Figure captions

Fig.1. The spectral dependence of the reflection function in the oxygen A-band for various cloud models. It is assumed that the combined cloud optical thickness is equal to 60 for all cases (1-two layers (0.5-1.4 km, 10-11km), 2 - two layers (2-8km, 10-11km), 3-a single layer (0.5-1.4km), 4 - two layers (0.5-1.4km, 10-11km)). The optical thickness of the upper layer was equal to 1.0(case 1) and 10.0(cases 2 and 4).

Fig.2. The Active Remotely Sensed Cloud Locations dataset (Clothiaux et al., 2000) cloud mask as a function of altitude and time (UTC) at SGP for November 22, 2004.

Fig.3. MERIS browse image for November 22, 2004, 16:54:27 UTC. The position of the radar is denoted by the letter R.

Fig.4. Inter-comparison of radar and satellite cloud top heights for overcast scenes at SGP.

Fig. 5. Comparison of SCIAMACHY and radar CTHs for low-level clouds.

Fig. 6. Comparison of SCIAMACHY and radar CTHs for high-level clouds.

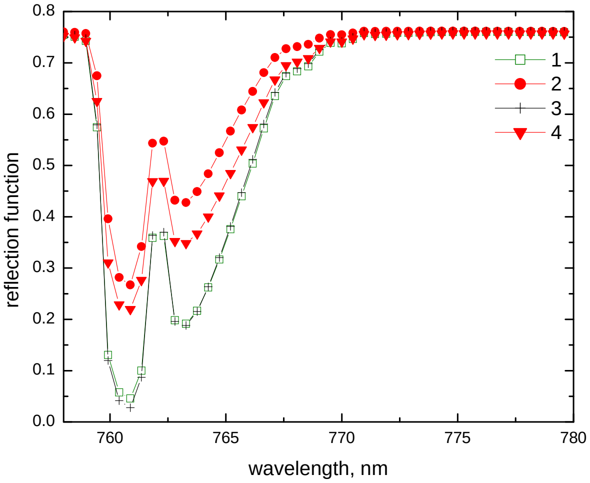

Fig.1. The spectral dependency of the modeled reflection function in the oxygen A-band for various cloud scenarios. It is assumed that the combined cloud optical thickness is equal to 60 for all cases (1-two layers (0.5-1.4 km, 10-11km), 2 - two layers (2-8km, 10-11km), 3-a single layer (0.5-1.4km), 4 - two layers (0.5-1.4km, 10-11km)). The optical thickness of the upper layer was equal to 1.0 (case 1) and 10.0 (cases 2 and 4).

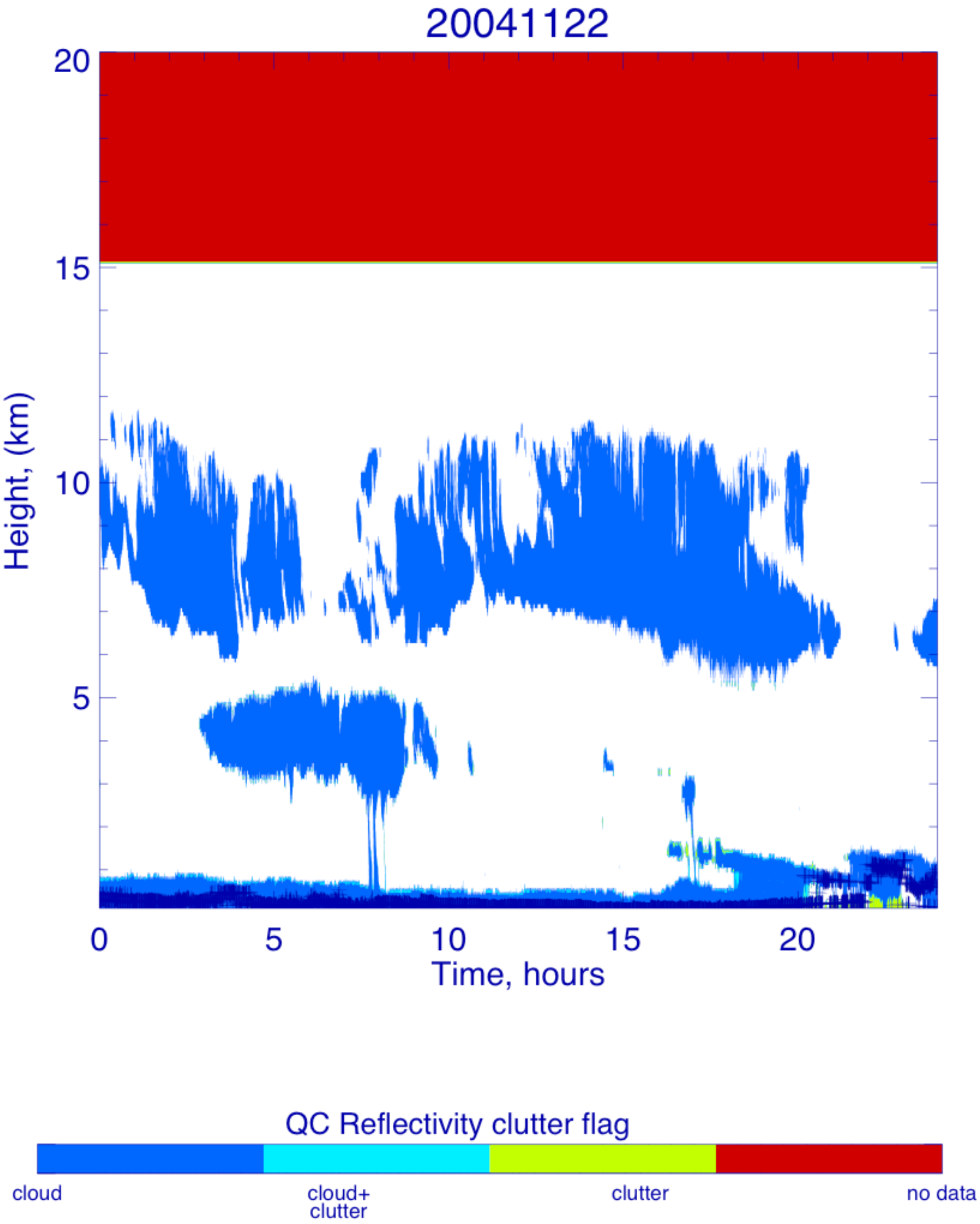

Fig.2. ARSCL Radar cloud mask as a function of altitude and time (UTC) at SGP for November 22, 2004.

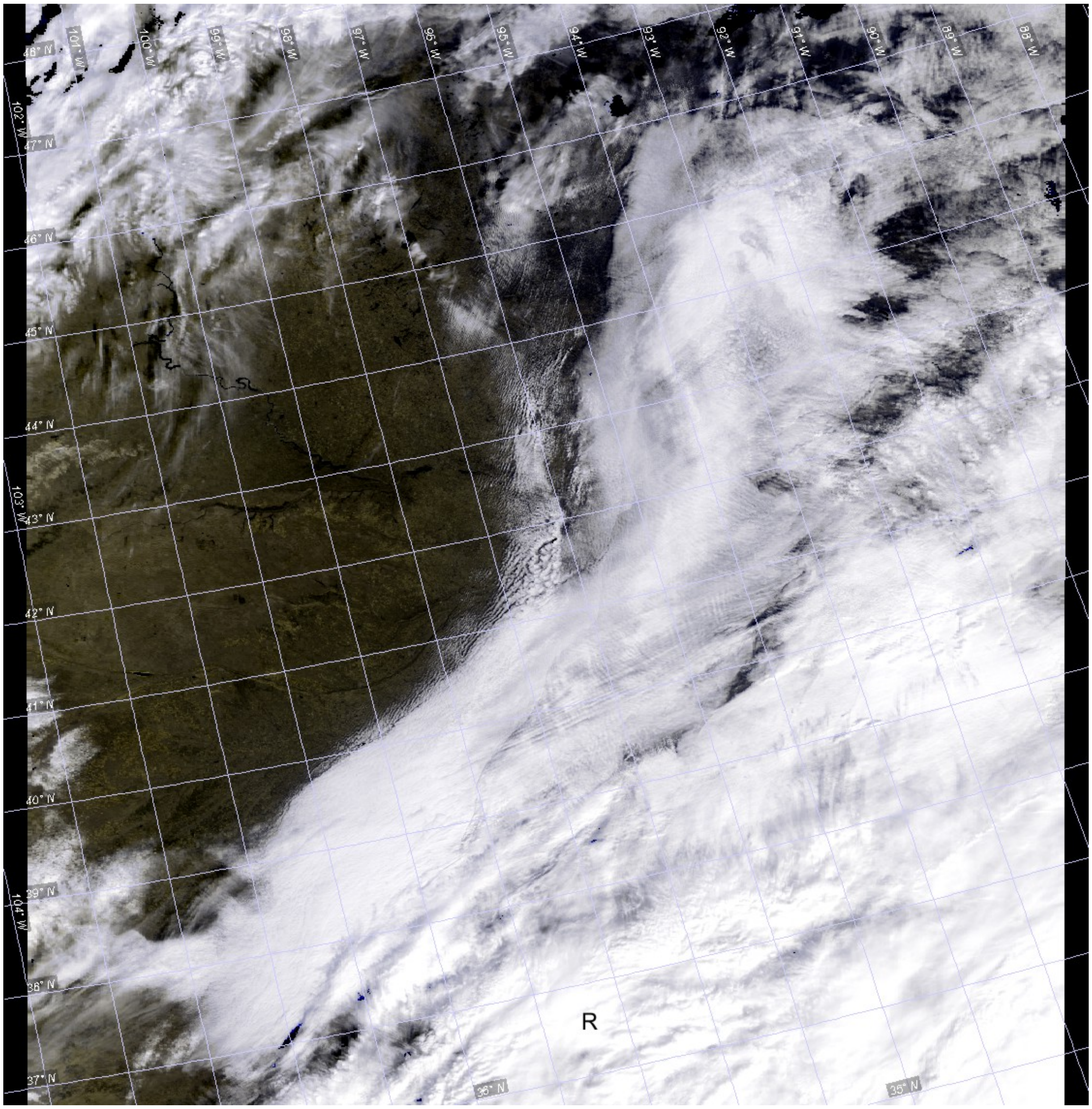

Fig.3. MERIS browse image for November 22, 2004, 16:54:27 UTC. The position of the radar is denoted by the letter R.

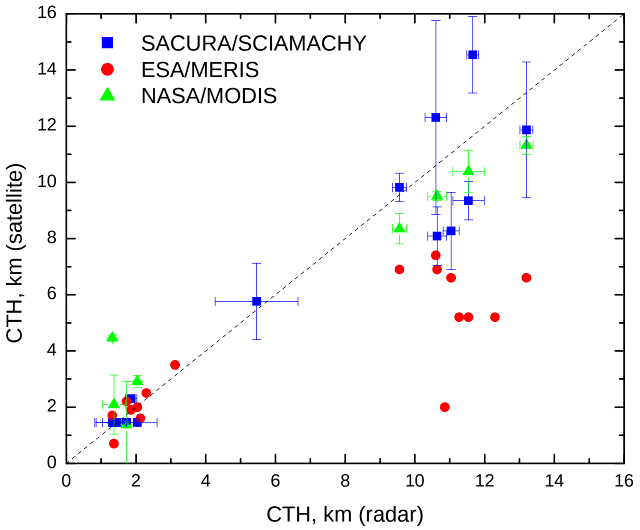

Fig.4. Inter-comparison of radar and satellite cloud top heights for overcast scenes at SGP.

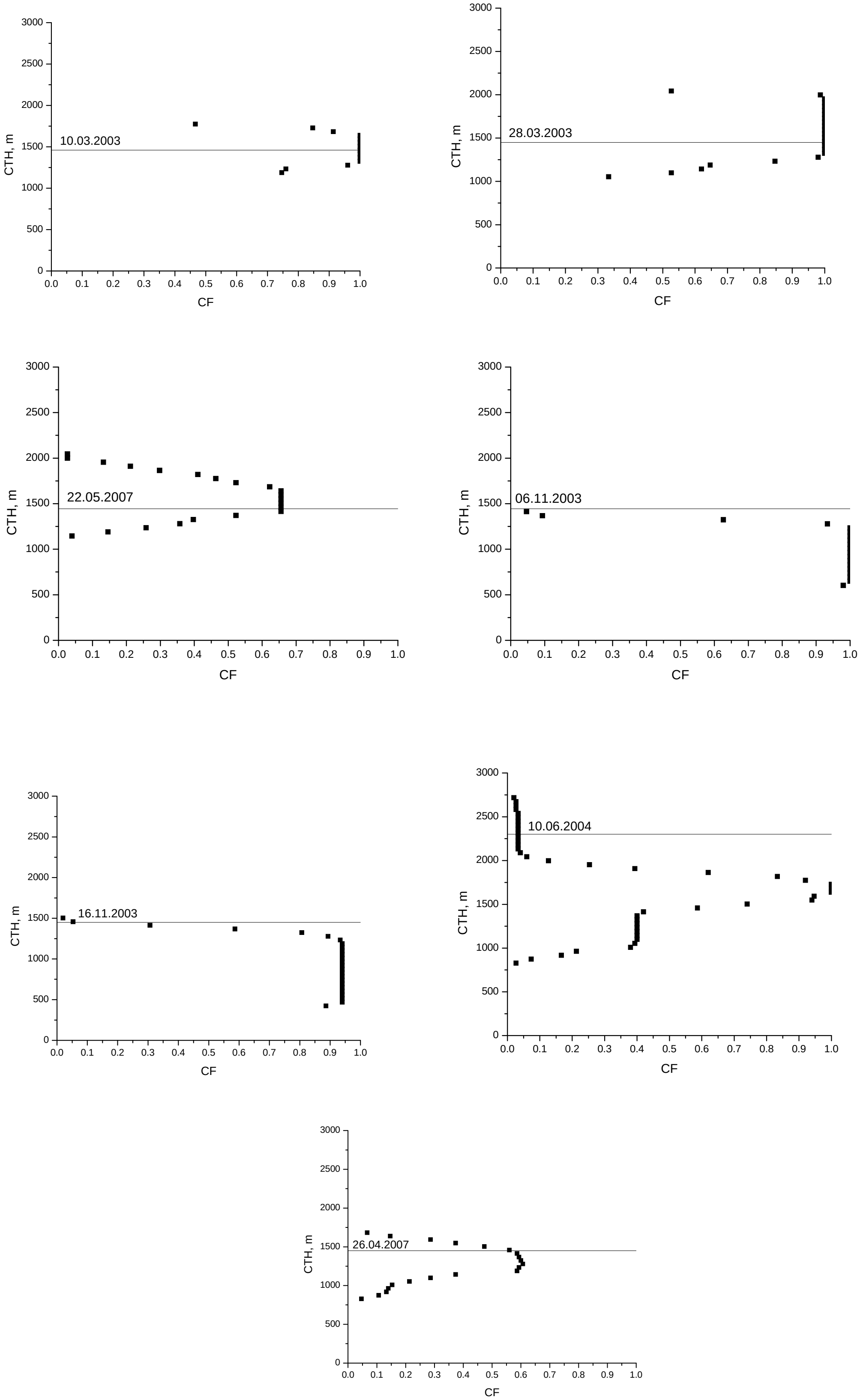

Fig. 5. Comparison of SCIAMACHY and radar CTHs for low-level clouds.

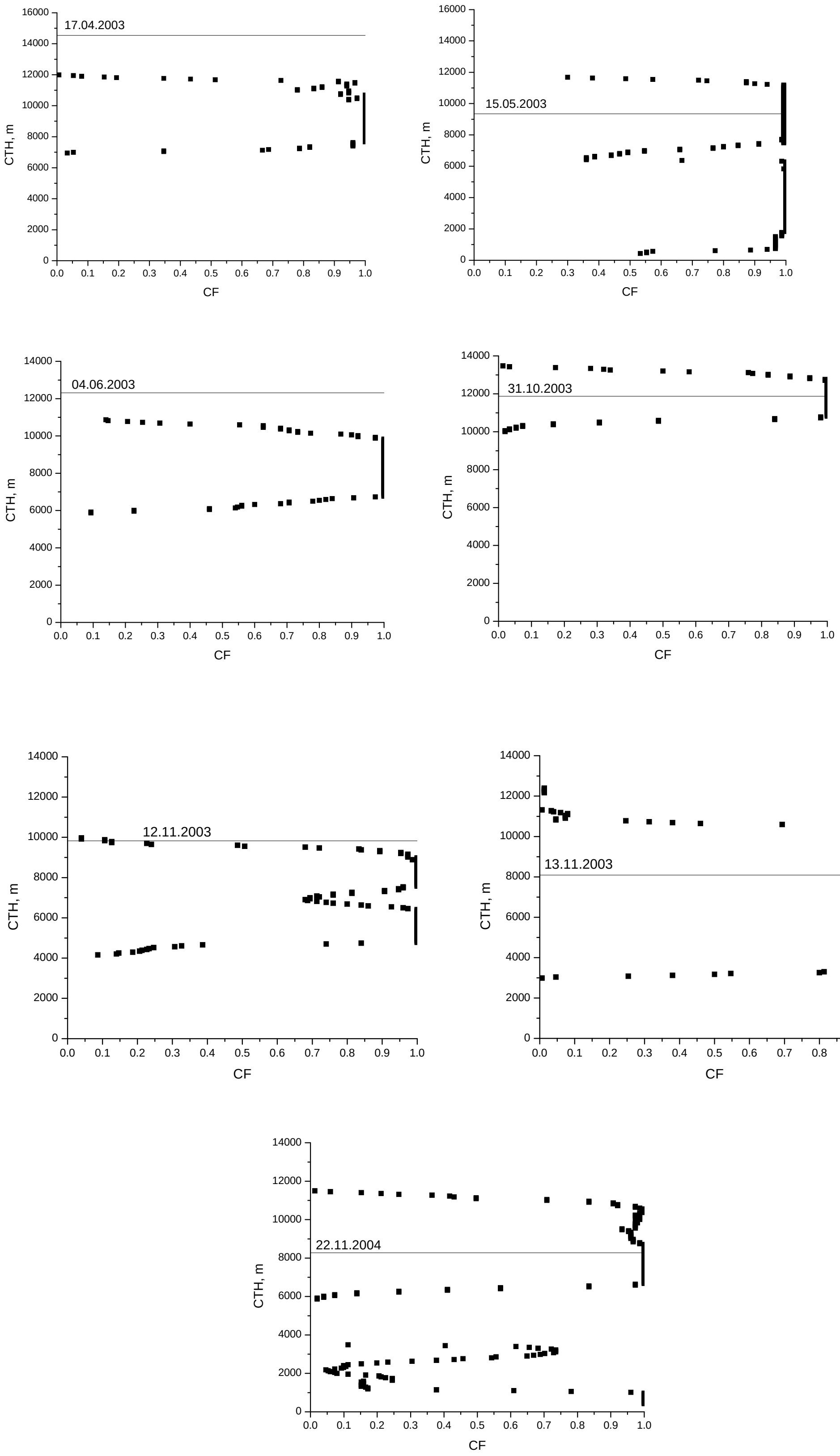

Fig. 6. Comparison of SCIAMACHY and radar CTHs for high-level clouds.