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Assessment of multispectral ATSR2 stereo cloud-top height retrievals

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Abstract

The Along-Track Scanning Radiometer 2 (ATSR2) instrument has a dual view capability that allows for stereo height retrievals. Stereo heights were retrieved for selected scenes over the United Kingdom Chilbolton Facility for Atmospheric and Radio Research and the United States Atmospheric Radiation Measurement program Southern Great Plains site from 1997 to 2000. Stereo cloud-top heights obtained with the 11 μm and 1.6 μm channels of ATSR2 were compared with ground-based millimeter-wave cloud radar measurements at both sites. On average ATSR2 11 μm channel cloud-top height retrievals were 350 m higher than those from radar with a standard deviation of 1 km. This difference increased with decreasing cloud-top height. One major problem found in the 11 μm channel cloud-top height retrievals was poor delineation between surface (i.e., clear) and low-altitude cloud pixels, though this tends to lower cloud-top heights rather than raise them. The ATSR2 1.6 μm channel stereo cloud-top heights had large discrepancies compared to radar because of the 1.6 μm channel sensitivity to a lower layer in the case of multilayer clouds or the terrain in the case of optically thin single-layer clouds. For single-layer clouds, the agreement between the ATSR2 1.6 μm channel and the radar cloud-top heights was similar to that between ATSR2 11 μm channel and radar cloud-top heights.

Keywords: Cloud-top height; Remote sensing; Stereo; ATSR2; Ground-based radar; Assessment

1. Introduction

One of the causes of uncertainty in future climate scenarios is cloud feedbacks (e.g. Cess et al., 1990). In particular, the presence and persistence of clouds at different levels of the troposphere can have opposite effects in terms of warming or cooling. It is thus important to monitor cloud properties and satellite-borne instruments are adequate tools for measuring and monitoring these.

The Along-Track Scanning Radiometer 2 (ATSR2) was launched in 1995 onboard the second European Remote-Sensing Satellite (ERS-2). It is a follow-on to the ATSR which was originally designed for sea surface temperature retrievals and launched in 1991 (Mutlow et al., 1994). In 2002, the Advanced ATSR instrument (AATSR) was successfully launched and completed the current series. ATSR2 is a dual-view scanning radiometer with two visible channels (an addition to the original ATSR) and two near infrared channels (0.55, 0.65, 0.86 and 1.61 μm) and three thermal infrared channels (3.70, 10.85 and 12.00 μm). ATSR2 views the same scene first in the forward direction at 55° to the scene-surface normal and then at nadir about 120 s later. This dual-view capability allows for stereo imaging techniques to retrieve cloud-top height information (Lorenz, 1985). Wind field retrievals would require at least one more non-symmetric view (e.g. Horvath & Davies, 2001; Zong et al., 2002). Stereo heights offer the undisputed advantage, relative to spectrally retrieved heights, of being a stand-alone technique without requiring any additional atmospheric information.

Muller et al. (in press) developed an algorithm for the automated retrieval of cloud-top heights using ATSR2 stereo radiances. This stereo height algorithm was implemented at the Rutherford Appleton Laboratory and applied there to three ATSR2 wavelength channels: the 0.65, 1.61 and 10.85 μm

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channels. These channels were chosen as the most representative of the visible, near-infrared and thermal infrared spectral regions.

Although the ERS-2 mission is still in operation, geolocation information from it necessary for stereo retrievals was degraded with the failure of a gyroscope in early 2001. The additional loss of onboard data recording in 2002 restricted data availability to only a few European receiving stations. As a result, the ATSR2 scenes for this study are limited to the time period from 1997 to 2000.

Two geographic locations with ground-based millimeter-wave cloud radars were used in the study: the United Kingdom Chilbolton Facility for Atmospheric and Radio Research (CFARR; 51.15°N, 1.43°W) and the United States Atmospheric Radiation Measurement program Southern Great Plains (SGP) site (36.62°N, 97.5°W). The Rutherford Appleton Laboratory processed 226 ATSR2 scenes collected from November 1998 through December 2000 over the CFARR site and 117 ATSR2 scenes collected from October 1997 to August 2000 over the SGP site. The stereo cloud-top heights retrieved from ATSR2 radiance processing are compared here with ground-based radar retrievals to assess relative accuracies of the two. The cloud-top heights retrieved with the ATSR2 0.65 μm and 1.61 μm channels tend to be similar, so we present results only for the 1.61 μm and 10.85 μm channels, hereafter referred to as the 1.6 μm and 11 μm channel retrievals. There were no visible channels on the first ATSR instrument so analysis of the 1.6 μm channel retrievals is also relevant to the data collected by the first ATSR instrument. These two channels do not have the same sensitivity to cloud optical properties. Stereo height retrievals are obtained through a matching procedure between features found in the two consecutive views (Muller et al., in press). This matching technique is sensitive to the texture of the content of the scene that will affect the contrast between the two different views. In situations where more than one cloud layer are present, the level with the highest contrast is not necessarily at the level of the highest cloud top. At 11 μm radiances are sensitive to the emitting portion of the cloud and at 1.6 μm to the reflecting properties, so we expect different characteristics between stereo heights derived at these two wavelengths. In situations where more than one cloud layer occur, the level of higher contrast may differ between the two wavelengths.

ATSR2 stereo cloud-top heights were previously assessed using a limited number of scenes over the CFARR site and compared with those from ground-based radar, radiosonde and a second satellite sensor (Naud et al., in press). This earlier (smaller sample) study revealed a high bias in the 11 μm channel stereo cloud-top height retrievals and a tendency for the 1.6 μm and 0.65 μm channel stereo cloud-top heights to have problems in multilayer cloud situations. Here, we significantly expand upon this first study by using a much larger number of scenes collected over a longer time period and from two different locations. In addition, the effects of wind advection of clouds between the two consecutive views on retrieved cloud-top heights are taken into account in this study.

Section 2 presents the data used for this study and Section 3 describes the methods used to compare ATSR2- and radar-derived cloud-top heights. Results of the study are in Section 4 with a discussion of them in Section 5. Concluding remarks follow in Section 6.

2. Data

The data for this study are ATSR2 stereo cloud-top height retrievals and cloud-top heights inferred from ground-based millimeter-wave cloud radar measurements.

2.1. ATSR2 stereo cloud-top heights

The ATSR2 stereo cloud-top height retrieval algorithm is fully described in Muller et al. (in press). Each ATSR2 scene is 512 × 512 pixels with each pixel having a spatial resolution of 1 km × 1 km. Theoretical cloud-top height retrieval accuracy was estimated to be better than 1 km (better than 1 pixel accuracy) and was verified on clear-sky scenes using surface height retrievals (Denis et al., in press). The retrieval algorithm retrieves stereo heights of all objects in the ATSR2 stereo radiance imagery and subsequent processing must separate cloud and surface features, remove "blunders" (stereo heights anomalously high compared to the surrounding pixels) and correct for wind advection of clouds (clouds will move between the views and this will affect the stereo height retrievals, see Zong et al., 2002).

Separating cloud from surface features is accomplished through thresholding, whereby retrieved features more than 1 km (i.e., the theoretical uncertainty) above the surface are interpreted as clouds. Any stereo height less than 1 km above the surface was interpreted as from a cloud-free pixel and discarded. The surface heights at the CFARR and SGP sites are approximately 100 m and 300 m above mean sea level, respectively. Clouds with a top altitude below 1.1 km at CFARR and 1.3 km at SGP occurred 11–13% over all cases studied at these sites. (For SGP we only used the cold months from November to March to avoid clutter, vegetation debris and insects with returns similar to those from clouds.)

Errors in the matching procedure, otherwise known as blunders, can sometimes produce anomalously high values of stereo heights compared to surrounding retrievals (by extension we refer to these high values as blunders here). Blunder detection and removal is not trivial. In this study an arbitrary threshold on cloud-top height was set. Any heights greater than the average tropopause altitude of 12 km at CFARR and 15 km at the SGP site were discarded.

Stereo cloud-top height retrieval requires measurement of the displacement of cloud features between the ATSR2 forward and nadir views, which are separated in time by about 120 s. During this time interval wind advection of clouds leads to errors in stereo cloud-top heights. ECMWF re-analysis wind profiles were used to derive a cloud-top height correction (Δh) by application of the following relationship (Seiz & Baltsavias, 2000):

$$\Delta h = -v\frac{\Delta t}{\tan\theta_{\mathrm{f}} - \tan\theta_{\mathrm{n}}}, \quad (1)$$

where v is the along-track cloud motion speed, Δt is the time difference between the nadir and forward views, θ_f is the forward camera angle and θ_n is the nadir camera angle. Southerly winds cause retrieved cloud-top heights to be overestimated. The cloud-top height correction (Δh) was found by iteratively searching the ECMWF re-analysis wind profile for that height whose wind speed led to a corrected cloud-top height retrieval within 100 m of itself. The cloud motion speed is not necessarily the same as the wind speed but this is mainly a problem in mountainous regions and not for fairly flat areas (Gabriella Seiz, 2003, personal communication) such as the southern UK or the Great Plains.

2.2. Millimeter-wave radar cloud-top heights

Millimeter-wave cloud radars (MMCRs) at the CFARR and SGP sites provide routine vertical profiles of cloud boundaries every 10 s at 45 m (SGP) and 60 m (CFARR) vertical resolution. The CFARR radar is a 94-GHz vertically pointing radar whereas the SGP radar operates at 35-GHz. The latter possesses a larger antenna and uses pulse coding and is believed to be more sensitive to high thin clouds. At millimeter wavelengths cloud particle reflectivities are proportional to the sixth power of the particle diameter, hence MMCRs lack sensitivity to small drops (less than approximately 10 μm in diameter) more than 4–5 km from the radar. Millimeter-wavelength signals are severely attenuated by heavy precipitation.

The algorithm developed by Clothiaux et al. (2000) was applied to both sets of MMCR data to detect significant cloud and clutter (e.g. vegetation debris and insects) returns for each vertical range gate at 10 s intervals. A mask is generated by the algorithm that identifies each significant return as being the result of hydrometeors only or a mixture of clutter and hydrometeors. The mask also identifies range gates with no significant power returns from the atmosphere as well as vertical profiles with no data. The algorithm uses ceilometer and micropulse lidar data from the CFARR and SGP sites to retrieve unambiguously the lowest cloud boundary, which is often obscured by precipitating particle and insect contributions to the radar return signals.

For this study the mean, median, minimum, maximum and standard deviation of the radar cloud-top heights for the four sampling periods of 640 s, 1280 s, 5120 s and 10 980 s centered on the ATSR2 nadir view time were computed from the 10 s profiles. The time between two consecutive ATSR2 views is approximately 120 s with an additional 75 s necessary for scanning the two sets of 512 × 512 radiances. That is, it takes approximately 200 s for the site to be scanned by both ATSR2 views. For temporal consistency we center the radar collection time on the start of the ATSR2 collection time. The radar collection times are the ATSR2 collection time of 200 s padded by ±60 s, for a period of 320 s, and then doubled to 640 s, 1280 s, etc. At each vertical level the total number of radar range gates that contained a cloud or a mixture of cloud and clutter contributions to the return signal was counted over the sampling period. These data provided for vertical profiles of cloud occurrence and the number of cloud layers over the time period.

3. Methods of comparison

Comparison between cloud-top heights retrieved from instantaneous satellite measurements of horizontally varying radiance and ground-based time series of vertical profiles of radar reflectivity presents challenges, especially in frontal and broken cloud situations. For ATSR2 the pixel resolution is 1 km and a 120 s elapses between the forward and nadir camera views. Within a view it takes 75 s to scan the 512 × 512 pixels in a complete ATSR2 scene. During this scan time clouds are advecting across the scene at a rate determined by the wind speed at the altitude of the cloud. The wind speed also determines the rate at which cloud elements advect over the ground-based radars. Table 1 shows the median, standard deviation, minimum and maximum values of the wind speeds, extracted from ECMWF wind profiles, at the level of radar cloud-top heights evaluated over periods of 640 s, 1280 s, 5120 s and 10 980 s for all case study periods at the CFARR and SGP sites. The median speeds were approximately 10 m s^{-1} for the different time intervals but no single direction was associated with this median value, indicating that the wind can have any orientation relative to the satellite track. This is no surprise given that these are baroclinic wave regimes and the flow direction is controlled by cyclonic/anticyclonic flow in association with synoptic lows and highs. Despite similar median wind speeds at cloud-top altitude for the two sites, larger standard deviations and maximum values at the SGP site indicate that occasional strong winds occurred more often at the SGP site.

In this study statistics of cloud-top heights over predetermined spatial domains (for ATSR2) and time intervals (for radar) are computed and compared with the hope that the statistics are representative of the same clouds and their top heights. We arbitrarily chose the size of the latitude-longitude box for ATSR2 to be 0.2°. A scene width of 0.2° for the analysis corresponds to about 400 ATSR2 1-km resolution pixels in a

Table 1
Median, standard deviation, minimum and maximum wind speeds at the level of radar cloud-top height for sampling periods of 640 s, 1280 s, 5120 s and 10 980 s at CFARR and the SGP site

Site	CFARR				SGP			
Time period (s)	640	1280	5120	10 980	640	1280	5120	10 980
Median wind speed (m s^{-1})	9.94	10.28	11.07	10.52	10.50	10.39	10.62	9.46
Standard deviation (m s^{-1})	6.20	6.22	6.43	6.44	6.63	6.60	6.88	6.45
Minimum wind speed (m s^{-1})	0.37	0.37	0.74	0.74	0.53	0.53	0.57	0.51
Maximum wind speed (m s^{-1})	29.49	28.82	29.82	34.88	36.85	36.85	37.83	37.83

20 km × 20 km area. A cloud travelling diagonally from one corner of the box at 10 m s^{-1} will take about 1400 s to pass over the radar if it is centered in the middle of the scene. The radar analysis time period should be large enough to take this cloud motion into account but not so large that it includes clouds not viewed by ATSR2. This prompted the use of analysis time intervals for the radar that ranged from 1280 s to 5120 s.

As in Naud et al. (2005), comparisons between satellite- and ground-based cloud-top height retrievals were performed after eliminating ambiguous scenes. Ambiguous scenes were defined as those with retrieved cloud-top heights that satisfied one of three conditions: (1) the standard deviation of the radar cloud-top heights during the analysis period was greater than 2 km; (2) the difference between the maximum and median radar cloud-top heights for the analysis period was greater than 3 km; and (3) the number of 10 s intervals containing a cloud or a mixture of cloud and clutter, no matter the altitude, was less than 10% of the total number of 10 s intervals in the analysis period. Table 2 summarizes the scenes for this study after elimination of ambiguous ones and illustrates variations in the statistical measures of cloud-top height from one analysis period to the next. These variations also underlay the criteria used for identifying ambiguous scenes, as discussed henceforth.

For nearly all time periods at CFARR there were more multi-layer cloud cases than single-layer cloud cases (Table 2). The large percentage of cases at CFARR with more than three cloud layers (nearly 10% for 5120 s) indicates that the vertical distribution of cloud layers was often complex. The cloud fraction decreased rapidly with increasing analysis period, indicating that clouds were generally not present for long periods of time over the site and that broken cloud situations occurred quite often. This was accompanied by an increase in the standard deviation of the cloud-top heights that most likely resulted from contributions of different cloud layers (e.g., high scattered clouds over lower cloud layers), as well as from cloud layers with large variations in cloud-top height. These types of cloud conditions make it difficult to determine if the radar and satellite are observing the same cloud and are eliminated from the study using the first two ambiguity tests described above.

As Table 2 shows, the frequencies of occurrence of single-layer clouds were larger than for multi-layer clouds at the SGP site using the shorter analysis periods and were found with median cloud fractions approaching 1. However, a number of cases contained only single-layer, isolated cloud elements that occurred for extremely short periods of time. The reliability of the radar returns for these cases was questionable and these cases were eliminated by the third ambiguity test on cloud fraction.

The types of clouds eliminated by the ambiguity tests at the two sites were different and the remaining cases at the two sites were for different cloud types as well. Comparison of ground-based radar and satellite-based ATSR2 cloud-top height retrievals will not be for the same types of clouds and synoptic conditions at the two sites, with mainly low clouds at CFARR and mostly high clouds at the SGP site. As a result, the analysis periods that lead to the largest number of cases for comparison with acceptable numbers of outliers will be different for the two sites, with a 5120 s interval chosen for CFARR and a 1280 s period for the SGP site.

For the CFARR site the radar was functioning and observing some type of cloud during the 5120 s analysis period for 96 of the ATSR2 overpasses. Of these 96 scenes, 59 (61.5%) of them passed the ambiguity tests with most of the cases that were removed occurring in the summer and winter being the least affected. Another 4 CFARR cases had to be removed because of problems with the ATSR2 11 μm cloud-top heights retrievals, leaving 55 cases for this site. The distribution of the 55 cases across the seasons was fairly uniform with slightly more cases in autumn and fewer in spring. For the SGP site there were initially 70 cloud-containing ATSR2 scenes of which 57 (81.4%) survived the ambiguity tests for the 1280 s analysis period. The number of cases left for summer was slightly larger

Table 2
Summary of cloud radar measurements obtained at CFARR and the SGP site for periods of 640 s, 1280 s, 5120 s and 10 980 s centred on ATSR2 nadir-view start time

Site	CFARR				SGP			
Time period (s)	640	1280	5120	10 980	640	1280	5120	10 980
Number of cloudy cases	74	79	96	108	67	70	81	86
Percentage of single level cloud cases	46.9	51.9	42.7	47.2	65.6	65.7	51.9	46.5
Percentage of 2-layers, 3-layers and more than 3 layers	35.1	25.3	33.3	32.4	22.4	22.9	27.1	33.7
	12.2	13.9	14.6	13.0	6.0	5.7	16.1	12.8
	6.8	8.9	9.4	7.4	6.0	5.7	4.9	7.0
Median number of cloud layers	2	1	2	2	1	1	1	2
Median cloud fraction	1.0	1.0	0.96	0.66	1.0	1.0	1.0	0.95
Percentage of cases with fraction = 1	62.2	50.6	30.2	16.7	74.6	65.7	45.7	37.2
Median radar standard deviation (km)	0.49	0.86	0.93	1.33	0.15	0.43	1.52	1.33
Median CTH (km)	4.42	3.64	4.6	3.10	8.92	8.92	7.89	8.70
Median max CTH (km)	6.58	6.58	7.3	8.14	9.10	9.10	10.23	10.36
Percentage of cloudy cases left when all three thresholds applied	85.1	74.7	61.5	46.3	89.6	81.4	59.3	55.8

For each time period the following quantities are provided: the total number of cloudy cases detected by the radar, the proportion of cases with single- and multi-layer clouds, with multi-layer clouds divided into cases with two layers, three layers and more than three layers, the median number of cloud layers, the median cloud fraction (i.e., number of 10 s intervals with cloud over the total number of intervals during the sampling period), the number of cases with cloud fraction equal to 1, the median standard deviation of radar cloud-top heights, the median radar cloud-top height and the median of the maximum radar cloud-top heights. The shaded columns highlight the results between ATSR2 stereo and radar cloud-top height retrievals discussed in the text.

Table 3
Summary of the ATSR2 stereo and radar median cloud-top height differences for all cases that were not eliminated by the three ambiguity tests

	Stereo 11 μm − radar CTH (km)		Stereo 1.6 μm − radar CTH (km)	
Situation	CFARR	SGP	CFARR	SGP
All clouds	0.49±1.96 (55)	0.32±1.89 (57)	−0.43±2.67 (54)	−2.10±4.10 (57)
Low clouds (<4 km)	1.24±1.45 (22)	0.72±0.96 (17)	1.28±1.13 (21)	0.95±1.10 (17)
High clouds (>4 km)	−0.01±2.12 (33)	0.15±2.16 (40)	−1.52±2.80 (33)	−3.4±4.22 (40)
Within one standard deviation	0.35±0.94 (39)	0.34±0.94 (43)	0.43±1.21 (40)	0.02±1.83 (43)
All single clouds	1.12±1.4 (30)	0.59±1.21 (40)	0.5±2.21 (29)	−1.01±3.48 (40)
Low single clouds	1.28±1.53 (19)	0.51±0.97 (13)	1.36±1.19 (18)	0.98±1.18 (13)
High single clouds	0.85±1.25 (11)	0.63±1.32 (27)	−0.89±2.80 (11)	−1.97±3.82 (27)
All single clouds, no outliers	0.44±0.73 (18)	0.21±0.75 (28)	0.91±1.12 (23)	0.10±1.75 (35)

The first column, labeled "Situation", describes the subset of cases that were used to calculate the average and standard deviation of the median differences between stereo and radar cloud-top heights for both sites and both ATSR2 channels. For each subset, the number of cases used to calculate the mean and standard deviation are given in parentheses.

than for the other seasons, with more cases being removed for winter.

4. Cloud-top height retrieval assessment

Cloud-top height retrievals from ground-based radar are first compared to ATSR2 11 μm channel cloud-top height retrievals (Section 4.1) and then to ATSR2 1.6 μm channel cloud-top height retrievals (Section 4.2). In the results to follow the median cloud-top height is computed for both the ATSR2 11 μm and 1.6 μm channel cloud-top height retrievals for the 0.2° domain and the radar cloud-top height retrievals for the designated analysis period of 5120 s for CFARR and 1280 s for the SGP site. The means and standard deviations of the differences of these two median cloud-top heights are then computed over the 55 CFARR and 57 SGP site case study periods.

4.1. ATSR2 11 μm channel and radar cloud-top height retrievals

A summary of the comparison between the ATSR2 11 μm channel and radar-retrieved median cloud-top heights is given in Table 3. Relative to the radar-derived cloud-top heights the ATSR2 11 μm channel cloud-top height retrievals were high, on average, by 0.49 km at the CFARR site and 0.32 km at the SGP site. The standard deviation of the cloud-top height differences was 1.96 km at the CFARR site and 1.89 km at the SGP site. As Fig. 1a,b illustrates, agreement is better at the SGP site for the entire range of cloud-top heights with more scatter between the two cloud-top height retrievals at CFARR. Fig. 1c,d was obtained by sorting the radar cloud-top heights into 11 bins containing an equal number of cases and calculating for each bin the average radar cloud-top height (represented on the *y*-axis) and the corresponding average difference between stereo and radar cloud-top heights (represented on the *x*-axis). It shows how the average difference between the two retrievals decreases steadily from low to high clouds at CFARR with little change in the average difference at the SGP site from the surface up to heights of about 8 km. High and low cloud cases were partitioned into two subsets of data, one with radar cloud-top heights above 4 km and the other with radar cloud-top heights below 4 km. For both sites the average difference between the ATSR2 11 μm channel and radar cloud-top height retrievals is smaller for high clouds compared to low clouds but the standard deviation of the differences is larger for the higher clouds (Table 3; Fig. 1c,d).

To identify the cloud conditions with the largest discrepancies between the two retrievals the difference between the two median cloud-top height retrievals for each scene was compared to the standard deviation of the differences over all scenes.

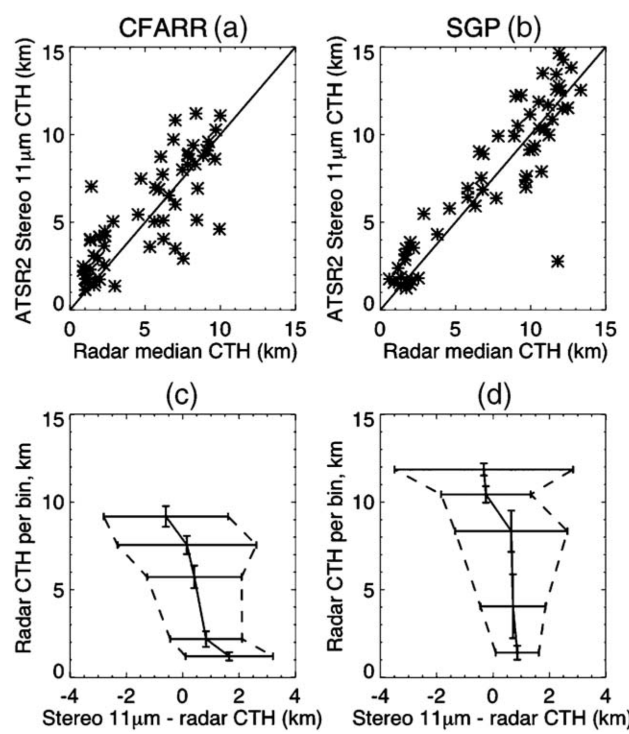

Fig. 1. ATSR2 11 μm channel stereo median cloud-top heights (CTH) versus radar median cloud-top heights (CTH) for (a) CFARR and (b) the SGP site. The ATSR2 retrievals are for a 0.2° by 0.2° domain and the radar data are sampled over 5120 s for CFARR and 1280 s for the SGP site. Radar cloud-top heights for the *y*-axis of the (c) CFARR and (d) SGP site comparisons are the averages of 11 cases per bin with a total of five bins and these bin average cloud-top heights are plotted against the difference between the ATSR2 11 μm channel and radar cloud-top heights.

4.1.1. The SGP site

Five cases were found at the SGP site for which the radar cloud-top height minus the ATSR2 11 μm channel cloud-top height was greater than the standard deviation over all scenes. For three of these five cases the ATSR2 11 μm channel cloud-top height retrieval was found below the highest cloud layer, whereas for the fourth case it occurred near the base of the highest layer. Either these clouds were too optically thin to be fully detected by the ATSR2 11 μm channel or there was an error in the wind correction. The largest difference was found for the fifth case with isolated high clouds present above the radar. On this occasion the ATSR2 11 μm channel detected the high cloud but problems were found with the surrounding cloud-free pixel retrievals that made these retrievals appear as low-altitude clouds and the three ambiguity tests did not remove them.

Nine cases were found at the SGP site for which the ATSR2 11 μm channel cloud-top height minus the radar cloud-top height was greater than the standard deviation over all scenes. On 8 of these 9 occasions, radar, like the ATSR2, indicated high clouds. The source of the large difference in cloud-top height between the ATSR2 and radar retrievals could be ATSR2 blunders, problems with the ATSR2 wind correction, small particles at the top of the cloud not detected by the 35-GHz radar, and potentially severe attenuation of the radar signal by precipitation for 3 of the 8 cases. Identifying which of these is contributing to the height differences is nontrivial, but the overall result is that ATSR2 11 μm channel cloud-top height retrievals are higher than those from radar. For the 9th case high broken clouds were detected by the ATSR2 11 μm channel that were detected by the radar only after the end of the sampling period.

Removing the 14 cases with the largest height differences from the sample pool of 57 cases at the SGP site leads to average median cloud-top height differences of 0.34 ± 0.94 km with the ATSR2 11 μm channel cloud-top heights being higher.

4.1.2. The CFARR site

At CFARR there were 5 cases for which the radar cloud-top height minus the ATSR2 11 μm channel cloud-top height was greater than one standard deviation over all scenes and 11 cases for which the ATSR2 11 μm channel cloud-top heights were higher by more than one standard deviation. For the 5 cases with radar cloud-top heights much greater than ATSR2 11 μm channel cloud-top heights the radar minimum cloud-top height and the ATSR2 11 μm channel cloud-top height were well within a standard deviation of each other. For these 5 cases broken high clouds were present over a lower cloud layer but only for part of the ATSR2 0.2° domain.

For 3 of the 11 cases for which the ATSR2 11 μm channel cloud-top heights were higher by one standard deviation the radar maximum cloud-top heights were close to them, suggesting that the highest clouds were broken. For another 3 of the 11 cases radar cloud-top heights were from low-altitude clouds with the ATSR2 11 μm channel cloud-top heights above 4 km. There was no evidence of clouds above 4 km in either the ATSR2 imagery or radar reflectivities and the ATSR2 11 μm channel cloud-top heights were most likely too high as a result of errors in the wind correction. One additional case from the 11 had low-altitude cloud retrievals for both instruments but the radar was on the edge of the ATSR2 swath. The remaining 4 cases were all high cloud cases with one case having bad radar data that was not flagged during processing and the other three cases having highly varying radar cloud-top height retrievals not removed by the three ambiguity tests.

For this site most of the outliers were caused either by broken high clouds above a lower cloud layer or by highly varying cloud-top heights. Removing these 16 outliers from the sample pool of 55 leads to a median cloud-top height difference of 0.35 ± 0.94 km again with the ATSR2 heights being higher on average.

4.2. ATSR2 1.6 μm channel and radar cloud-top height retrievals

At CFARR 54 cases survived the ambiguity tests with the ATSR2 1.6 μm channel cloud-top heights lower than those from radar by -0.43 ± 2.67 km and at the SGP site 57 cases survived the ambiguity tests with ATSR2 1.6 μm channel cloud-top heights lower by -2.10 ± 4.10 km (Fig. 2a,b; Table 3). Clouds above 4 km had an average difference of -1.52 ± 2.80 km at CFARR (33 cases) and -3.40 ± 4.22 km at SGP (40 cases), with the radar retrievals higher for both locations. The cases with clouds below 4 km had an average difference of 1.28 ± 1.13 km at CFARR and 0.95 ± 1.10 km at the SGP with the radar retrievals lower in both cases.

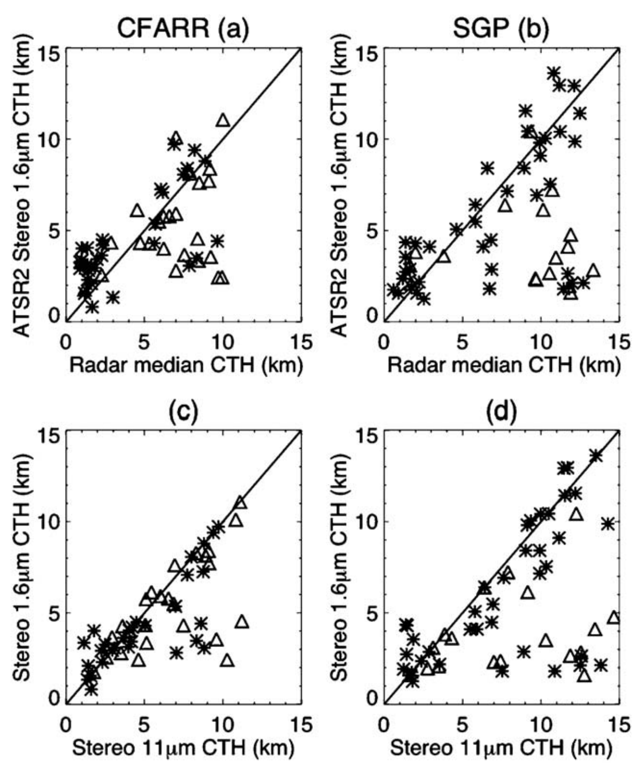

Fig. 2. ATSR2 1.6 μm channel versus radar cloud-top height retrievals for (a) CFARR and (b) the SGP site. ATSR2 1.6 μm channel versus ATSR2 11 μm channel cloud-top height retrievals for (c) CFARR and (d) the SGP site for single-layer cloud cases (★) and multi-layer cloud cases (△). The ATSR2 data are for a 0.2° by 0.2° domain and the radar data are sampled over 5120 s at CFARR and 1280 s at the SGP site.

4.2.1. The SGP site

At the SGP site 14 cases had radar cloud-top height retrievals more than one standard deviation above the ATSR2 1.6 μm channel retrievals. There was not a single case with an ATSR2 1.6 μm channel median cloud-top height more than one standard deviation above a radar height. Of these 14 cases 9 were of multi-layer clouds. Of these 9 multi-layer cases the ATSR2 1.6 μm channel cloud-top heights were between layers for 3 cases, below all cloud layers for 3 cases and at the top of the lowest cloud layer for 3 cases. Naud et al. (2002, 2004) report similar findings, which are the result of the layer of highest contrast, to which the stereo heights are assigned, often being optically thick, lower altitude clouds.

Of the 5 single-layer cloud cases the ATSR2 1.6 μm channel maximum cloud-top height was in agreement with the radar value for 1 case. For the remaining four cases the radar cloud-top height retrievals indicated a single high-level cloud. The ATSR2 1.6 μm channel cloud-top heights were found at an altitude where radar detected clutter so either referred to low-altitude clouds masked by clutter in the radar reflectivities or represented surface heights with the high altitude clouds optically too thin to be detected with the ATSR2 1.6 μm channel.

For the 40 single-layer cloud cases at SGP the median cloud-top height difference, on average, was -1.01 ± 3.48 km. Although the ATSR2 1.6 μm channel cloud-top heights are higher for single-layer clouds than multi-layer ones, they are still lower than radar cloud-top heights. Results were worse for high clouds than low clouds, as the difference for clouds below 4 km (13 cases) was 0.98 ± 1.18 km and for clouds above 4 km (27 cases) the difference was -1.97 ± 3.82 km. If the 5 single-layer cloud cases that were outliers were removed from the pool of 40, an average difference of 0.10 ± 1.75 km with a squared correlation of 0.81 is obtained. These results indicate that the identification of optically thin clouds in ATSR2 1.6 μm channel imagery and independent detection of lower altitude clouds (e.g. radar not affected by clutter) would substantially improve the results.

4.2.2. The CFARR site

At CFARR 10 cases had radar cloud-top height retrievals more than one standard deviation above the ATSR2 1.6 μm channel retrievals. For 7 of these 10 cases there was more than one cloud layer and the ATSR2 1.6 μm channel cloud-top heights were either at the top of the lowest layer detected by the radar or just below the highest layer detected by the radar. For single-layer cloud cases, of which there were 29 at CFARR, the ATSR2 1.6 μm channel cloud-top heights were higher, on average, than those from radar by 0.50 ± 2.21 km. Separating these results into clouds with radar tops below and above 4 km, the average difference for low clouds (18 cases) was 1.36 ± 1.19 km and for high clouds (11 cases) -0.89 ± 2.80 km with the ATSR2 heights once again too low. Of these 29 cases only 3 actually had ATSR2 heights lower than those from radar. They were cases of single-layer broken or optically thin high clouds with the maximum cloud-top height from the ATSR2 1.6 μm channel retrieval close to the median value from the radar.

For 3 cases ATSR2 1.6 μm channel cloud-top height retrievals were at least one standard deviation higher than those from radar. For 1 case both instruments detected a high cloud but either a blunder or errant wind correction biased the ATSR2 retrieval high. For the other two cases radar retrievals were for low clouds while the ATSR2 retrievals were for mid-level clouds (top height at 3–4 km); most of the ATSR2 0.2° domain was clear with the exception of some isolated high clouds, not detected by the radar, and a few low clouds over the radar for a short period of time.

Removing the 3 cases with ATSR2 stereo heights much smaller than radar cloud-top heights, plus the 3 others commented just above from the pool of 29 single-layer cloud cases, the average difference became 0.91 ± 1.12 km with a squared correlation of 0.81. These differences are comparable to those for the low altitude clouds and for the ATSR2 11 μm channel results though with a larger standard deviation.

5. Summary and discussion

The ATSR2 11 μm channel stereo cloud-top height retrievals were higher, on average, than those from radar by approximately 350 m with a standard deviation of 1 km. For multi-layer clouds and optically thin clouds ATSR2 1.6 μm channel cloud-top heights were significantly lower than those from radar. For single-layer cloud cases ATSR2 1.6 μm channel results were similar to the ATSR2 11 μm channel results, including better agreement with radar with increasing cloud-top height. Errors in surface-height retrievals, inaccurate wind corrections and blunders in the ATSR2 retrievals are three possible sources of this difference and could explain the variation of the difference with altitude.

To investigate ATSR2 retrieval performance for clear regions ATSR2 scenes (512×512 pixels) with at least 50% clear pixels were selected and the stereo height retrievals for the clear pixels were compared with digital elevation model (DEM) values at CFARR and the nominal 318 m altitude of the SGP site. Clear pixels were identified using the 11 μm/3.7 μm brightness temperature difference test, the 11 μm/12 μm brightness temperature difference test, and the 0.65 μm/0.87 μm ratio test from the Moderate Resolution Imaging Spectroradiometer (MODIS) cloud mask (Ackerman et al., 1998) and adapted for ATSR2. Comparing the ATSR2 11 μm channel surface height retrievals with known surface elevations, we found that for all scenes the ATSR2 retrievals were higher. The differences were larger at CFARR than for the SGP site. At CFARR the smallest median difference for a scene was 1.27 ± 1.34 km, the largest difference was 3.11 ± 1.34 km and the median of median differences over all 14 scenes was 2.05 ± 1.45 km. For the SGP site the smallest differences was -0.50 ± 0.32 km, the largest was 3.81 ± 1.20 km and the median of the median differences over all 20 scenes was 0.83 ± 1.35 km. The mean difference over all scenes for each site was 2.03 km for CFARR and 1.02 km for the SGP site.

These surface terrain-height biases are larger than for low altitude clouds and hence are consistent with an overall bias that decreases with increasing altitude. These results are in accordance with the findings of Denis et al. (in press) that showed that in clear sky conditions over rugged terrain the ATSR2 11 μm channel stereo heights are, on average, higher than the surface heights given by a digital elevation model (i.e., DTED-0), although Denis et al. (in press) did not find any relationship between this bias and the surface heights. However, they found a dependence of this bias on the camera model (the method used to transform the two-dimensional coordinates of each view into a three-dimensional coordinate system) that was used to match the nadir and forward camera image pixels. They tested two different camera models that gave differences in surface heights of 200 m on average. The camera model for this study was the one that was in better agreement with DTED-0 in Denis et al. (in press), although it, too, could be improved. Discrepancies between camera models do not explain the differences observed between CFARR and the SGP site.

Errors in wind advection corrections are difficult to assess as they are based on ECMWF profiles. Boutin et al. (1996) found a slight low bias in the ECMWF wind speeds when compared to buoy data but the bias was not even 1 m s^{-1}, over oceans where reanalyses are less accurate. Larger biases have been found at specific locations but they do not exceed 2 m s^{-1}, which would only cause an error of 170 m in an ATSR2 cloud-top height retrieval if these wind errors were along the ATSR2 track. The ECMWF wind profiles are at fairly low resolution (2.5° × 2.5°) and wind fields are highly variable in time and space, so we cannot exclude possible errors in the wind speeds used to correct the ATSR2 cloud-top height retrievals.

Blunders lead to overestimates of cloud-top height and they have a stronger effect on the median cloud-top height retrievals of low altitude clouds within a given subregion. We found that decreasing the maximum allowable stereo height, in particular at CFARR, slightly improved the retrievals. Developing a reliable and automated blunder detection method remains an important research topic and application of an improved blunder detection method to this data set should lead to improved ATSR2 retrievals of cloud-top height.

A fourth source of error in ATSR2 stereo height retrievals is a planimetric error that results from errors in geolocation (Shin et al., 1997). Visual examination of ATSR2 false colour images for clear regions over the United Kingdom revealed that about 20% of the scenes contained misalignment between the ATSR2 observations and digitally produced coastlines. This planimetric error mainly affects retrieval of cloud-top height when the spatial distribution of clouds is highly variable (there would be more edge detections at the surface that could be confused with cloud edges). This finding could explain the observed differences between CFARR and SGP site cloud-top height retrievals.

6. Conclusions

ATSR2 11 μm and 1.6 μm channel stereo cloud-top height retrievals were compared with those from ground-based radar measurements at the United Kingdom Chilbolton Facility for Atmospheric and Radio Research and the United States Atmospheric Radiation Measurement program Southern Great Plains site from 1997 to 2000. For the ATSR2 11 μm channel cloud-top height retrievals were higher than those from radar by approximately 350 m, on average, with a standard deviation of approximately 1 km. This difference increased as cloud-top height decreased. ATSR2 11 μm channel surface-terrain height retrievals were also higher than values in a digital elevation model (i.e., DTED-0). Sources for this high bias in the ATSR2 retrievals include errors in the stereo height wind correction, blunders, the camera model used in the stereo retrievals and geolocation errors.

For cloud-top height retrievals based on the ATSR2 1.6 μm channel results similar to those from the ATSR2 11 μm channel were found for single-layer cloud cases. For multi-layer clouds ATSR2 1.6 μm channel cloud-top height retrievals were significantly lower than those from radar. ATSR2 1.6 μm channel radiances are less sensitive to optically thin clouds than ATSR2 11 μm radiances, causing a low bias in cloud-top height retrievals when more than one cloud layer is present. These results suggest that a large discrepancy between the ATSR2 11 μm and 1.6 μm retrievals could be used as an indicator for the presence of a multi-layer cloud.

A long-term (i.e. 10-year) cloud-top height climatology is now possible using the first ATSR instrument, ATSR2 and the recently launched A-ATSR. This climatology would not have the same coverage as the International Satellite Cloud Climatology Project (ISCCP; Schiffer & Rossow, 1983), but would be an excellent complement as the cloud-top heights should be more precise. If multi-layer clouds can indeed be retrieved at different levels, additional information on multi-layer clouds, including height assignments for more than a single layer, would be available.

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