Comparison between ATSR2 stereo, MOS O_2-A band and ground-based cloud top heights

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ABSTRACT

A new method to retrieve cloud top heights stereoscopically using the dual-view facility of the Along Track Scanning Radiometer 2 (ATSR2) instrument is assessed. This assessment is performed through a comparison of the cloud top heights obtained from ATSR2 stereo and those derived from a 94-GHz radar, radiosonde profiles and independently from the Modular Optoelectronic Scanner (MOS) using the O_2-A band. The data for this study were collected over the United Kingdom from September 1998 through March 1999. The results show that the accuracy of the ATSR2 stereo heights is generally as predicted on theoretical grounds, with the errors in the 1.6 μm and 0.65 μm stereo heights rarely exceeding 2 km. Case study periods with disagreements between the ATSR2 heights and the ground-based retrievals are often due to the lack of precise match-ups between the ground-based and satellite scenes, while the MOS O_2-A band is shown sometimes to miss the tops of high clouds. Evidence that the 11 μm channel is more sensitive to high clouds than originally thought is given and a future application of multi-spectral stereo cloud top heights is proposed.

1. Introduction

The impact of clouds on the Earth's radiative balance has long been recognised as a major issue in climate and weather forecasting studies (e.g., Ramanathan et al., 1989). Depending on their composition and height, clouds may have either a warming or a cooling effect (Hartmann et al., 1992). In order to assess the overall effect of a cloud on the Earth's radiative balance, one must be able to assign precisely an average cloud top height (CTH) to the cloud layer. Otherwise, determining the temperature and composition (in terms of ice or liquid water) of the cloud layer, which are principal factors in cloud forcing, is not possible. Only satellite-based sensors with their global coverage are able to characterise cloud top heights on a scale sufficient for comprehensive climate and weather forecasting studies.

The Along Track Scanning Radiometer 2 (ATSR2) is a dual-view scanning radiometer that was launched in 1995. The ATSR2 observes the Earth with 7 channels across the visible, near-infrared and thermal infrared regions of the electromagnetic spectrum. The unique dual-view feature of ATSR2 allows the application of stereo-photogrammetric techniques to retrieve information on cloud top height (e.g., Lorenz, 1985; Harris, 1993). Other techniques in current use, such as the CO_2 slicing method (e.g., Menzel, 1983), the water vapour technique (Szejwach, 1982) and the O_2-A band technique (Fischer and Grassl, 1991; Preusker et al., this issue), are spectrally-based and often require ancillary information in their retrieval of cloud top height. For example, the CO_2-slicing and water vapour techniques require external information on the local atmospheric profiles of temperature, pressure and/or humidity, while the O_2-A band technique requires surface reflectivity data to identify thin clouds over land. Stereo matching has the advantage of being a stand-alone technique based only on geometric considerations and has already been applied successfully to cloud top height retrievals (e.g., Prata and Turner, 1997).

A new stereo matching technique and associated processing chain, collectively called M4 (Muller et al. and Denis et al., this issue), have been applied to the 0.65, 1.6 and 11 μm channels of ATSR2 in order to retrieve cloud top heights for scenes over the United Kingdom from September 1998 through March 1999. In their description of the M4 algorithm, Muller et al. (this issue) estimated that the theoretical expected accuracy of the method is 1 km. The objective of this paper is to assess the accuracy of the Muller et al. (this issue) technique by comparing the cloud top heights (CTHs) it retrieves to ground-based measurements obtained with a 94-GHz radar situated at Chilbolton (51.14°N, 1.44°W) and with radiosondes (RS) launched from the Aberporth (52.13°N, 4.57°W) and Hemsby (52.68°N, 1.68°E) stations. As these ground-based and in-situ measurements provide a full profile of information from the surface to the tropopause and allow the possibility of identifying multi-layered clouds, we compared the ATSR2 stereo-derived cloud top heights with the tops of the highest cloud layers detected by the ground-based instruments. It is not possible to give an absolute accuracy for the heights retrieved with these instruments, but independent comparisons with lidar retrievals have shown that cloud heights retrieved from radar agreed with the lidar measurements within 125 m at cloud base (Clothiaux et al., 1998) and the two radiosonde techniques used here have been shown to give cloud top heights 350 m ± 750 m higher than the radar cloud top heights retrieved at the Atmospheric Radiation Measurements (ARM) Program Southern Great Plains site (Naud et al., 2003). In a few cases, retrievals of cloud top pressure (CTP) derived from the Modular Optoelectronic Scanner (MOS; Zimmermann and Neumann, 1997) O_2-A band (Preusker et al., this issue) onboard IRS-P3 were coincident with the ATSR2 measurements, so we compared the two sets of retrieved cloud top heights. The accuracy of MOS O_2-A band CTP has been shown to be about 30 hPa for clouds with an optical depth of 5 at 550 nm (i.e. less than 500 m error in CTH for a standard mid-latitude winter atmosphere), but there is no reliable estimate available for clouds with optical depths less than 5 (Preusker et al., this issue).

This paper is divided into five sections apart from the introduction. We begin the analysis in section 2 with comparisons between ATSR2 and 94-GHz radar cloud top heights, while section 3 shows comparisons between ATSR2 and radiosonde-derived cloud top heights. In section 4 we compare both ATSR2 and ground-based cloud top heights with MOS cloud top pressure and in section 5 we extend the ATSR2 and MOS comparisons over the British Isles. Discussion of the results and our final conclusions are presented in section 6.

2. Comparison between ATSR2 stereo and 94-GHz radar-derived CTH over Chilbolton

Out of the 27 dates when ATSR2 stereo height retrievals over Chilbolton were possible, 11 scenes (Table 1) were deemed suitable for comparison with the ground-based radar data. We processed the 94-GHz data using an algorithm that was originally implemented and tested at the

ARM Southern Great Plains site (Clothiaux et al., 2000) and subsequently adapted to take advantage of the processing enhancements developed at the University of Reading specifically for the Chilbolton 94-GHz cloud radar. This algorithm provides a reflectivity clutter flag product that indicates, as a function of time and height, clear, cloudy, a mixture of cloud and clutter or clutter only contributions to the radar returns from each resolution volume. The clutter may be insects, vegetation, or any other non-hydrometeor particles.

We extracted the median, mean and maximum cloud top height contained in the radar mask over a time interval centred on the nadir ATSR2 scan of the Chilbolton site. The minimum time interval for the radar data sampling has to include the time it takes from the forward to the nadir view over Chilbolton, which we estimated to be about 195 s. We tested various time durations for the comparison from 200 s to 7200 s and found that a ±320 s time interval was the most reliable one for picking up clouds in broken cloud or strong wind conditions for all the cases analysed here. We computed the median and mean radar CTH over the time interval for those clouds detected by the radar and calculated the fraction of this interval to the total sampling time period. The median CTH was used for the comparison, but for some cases the maximum value gave a more consistent comparison with the ATSR2 stereo-derived heights in scattered cloud conditions. In the comparisons with the 94-GHz radar-derived cloud top heights the ATSR2 stereo heights are selected over a ±0.02° latitude-longitude box centred on Chilbolton and the spatial mean, median and standard deviation are calculated. The use of a latitude-longitude box around the ground-based station overcomes the potential ATSR2 geolocation problems, so that if the clouds are uniform, the pixels shift has no impact, if the clouds are broken and sparse, they are potentially still within the box.

A summary of the median ATSR2 stereo and radar CTHs, with corresponding standard deviations, for the 11 dates from 1998-11-11 through 1999-02-11 is presented in Table 1. In Figure 1, the ATSR2 stereo median CTHs that were derived from the ATSR2 0.65 μm, 1.6 μm and 11 μm channels are plotted against the radar median cloud top heights over the observational time period. On three occasions (1998-11-24, 1998-12-03 and 1999-01-07) all three ATSR2 channels detected a cloud at the same level as detected by the radar. For another three scenes one ATSR2 channel retrieval disagreed with the other two ATSR2 channel retrievals as well as the radar-derived median CTHs. For 2 scenes (1999-01-20 and 1999-01-23), the radar median CTH was much lower than the three ATSR2 CTHs, but the radar maximum CTH agreed with at least one of the ATSR2 channel CTHs. These scenes were similar in that they contained high scattered clouds over a lower cloud layer as illustrated on the radar reflectivity plot. On one occasion (1998-12-10) the radar CTH indicated a low single cloud layer whereas the three ATSR2 channels agreed on the presence of a mid-level cloud. The radar reflectivity plot showed that the cloud vertical extent was increasing during and after the ATSR2 overpass, suggesting that the area observed by ATSR2 may have been covered with the higher part of the cloud system whereas the part that predominantly travelled over the radar during the observational time period was lower. Another case (1999-02-11) showed a multilayer scene and the three ATSR2 CTHs referred to the top of the layer below the highest one detected by the radar. Finally, on one occasion (1998-11-17) the three ATSR2 channels detected a high cloud that the radar did not detect and a longer sampling period did not show any cloud in the radar reflectivity plots. One cause of this problem may be that these high clouds detected by ATSR2 were composed of particles too small to be detected by the radar.

Removing the last three case study periods mentioned above from the data pool (1998-12-10, 1999-02-11 and 1998-11-17), we were left with 8 cases when ATSR2 stereo and radar-derived median CTHs could be compared (using radar maximum CTH when appropriate). On five of these occasions, the ATSR2 0.65 μm channel retrieved higher CTHs than the radar. For four of these cases both instruments detected a high CTH and one case only showed a low cloud layer. On two of the remaining occasions, the ATSR2 0.65 μm channel CTH was lower than the radar CTH and for both cases the cloud was at mid-level (between 3 and 7 km). Finally, on 1999-01-20 the ATSR2

0.65 μm channel CTH was far too high for a mid-latitude winter cirrus, which means that the stereo height estimate could be affected by blunders. These blunders occur sometimes, but not usually for more than 1% of all pixels matched (Muller et al., this issue). Overall, the difference between the radar and ATSR2 0.65μm derived CTHs varied between –1.9 and 0.4 km with an average difference of –0.9 km and a standard deviation of 0.8 km.

For the same 8 cases above the ATSR2 1.6 μm channel CTH was lower than the radar CTH on 3 occasions, but for two of these cases the height differences were less than 1.5 km of altitude (same mid-level cloud cases as for the ATSR2 0.65 μm channel). For the third case (1999-02-02) the ATSR2 1.6 μm channel failed to detect the highest cloud layer, reporting instead the CTH of a lower level cloud layer. Nevertheless, a histogram of all ATSR2 1.6 μm channel CTHs selected in the 0.02° latitude-longitude box showed that the high cloud was in fact detected, but only over a limited area. For the remaining four dates the ATSR2 1.6 μm channel CTH was always higher than the radar CTH. Of these four cases, high cloud layers were detected on three occasions and the difference could be due to insufficient radar sensitivity to detect the top of these clouds. The low cloud case (1998-12-03) only shows a difference of 1 km. Similar to the ATSR2 0.65 μm channel CTHs on 1999-01-20, the ATSR2 1.6 μm channel CTHs were far too high for a mid-latitude winter cirrus and again this is probably caused by blunders. Overall, the difference between the radar and ATSR2 1.6 μm channel CTHs for 7 of these cases was between –1.7 km and 5.7 km, giving an average difference of 0.1 km and a standard deviation of 2.6 km. If we remove the 1999-02-02 case from the pool, the average becomes –0.8 km with a standard deviation of 0.9 km.

The ATSR2 11 μm channel CTH was lower than the radar CTH on one occasion only out of the 8 scenes when a comparison was possible, this case being 1998-11-27 when the highest layer was missed by the ATSR2 11μm channel stereo CTH retrieval. At 11 μm the contrast between the nadir and forward views when low clouds are present may not be enough for the stereo matcher to perform accurately. For the remaining seven cases the ATSR2 11 μm channel reported higher cloud top heights than the radar, most of the heights being above 7 km, except for the 1998-12-03 case, where a low cloud was present and the difference was only 1 km. For these 8 cases the difference between the radar and ATSR2 11 μm channel CTHs varied between –4 km and 2.5 km with an average of –1.1 km and a standard deviation of 1.8 km. Presumably, the sensitivity of the ATSR2 11 μm channel to the highest levels within a high cloud layer must have been greater than the sensitivity of the radar to the particles at these altitudes.

Overall, the agreement between ATSR2 stereo and 94-GHz radar CTH was generally within 2 km, but there was a tendency for the radar to underestimate CTH for high clouds. This is for two main reasons. Firstly the minimum detectable signal increases with range from the radar, from around –51 dBZ at 1km to –31 dBZ at 10km (taking into account the two-way attenuation by water vapour and oxygen in the lower atmosphere of 1-2dB). Secondly ice clouds of a given optical depth tend to contain smaller particles at higher altitudes, making them more difficult to detect using radar. The presence of low-level liquid water clouds can cause an additional uncertain attenuation, although the attenuation by ice clouds is very small in comparison. The ability of the Chilbolton 94GHz radar to detect ice clouds at different heights was discussed further by Hogan et al. (2001).

3. Comparison between ATSR2 stereo and radiosonde-derived CTH over Hemsby and Aberporth

We used two techniques to retrieve cloud boundaries from radiosonde profiles. One technique was based on relative humidity thresholds (Wang and Rossow, 1995; hereafter WR95), while the second method was based on the sign of the second derivatives of humidity and temperature profiles together with a threshold on dew point depression (Chernykh and Eskridge, 1996; hereafter CE96). In this second approach two different thresholds on cloud amount were tested, an 80% threshold applying when the cloud amount must be at least 80% for a layer to be considered cloudy and a 60% threshold holding when the cloud amount was at least 60% in a cloudy layer (CE96).

When no distinction between the WR95 and CE96 methods is necessary, we refer to them both as the radiosonde (RS) techniques.

We compared radiosonde-derived CTH of the highest detected cloud with those derived from ATSR2 from August 1998 through March 1999. During this time period, high-resolution (i.e. 2 s) radiosonde data were coincident with interesting ATSR2 overpasses 17 times at Aberporth and 5 times at Hemsby. As for the radar comparisons, the ATSR2 CTHs were derived by averaging all CTHs within a ±0.02° latitude-longitude box centred at the relevant radiosonde launch site. Unfortunately, latitude and longitude information were not provided by the radiosondes during ascent, preventing us from precisely aligning radiosonde measurements with ATSR2 pixels. In order to overcome this problem larger latitude-longitude boxes were used to sample ATSR2 CTHs and assess their frequency of occurrence.

Results of comparisons between CTH derived from the three ATSR2 channels using stereo and CTH obtained by applying the WR95 and CE96 techniques to radiosonde data are illustrated in Figure 2 and summarized in Table 2. The top row in Figure 2 shows results for WR95, while the bottom row in Figure 2 shows results from CE96. Wang et al. (1999) demonstrated that layers close to the surface with high humidity levels are sometimes cloud free. As both the WR95 and CE96 methods use thresholds on humidity to select cloud layers, they both have the potential to specify clouds near the surface during clear-sky periods. In their original work WR95 suggested that all cloud layers with a top below 500 m should not be considered as cloudy and we have followed their rule. Consequently, for the RS techniques we considered a case to be clear if the RS technique gave a cloud top height less than 0.5 km, while for the ATSR2 stereo CTH we considered an area to be free of cloud if the retrieved height was less than 0.7 km.

Considering both the Aberporth and Hemsby stations, there was a pool of 22 radiosonde profiles coincident with ATSR2 overpasses for which we compared cloud retrievals. Of these 22 profiles 5 cases were indicated clear by the radiosondes but only 1 of these 5 cases was indicated as clear by the three ATSR2 channel retrievals. The other four cases contained scattered clouds that were not systematically detected by all three ATSR2 channels. The RS did not detect these clouds in these 4 cases either because the sonde travelled between broken clouds or the clouds were too dry for the thresholds on humidity used by both methods.

For the remaining 17 cases, which were cloudy, CTHs were categorised according to a high (CTH > 7 km), mid-level (3 < CTH ≤ 7 km) and low (CTH ≤ 3 km) cloud classification. For 6 cases the three ATSR2 channel retrievals agreed on the cloud top level, following the high-mid-low classification, and they also agreed with at least one of the RS CTHs. For 5 of these 6 cases the clouds were high with a CTH above 7 km. The largest difference between the ATSR2 and RS CTHs was found on 1999-01-07 when the ATSR2 CTHs were more than 2 km above the RS CTHs. For 8 cases there was at least one ATSR2 CTH that agreed with at least one RS CTH. All these cases contained more than one cloud layer in the RS profile. Out of these 8 cases ATSR2 11 μm channel CTHs were close to RS CTHs in 4 cases, were higher than RS CTHs in 3 cases and were below the highest layer detected by RS in one case. The ATSR2 1.6 μm channel CTHs agreed with RS CTHs for 3 cases, referred to the top of a lower layer in 2 cases, did not detect a cloud at all in 2 cases, and referred to a cloud above the highest RS cloud for one occasion. The ATSR2 0.65 μm channel CTHs agreed with RS CTHs for 2 cases, were well above the RS CTHs for two occasions and referred to the top of a lower layer for 4 occasions.

For 2 of the 17 cloudy scenes (1998-10-13 and 1998-11-01) the three ATSR2 channel retrievals yielded CTHs close to each other but between lower cloud layers detected by the RS methods. These results could be from a colocation problem as the RS may detect clouds beyond the latitude-longitude limits set for the selection of ATSR2 CTHs. The remaining scene (1998-12-22) shows good agreement between ATSR2 11 μm and 0.65 μm channel CTHs, although the CTHs correspond to a lower layer than the highest one detected by the RS methods, whilst the ATSR2 1.6

μm channel failed to detect a cloud. The highest RS layer may be either too optically thin for all 3 ATSR2 channels to detect, outside of the ATSR2 latitude-longitude box or a moist cloud-free layer.

Reviewing the discrepancies discussed above, some are no doubt a result of the RS techniques ascribing cloud to a cloud-free moist layer or failing to properly identify cloud in a dry layer. We noticed that the ATSR2 11 μm channel tended to detect higher clouds when the other techniques either detected a lower altitude cloud or no cloud at all. These anomalous high cloud detections by the ATSR2 11 μm channel could be again the result of blunders, as mentioned in section 2, or due to high thin cloud which the other two channels did not detect. The RS CTHs were in best agreement with the ATSR2 11 μm channel CTH retrievals with 9 cloudy scenes out of 17 having differences within 2 km. Relative to the RS CTHs, the ATSR2 0.65 μm channel tended to underestimate CTH and the ATSR2 1.6 μm channel tended to miss clouds. Overall, for 9 of the 22 cases when all techniques detected cloud the cloud top height differences between the different techniques were within 2 km.

For all three channels the agreement was on average better when compared to the CE96-60% CTHs. Removing cases when there were known problems from the data pool, we found an average difference between RS CE96-60% CTHs and a) ATSR2 11 μm channel CTHs of –0.3 km with a standard deviation of 1.3 km for 9 cases, b) ATSR2 1.6 μm channel CTHs of –0.1 km ± 1.9 km for 9 cases and c) ATSR2 0.65 μm channel CTHs of 0.2 km ± 2.1 km for 7 cases. When there were height disagreements in the remaining cases, they were the result of ATSR2 either detecting high clouds that were beyond the detection limit of the radiosonde (in terms of accuracy of the relative humidity measurements or spatial coincidence of the radiosonde with the cloud) or failing to detect high clouds in multiple layer cases. Optically thin clouds above lower level clouds and scattered, broken clouds were the most difficult cloud types to simultaneously detect from both ATSR2 and radiosonde observations.

4. Comparison between MOS O_2-A band CTP and ATSR2-stereo and ground-based CTH

During the validation campaign from August 1998 through March 1999, we identified fourteen MOS scenes over the United Kingdom that occurred within half an hour of an ATSR2 overpass. Using the O_2-A band technique (Fischer and Grassl, 1991), Preusker et al. (this issue) converted the MOS radiances into estimates of cloud-top pressure that were subsequently transformed into geopotential heights using ECMWF re-analysis profiles (ERA-15). Of these fourteen scenes, one was also coincident with 94-GHz radar observations and four were coincident with radiosonde launches from either Aberporth or Hemsby stations. We sampled the MOS- and ATSR2-derived cloud top heights across the same ±0.02° latitude-longitude boxes centred at Chilbolton, Aberporth and Hemsby as before. A summary of CTHs retrieved from the MOS instrument is presented in Tables 1 and 2.

There was only one pass over Chilbolton when MOS O_2-A band, ATSR2 and the radar indicated a cloud. On this day (1998-11-27) the CTH differences between the radar, MOS O_2-A band and ATSR2 1.6 μm and 0.65 μm channel CTHs were within 1 km, while the ATSR2 11 μm channel CTH was about 2 km lower than the others.

For the Aberporth and Hemsby comparisons on 1999-01-14 only MOS and the ATSR2 0.65 μm and 1.6 μm channels detected a cloud with the ATSR2 0.65 μm channel CTH being higher. For the second case study period (1999-01-23) the MOS CTH was between the ATSR2 1.6 μm and 0.65 μm channel CTHs, while the ATSR2 11 μm channel CTH was unrealistically high for mid-winter cirrus. For this case the RS methods detected a cirrus layer at 11 km, also detected by the ATSR2 1.6 μm channel, but missed by the MOS and ATSR2 0.65 μm channel retrievals. Furthermore, the standard deviations for ATSR2 CTHs were generally large compared to the MOS CTH standard deviation, indicating a larger uncertainty in true cloud top height for this case. On 1999-02-11 the RS techniques indicated a multilayer cloud system and MOS CTH referred to the next to highest cloud layer, in agreement with the ATSR2 0.65 μm channel retrieval. On the last comparison day of

1999-03-02 the RS methods indicated a cloud layer from the surface up to an altitude of 12 km, most likely indicating the presence of a multi-layer cloud system. If multiple cloud layers are present and the upper layers are thin, the increase in photon path length due to multiple scattering between layers will always lead to the MOS O_2-A band retrievals underestimating the CTH (Preusker et al., this issue). For this multi-layer cloud case the MOS O_2-A band CTH was lower than all of the other retrievals.

There were another four dates when MOS passed over Aberporth or Hemsby near the time of radiosonde launches, so we have in total eight dates to compare the RS and MOS CTH retrievals (Table 3, Figure 3). We found that for clouds retrieved below 5 km by the RS techniques the MOS CTHs were higher, whereas for clouds with tops above 10 km in the RS approaches MOS had much lower CTHs. For the latter cases we found that on three occasions the MOS CTH was within the highest layer detected by the RS techniques, on one occasion the MOS CTH was close to the CTH of the layer below the highest one detected by the RS techniques, and on two other occasions the MOS CTH was between two RS layers. Overall, in most cases, the MOS approach detected the same layer as the RS methods but failed to pick up the highest levels of the layer. This result was not surprising in the context of our statements above, where we emphasized that MOS CTHs tend to underestimate the true cloud top height in instances of optically thin cloud over lower level clouds. This problem led to the average difference between RS and MOS CTHs of 4.3 ± 4.6 km for all cases. For the 4 cases with an agreement on cloud level the difference was 2.8 ± 4.0 km.

5. Comparison between MOS O_2-A band CTP and ATSR2 stereo CTH over the British Isles

In addition to the localised comparisons in section 4 we also performed a pixel-by-pixel comparison of MOS and ATSR2 CTH retrievals when scenes from the two instruments overlapped. To this end we re-projected MOS CTHs into the ATSR2 latitude-longitude grid and compared the retrieved CTHs pixel-by-pixel. This was also performed the other way round (i.e. ATSR2 projected into MOS grid) which indicated negligible differences caused by resampling. Examples of MOS and ATSR2 CTH retrievals for 1998-10-10 and 1998-10-29 are illustrated in Figures 4 and 5. As Figure 5 suggests, the MOS and ATSR2 mean CTHs were fairly consistent for these two scenes. However, for high clouds the ATSR2 11 μm channel CTHs were generally higher than the MOS CTHs, whereas for low clouds the ATSR2 11 μm channel CTHs were generally lower. For both scenes large CTH differences between the two approaches were noticeable. One potential cause of these differences was that the MOS CTH retrievals tended to be much smoother than the ATSR2 retrievals, as there are large variations in the stereo-derived CTHs with potentially significant contributions of noise (Figure 4).

Area-based comparisons for four different scenes occurring on 1998-09-02, 1998-09-12, 1998-10-10 and 1998-11-27 are illustrated in Figure 6, where we plot the relative frequency of occurrence of CTH in the scene that results from each retrieval. Again, in multiple layer cloud cases the MOS CTH retrieval either missed the highest CTH (1998-09-02 and 1998-09-12) or underestimated the CTH of clouds above 7 km (1998-10-10). On 1998-10-10 the lowest clouds were detected at a higher level by MOS CTH compared to the ATSR2 stereo CTHs. For the last scene (1998-11-27), which contained mainly low- or mid-level clouds, the agreement between all retrievals was high, except for the ATSR2 11 μm channel brightness temperature retrieval.

6. Discussion and conclusions

We compared stereo-derived cloud top heights from Along Track Scanning Radiometer 2 (ATSR2) 0.65 μm, 1.6 μm and 11 μm channel observations over the United Kingdom from September 1998 through March 1999 with cloud top heights derived from radar, radiosondes and the Modular Optoelectronic Scanner (MOS) instrument onboard the IRS-P3 satellite. The comparison between ATSR2 and ground-based CTH retrievals was complicated, as it involved comparing instantaneous, large spatial coverage satellite data with point measurements that covered long time periods. The main problem in our comparisons was the presence of broken clouds, which were not always detected by ground-based instruments, e.g., the Chilbolton 94-GHz radar, but were present within the ATSR2 stereo scenes.

Overall, the agreements between the ATSR2 and 94-GHz radar cloud top height retrievals were within the ±1 km theoretical limits expected of the ATSR2 0.65 μm and 1.6 μm channel retrievals in more than half of the cases that we examined. The differences were larger for the ATSR2 11 μm channel CTHs, although within 2 km. At high altitudes the ATSR2 stereo method gave consistently higher CTHs than radar, which was not surprising given that the radar sensitivity decreases as the inverse square of range, and that smaller particles in these high clouds can make their detection by radar problematic. At altitudes below about 6 km the 94-GHz radar CTHs were generally higher than those retrieved from the ATSR2 stereo method.

The comparisons with radiosonde profiles also presented problems, especially the spatial colocation of the radiosonde measurements relative to the ground- and satellite-based observations. Notwithstanding the drift of radiosondes outside of the latitude-longitude box centred on the station of interest, radiosondes travelling through clear areas between clouds in broken cloud situations, and general problems using radiosondes to identify cloud layers, more than half the case study periods showed similarities between the radiosonde and ATSR2 CTH retrievals. The differences in CTH for these cases were usually less than 2 km, which was not unexpected as ATSR2 stereo cloud top height retrieval accuracy can range from 1 km up to 4 km in the presence of strong winds (Seiz et al., this issue).

Overall, we found that the ATSR2 11 μm channel was much more efficient at detecting high clouds in multilayer cloud conditions. During these conditions, the ASTR2 0.65 μm channel CTHs tended to be assigned to the top of a lower layer and the ATSR2 1.6 μm channel CTHs tended to miss clouds altogether. These results suggested that through the use of a combined ATSR2 11 μm and 0.65 μm, or 1.6 μm, channel retrieval, multiple cloud layers could be detected when the upper cloud layer is thin.

We compared radar, ATSR2 stereo and MOS O_2-A band cloud top height retrievals for the one scene that was available over the duration of the campaign. We found that for low clouds the MOS CTHs were lower than the radar CTH and the ATSR2 1.6 μm and 0.65 μm channel CTH retrievals, but higher than the ATSR2 11 μm channel CTH retrievals. This result, combined with the comparison with ground-based retrievals, suggests that the ATSR2 11 μm channel may not be suitable for low cloud CTH assignments because of lack of contrast between the two ATSR2 views at this wavelength in the case of opaque clouds. Additionally, we identified the ATSR2 stereo matchers occasionally matching ground pixels, resulting in a reduction in ATSR2-derived mean CTH as one possible source of this bias.

A comparison between ATSR2, MOS and radiosonde CTH retrievals showed that, in the presence of multi-layered cloud systems containing high thin clouds, the MOS CTHs were not reliable, as the MOS retrieval was not sensitive to high thin clouds and underestimated the cloud top heights. This feature of the MOS retrieval was not unexpected, as information from a single O_2-A band absorption channel does not contain enough information for the discrimination of multi-layer clouds. Another comparison between ATSR2 and MOS CTH retrievals, which took into account the spatial distribution of the retrievals, revealed that the mean values produced by all three techniques, i.e., stereo, brightness temperature and oxygen absorption, agreed quite well, although the ATSR2 stereo CTHs showed a higher noise level with more variability.

This first attempt to estimate the accuracy of ATSR2 stereo heights showed that, overall, the retrieval scheme was performing adequately with some indication that high clouds were more likely to be detected with the ATSR2 11 μm channel than with the other two ATSR2 channels. The apparent enhanced sensitivity of the ATSR2 11 μm channel will be investigated further as a way to discriminate between low and high clouds in multi-layer cloud cases when used in conjunction with the other two ATSR2 channels that were used in this study.

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References

CHERNYKH I.V. and R. E. ESKRIDGE, 1996, Determination of cloud amount and level from radiosonde soundings. *J. Appl. Meteorol.*, **35**, 1362-1369.

CLOTHIAUX, E.E., G.G. MACE, T.P. ACKERMAN, T.J. KANE, J.D. SPINHIRNE and V.S. SCOTT, 1998, An automated algorithm for detection of hydrometeor returns in micro pulse lidar data. *J. Atmos. and Oceanic Technol.*, **15**, 1035-1042.

CLOTHIAUX E. E., T. P. ACKERMAN, G. C. MACE, K. P. MORAN, R. T. MARCHAND, M. A. MILLER and B. E. MARTNER, 2000, Objective determination of cloud heights and radar reflectivities using a combination of active remote sensors at the ARM CART sites. *J. Appl. Meteorol.*, **39**, 645-665.

DENIS M.-A., J.-P. MULLER, H. MANNSTEIN, Assessment of stereo camera models for ATSR2 cloud-top height extraction, this issue.

FISCHER J. and H. GRASSL, 1991, Detection of cloud top heights from backscattered radiances within the Oxygen A band. Part 1: theoretical study. *J. Appl. Meteorol.*, **30**, 1245-1259.

GIBSON J. K., P. KALLBERG, S. UPPALA, A. HERNANDEZ, A. NOMURA and E. SERRANO, 1999, ERA-15 description. *ECMWF Re-Analysis Project Report series V2*.

HARRIS A. R., 1993, Cover-cloud stereo from ATSR. *Int. J. Remote Sens*., **14**, 1835-1837.

HARTMANN D., OCKERT-BELL M. and M. L. MICHELSEN, 1992, The effect of cloud type on Earth's energy balance: global analysis. *J. Clim*., **5**, 1281-1304.

HOGAN R.J., C. JAKOB and A. J. Illingworth, 2001, Comparison of ECMWF winter-season cloud fraction with radar-derived values. *J. Appl. Meteorol.*, **40**, 513-525.

LORENZ D., 1985, On the feasibility of cloud spectroscopy and wind determination with the along-track scanning rasdiometer. *Int. J. Remote Sens*., **6**, 1445-1461.

MENZEL W.P., W.L. SMITH and T. R. STEWART, 1983, Improved cloud motion wind vector and altitude assignment using VAS. *J. Clim. Apl. Meteor*., **22**, 377-384.

MULLER J.-P., M.-A. DENIS, R. DUNDAS, K. MITCHELL, H. MANNSTEIN and C. NAUD, Stereo cloud-top height and amount retrieval from ATSR2, this issue.

NAUD C, J.-P. MULLER and E. E. CLOTHIAUX, 2003, Comparison between active sensor and radiosonde cloud boundaries over the ARM Southern Great Plains site. *J. Geophys. Res*., **108 (D4)**, AAC 3-1—AAC 3-12.

PRATA A. J. and P. J. TURNER, 1997, Cloud top height determination using ATSR data. *Rem. Sens. Env.*, **59**, 1-13.

PREUSKER R. and J. FISCHER, Cloud-top Pressure retrieval using the Oxygen A-band in the IRS-3 MOS Instrument, this issue.

RAMANATHAN V., R. D. CESS, E. F. HARRISSON, P. MINNIS, B. R. BARKSTROM, E. AHMAD and D. HARTMANN, 1989, Cloud-radiative forcing and climate: results from the earth radiation budget experiment. *Science*, **243**, 57-63.

SEIZ G., E. O. BALTSAVIAS and A. GRUEN, Correction of motion errors in ATSR2 stereo cloud top heights, this issue.

SZEJWACH G., 1982, Determination of semi-transparent cirrus cloud temperature from infrared radiances: application to METEOSAT. *J. Appl. Meteorol.*, **21**, 384-393.

WANG J. and W. B. ROSSOW, 1995, Determination of cloud vertical structure from upper-air observations. *J. Appl. Meteorol.*, **34**, 2243-2258.

WANG J., W. B. ROSSOW, T. UTTAL and M. ROZENDAAL, 1999, Variability of cloud vertical structure during ASTEX observed from a combination of rawinsonde, radar, ceilometer and satellite. *Month. Weath. Rev.,* **127**, 2484-2502.

ZIMMERMANN G. and A. NEUMANN, 1997, MOS- A space-borne imaging spectrometer for ocean remote sensing. *Backscatter*, **8**, 9-13.

Tables

	Date	Cloud condition	ATSR2-11μm median CTH (km)	ATSR2-1.6μm median CTH (km)	ATSR2-0.65μm median CTH (km)	MOS median CTH (km)	CRF radar median CTH (km)
3 ATSR2 channels and radar detect same layer	98-11-24	Thick single layer	9.8±0.0	9.8±1.8	9.8±0.0		8.3±0.1
	98-12-03	Single low cloud	2.2±0.0	2.2±8.4	2.2±0.0		1.2±0.1
	99-01-07	Thick single high cloud	8.9±0.7	8.9±0.4	9.6±0.7		7.7±0.2
2 ATSR2 channels agree with radar	98-11-11	Mid-level, scattered	10.3±0.2	6.2±1.6	6.2±2.0		6.3±0.3
	98-11-27	2 layers	2.8±0.4	4.9±0.2	4.9±0.0	4.5±0.2	5.3±0.1
	99-02-02	Scattered high	9.0±0.0	1.5±5.4	8.3±5.7		7.2±0.2
Max radar CTH agree with at least one ATSR2 channel	99-01-20	2 layers, scattered high	9.6±1.1	16.5±3.7	15.8±5.2		5.6±1.2
	99-01-23	Scattered high over low	10.6±0.0	11.3±2.2	10.6±3.9		1.0±3.0
ATSR2 CTHs > radar CTH	98-12-10	Low to mid level layer	4.1±0.4	4.1±0.0	4.1±3.9		1.3±0.0
ATSR2 CTHs < radar CTH	99-02-11	Multilayer	3.0±0.0	3.7±0.0	3.0±0.0		8.5±0.5
False positive	98-11-17	High cloud	8.7±0.3	11.1±0.4	8.7±0.4		0.0±0.0

Table 1: ATSR2 11 μm, 1.6 μm and 0.65 μm channel stereo, together with MOS and 94-GHz radar, median CTHs and standard deviations centred on Chilbolton. The ATSR2 and MOS CTHs were averaged over a ±0.02° latitude-longitude box around Chilbolton. The radar data have been processed using the algorithm from Clothiaux et al. (2000) and the radar-derived cloud top heights correspond to the median height detected over a time period equivalent to twice the time it takes from the forward ATSR2 view of Chilbolton to the nadir ATSR2 view of Chilbolton, centred on the nadir ATSR2 view start-time. The cloud conditions are derived from the radar profiles to decide if the situation is single or multiple layers, and from ATSR2 CTHs distributions within the latitude-longitude box to decide if the highest layer is scattered or overcast.

	Date	Cloud	11μm ATSR2	1.6μm	0.65μm	MOS	CE96-	CE96-	WR95

		condition	median CTH (km)	ATSR2 median CTH (km)	ATSR2 median CTH (km)	CTH median (km)	80% CTH (km)	60% CTH (km)	CTH (km)
False positive	98-09-08	Low, scattered	2.1±0.6	1.4±0.4	1.4±0.0		0.00	0.00	0.00
	99-01-01	High scattered clouds	11.4±0.3	12.1±5.5	11.4±0.4		0.0	0.4	0.5
	99-01-10	Clear, scattered clouds	0.7±0.0	0.7±0.0	11.0±3.6		0.0	0.0	0.0
	99-01-14	Clear, scattered clouds	0.7±0.0	1.4±3.4	4.1±0.0	1.8±0.6	0.0	0.0	0.0
All clear	99-01-17	Clear	0.7±0.0	0.7±0.0	0.0±0.0		0.0	0.0	0.0
Cloudy: All 3 ATSR2 channels agree with 1 RS	98-08-20	Multilayer, overcast	17.8±4.1	10.7±0.4	9.3±3.7		0.9	12.2	5.5
	99-01-07	Multilayer, overcast	11.4±0.0	11.4±0.0	11.4±0.0		8.4	8.6	8.7
	99-01-26	Single layer, overcast	7.6±0.0	7.6±0.0	7.6±0.0		7.2	7.4	7.2
	99-03-02	Single layer, overcast	12.5±0.6	9.0±0.7	10.4±0.0	4.9±0.2	11.9	12.0	12.3
	98-11-17	Multilayer, overcast	9.7±0.3	12.5±4.0	10.4±0.0		10.5	10.9	11.3
	99-02-27	Multilayer, overcast	5.2±0.2	3.7±0.0	3.7±0.0		4.0	5.1	4.9
At least one ATSR2 channel agrees with one RS	98-10-29	Multilayer, overcast	10.0±0.0	2.9±0.4	2.9±0.4		8.7	9.2	9.3
	98-12-29	Multilayer, scattered	13.7±0.0	6.2±0.0	9.6±0.3		6.1	6.5	6.0
	99-01-23	Multilayer, scattered	17.3±0.7	11.2±4.6	4.5±8.6	7.3±0.1	10.6	11.2	11.2
	99-02-11	Multilayer, scattered	13.6±3.4	0.7±0.0	4.3±0.3	3.9±0.0	3.4	12.3	11.8
	98-12-03	Multilayer, overcast	6.4±0.0	2.9±2.5	13.6±4.6		0.00	7.4	7.5
	99-02-08	Multilayer, scattered	4.9±3.4	12.9±3.4	12.9±4.1		9.5	10.6	10.6
	98-09-05	Multilayer, scattered	9.7±4.5	0.00±0.0	1.5±0.0		0.00	10.8	1.4
	98-12-10	Multilayer, scattered	13.1±3.0	9.7±4.3	5.5±4.0		0.1	6.2	3.3
All ATSR2 CTH < RS CTH	98-11-01	Multilayer, scattered	2.1±0.0	2.7±2.9	2.1±0.3		8.2	10.8	8.6
	98-10-13	Multilayer, scattered	4.2±0.3	3.5±0.2	3.5±4.4		1.2	6.00	5.8
ATSR2 CTHs lower than RS	98-12-22	Multilayer, overcast	6.9±0.4	0.7±2.2	6.9±3.4		0.2	11.4	10.7

Table 2: ATSR2 11 μm, 1.6 μm and 0.65 μm channel stereo, together with MOS, CE96-80%, CE96-60% and WR95, median CTHs and standard deviations over Aberporth and Hemsby. The

ATSR2 and MOS CTHs are selected within ±0.02° latitude-longitude centred on the radiosonde stations. The cloud conditions are derived from the RS cloud boundary retrieval to decide if the situation is single or multiple layers, and from ATSR2 CTHs distributions within the latitude-longitude box to decide if the highest layer is scattered or overcast.

	Date	Cloud condition	MOS median CTH (km)	CE96-80% CTH (km)	CE96-60% CTH (km)	WR95 CTH (km)
False positive	99-01-14	Clear, scattered single clouds	1.8±0.6	0.0	0.0	0.0
MOS CTH>RS CTH	98-12-26	Single overcast mid-level layer	6.3±0.1	2.5	3.8	4.6
MOS CTH < RS CTH but same layer	98-12-25	Multilayer overcast highest layer	7.7±0.1	9.2	10.4	10.5
	99-03-02	Single overcast layer	4.9±0.2	11.9	12.0	12.3
	99-01-23	Multilayer overcast highest layer	7.3±0.1	10.6	11.2	11.2
MOS CTH < RS CTH but layer below highest	99-02-11	Multilayer, scattered	3.9±0.0	3.4	12.3	11.8
MOS CTH between 2 RS layers	99-03-12	Multilayer	2.5±0.2	10.6	11.8	10.5
	99-03-31	Multilayer	4.0±1.6	1.1	11.6	11.7

Table 3: MOS O_2-A band, RS CE96-80%, CE96-60% and WR95 median CTHs and standard deviations over Aberporth and Hemsby. The MOS CTHs were selected within a ±0.02° latitude-longitude bon centred on the radiosonde stations. The cloud conditions are derived from the RS cloud boundary retrieval to decide if the situation is single or multiple layers, and from MOS CTHs distributions within the latitude-longitude box to decide if the highest layer is scattered or overcast. When MOS does not detect a high cloud layer in multilayer conditions, either ATSR2 CTH distributions are used if available or the case is undecided.

Figures:

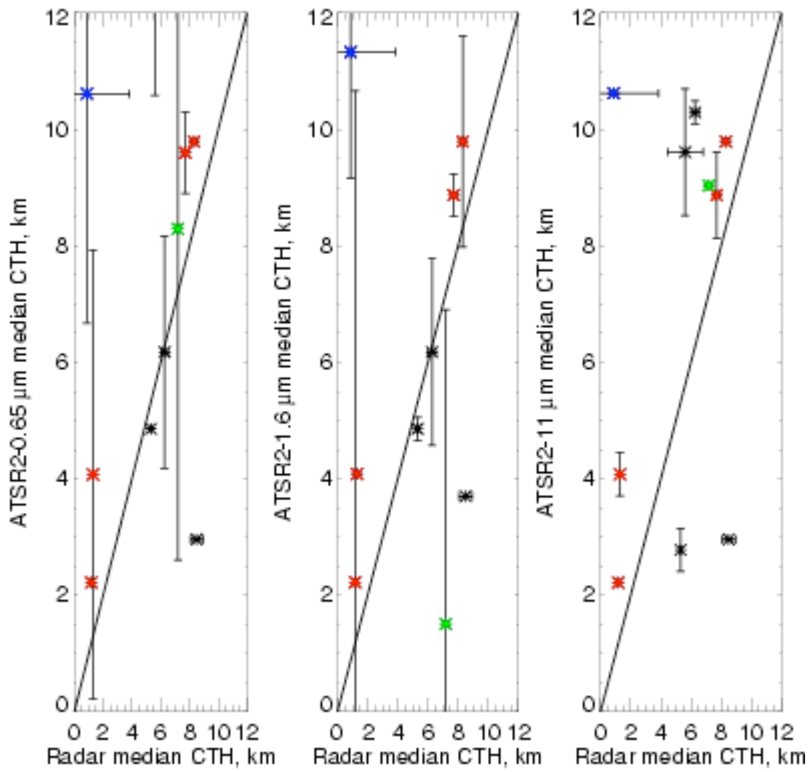


Figure 1: Comparison between ATSR2 stereo and radar median CTHs over Chilbolton. The vertical lines correspond to ± one standard deviation calculated for the ATSR2 latitude-longitude box centred at Chilbolton and provide information on how much ATSR2 CTH varied in the vicinity of the radar and how broken the highest clouds were. Black shows multilayer with highest layer scattered, red shows single overcast clouds, blue shows multilayer with highest layer overcast and green shows single scattered clouds.

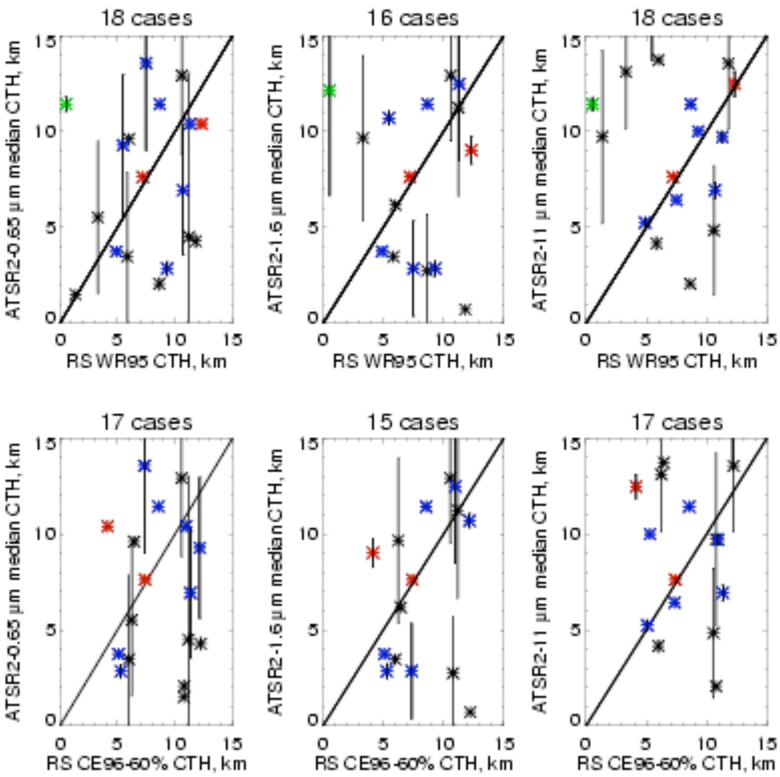


Figure 2: Comparison between the ATSR2 0.65 μm, 1.6 μm and 11 μm channel stereo CTHs and WR95 CTHs (top panel) and CE96-60% CTHs (lower panel) for Hemsby and Aberporth. The vertical lines correspond to ± one standard deviation calculated for the latitude-longitude box centred on the radiosonde stations and provide information on how much ATSR2 CTH varied in the vicinity of each site and how broken the highest clouds were. Black shows multilayer with highest layer scattered, red shows single overcast clouds, blue shows multilayer with highest layer overcast and green shows single scattered clouds.

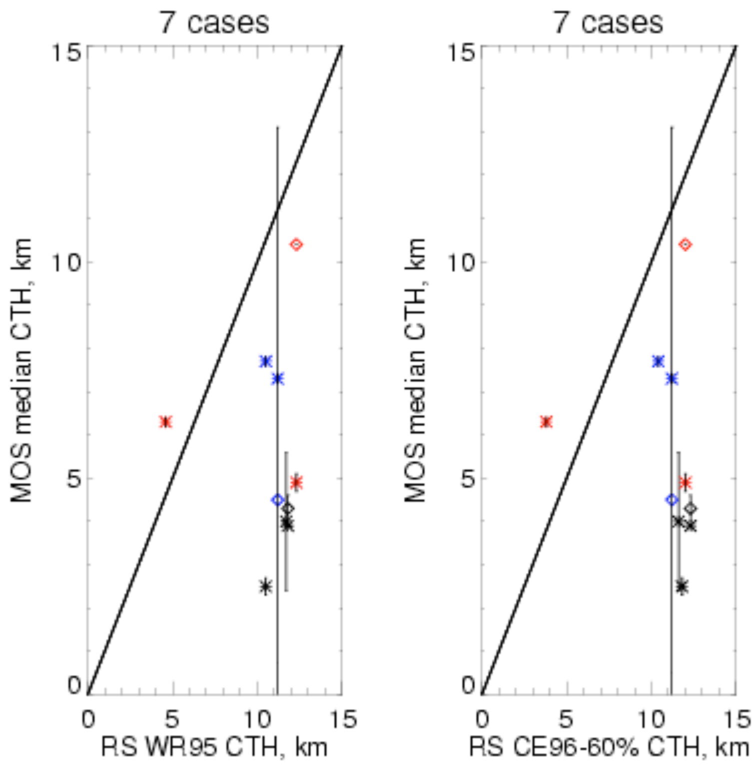
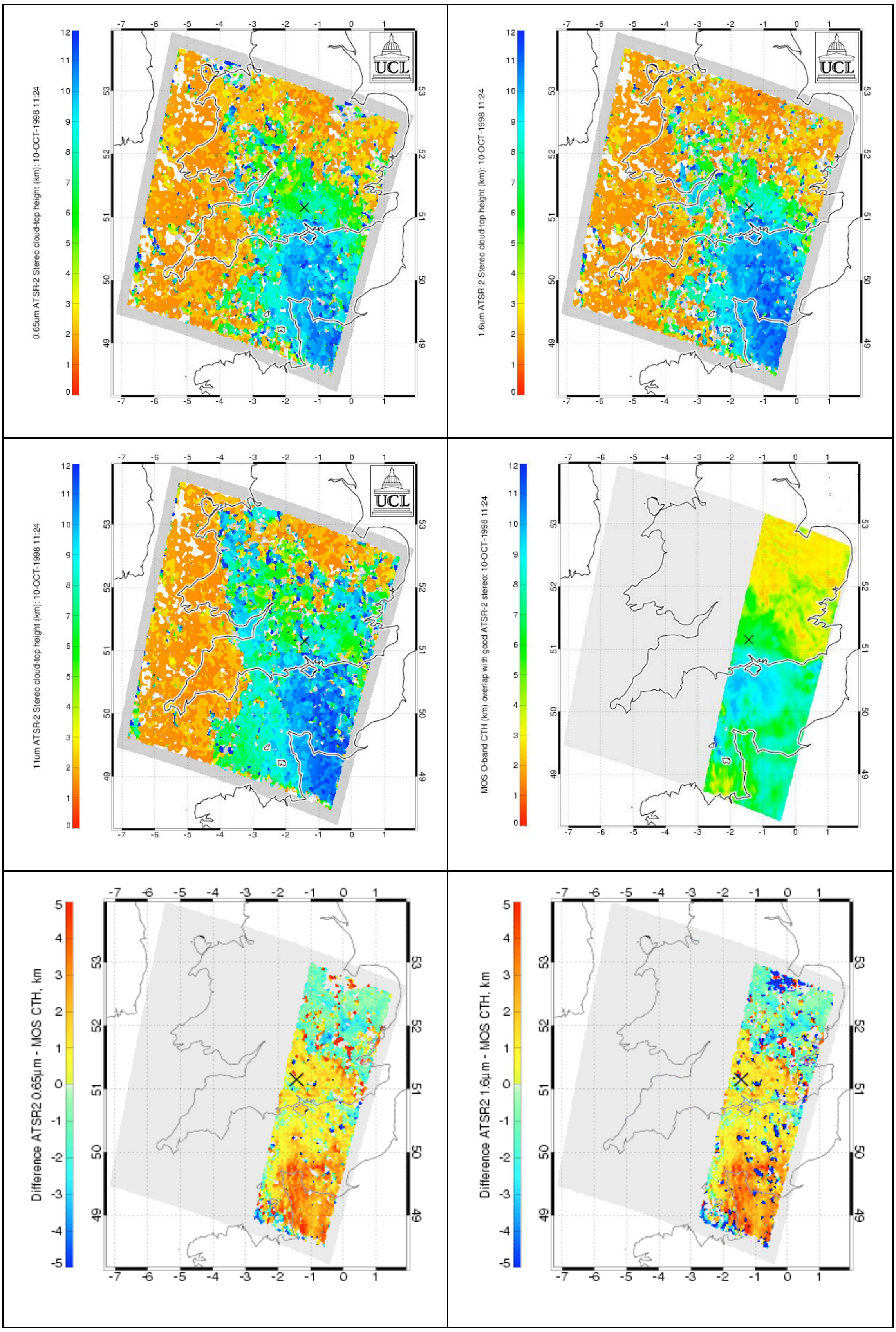


Figure 3: Comparison between MOS O_2-A band, WR95 and CE96-60% median CTHs over Aberporth and Hemsby (*). When ATSR2 CTHs are available (3 dates), the ATSR2 0.65 μm channel CTHs are plotted against corresponding CE96-60% and WR95 CTHs (diamonds). Black shows high thin or scattered clouds over lower level clouds, blue refers to multilayer with highest levels overcast, red refers to single level overcast clouds.



0.65um ATSR-2 Stereo cloud-top height (km): 10-OCT-1998 11:24
UCL
1.6um ATSR-2 Stereo cloud-top height (km): 10-OCT-1998 11:24
UCL
11um ATSR-2 Stereo cloud-top height (km): 10-OCT-1998 11:24
UCL
MOS O-band CTH (km) overlap with good ATSR-2 stereo: 10-OCT-1998 11:24
Difference ATSR2 0.65µm - MOS CTH, km
Difference ATSR2 1.6µm - MOS CTH, km

Figure 4: ATSR2 0.65 μm channel (top left), ATSR2 1.6 μm channel (top right) and ATSR2 11 μm channel (center left) stereo and MOS O_2-A band (center right) CTHs for 1998-10-10. Difference between ATSR2 and MOS CTHs for ATSR2 0.65μm (lower left) and 1.6μm (lower right) channels.

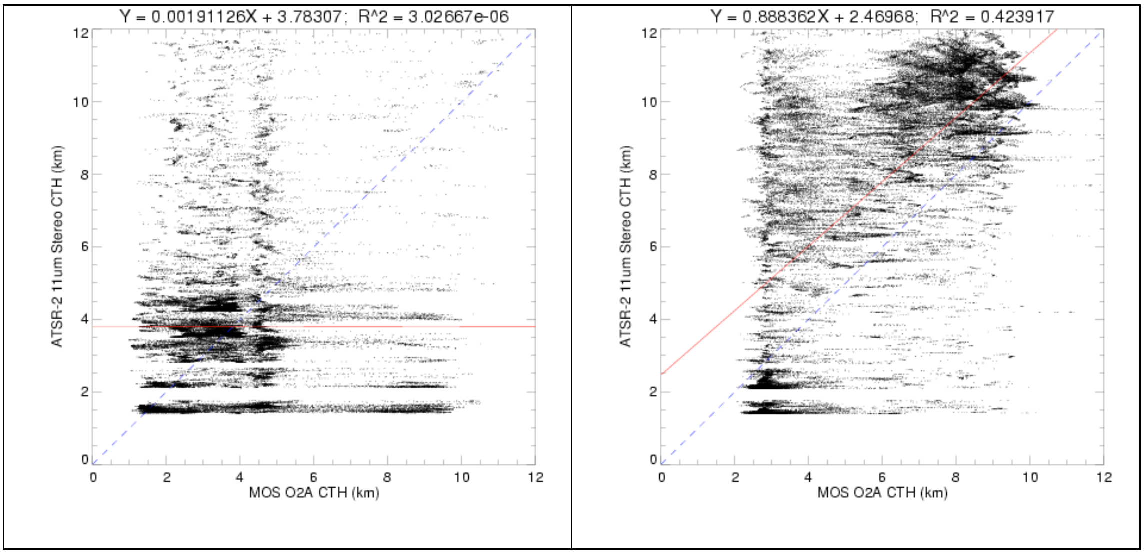
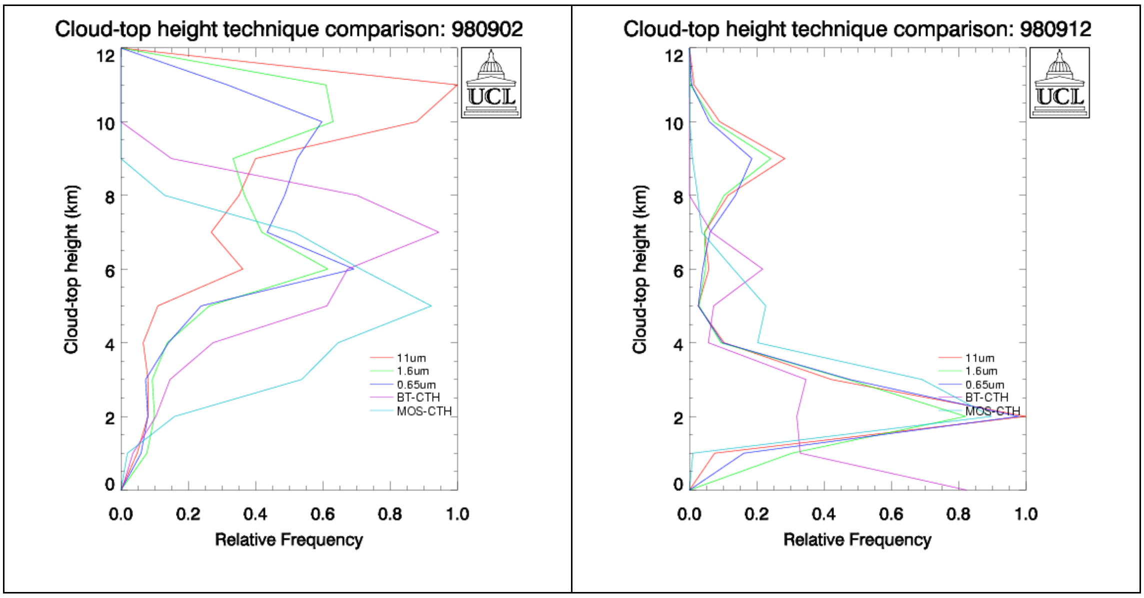


Figure 5: Pixel-by-pixel comparison of ATSR2 11 μm channel stereo and MOS O_2-A band CTHs. *Left image:* 1998-10-29, mainly low clouds. *Right image:* 1998-10-10, high clouds.



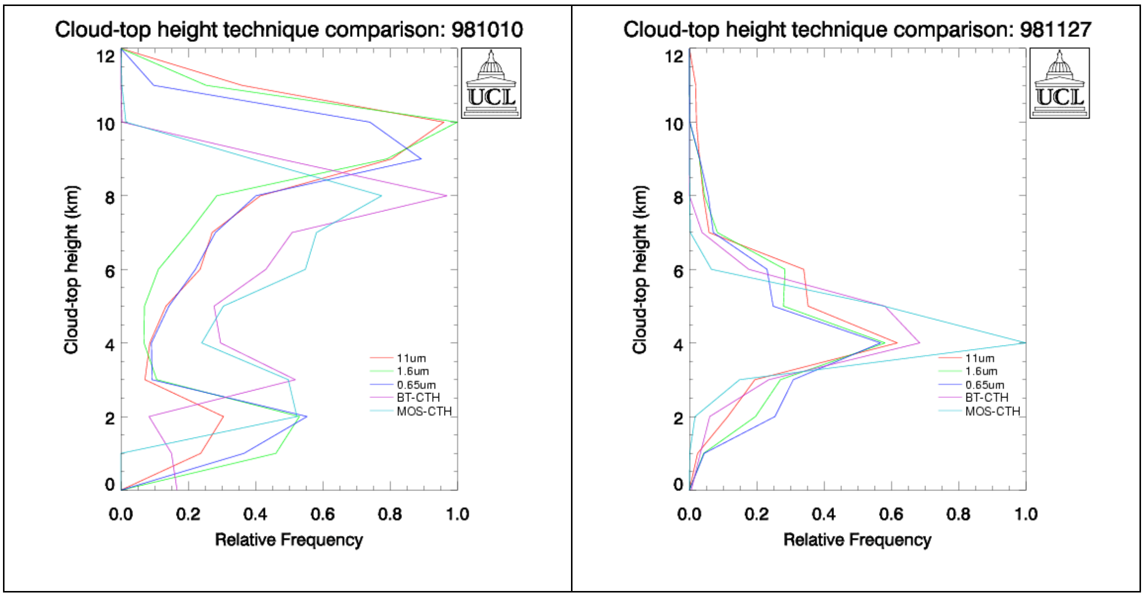


Figure 6: Area-based comparison of CTHs using several different techniques for four dates: ATSR2 stereo CTH for three channels, MOS O_2-A band CTH and CTH obtained from ATSR2 nadir 11μm brightness temperatures transformed into heights using ECMWF profiles (BT-CTH). (a) *Top left*, 1998-09-02, illustrating poor agreement between all techniques, including ATSR2 stereo retrievals at different wavelengths. (b) *Top right*, 1998-09-12, illustrating good agreement between MOS O_2-A band CTH and ATSR2 stereo techniques. (c) *Bottom left*, 1998-10-10, illustrating good agreement between ATSR2 BT-CTH and MOS O_2-A band CTH. (d) *Bottom right*, 1998-11-27, illustrating good agreement between all techniques.