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Determination of cloud top heights using weather radar and satellite data

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Abstract. Accurate cloud top temperature and height information is very important, for example, in aviation forecasting. For this reason, the EUMETSAT SAFNWC framework has developed a product called Cloud Top Height and Temperature (CTTH), which aims providing estimates of these quantities for all cloudy pixels within an AVHRR satellite scene.

A new approach for the validation of the cloud top height of the CTTH product is presented. The method uses three-dimensional C-band weather radar data provided by the Finnish Meteorological Institute (FMI). The extraction of the cloud top height from the radar data is done by using the TOPS product.

The time period selected for the study was April and May 2003. The emphasis was on opaque and semi-transparent high clouds. Radar reflectivities of $-5\,\mathrm{dBZ}_e$ and $-10\,\mathrm{dBZ}_e$ were considered to represent the true tops of ice clouds. Good agreement between the CTTH and TOPS products were found in the case of opaque high clouds when the $-10\,\mathrm{dBZ}_e$ threshold value was applied. Essentially all the comparisons made in the semi-transparent high cloud category were unsuccessful. In these cases the $-10\,\mathrm{dBZ}_e$ threshold value proved to be too high, suggesting that lower values should have been applied.

1 Introduction

Weather radars are routinely used to extract precipitation information. However, the present-day weather radars are rather sensitive systems—a modern C-band weather radar has a detection threshold of −45 dBZ at a range of 1 km. It can thus be employed for cloud detection at short distances from the radar site. The operational weather radar network in the Nordic countries is rather comprehensive with good spatial and temporal resolution. Such a cloud top height data is extremely valuable for validating the CTTH product.

For optically thick clouds at high latitudes a weather satellite measurement provides a reasonable estimate for the cloud top temperature. The atmospheric absorption above the cloud may be neglected and the brightness temperature of a window channel may be taken for the thermodynamic cloud top temperature. However, in case of semi-transparent cloudiness the direct use of the measured brightness temperature will often lead to a significant overestimation of the true cloud top temperature and hence underestimation of the cloud top height. The CTTH product was developed with the objectives to compensate both for the semi-transparency effect and the small atmospheric radiation absorption above the cloud.

The validation of the CTTH product using weather radar data is recognized as being highly ambitious. Both methods are based on a number of assumptions, and several different error sources may be assigned to them. Nevertheless, an objective comparison between the two independent methods is possible to perform.

2 Cloud top height retrievals

In the determination of the cloud top height both with weather radar or satellite, the same difficulties are encountered concerning high thin clouds. Optically thin clouds are difficult to detect as the received signal may barely exceed the detection threshold of an instrument.

2.1 Radar echoes from clouds

The echoes from non-precipitating ice clouds are often more intense compared to non-precipitating water clouds (Poutiainen, 1999). This can be explained by the particle size distribution—the radar reflectivity factor is proportional to the sixth power of the particle diameters in a pulse volume. This means that the presence of just a few large particles increases the returned power significantly. Sizes of ice crystals

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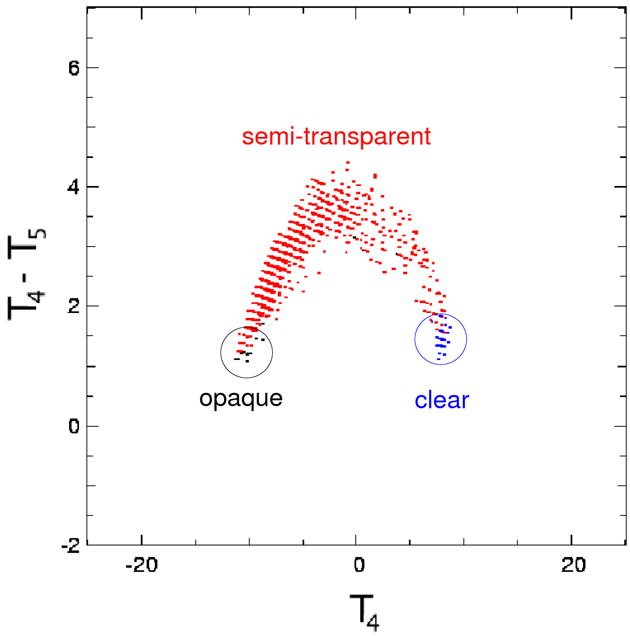

Fig. 1. Example distribution of pixels from a 32×32 sized image segment from an AVHRR scene. The units for the axes are C.

in various cirrus clouds can range up to the order of millimetres. A typical mode radius for various water clouds is 3.5–5.0 μm (Liou, 1990).

The advantage of a radar measurement, compared to a satellite, is that it is in a way a "direct" measurement. It provides the height of an echo in proportion to the radar site. The problem with weather radar is to determine a proper threshold value for an echo to be considered as the "cloud top". At the FMI the relation between radar reflectivities and cloud top heights has been studied using simultaneous flight observations and radar measurements. According to the results, the top height of a cloud consisting of significant amounts of ice particles corresponds to a radar reflectivity of $-10\,\mathrm{dBZ}_e$. In this study radar reflectivities of $-5\,\mathrm{dBZ}_e$ and $-10\,\mathrm{dBZ}_e$ are considered to represent the true top of high ice clouds.

The extraction of the cloud top height from the radar data is done by using the TOPS product, available in the IRIS software package. For each measurement bin, the TOPS algorithm gives the height of the highest occurrence of a user-defined threshold value of dBZ_e. With the given threshold value the algorithm makes a downward search in cylindrical coordinates at constant range until the threshold value is exceeded. After this it interpolates in height, if possible, to find the actual height of occurrence of the threshold value (SIGMET Inc., 2003). The vertical resolution of the product is 100 m. This resolution is achieved by the interpolation, not by the radar measurement itself. The vertical resolution in a radar measurement decreases with the increasing distance as the gap between the adjacent elevation angles grows.

2.2 Cloud Top Temperature and Height product

The CTTH retrieval consists of two algorithms, one for opaque and one for semi-transparent clouds. The selection of the CTTH retrieval method to be invoked for a certain image segment is based on the SAFNWC Cloud Type (CT) product classification. The vertical resolution of the CTTH product is 200 m.

For each opaque pixel the measured AVHRR channel 4 (10.8 μm) brightness temperature (T_4) is compared against a vertical T_4 profile simulated by a radiative transfer model (RTM), after which pressure level with the best fit is selected. The the corresponding cloud top height and the thermodynamic cloud top temperature are taken from a numerical weather prediction (NWP) model.

The method used in the semi-transparent/sub-pixel retrieval is based on the work of Inoue (1985) and Derrien et al. (1988), and it uses AVHRR channel 4 (10.8 μm) and 5 (12.0 μm) brightness temperatures (T_4 and T_5). The implementation for the CTTH product was done by Korpela et al. (2001).

The observed arc-like structure in a two-dimensional $T_4 - T_5$ versus T_4 histogram, shown in Fig. 1, can be described mathematically when making a few simple assumptions:

1. Single cloud layer
2. Constant absorption coefficient throughout the cloud layer
3. Brightness temperature depends linearly on radiance
4. No atmospheric absorption
5. Local thermodynamic equilibrium

With these assumptions the thermodynamical cloud top temperature of a semi-transparent cloud can be resolved, after which the top height corresponding to the retrieved temperature is taken from the NWP. The resulting cloud top height is then applied to all pixels classified as semi-transparent within the chosen 32×32 sized image segment.

3 Data

The time period selected for the study was April and May 2003. In total, 301 overpasses were locally received at Norrkping from the NOAA-16 and NOAA-17 operational polar orbiting satellites during the selected time period.

The radar data for the study are provided by the FMI. The temporal resolution on the data is 15 minutes. The use of the Finnish radar network is essential, because it offers better sensitivity compared to the SMHI radars.

The minimum ranges for detecting a cloud top height of 10 km and the maximum ranges for detecting the threshold values of $-10\,\mathrm{dBZ}_e$ and $-5\,\mathrm{dBZ}_e$ are presented in Table 1. Due to these ranges each radar has certain coverage areas

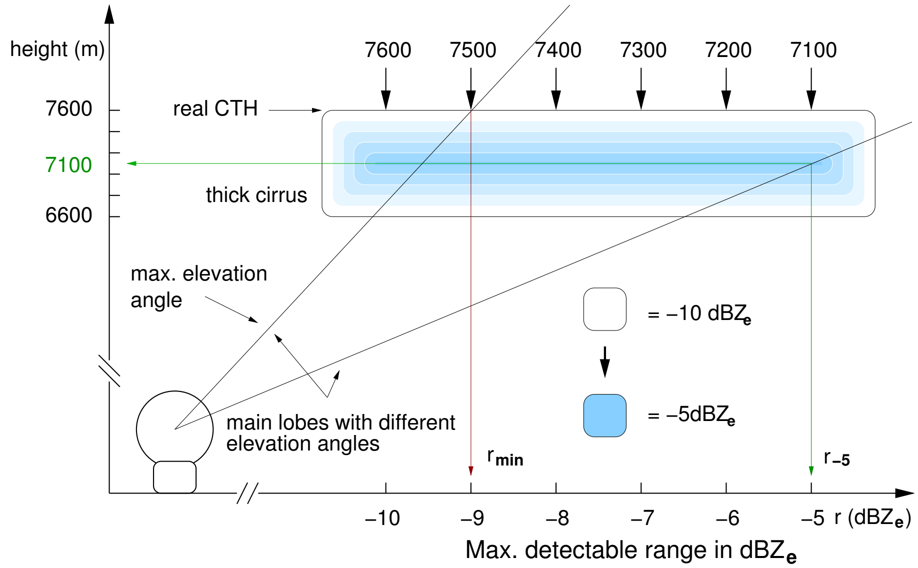

Fig. 2. An illustration of a situation in which the $-10\,\mathrm{dBZ}_e$ threshold value is applied in areas beyond the range of r_{-10}. As a result, the cloud top appears to become lower (r_{-5}=7100 m.) The horizontal axis is the maximum detectable range for different threshold values in dBZ_e, while the vertical axis is the height in metres.

suitable for collecting cases. Both areas form a doughnut around the radar.

As mentioned, the threshold value used in the TOPS product is selectable by the user. If the $-10\,\mathrm{dBZ}_e$ threshold value is applied for areas beyond the range of r_{-10}, the cloud top will most likely be underestimated, and the magnitude of the underestimation is increasing with the distance. This feature is illustrated in Fig. 2.

The short-range NWP forecast results used in the derivation of the CTTH product were taken from High Resolution Limited Area Model (HIRLAM). The NWP fields used were always the closest ones in time to the satellite overpass. The RTM used was the Radiative Transfer Model for TOVS (RTTOV).

4 Intercomparison

The cases for the study were selected by using the AVHRR channel combination images together with the Cloud Type and CTTH product outputs. Naturally, all the cases had to lie within r_{-5} or r_{-10} radar coverage areas. Due to this, the cases are divided into two sub-categories, i.e. $-10\,\mathrm{dBZ}_e$ and –5 dBZ_e cases. A case in this study is a 32×32 pixel sized image segment from an AVHRR scene (see Fig. 1). Table 1 implies that only the Radar Utajrvi is providing sufficient coverage for collecting the –10 dBZ_e cases, i.e. $r_{-10}-r_{min}>32$ km. Radar Utajrvi uses 45 degree maximum elevation angle, other radars use 20 degrees.

The data sets are averaged in a way that the results are classified into histograms with 200 m class intervals, which evens out the resolution difference between the two products. The modes of the resulting cloud top distributions are taken

Table 1. The minimum ranges, r_{min}, for detecting a cloud top height of 10 km and the maximum ranges, r_{-10} and r_{-5}, for detecting radar reflectivity values of –10 dBZ_e and –5 dBZ_e for the FMI radars.

Radar site	r_{min} (km)	r_{-10} (km)	r_{-5} (km)
Anjalankoski	28	29	52
Ikaalinen	28	42	74
Kuopio	28	38	68
Luosto	28	28	50
Utajrvi	10	56	99
Vantaa	28	29	52

as the results of the products. The comparison is then simply made by examing the difference between the TOPS and CTTH results. The general performance of a cloud category is retrieved by classifying the individual mode differences into a histogram with 500 m class intervals and examing the dispersion and the central tendency of the resulting distribution.

The closest 15-minute radar data set used in the comparison is selected in a way that the radar measurement is always done before, or at the best at the same time as the satellite is scanning the area of interest.

5 Results and discussion

As stated at the beginning, neither the satellite nor the radar provides ground truth concerning the true cloud top height. Despite of this, the CTTH opaque retrieval can be expected to

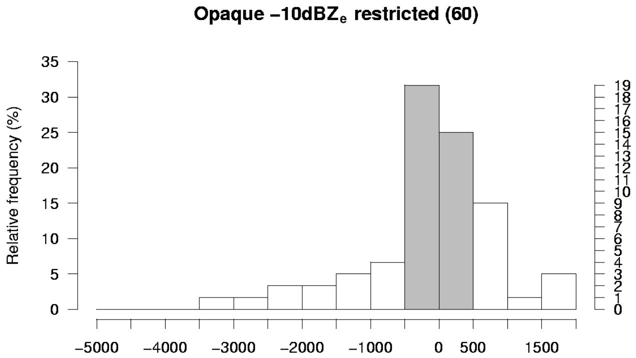

Fig. 3. The opaque high cloud category TOPS–CTTH mode difference distribution. All the cases were applied with the $-10\,\mathrm{dBZ}_e$ threshold value. The horizontal axis is the mode difference in metres. The vertical axis on the right-hand side is the count frequency. Cases where the mode difference was +2000 m or more are included in the last class.

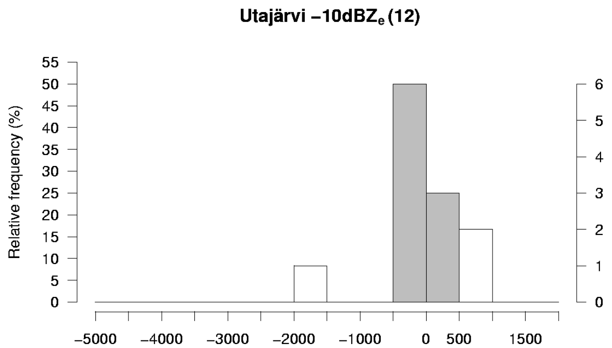

Fig. 4. TOPS–CTTH distribution of the opaque high cloud cover cases collected from the Radar Utajrvi $-10\,\mathrm{dBZ}_e$ coverage area. The TOPS product was applied with the $-10\,\mathrm{dBZ}_e$ threshold value. See Fig. 3 for details.

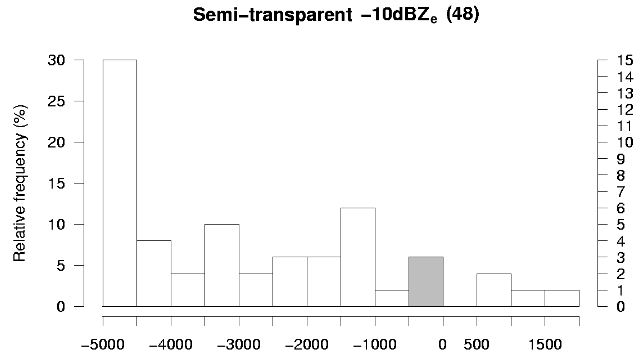

Fig. 5. TOPS–CTTH distribution of the semi-transparent high cloud category. See Fig. 3 for details. Cases where the mode difference was –4500 m or more are included in the last class.

be relatively good, since it uses window channel brightness temperatures. Good results, obtained by using a similar window channel technique on opaque clouds, has been reported in Lin and Minnis (2003).

5.1 Opaque high clouds

Figure 3 presents the result of the opaque high cloud category. In order to neglect the effect of possible low echoes, all the cloud top heights below 2000 m in the TOPS product were discarded. After this, only those cases in which the TOPS product had a result for more than 30% of the pixels within the image segment were accepted to the comparison. The number of successful cases is 34 (57%), which suggests that the $-10\,\mathrm{dBZ}_e$ is a good first guess for the cloud top height of thick ice clouds. Successful comparison is assumed if the mode difference is ± 500 m.

The $-5\,\mathrm{dBZ}_e$ cases were dominant in this category. For this reason it is possible that the TOPS product yielded too low cloud top heights. Figure 4 presents the result of a new comparison. This time only the high opaque cloud cases within a range of r_{-10} from the Radar Utajrvi were selected. No further restrictions were made. The TOPS product was applied with the $-10\,\mathrm{dBZ}_e$ threshold value. It can be seen that 9 out of 12 comparisons are successful (75%), which supports the conclusion made from the previous result – the $-10\,\mathrm{dBZ}_e$ appears to indicate the top height of a thick ice cloud in a radar measurement. All the conclusions are made under the assumption that the satellite retrieval is accurate.

5.2 Semi-transparent high clouds

Figure 5 presents the result of the semi-transparent high cloud category. The $-10\,\mathrm{dBZ}_e$ threshold value is applied to all the cases, since the previous results have already shown that it is more appropriate for ice clouds. No further restrictions are made. It can be seen that essentially all the comparisons are unsuccessful. A closer look to the individual cases suggested that even the $-10\,\mathrm{dBZ}_e$ threshold value was too high for this category. Echoes from thin cirrus clouds may be as weak as $-15\,\mathrm{dBZ}_e$ or $-20\,\mathrm{dBZ}_e$ (Poutiainen, 1999), which suggests that more sensitive threshold value should have been applied. This, however, was not possible, since the FMI radar network cannot provide sufficient radar coverage for more sensitive threshold values with the present values of maximum elevation. Another reason for the unsuccessful comparisons could be the histogram method used in the CTTH semi-transparent retrieval. It is not perfect, and large errors may be encountered.

6 Summary and conclusions

In this study a new approach for validation of the EUMETSAT SAFNWC Cloud Top Temperature and Height (CTTH) product has been introduced. The approach presented here used three-dimensional weather radar data provided by the FMI. The cloud top height extraction from the radar data was done using the TOPS product from the IRIS software package. Threshold values of $-10\,\mathrm{dBZ}_e$ and $-5\,\mathrm{dBZ}_e$ were selected to represent the true cloud top in the TOPS product. In general, a robust and automated validation of the CTTH product with weather radars proved to be too ambitious an objective. This was already acknowledged at the beginning of the study.

The cases collected from the Radar Utajrvi within the range of r_{-10} proved that the $-10\,\mathrm{dBZ}_e$ threshold value is a good first guess for the top heights of thick ice clouds – 75% of the comparisons were successful. This suggests that radars can offer valuable information concerning the cloud top height of thick ice clouds when operating within the r_{-10} coverage area.

The result of the semi-transparent high cloud category was disappointing, having only three successful comparisons out of 48 cases. The $-10\,\mathrm{dBZ}_e$ threshold value turned out to be too high for thin cirrus. For this reason, the CTTH semi-transparent retrieval could not be properly validated. Another possible reason for the unsuccessful comparisons was that the CTTH semi-transparent retrieval method contains numerous error sources and large errors can be encountered.

The lack of a 45-degree elevation angle in the most of the radar measurements limited the selection of proper $-10\,\mathrm{dBZ}_e$ cases to only one radar. This highlights the importance of high elevation angles in present-day radar measurements. The higher the elevation angle the more sensitive threshold values could be applied in the TOPS product. If so, more accurate information concerning the true cloud top height could be retrieved, particularly that relating to high clouds.

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