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An enhanced algorithm for the retrieval of liquid water cloud properties from simultaneous radar and lidar measurements. Part II: Validation using ground based radar, lidar, and microwave radiometer data

O. A. Krasnov and H. W. J. Russchenberg

International Research Centre for Telecommunications-transmission and Radar, Faculty of Information Technology and Systems, Delft University of Technology Mekelweg 4, 2628 CD Delft, The Netherlands

Abstract. The possibilities to use the ratio between simultaneously measured radar reflectivity and optical extinction profiles for the detection of drizzle fraction in water clouds and the estimation of its influence on remote sensing measurements are studied. This parameter is used for the classification of clouds type into three classes – "the cloud without drizzle fraction", "the cloud with light drizzle", and "the clouds with heavy drizzle". The subsequent application for every resulting type of the cloud the specific Z-LWC relationship allows to minimize the influence of the drizzle fraction in clouds on the results of the LWC retrieval. Such enhanced algorithm has been applied for real radar and lidar data and the retrieval results were then validated using liquid water path that was measured simultaneously with microwave radiometer.

1 Introduction

In this paper we present some results of the application an enhanced algorithm for the retrieval of liquid water cloud properties to data that were simultaneously measured with ground based radar and lidar. This algorithm was derived from the study the particle size spectra that were measured with aircraft-mounted in-situ probes during a few field campaigns, in the different geographical regions, and inside the different types of water clouds (Krasnov and Russchenberg, 2002). It uses the possibilities to detect and characterize the drizzle fraction in water clouds using the ratio between simultaneously measured radar reflectivity and optical extinction profiles. The features of this ratio allow to use it values for the classification of the cloud's type into three classes – "the cloud without drizzle fraction", "the cloud with light drizzle", and "the clouds with heavy drizzle". The subsequent application for every resulting type of the cloud's cells the specific Z-LWC relationship allows to retrieve the LWC of water clouds.

Correspondence to: O. A. Krasnov
(o.krasnov@irctr.tudelft.nl)

In this study we have applied this enhanced algorithm for real remote sensing data that were measured during the BBC campaign. We have used the radar and lidar data for the retrieval of the liquid water content in the water cloud, and the radiometer data about liquid water path (LWP) for the validation of the retrieval results.

2 Datasets and processing details

2.1 Observational data used

For this study we have used the simultaneous and collocated radar, lidar and microwave radiometer data that were measured during the cloud observation Baltex Bridge Cloud (BBC) campaign that took place in August and September 2001 in the Netherlands in the framework of CLIWA-NET and the 4D-WOLKEN projects. Most of the ground-based observations were taken at the central site of Cabauw, and include radars, lidars, microwave radiometers, radiation measurements and meteorological observations (such as temperature, wind, etc.). During the campaign, 3 aircraft took measurements over the area. The preliminary results of the BBC campaign are available through the site http://www.knmi.nl/samenw/cliwa-net/index.html. Below we give the brief description of the used data.

Radar For this study we have used the radar reflectivity profiles that were measured with the vertically pointed GKSS 95 GHz polarimetric cloud Doppler radar MIRACLE (Danne et al., 1999). The available calibrated data have range resolution 82.5 m and 5 s averaging time. The data were filtered with cloud mask using threshold value – 54.0 dBZ.

Lidar The 905 nm Vaisala CT75K vertically pointed ceilometer (KNMI) measured the profiles of backscatter coefficients with range resolution 30 m and 30 s averaging time. For the reduction of the noise level and increasing the stability of the inversion algorithm for optical extinction estimation we have filtered the daily data with 3×3 median filter.

Microwave radiometer The multichannel passive microwave radiometer MICCY (MIcrowave Radiometer for Cloud CarthographY) (the Meteorological Institute at the

University of Bonn) (Crewell et al., 1999) during BBC campaign produced the retrieved LWP with 1-second sampling ratio. The upper limit of the trusted retrieved LWP was 500 g/m^2 and in this interval the algorithm evaluation gives the bias of estimated LWP between -2.8 and 1.5 g/m^2 and RMS 14.0–15.7 g/m^2.

The available data for every instrument have their own range and time sample ratios, and the procedure for their unification in the framework of some reference grid has to be used. The lidar's range-time grid for this study was selected as such reference grid for other instruments. The radar profiles were interpolated into lidar range grid using the nearest neighbors method and then were averaged inside lidar's time cells. The similar time-averaging procedure inside lidar's time cells was used for radiometer's liquid water path.

2.2 Estimation of the lidar extinction profile

In this study for the lidar extinction profiles estimation we have used Klett (1981) inversion algorithm that involves only one boundary value for the solution of the lidar equation: the absolute extinction on some reference level, which have to be as far from the lidar as possible. This method requires assuming power-law relationship between range dependent lidar backscattering coefficient $\beta(h)$ and optical extinction $\alpha(h)$ of the form $\beta(h) = k_1 \cdot \alpha(h)^{k_2}$. For water clouds that are optically thick the k_2 coefficient is considered to be unity in almost all studies (Rocadenbosch and Comeron, 1999; Rogers et al., 1997). For the reduction of the noise influence on stability of the inversion algorithm in this study we have used clipping procedure for zeroing nearest to lidar range cells and all range cells in profile that are less then some threshold value. This threshold noise level has been calculated for every profile. After such clipping as reference level for each profile was use farthest non-zero range bin.

2.3 Lidar determination of cloud-base height

In this study for differentiation of cloud and precipitation regions on radar and lidar profiles was used cloud base height. This parameter has been estimated from lidar data as described in Pal et al. (1992). This algorithm is based on the general observation that the backscatter lidar signal increases very rapidly as soon as the cloud penetrated and it therefore defines the cloud base as the point where the gradient of the lidar signal exceed some threshold value. An advantage of method is that no information is needed about the absolute scaling of the lidar signals and that the sensitivity of the method is self-adaptive to noise.

2.4 The LWC retrieval procedure

Follow Krasnov and Russchenberg (2002), for the retrieval algorithm we have used the value of the radar reflectivity to lidar extinction ratio for the classification of the every cloud range cell on vertical profile into three classes:

(a) "the cloud without drizzle fraction" $\log_{10}(Z/\alpha) < -1$,
(b) "the cloud with light drizzle" $\log_{10}(Z/\alpha) < 1.8$,
(c) "the cloud with heavy drizzle" $\log_{10}(Z/\alpha) > 1.8$,

where Z is in [mm^6/m^3], and α – in [1/m]. These classes reflect the statistical features of the drop size distribution in given range cell and their names, proposed for cloud in-situ data interpretation, have to be used carefully for profile regions below cloud base.

For every resulting class the different Z-LWC relationship were applied:

- For the (a) class "the cloud without drizzle fraction" can be used such relations from Fox and Illingworth (1997)

  $$Z = 0.012 \cdot LWC^{1.16} \tag{1}$$

  or from Sauvageot and Omar (1987)

  $$Z = 0.03 \cdot LWC^{1.31} \tag{2}$$

  or from Atlas (1954)

  $$Z = 0.048 \cdot LWC^{2.0} \tag{3}$$

- For the (b) class "the cloud with light drizzle" we have used relationship from Baedi et al. (2000)

  $$Z = 57.54 \cdot LWC^{5.17} \tag{4}$$

- And for (c) class "the cloud with heavy drizzle" the best fit of all data for the CAMEX-3 campaign and the CLARE'98's data for the drizzle clouds was used:

  $$Z = 323.59 \cdot LWC^{1.58} \tag{5}$$

The big values of the optical extinction in water clouds cause the situations when ground-base lidar backscattering profile (and derived optical extinction) does not cover whole region where cloud radar reflectivity is presented. As result for such upper regions in cloud the radar reflectivity to optical extinction ratio is unknown and described above classification algorithm could not be used. For such cloud cells in this study we used simplified classification algorithm that uses only information about the radar reflectivity. For the differentiation of the described above classes of cloud cells the two threshold values of radar reflectivity were used. The lower value -30 dBZ were used for the classification of the "cloud without drizzle fraction" class. This value was estimated from the CLARE'98 in-situ measured cloud particles size spectra and has good agreement with others campaigns data for stratiform clouds. The second threshold value for differentiation the clouds with "light" and "heavy" drizzle fraction using the similar procedure was selected to be equal to -20 dBZ. This value has much less stable character for in-situ datasets and during application of the algorithm to the real remote sensing data it was used like tuning parameter with control of the retrieval results.

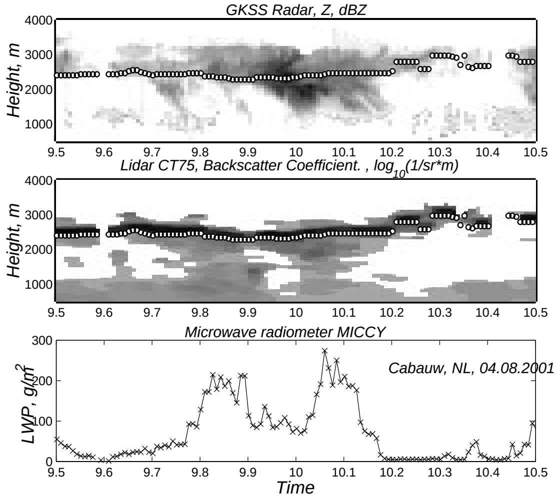

Fig. 1. The results of simultaneous and spatially matched radar, lidar and radiometer measurements for analyzed observational period. Here and on subsequent images the white circles represent the lidar derived cloud base.

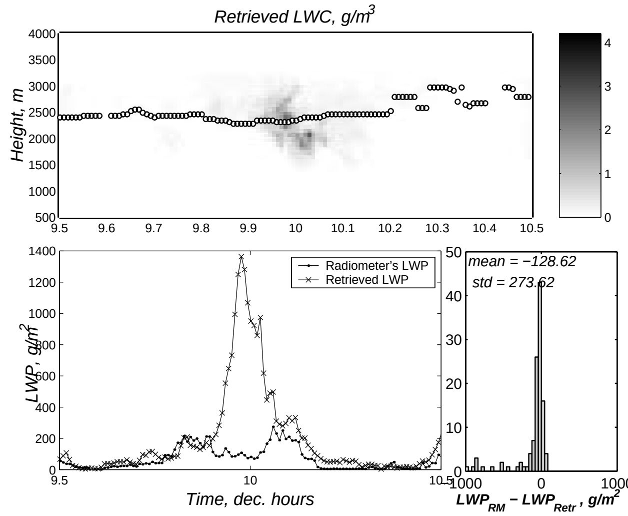

Fig. 2. The application of the Z-LWC relationship from Atlas (1954): the retrieved LWC profiles (top) and the comparison of the microwave radiometer's and retrieved LWP as time series and histogram of differences (bottom).

The resulting retrieval procedure can be summarized as follows. From the simultaneous and spatially matched radar and lidar data the classification map for cloud cells using Z/α (where this parameter was available) and/or Z values was produced. For every of three resulting cloud cells classes – "the cloud without drizzle fraction", "the cloud with light drizzle", and "the cloud with heavy drizzle", there was possibility to select the Z-LWC relationship. The application of such relationship to the radar reflectivity profiles produces the LWC profiles. From these profiles we have calculated the retrieved LWP and made comparison with LWP from the microwave radiometer.

3 Observational results

In this paper we present the results of the application of the developed algorithm for LWC retrieval for one case – 4 August 2001, 09:30–10:30 UTC. The Fig. 1 presents the results of simultaneous and spatially matched radar, lidar and radiometer measurements for this observational period.

During selected period of observation the different radar reflectivity levels, thicknesses of cloud layer, the visible changes in lidar's cloud base height and in radiometer's LWP were observed. From the full-range radar's and lidar's profiles follows that there were no clouds above 4-km height level during analyzed period. The data from the collocated with radar and lidar ground-based rain gage show the presence of light precipitation with the 10-min averaged rain amount on the 0.001 mm level after 10:20 UTC.

We have begun the analysis of selected data with application to the radar reflectivity profiles every described in Sect. 2.3 Z-LWC relationship alone. As example, on Fig. 2 the results of the application of relationship (3) to the observed radar reflectivity profiles are presented. On the top graph we show the retrieved LWC profiles and on bottom graph the comparison of the radiometer's and retrieved LWP time series and the histogram of the differences between these variables are presented. The big variability of the cloud's character during selected period of observation gives the possibility for every analyzed Z-LWC relationship (1)–(5) to find short time interval with good agreement of the retrieval results with measured LWP. But application of such relationships for whole observational period show physically unreasonable results – LWC is up to 4 g/m^3 for the Atlas parameterization (3) and up to 35 g/m^3 for the Fox-Illingworth parameterization (1). The comparison LWPs from relationship (3) and microwave radiometer measurements gives the mean bias 128 g/m^2 and standard deviation around 273 g/m^2 for 1 hour observational period.

After conclusion about non-applicability of the unique Z-LWC relationship to the whole-observed dataset we have applied described in Sect. 2.3 algorithm. On Fig. 3 the profiles of optical extinction, estimated with Klett's inversion algorithm, (top graph), and profiles of calculated radar reflectivity to lidar extinction ratio (bottom graph) are presented. The estimated from the remote sensing data values of the Z/α ratio show the distribution that are in good agreement with values that were calculated from in-situ measured particle size spectra (Krasnov and Russchenberg, 2002). Two procedures for cloud cells classification were applied – using only radar reflectivity threshold values (the resulting map is presented on Fig. 4) and complete procedure that uses radar reflectivity and Z/α ratio (the resulting map is presented on Fig. 5). From the comparison of these maps follows that using only radar information incorrectly characterizes most of the point on radar profiles below cloud base as "cloud without drizzle fraction". In the same time, the classification of the points on profile with the values of the Z/α ratio produces physically

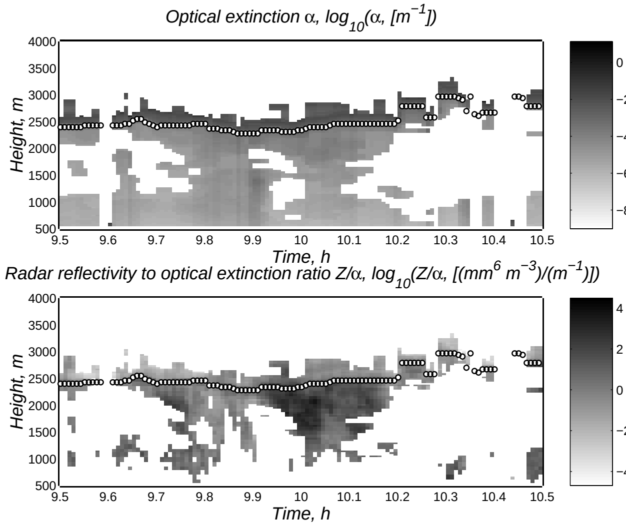

Fig. 3. The profiles of optical extinction, estimated with Klett's inversion algorithm (top graph), and profiles of calculated radar reflectivity to lidar extinction ratio (bottom graph).

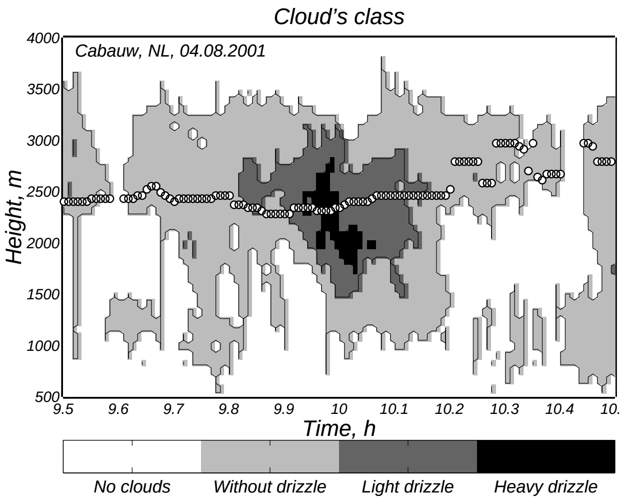

Fig. 4. The map of the results for cloud cells type classification using radar reflectivity only.

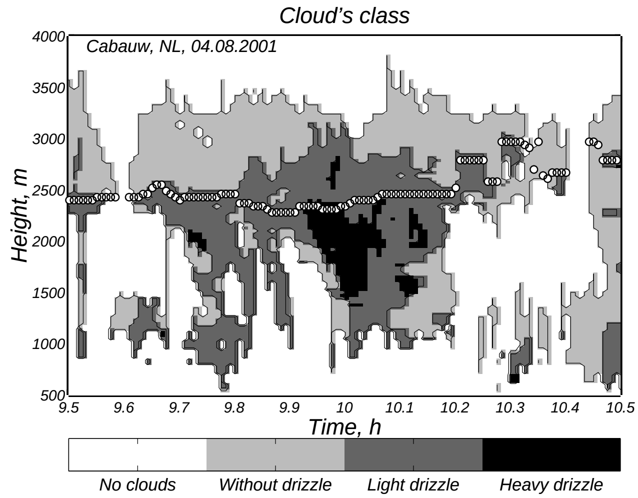

Fig. 5. The map of the results for cloud cells type classification using radar reflectivity to optical extinction ratio.

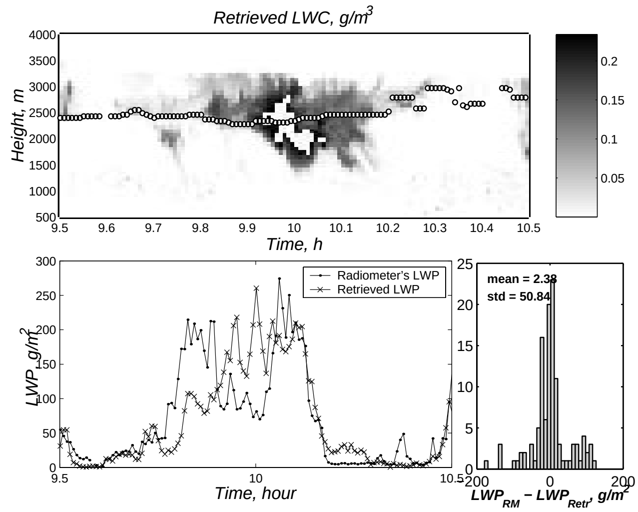

Fig. 6. The application for the LWC retrieval the algorithm that use only radar reflectivity values: the retrieved LWC profiles (top) and the comparison of the microwave radiometer's and retrieved LWP as time series and histogram of differences (bottom).

realistic image of the drizzle distribution in the atmosphere.

The different combinations of the described above Z-LWC relationships (1)–(5) were applied for the radar reflectivity profiles using this map of cloud types and resulting retrieved LWC profiles were used for calculation of the LWP. For every combination of the Z-LWC relationships that were applied for every class, the agreement between retrieved LWP and microwave radiometer's LWP was estimated. The best agreement was achieved for the combination: the relationship (1) for "the cloud without drizzle fraction", the relation (4) for "the cloud with light drizzle", and the relation (5) for "the clouds with heavy drizzle". The resulting LWC profiles, LWPs time series and the histogram of error in retrieved LWP relatively radiometer's LWP are presented on Fig. 6 for classification from radar reflectivity and on Fig. 7 for complete proposed technique. For both methods the retrieved LWC demonstrate the physically reasonable distribution of their values, but using lidar extinction profiles gives more realistic spatial distribution of LWC and less standard deviation of the distribution of error relatively microwave radiometer's LWP. The distribution of differences between the retrieved and measured with microwave radiometer LWP has relatively small bias 13 g/m^2 and standard deviation 41 g/m^2.

4 Conclusions

The algorithm for the retrieval of the LWC in water clouds from simultaneous and spatially matched radar and lidar data have been studied using measured during BBC campaign re-

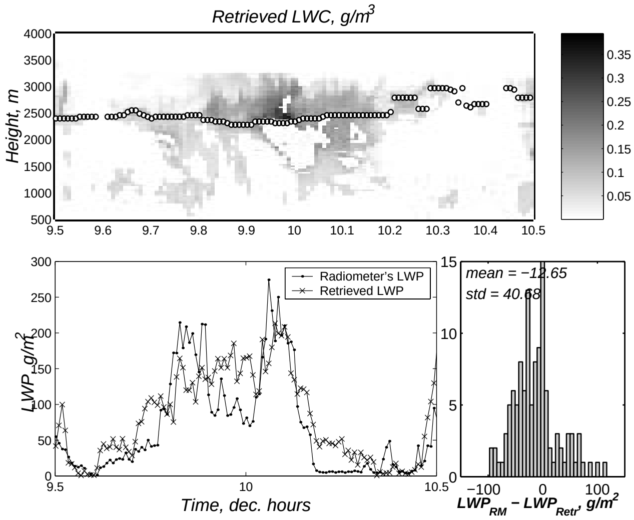

Fig. 7. The application for the LWC retrieval the algorithm that use both the Z/α ratio values and the radar reflectivity values: the retrieved LWC profiles (top) and the comparison of the microwave radiometer's and retrieved LWP as time series and histogram of differences (bottom).

mote sensing data. The impossibility to use unique Z-LWC relationship for the retrieval of the LWC from radar reflectivity profile is demonstrated. The new method for the retrieval of the LWC from radar reflectivity profiles is described. This method uses the value of the ratio of radar reflectivity to lidar optical extinction for the classification of cloud's range cells into three types – "the cloud without drizzle fraction", "the cloud with light drizzle", and "the clouds with heavy drizzle". The subsequent application for every resulting type of the cloud's cells the specific Z-LWC relationship allows to reach the good agreement between retrieved liquid water content and independently measured with microwave radiometer LWP. For the selected observational period the bias in retrieved LWP relatively radiometer's LWP was equal to 13 g/m^2 and standard deviation 40 g/m^2.

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