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Radar based remote sensing of cloud liquid water—application of various techniques—a case study

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Abstract

During the BALTEX BRIDGE Campaign (BBC) of CLIWA-NET, conducted at Cabauw, The Netherlands, from 1 August through 31 September 2001, cloud radar parameters like reflectivity, linear depolarization ratio and Doppler velocities have been observed using a 95 GHz cloud radar. These observations along with other remotely sensed parameters from the ground, have been used to derive the liquid water content of clouds which is one of the most important parameters to be known when the radiative transfer of clouds needs to be calculated.

Simultaneously a multi-channel passive microwave radiometer and a lidar ceilometer have been operated close to the radar. While drizzle could be ruled out to have a significant impact on the return signal, corrections due to atmospheric absorption (gaseous) and attenuation due to clouds (mainly loss of signal due to absorption) had to be applied to the radar data. The corrections will be discussed in detail and have been applied to the radar reflectivity profiles before estimating cloud liquid water profiles. After the liquid water content profile has been calculated (for a fixed integrated liquid water path) the maximum in liquid water content of the cloud increased by about 14% and shifted upward within the cloud. The applied corrections bring the liquid water profile closer to adiabatic in the middle and upper part of the cloud. Examples of time series of corrected vertical profiles and average profiles are shown and are discussed. The ground based remotely sensed liquid water profiles show,

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on average, excellent agreement with simultaneously in situ measured liquid water content from aircraft measurements.

Keywords: Cloud liquid water content; Remote sensing of clouds; Cloud radar application; Ground based remote sensing

1. Introduction

Even though only a tiny amount of total water available on Earth is (temporarily) stored in clouds, they play a major role in climate and weather on a wide range of spatial and temporal scales, mostly through their ability of changing the radiation budget at the surface and of the atmosphere and through redistribution of heat, moisture, and chemical species vertically and spatially. The representation of clouds in models and their impact on the radiative transport in regional and global scale numerical models is only crude. The most challenging aspect is their high temporal and spatial variability, as well as the high variability of their microphysical properties. Typical atmospheric models can not resolve all relevant scales of clouds i.e. their internal variability below their spatial resolution. Hence, parameterizations for those sub-grid cloud processes need to be applied. The cloud parameterizations in current atmospheric models, however, are not sufficient, leading to large errors in heating and cooling rates which consequently couple back to the dynamics and transports (Stuhlmann and Smith, 1988).

To overcome some of these shortcomings described above, it is mandatory to improve these parameterizations of clouds by first characterizing radiation relevant cloud micro- and macro-physical parameters, such as liquid water path, liquid water content, droplet size spectra, their lower and upper boundaries, to list only the most important factors. During BBC of CLIWA-NET a comprehensive dataset has been produced from which various cloud properties can be estimated.

One central aspect, which is essential for the calculation of radiative transfer in the atmosphere and forms the focus of this paper, is the parameterization of the effect of liquid water content (LWC) on radiative transfer. With the instruments used in this study there are in general several different approaches which are capable of retrieving LWC: 1) in situ measurements of LWC by means of aircraft, 2) different Z–LWC relationships (classical methods) which have been derived from theoretical calculations using measured droplet size spectra, 3) a combination of the 95 GHz reflectivities can be used together with the liquid water path (LWP) from passive microwave radiometer measurements, supported by radiosoundings and cloud base information from ceilometer data, 4) a combination of 95 GHz radar reflectivities with the reflectivities of a collocated 35 GHz radar in conjunction with radiosonde data, 5) so-called radar/lidar algorithm that make use of the ratio between radar and lidar backscatter signal to estimate LWC.

This study focuses on pure water clouds only, hence combinations of radar and lidar algorithm (i.e. Donovan and van Lammeren, 2001) are not applicable due to the very high optical depth of water clouds. Furthermore for our purpose of developing enhanced cloud parameterizations we need to have LWC profiles with highest possible resolution in time and space. In this respect the dual wavelength technique is not feasible, since an average of at least 40 m in the vertical and 100 s in time (here ~1100 m) is necessary to obtain reliable values from this method (Hogan et al., 1999). The data for this case study used and presented here originates from the joint field phase of the BALTEX Cloud Liquid Water Network (CLIWA-NET) (Van Lammeren et al., 2001) and 4D-CLOUDS, which took place in Cabauw/Netherlands in August and September 2001. It comprises a comprehensive data set, which is ideal for the purpose of this study. Cloud radars, passive microwave radiometers, ceilometers, have been operated simultaneously side by side, probing almost the same cloud volume from the ground. In addition to these measurements this data set is made unique by radiosondes launched at Cabauw with a frequency of up to once per hour and by in situ measurements of LWC from aircraft over the Cabauw area.

In this paper a case study is conducted on a dataset gathered during the morning hours of 23 September 2001. This date has been chosen, since the conditions for this intercomparison study were ideal:

1) there was a homogeneous stratocumulus layer present for several hours in the morning, with no clouds above, and negligible drizzle in an underneath the cloud base. Drizzle, in general tends to dominate the radar reflectivity in many cases, since the reflectivity is proportional to the 6th power of the droplet diameter, while the liquid water content only increases with its 3rd power. Therefore, a small amount of drizzle often dominates the signal, but at the same time does not contribute substantially to the liquid water content of the cloud.
2) aircraft observations took place spread over the entire morning, probing the same cloud layer at different altitudes,
3) radiosondes have been launched during the morning hours from the Cabauw site, giving an excellent overview of the atmospheric stratification and its development.

A brief description of the equipment used in this study will be followed by a description of the of the synoptic situation for this case. The fourth section will describe the various methods applied to the data sets and combinations thereof. An intercomparison of LWC from the various methods is shown in the last section as well as an intercomparison with in situ LWC from aircraft.

2. Equipment used

For this study we made use of combinations of a 95 GHz cloud radar, a passive microwave radiometer and a ceilometer operated side by side, simultaneously probing almost the same cloud volume. In the following the instruments used for this study are described in brief.

2.1. 95 GHz cloud radar

The 95 GHz cloud radar used is the GKSS operated polarimetric Doppler radar (MIRACLE). This W-band radar can detect most water clouds with typical droplet size distributions and number densities. Beside other parameters such as pulse repetition frequency and polarization, the pulse length can be selected top give a vertical resolution between 7.5 m and 82.5 m. The narrow beam width of 0.17° leads to a horizontal resolution of about 3 m at a distance of 1 km. With this capability it is possible to detect low level water clouds with a sufficient temporal and spatial resolution. The accuracy of the radar for averages of at least 0.1 s has been estimated to be about 2 dB, through direct intercomparison with a calibrated radar of the same kind. Intercomparison with other radars at Cabauw shows the same accuracy. The threshold detection signal is set to −54 dBZ. A more detailed description of the radar system can be found in Quante et al. (2000). The advantages of being able to detect weak cloud reflectivity signals due to the high frequency and the design of the instrument are traded against some disadvantages resulting from the frequency of the cloud radar that needs to be accounted for: attenuation due to cloud liquid water, gaseous absorption (water vapor and oxygen), near field effects, and leaving the region in which the Rayleigh approximation is valid at particle sizes of about 300 μm (drizzle effect on radar reflectivity).

2.2. Passive microwave radiometer

A passive microwave radiometer from University of Bonn (MICCY) (Crewell et al., 2001), measured atmospheric emission at 21.3, 23.8, and 31.7 GHz. With an appropriate calibration of the instrument (Hogg et al., 1983) it is possible to calculate the liquid water path (LWP) to an accuracy of 10–30% (Westwater, 1978). The field of view of the radiometer is 0.9° and the temporal resolution is 30 s.

2.3. Ceilometer

As a third parameter, the ceilometer derived cloud base height from KNMI owned ceilometer was used to determine an estimate of the lower cloud boundary at visible wavelengths. The ceilometer used is the commercially available Vaisala CT75 lidar, which measures the backscatter signal at 905 nm wavelength. It has a vertical resolution of 15 m and a temporal resolution of 30 s. A more detailed description of this instrument and its operation can be found in Russchenberg et al. (1998).

3. Synoptic situation on the morning of 23 September 2001

The data discussed here were taken on 23 September 2001. During the entire morning until about noon, a stratocumulus layer of about 300 m thickness was observed underneath a weak inversion, with in general increasing altitude and decreasing thickness with time. Later, around noon time the closed layer broke up into cloud streets. From radar as well as airborne observation there were no cloud layers observed above this stratocumulus deck for the entire morning and early afternoon. The freezing level was at about 2 km altitude, well above the top of the cloud layer, so the entire cloud can safely be considered a pure water cloud. Air masses originated from central Europe with a short fetch over the south western tip of the Baltic Sea, southern tip of Sweden and Denmark before it turned counter clockwise to go over the Cabauw site from the NE (Boers and Krasnov, 2003).

4. Estimating cloud liquid water profiles from ground base remotely sensed parameters

4.1. Classical Z–LWC relationships

In general there are several different ways to derive the liquid water profiles of low-level water clouds from ground based radar data. The easiest would be to simply apply a quadratic relationship between reflectivity and liquid water content to the radar reflectivities, which has been developed for instance by Atlas (1954), Sauvageot and Omar (1987), Fox and Illingworth (1997), and Baedi et al. (2000), to name only a few. These classical relationships were derived by calculating radar reflectivities from in situ airborne droplet size distribution measurements and relating those to the measured liquid water content. Most critical applying these classical relationships is the fact that small differences in number concentration of the large droplets can lead to very large difference in reflectivity in the radar measurements, since radar reflectivity increases with the 6th power of droplet diameter while LWC grows only proportional to the 3rd power of droplet diameter. All these so-called Z–LWC relationships can be brought into the common format:

$$q = \left(\frac{10^{Z/10}}{a} \right)^{1/b} \tag{1}$$

with radar reflectivity Z, the liquid water content q, and coefficients a and b as listed in Table 1.

4.2. Frisch type algorithm

Another more sophisticated approach was developed by Frisch et al. (1998) who used a combination of liquid water path estimates (hereafter LWP) derived from passive microwave radiometer radiances and cloud radar reflectivity profiles to derive the profiles of liquid water content. Assuming that the sixth moment of the size distribution is proportional to its third moment squared, and the number concentration of cloud particles is constant with height, they find a relationship between LWP, radar reflectivity and liquid water content (LWC), which is then even independent of the calibration of the radar used.

Table 1
Coefficients for some classical Z–LWC relationships

	a	b
Atlas (1954)	0.048	2.00
Sauvageot and Omar (1987)	0.030	1.31
Fox and Illingworth (1997)	0.031	1.56
Baedi et al. (2000)	57.544	5.17

Before applying the Frisch type algorithm to our 95 GHz radar data some corrections are needed:

4.3. Near field correction

The near field correction is necessary since the radar equation is strictly derived for the so-called antenna far field, which involved several assumptions about the antenna gain and pattern shape. This leads to the necessity to correct the received signal for this error as long as the considered range gate is below this far field threshold. For the correction we followed a suggestion of Sekelsky (2002). At 95 GHz the far field starts at 933 m distance from the antenna. For all range gates below 933 m the near field correction needs to be applied. For extremely close targets (for instance ~200 m) a correction of about 2 dB would be necessary. This becomes especially important if low boundary layer clouds are observed. The near field correction for the case considered here is relatively unimportant, since it is in the same order of magnitude as the accuracy of the radar.

4.4. Atmospheric absorption

Even though atmospheric absorption is weak at 95 GHz there is still a non-negligible absorption by water vapor and oxygen. Compared to 3 and 35 GHZ radars the absorption due to water vapor and oxygen is more than an order of magnitude stronger in the 95 GHz region. Following an empirical function to calculate water vapor and oxygen absorption given by Ulaby et al. (1981) we applied the correction of the signal due to these two gases. The necessary temperature, pressure and water vapor density profiles were taken from a radiosounding that was launched from Cabauw at 8:58 UTC. From these profiles the water vapor as well as oxygen absorption coefficients have been calculated. An example of the magnitude of this correction is given in Fig. 1, which has been calculated for a vertical two way signal path (to and from the scattering volume). The dotted line is the correction that needs to be applied to the received radar signal due to oxygen absorption alone. The dashed line is for the water vapor absorption and the solid line for the combined effect. As can be seen from the graph, even for a medium humid atmosphere with an integrated water vapor content of about 15–16 kg m^{-2} a correction of up to 2.5 dBZ needs to be applied to the signal, even for a vertical pointing antenna. It is clear from these calculations that it is necessary to apply even for a low cloud situation if the reflectivity signal is used to derive quantitative estimates of LWC.

4.5. Attenuation correction due to cloud liquid water

The attenuation correction regarding hydrometeors has been applied similar to the approach described by Löhnert et al. (2001) but with a different method for calculating the liquid water content. If the Rayleigh approximation holds (Ulaby et al., 1981), the absorption coefficient k_c can be calculated by

$$k_c = \frac{6\pi}{\lambda} \cdot Im(-K) \cdot q(Z, Q), \tag{2}$$

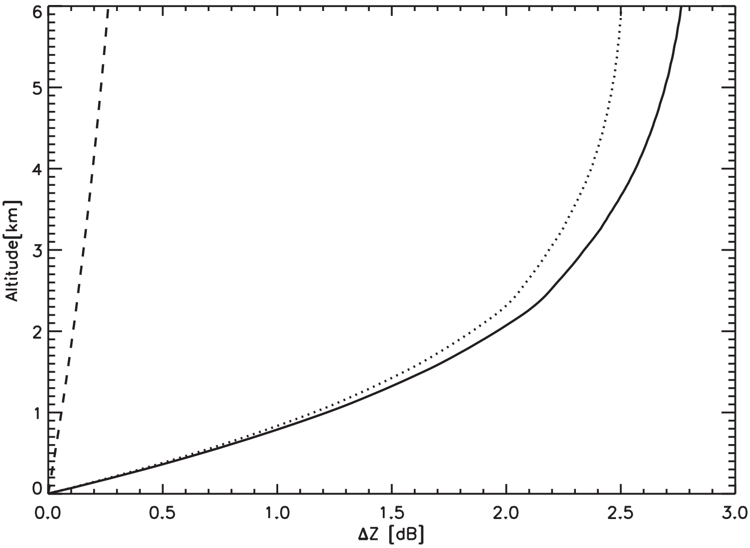

Fig. 1. Water vapor and oxygen two way optical depth (in dB) calculated for 95 GHz for vertical pointing radar on 23 September 2003, 8:58 UTC as a function of altitude (dashed: oxygen only, dotted: water vapor only, solid: combined effect).

with

$$K = \frac{k^2 - 1}{k^2 - 2}, \tag{3}$$

and k denoting the complex refractive index of water and λ being the wavelength of the radar. The liquid water content q is being calculated using the approach by Frisch et al. (1998), which basically spreads the total liquid water path Q derived from the passive microwave radiometer to the entire cloud column as detected by the radar, weighted by the reflectivity profile retrieved from the radar in the following manner:

$$q_n = \frac{Q \cdot \sqrt{Z_n}}{\sum_{n=1}^{N} \sqrt{Z_n} \cdot \Delta z_n} \tag{4}$$

The index n denotes the respective range gate or level, N is the total number of range gates in the cloud column under consideration. Z_n is the reflectivity in the n-th range gate and Δz_n is the respective range gate spacing, which is a constant for all range gates in each profile. Assuming that Z in the lowest cloud layer (n=1) is not attenuated by the cloud, the radar attenuation of that layer can be calculated using

$$\tau_n = \sum_{i=1}^{n} k_i \cdot \Delta z_i \tag{5}$$

which is the cumulative attenuation integrated from the lowest layer (i=1) up the actual layer considered (i=n). The corrected reflectivity of the second layer from below is than calculated using $Z_n^c = Z_n \cdot e^{2\tau_n}$ with the index c denoting the corrected radar reflectivity of the n-th layer. This can be done for all cloud layers from the bottom to the cloud top recursively.

Even though the Frisch algorithm is essentially independent of the radar calibration, the applied corrections due to absorption results in redistribution of higher LWC values to higher levels, thus intensifying the maximum of LWC in the uppermost layers and consequently increasing the rate of change of LWC with height. The maximum in liquid water content is enhanced, while LWC in the lower layers decreases slightly. This is due to the increasing underestimation of radar reflectivities with increasing cloud thickness for uncorrected data. If we account for the drizzle underneath the cloud by cutting off all radar reflectivities underneath the ceilometer detected cloud base height, there is even more pronunciation of the upper level maximum. This assumption is only very crude, since it can always be expected that, if drizzle leaves the cloud at its base there is certainly drizzle inside the cloud as well. Since the reflectivity introduced by the drizzle underneath the cloud base is around −50 to −45 dBZ and the cloud reflectivity is above −40 dBZ it can savely be assumed for this case that drizzle inside the cloud does not effect the mixed (cloud dropplet plus drizzle) return signal, but is dominated by the signal from the LWC.

5. Results

We have applied the above mentioned techniques for retrieval of the LWC by combining the data from various instruments as mentioned above. The results are displayed and discussed in this chapter.

First of all, Fig. 2(a) gives an overview of the time series of the 95 GHz radar data we have used for evaluation of the different techniques. It displays a time height cross-section of 95 GHz radar reflectivities during the morning of 23 September between 8:00 UTC and 10:00 UTC. This two hour interval can be interpreted as cloud field of 75.6 km horizontal extension (note: the aspect ratio of displayed structures seen is far beyond 1), when making use of the fact that the drift speed of the cloud layer was on average 10.58 ± 1.45 m/s from direction of $46.6 \pm 4.5°$. The average wind velocity has been taken from the research aircraft Merlin, which crossed the cloud field several times during the morning between 8:30 and 10:00 UTC at various altitudes. A relatively homogeneous layer of stratocumulus was observed over most of the time until around 10:00 UTC when the layer began to break up and cloud streets started to form during early afternoon. The black line in the upper panel a) depicts the cloud base height as calculated from the CT75 ceilometer. For most of the time the radar cloud base height is about the same as the ceilometer cloud base height. For some cases, however, there is considerable disagreement between both estimates. This is caused by drizzle drops (diameter between 50 and 400 μm) which leave the lower boundary of the cloud and evaporate on their way down, never reaching the surface as precipitation. Since radar reflectivity is proportional to the 6th power of drop diameter a very small number of drizzle sized drops produce a detectable back scattering signal. The backscattering signal in the visible to near infrared wavelengths (as detected by the ceilometer) on the other hand, increases only with the square of the droplet diameter. This is why the ceilometer does not detect those drizzle sized drops, since their number

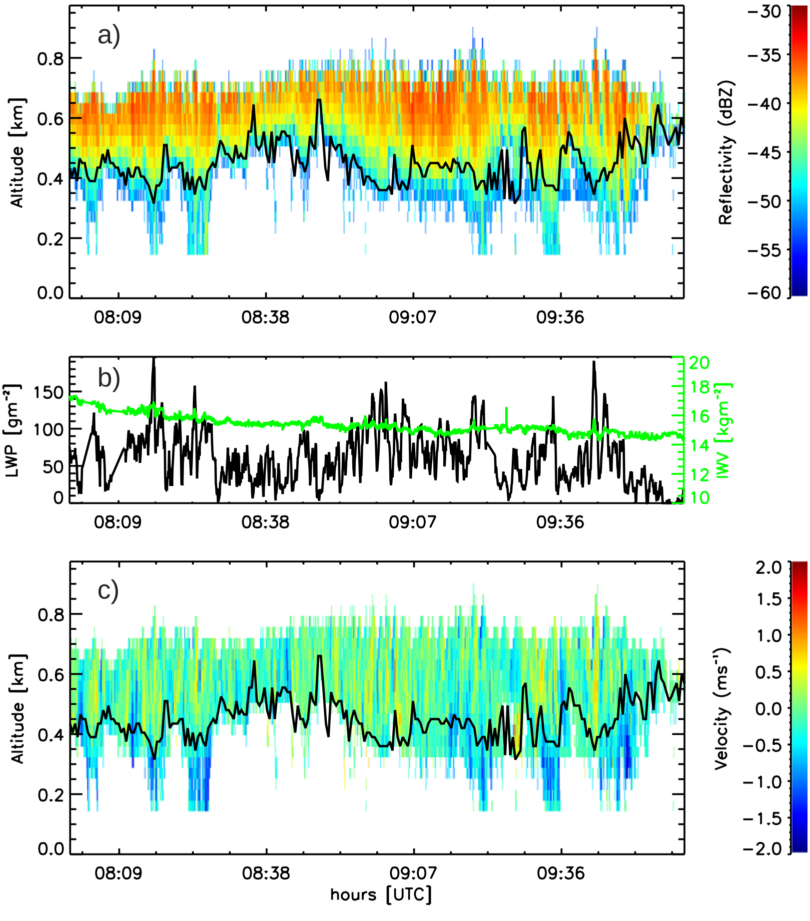

Fig. 2. Time series of (a) uncorrected radar reflectivities, (b) liquid water path and integrated water vapor as derived from passive microwave radiometer, and (c) Doppler velocity from cloud radar as observed on 23 September 2001 between 7:57 and 9:57 UTC. The black lines in (a) and (c) are the lower cloud boundary as derived from ceilometer measurements.

density is not high enough. The latter exhibits a general problem with radar reflectivities if drizzle sized droplets are present. Despite their high backscatter signal drizzle sized drops are not adding significant amounts of liquid water (Fox and Illingworth, 1997), since their number density is in general much lower than that of cloud droplets.

Fig. 2(b) just underneath the reflectivity plot is the time series of liquid water path (LWP) and integrated water vapor (IWV) as derived from the microwave radiometer MICCY. The IWV (as an indicator for the attenuation correction) decreases during the morning hours from about 17.5 kg m^{-2} at about 8:00 UTC to 15.5 kg m^{-2} at around 9:00 UTC. Fig. 2(c) shows the vertical velocity of cloud particles from the 95 GHz radar. Again the cloud base height is overlaid. While most of the vertical velocities above the cloud base are scattered around 0 m s^{-1}, indicating small particles which underlie the turbulent and convective movements, it can be seen that in most drizzle 'curtains' underneath the cloud base there is considerable negative velocity, which is an indication of falling particles. The terminal velocity of cloud droplets is in general a function of the cloud droplet size distribution (Khvorostyanov and Curry, 2002). This is supporting the assumption of drizzle sized drops leaving the cloud at the lower boundary occasionally. The region above the 'drizzle curtains' is also believed to host drizzle since usually drizzle originates in the upper part of the cloud, falling down and leaving the cloud at its base.

Fig. 3 shows for a typical LWC profile at 8:16 UTC the retrieved values for some methods mentioned above. It can clearly be seen that the classical *Z*–LWC relations show significantly lower values of LWC when compared to the more sophisticated methods like Frisch (1998) and modified Frisch. The Baedi et al. (2000) method is somewhat between the two, since it is developed to allow for some drizzle inside clouds and therefore starts at slightly different assumptions regarding the droplet size distribution. For this case study this is a general finding not only for the individual profile shown in Fig. 3. Even small variations in the number concentration of particles of increased sizes will strongly change any modeled relationship between LWC and radar reflectivity due to the d^6-dependency of the radar reflectivity. Since this cloud layer is of continental origin with an increased number of small particle which do not produce such a high reflectivity it is clear that the classical relationships which have been developed for maritime stratus must lead to very low LWC when applied to a cloud of continental origin. The maximum LWC possible is overlaid to the plot as well. This is the LWC calculated, assuming adiabatic equilibrium. For this calculation the vertical profiles of temperature, pressure and humidity have been used from a radiosounding launched at 8:58 UTC from Cabauw. Relative humidity inside the cloud (whenever the radar reflectivity was not equal zero) has been assumed to be

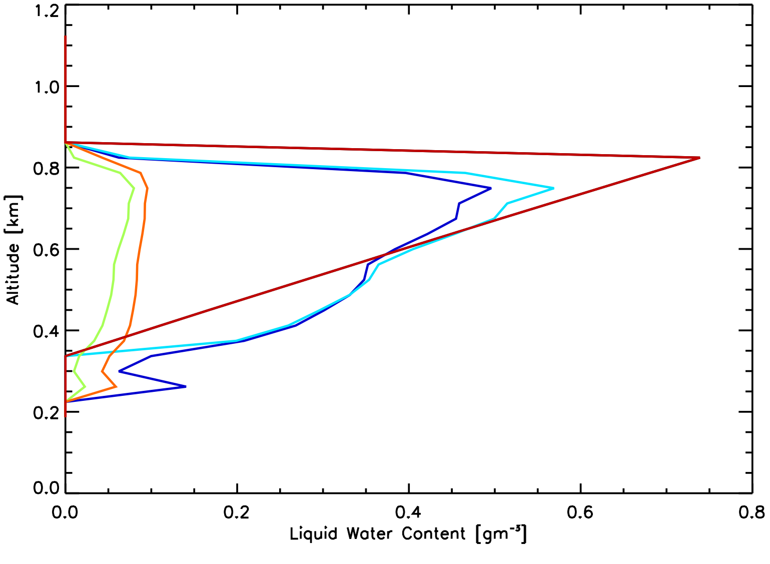

Fig. 3. Example vertical profile of liquid water content at 8:16 UTC, displayed for the various retrieving algorithms. Green: Atlas (1954), orange: Baedi (2002), dark blue: Frisch (1998), light blue: corrected Frisch, red: adiabatic.

100% at all times. The latter assumption leads to the very sharp decrease in LWC at the uppermost cloud level. In general the adiabatic liquid water content can theoretically be reached, but never be exceeded.

Fig. 4 shows the time series of (a) the Frisch algorithm, (b) the Frisch algorithm using corrected radar data and (c) the adiabatic liquid water content as calculated between the observed cloud boundaries for the observed temperature and humidity profile. The Frisch and modified Frisch algorithms show similar patterns, but with higher values in the upper part of the cloud indicated by the modified Frisch. This is due to the correction of radar

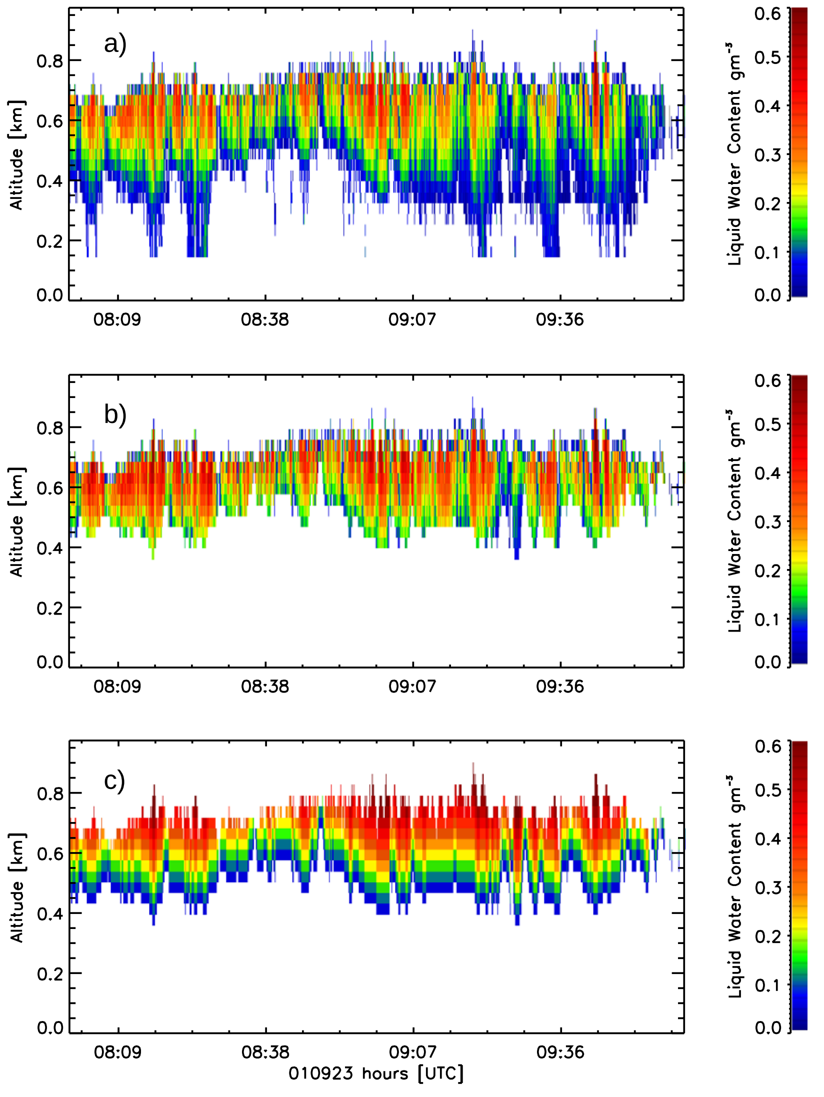

Fig. 4. Time series of liquid water path (a) using Frisch (1998), (b) corrected Frisch, and (c) adiabatic LWC.

reflectivities and cut off of clouds/drizzle curtains underneath the ceilometer cloud base, redistributing the total LWP from the microwave radiometer to a smaller vertical column. The horizontal structure of the two methods originates mainly from the strong temporal variability of the LWP from the microwave radiometer measurements. Note that the variability in the Reflectivity seems to be much less compared to the LWP, but since the Reflectivity is in logarithmic units it is in the same range as the variability of the LWP. The third panel (c) shows for comparison the adiabatic liquid water content. The adiabatic value is the upper threshold for LWC and does not account for any turbulent mixing like entrainment at the lower and/or upper cloud boundaries. The highest values of LWC are therefore observed in the uppermost layer of the cloud, which is far beyond the real value. The vertical structure is exclusively determined by the temperature and water vapor mixing ratio at the lower cloud boundary. The horizontal (temporal) structure is a strong function of the cloud boundaries. The increase of LWC with height above the cloud base for the Frisch type algorithm is little stronger than the adiabatic value, but in the middle to upper third of the cloud (except the uppermost levels) is less for the Frisch type algorithms when compared to the adiabatic LWC profiles.

When comparing the remotely sensed values of LWC with in situ measured LWC it becomes evident that the methods combining different parameters (Frisch type algorithm) are much closer to the in situ measured properties (Fig. 5). However, It can be shown that a point intercomparison of remotely sensed values with in situ values is not feasible, since very difficult collocation issues which depend on wind speed and direction and internal development of the cloud if the in situ sensed cloud parcel is moving into the radar backscattering volume at a different time. From our data sets there is LWC available from in situ measurement with a resolution of 10 s, which always represents an average of about

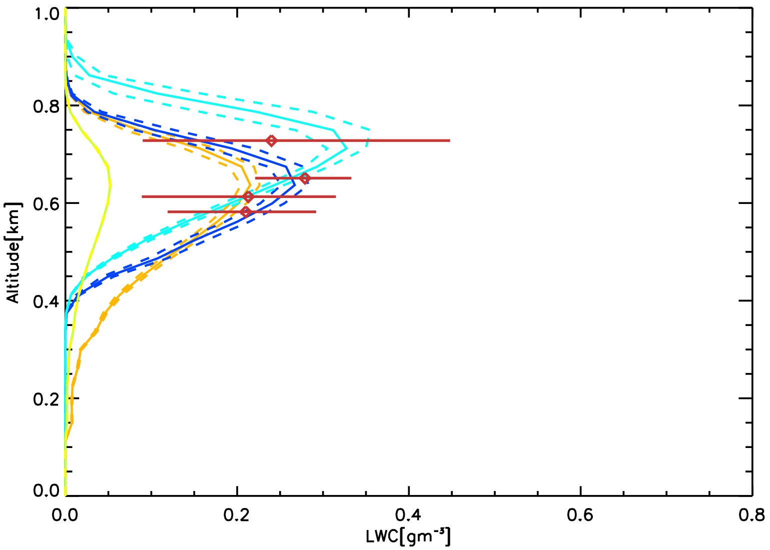

Fig. 5. Average liquid water profile for Atlas (1954) (yellow), Frisch (orange), corrected Frisch (blue), adiabatic (turquoise), and LWC from in situ aircraft observation (red diamonds, bars indicate the range).

700 m, at a true air speed of the aircraft of about 70 m/s. With the setup here it is only feasible to intercompare an average LWC profile derived from radar/radiometer combination with the typical LWC from the aircraft within a radius of 5 km around the radar location. During the time period between 8:00 and 10:00 UTC there were 5 overpaths of the aircraft inside this circle at five different altitudes, ranging from the lower to the upper part of the cloud. While the in situ measured values of LWC within their range of values do compare well to the Frisch type algorithm LWCs the classical methods produce much lower values (56). This is in accordance with the Integrated Profiling Technique (IPT) developed by Löhnert et al. (2001).

The combined errors introduced by applying the Frisch type and modified Frisch type algorithms have been estimated with Gaussian error propagation. We have used an uncertainty of 30% (worst case, Westwater, 1978, see above) for the LWP value and a 2 dB (60%) uncertainty (as already stated above) for the radar reflectivities. In general the absolute error increases with height. This is not supprising, since the LWC values increase as well and they are depending strongly on the reflectivity. The relative error increases as well, reaching maximum values in the region of maximum LWC values of the cloud of 75–80%. The change in error due to the recursive correction looks little different. While the change in absolute error increases with height (like the corrected LWC does) the relative error decreases slightly at the same time to maximum values of 70–75%. These errors are in the same range as the uncertainties from in situ measured values as can be seen from the error bars in Fig. 5.

It can clearly be seen from these plots that in general, for fixed liquid water path as dictated by using the Frisch (1998) algorithm, the liquid water content in the lower part of the cloud is shifted to higher levels, even more pronouncing the maximum liquid water content in the upper part of the cloud. When comparing LWC derived before and after applying all corrections we find that the gradient in LWC is increased from 1.2 to 1.4 g m^{-3} km^{-1} below the height of LWC maximum. The adiabatic LWC gradient is at 1.53 g m^{-3} km^{-1} for the atmospheric profile and cloud geometry in this example, bringing the corrected profiles closer to adiabatic. This makes clear that one must account for the corrections applied in this study if deriving physical quantities from the radar data, even in cases of relatively low liquid water content and short path through a humid boundary layer. The decrease of liquid water from its maximum in the upper third of the cloud layer towards the upper boundary seems to be smeared out, possibly by entrainment in the uppermost layers of the cloud but certainly by interpolation techniques applied to the variable upper cloud boundaries, as well as only partially filled cloud pixels in that part.

6. Conclusions

Is has been shown that using a combination of cloud radar, passive microwave radiometer, ceilometer and radiosoundings we need to correct radar reflectivities for near field effects, gaseous absorption, and attenuation due to cloud liquid water itself, before using it to derive physical quantities such as liquid water profiles. If drizzle can be detected underneath the cloud (by differences in lower cloud boundary estimates between radar and ceilometer) it is also useful to reject these data when deriving cloud liquid water profiles, since drizzle increases the radar reflectivities substantially, but at the same time does not contribute substantially to the liquid water content.

The corrections applied here have been made under the following major assumptions:

Clouds consist of pure water droplets at a fixed temperature.
No significant amount of drizzle sized drops are inside the cloud.
The 6th moment of droplet size distribution is proportional to their 3rd moment squared.
The number density is constant with height.

The authors are aware, however, that the procedure described in this work is only applicable if the above mentioned assumptions are all (at least approximately) fulfilled. Most important to make this procedure work for a wider range of situations would be to detect drizzle inside clouds and find out the drizzle impact on radar reflectivity and reliably detect and quantify in terms of reflectivity and correct for it. If this can be achieved, liquid water content even of drizzle containing clouds could be estimated. Additional information like full Doppler velocity spectra (which were not available during this experiment) could help determine the drizzle influence on the reflectivity signal.

Taking into account the good validation by high quality in situ measurements that have been available for this case study, the procedure used to derive the LWC from radar and the fact that the temporal and spatial variability in LWC is very high this result can be taken as very promising in retrieving LWC from cloud radar based techniques.

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