Radar observations of stratocumulus compared with in situ aircraft data and simulations

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Abstract

During the Baltex Bridgs Campaign in 2001 at the Cabauw site in The Netherlands, a whole set of instruments was used to probe the water clouds. An important element of the BBC-campaign was to develop and test advanced remote sensing techniques to measure cloud properties, especially the combination of radar, lidar and microwave radiometers. One of the preliminary findings of the campaign is the *radar discrepancy*, which is the systematic difference (although depending on the cloud type) between radar observations of reflectivity factor Z and the aircraft/balloon predictions of the same quantity. As the radar reflectivity is one of the key elements in many sensor synergetic retrieval algorithms, it is essential to understand the phenomenon.

1   Introduction

Over the last decade, cloud radars have become important tools for the study of cloud properties. Detailed observations of the structure of a cloud as well as its microphysical properties are done routinely now at several observatories in the world. The main drive

behind this development was and still is the need for reliable observations that are necessary to reduce the uncertainties in climate models due to indirect aerosol effects.

The fundamental radar observable is the radar reflectivity factor Z. Similar to traditional weather radar systems, with which the radar reflectivity facor is used to estimate the rainfall rate, relationships between Z and the cloud liquid water content were developed. However, it was soon recognized that the impact of even a small amount of drizzle droplets in the cloud would lead to large errors. Furthermore, the reflections from the droplets at the cloud base are not always strong enough to enable detection by radar. To overcome these problems, cloud radars have to be combined with other instruments like a microwave radiometer and a lidar.

The existing relationships between the radar reflectivity factor and the liquid water content were developed either based on a parametrizaton of the dropsize distribution, like a log-normal or gamma distribution, or statistical regression techniques through measured cloud dropsize distributions. (e.g, REFS). The use of these relationships requires a well-calibrated radar system, and measurement conditions such that they match the assumptions underlying the Z-LWC relationships. In this paper we will address the latter.

2   The Z-LWC relationship of stratocumulus

The Z-LWC relationship takes the form of a power law:

$$Z = \alpha LWC^{\beta} \tag{1.1}$$

in which α and β are constants that depend on the range of variation of the dropsizes and the number concentration. In case of a monomodal dropsize distribution β varies between 1 and 2. However, for bi-modal dropsize distributions (e.g, in case of drizzle formation), β can become much larger than 2.

The radar reflectivity factor is derived from the received radar power, and, consequently, the Z-LWC relationship is based on several assumptions:

- Rayleigh scattering of the radar waves, linking the radar reflection to the 6th moment of the dropsize distribution *n(D)*:

$$Z = \int n(D) D^6 dD \qquad (1.2)$$

Given the small size of cloud droplets (in the order of 10 − 20 micron radius) and the millimeter to centimeter wavelengths of the radars, this assumption is valid.

- The received radar signal is due to the incoherent summation of the individual backscatered radar waves. This requires that during the observation time the cloud droplets are moving fast enough to change the inter-particle distance by more than half a wavelength. Standard cloud radars use a wavelength in the order of 8 to 3 millimeter, which means that the velocity *differences* of the separate cloud droplets should be of the order of 2 to 4 mm/s. This is probably valid for most stratocumulus clouds, especially if turbulence air motions randomizes the velocities of cloud droplets, or if drizzle dominates the backscattering. However, it is not self-evident that in all circumstances the differences are large enough to cause incoherent scattering. Under wind free conditions the fall velocity of cloud droplets is given by

$$v = \varepsilon \cdot D^2 \qquad (\varepsilon \text{ equals 4.75e-5 when } D \text{ is in micron}) \qquad (1.3)$$

For particles smaller than 14 micron, the fall speed is less than 10 mm/s. Large particles of 40 micron have a fall speed of 76 mm/s. These small numbers show that in the absence of external forces like turbulence, the average inter-particle velocity difference can easily be of the order of half radar wavelenght per second or smaller. Under such circumstances the backscattered radar signal will consist of a coherent as well as an incoherent term.

- The radar reflectivity factor is determined from the radar equation

$$Z = \frac{P_r \cdot r^2}{C}$$

wih P_r as the received power, r as the distance of the radar volume and C as the radar constant, taking all system parameters into account; among these the size of the radar volume. The radar reflectivity factor is derived assuming that the radar volume is uniformly filled with cloud droplets and that no spatial gradients of the dropsize distribution occur inside the radar volume.

In ideal adiabatic clouds the particles grow while they ascend deeper into the clouds and reach a maximum at the cloud top. They will evaporate at the cloud boundaries or if they grow large enough, leave the cloud as drizzle. This means that care has to be taken with the assumption of uniform volume filling, especially in case of adiabatic clouds in which a spatial gradient of the liquid water content is to be expected.

Figure 1 shows examples of simulated Z-LWC relationships. These relationships are calculated with dropsize distributions that are obtained with airborne particle probes inside the clouds. The measurements were done in different campaigns in the US and Europe. Quite clearly, three regimes can be distinguished: one for low radar reflectivities through which regressions fits (8, 9 and 10) are drawn that were obtained either through theoretical considerations of non-drizzling stratocumulus clouds or other in sute data sets, one for the high radar reflecties of drizzle (curve fit 12), and a transition region (curve 11). These plots were calculated with the above mentioned assumptions in mind, and can in principle be used to derive the liquid water content once the right regime has been identified (see for instance May et al, 2004). However, because of the implicit assumptions in the retrieval schemes, the question 'How does the measured radar reflectivity factor compare to the simulations?' arises. To this end radar observations at the CESAR Observatory in Cabauw (The Netherlands) were compared with aircraft data and data obtained with a fssp-equipped tethered balloon. The measurements were done during the Baltex Bridge Campaign in 2001.

3   Comparison of radar measurements and airborne simulations

During the BBC campaign in 2001 a large set of ground-based remote sensing instrument was installed at Cabauw. At selected days, airborne data of cloud dropsize distributions was collected with instrumented aircrafts and occasionally with a tethered balloon. Figure 2 shows ground observations of stratocumulus. The top panel shows the radar reflectivity factor obtained with a 95 GHz cloud radar, the middle panel the lidar-ceilometer backscattered signal, and the lower panel shows the liquid water path, which is the total cloud liquid water in a column of 1 m^2 cross-section. The liquid water path is derived from multi-frequency radiometer data. The cloud reflections are very low (less than –30 dBZ); the cloud thickness varies around 300 meter.   The circles in the top panel denote the cloud base observed the ceilometer: it does not alwys coincide with the cloud base that the radar observes. This due to a difference in sensitivity of the two instruments.

Figure 3 shows Z-LWC relationship that is derived from the aircraft data that was sampling the same cloud field as the instruments at Cabauw were observing. The solid lines in the figure are the same regression fits as in Figure 1. They confirm that the cloud situation is similar to clouds observed in other campaigns. Figure 4 shows the histograms of the radar reflectivity factor observed by the radar and its simulation with the aircraft data. A large difference exists: 13 dB. What is the reason for this?

Apart from the example, more days were analyzed. Many of them showed the same trend, although not always with such a large difference of 13 dB: the difference can vary between none and 17 dB. One of the first questions in these types of problems is: are the instruments well-calibrated? The 95 GHz radar was compared with a 35 GHz radar which was located close to the system, but no big differences between the observations of the two instruments were seen. Furthemore, given the fact that the regression fits obtained at other campaigns also fit the aircraft data of this campaign, it is also unlikely that the airboren instruments were faulty. An another important consideration relates to the measurement strategy. Are the

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instruments sensing the same clouds? The answer is: no. The aircrafts is flying long horizontal tracks and the radar is measuring in a fixed vertical column. This means that a one-to-one comparison can not be made; a statistical approach has to be used. To decrease the influence of distance between the aircraft and radar, a subset of the data was analyzed in which the aircraft was flying in the vicinity of Cabauw. This did not reduce the difference. To further explore the impact of distance, a comparison was made with data obtained (albeit at a different day) with a particle measument probes attached to tethered balloon, a couple of hundred meters away from the radar. Also in this case, the radar reflectivity factor was significantly smaller than the simulated values. In {Frisch et al, 2000], a similar difference between radar measurement and aircraft simulation was seen.

4   Synergy of radar, lidar and microwave radiometry

Cloud microphysical properties can not be obtained without sensor synergy. To this end techniques that combine radar, lidar and microwave radiometry have been developed. For instance, the liquid water path obtained with the microwave radiometer can be used to constrain the vertical integration of the liquid water content that is derived through the application of the Z-LWC relationship to real radar data. One such technique [Frisch et al, 2000] fixes β of the Z-LWC relationship and varies α until a good fit is obtained with the liquid water path. The resulting values can then be used to calculate vertical profiles of LWC in the cloud. See Figure 5 for an example. The right panel shows Z-LWC scatter diagram again, but with the radar-derived Z-LWC relationships superimposed on it. Also in this case, the Z-LWC relationships based on real radar data are far below the aircraft simlations. Further analysis revealed that to obtain these fits, number concentrations of cloud droplets are needed that are far more than observed: a 1000 –2000 per cm^3 while the measured values are of the order of several hundreds. So, also in this indirect way a smaller radar reflectivity was observed than could be expected. Similar results were obtained with the IPT-technique of Loehnert et al [2001].

5   Possible reasons for the radar discrepancy

In [Frisch et al, 2000], the difference between radar measurement and aircraft simulation was attributed, albeit without quantitiave motivation, to system inaccuracies and horizontal cloud inhomogeneity. These issues were investigated with the BBC data base, and the obvious effects, like radar calibration, collocation of instruments, antenna near field effects, could be ruled out, leaving more the fundamental question open: is it something physical?

Cloud inhomogeneity will have an effect on the measured radar reflectivity if it has a spatial scale smaller than the radar antenna beamwidth or when the cloud field is passing through the radar beam fast compared to the integration time of the radar. If the latter were a dominant effect, than shortening the integration time would change the variance of the radar reflectivity with the maximum values at least corresponding to a uniformly radar volume. The radar data of the example of Figure 1 was re-processed with a an integration time of 0.06 seconds. No significant effect was seen, meanng that the cloud deck was rather homogeneous. This leaves the other mode of cloud inhomogeneity: variations at the sub-volume scale. As stated in section 2, an obvious sub-volume variation results from the level of adiabicity of stratocumulus. The latter leads to a linear increase of the liquid water content with height and the steeper the slope of this increase the more inhomogeneous the cloud will be. In the radar equation such inhomogeneity is not considered, which can lead to errors. Figure 6 shows the imapct it may have. The κ-parameter is the ratio between LWC at the top and the base of the radar volume; β is the slope of the Z-LWC relationship. On the vertical the axis, the error due to inhomogeneous volume filling is given. Depending on β and κ, an underestimate of a few dB can be made. Although this may explain part of the observed the difference, it is not sufficient to explain to larger observed differences of Figure 2.

A combination of coherent and incoherent addition of the radar waves can also contribute to the observed radar discrepancy. When all cloud droplets act as perfect tracers of wind (there is no influence of the intrinsic fall speed due the particle weight anymore), scattering will occur coherently – unless turbulent air motions at scales smaller than the radar volume randomizes the phases of the radar signals emanating from the individual cloud droplets. The imact of coherent addition will depend on the number of samples used for integration before Z is calculated, as well as the degree of turbulence and the radar wavelength: the shorter the wavelength the lesser the sensitivity to coherent backscatter. Simulations have shown that this

effect can amount to several dB for short integration times. An example of this is shown in Figure 7.

6 Conclusions

This paper presented a puzzling difference between radar observations and expectations based on in situ measured dropsize distributions and results obtained from synergetic use of remote sensing instruments. Several possible explanations for the difference were presented, but no definitive conclusions could be drawn yet. However, it is clear that care has to be taken when radar measurements of stratocumulus are used to retrieve cloud microphysical parameters.

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