P1.20 RETRIEVAL OF CLOUD DROPLET CONCENTRATION OF LIQUID-WATER CLOUDS FROM GROUND BASED REMOTE SENSING OBSERVATION

Ela Grzeszczak,[1] * Hanna Pawlowska[1], Reinout Boers[2], Henk Klein Baltink[2]
[1] Institute of Geophysics, Warsaw University, Poland
[2]KNMI, De Bilt, The Netherlands

1. INTRODUCTION

The environment in which clouds develop is crucial for the cloud microphysics and therefore the cloud radiative properties. The impact of aerosols on climate via modification of cloud radiative properties is called the aerosol indirect effect. Twomey (1977) recognized the connection between increasing concentration of aerosols acting as cloud condensation nuclei and thus increasing cloud droplet number concentration, decreasing droplet size and increasing cloud reflectance. Among different cloud types, low-level clouds such as stratocumulus affect mostly solar radiation reaching the surface because their radiative temperature is not much different of the underlying surface. These clouds are also mostly affected by changing aerosol loading in the atmospheric boundary layer.

Satellite measurements have shown evidence of the impact of the local enhancement of the atmospheric aerosol on cloud reflectivities known as the 'ship tracks' effect (Radke et al. 1989, Durkee et al. 2000). Brenguier et al. (2000) found experimental evidence of the first indirect aerosol effect in Scu clouds from in-situ measurements during ACE-2.

Observation of the aerosol indirect effect is difficult because the effect depends on microphysical and macrophysical, thus dynamical properties of stratocumulus clouds. In order to assess the aerosol indirect effect continuous monitoring of cloud properties is needed. Presently this can be realized by remote sensing observation. One of the most important characteristic of cloud is the cloud droplet number concentration. The methods to retrieve such cloud properties rely model simulations, which describe clouds in a simplified manner by only using a few parameters.

This paper presents a method to retrieve the droplet concentration for boundary layer, nonprecipitating, water clouds using collocated ground-based remote sensing observations from radar, ceilometer and microwave radiometer. Section 2 describes the method to retrieve droplet concentration with the necessary assumptions. Section 3 introduces radar signal analysis with the result based on Large-Eddy-Simulation of Stratocumulus data. Section 4 presents results of droplet concentration retrievals from real data collected at Cabauw. Section 5 summarizes the results.

2. THE METHOD

Ground based remote sensing instruments that are used for continuous monitoring cannot measure the microphysical properties of clouds directly. However, they can measure the parameters which are related to the moments of the droplet size distribution. The remote sensing based input data used by our retrieval method are: cloud base height measured by ceilometer, cloud top height and reflectivity factor profile measured by radar, liquid water path measured by microwave radiometer and temperature and pressure at the cloud base from radiosounding measurements. The method is based on Frisch method (Frisch et al., 1994), where droplet concentration is assumed to be constant with height. This assumption is only valid in adiabatic clouds i.e. a cloud growing only by condensation without any entrainment/mixing events or drizzle formation process. We will therefore limit our droplet concentration retrievals to cloud samples that are not far away from adiabatic assumption. Clouds particles in these clouds are Rayleigh scatters; the particle size is much smaller than the radar wavelength. Hence, the radar reflectivity factor $Z(z)$ can be described by equation:

$$Z(z) = 64\, N\, \left\langle r^6 \right\rangle \qquad (1)$$

where z - height above cloud base, N - droplet concentration, $\left\langle r^6 \right\rangle = \int_0^\infty n(r) r^6 dr / \int_0^\infty n(r) dr$ is the sixth moment of the droplet size distribution $n(r)$. This moment can be indirectly retrieved from the liquid water content formula:

$$LWC(z) = \frac{4}{3}\pi \rho_w \left\langle r^3 \right\rangle N \qquad (2)$$

where ρ_w - water density and $\left\langle r^3 \right\rangle = \int_0^\infty n(r) r^3 dr / \int_0^\infty n(r) dr$ is the third moment of the droplet size distribution. We assume that the third and sixth moments of the droplet size distribution are related as follows:

$$\left\langle r^6 \right\rangle = k_2^2 \left\langle r^3 \right\rangle^2 \qquad (3)$$

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[*] *Corresponding author address*: Ela Grzeszczak, Institute of Geophysics, Warsaw University, ul. Pasteura 7, 02-093 Warszawa, Poland; e-mail: ela@igf.fuw.edu.pl

where k_2 coefficient was estimated based on in situ measurements of droplet spectra in clouds during ACE-2 and DYCOMS-II campaign and set to number $k_2 = 1.1$.

By using equations (1)-(3) the reflectivity factor profile is related with the liquid water profile as following formula presents:

$$Z(z) = 36\frac{LWC(z)^2 k_2^2}{\pi^2 \rho_w^2 N} \qquad (4)$$

If the liquid water content profile is known, the droplet concentration can be calculated from equation (4) by fitting radar reflectivity factor profile $Z(z)$ to the $LWC(z)$ profile. It is evident that the liquid water content profile strongly affects the retrieval. In adiabatic clouds the droplet concentration is constant with height and the liquid water content increases linearly with height with a constant condensation rate (Brenguier, 1991). In stratocumulus clouds the cloud top is strongly affected by entrainment, hence the LWC is substantially reduced. To account for these deviations, a nonlinear shape of LWC has been assumed; this shape has been constrained by the information from remote sensing data.

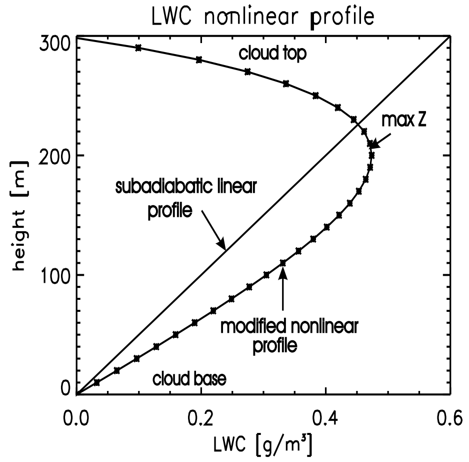

Fig. 1: A new nonlinear LWC profile constrained by the remote sensing data is compared with linear LWC profile.

The LWC shape used in our method relies on several assumption: 1) LWC is distributed in the estimated cloud boundaries with $LWC(z = z_{base}) = 0$ and $LWC(z = z_{top}) = 0$ and satisfies the relation $LWP = \int_{z_{base}}^{z_{top}} LWC(z)dz$, where LWP is known from the microwave radiometer measurements, 2) the height of the maximum value of the LWC corresponds to the height of the maximum value of reflectivity factor z_{max}. The mathematical formula that satisfies these conditions is:

$$LWC(z) = A\left(C_w\frac{z}{H} - B\left(exp(\frac{z}{Hz_0}) - 1\right)\right) \qquad (5)$$

where H - cloud thickness, C_w - corresponds to the linear relationship between LWC and z ($LWC(z) = C_w z$) and for a known liquid water path is calculated from relation $LWP = \frac{1}{2}C_w H$. Parameters A, B and z_0 are calculated to meet above two assumptions. The shape of the LWC profile is shown in Figure 1.

3. LARGE-EDDY-SIMULATION DATA AND RADAR SIGNAL ANALYSIS

The non-hydrostatic mesoscale atmospheric model of the French community (Meso-NH model) computes 3D dynamics (Homepage of the Meso-NH model documentation). The model is intended to be applicable to all scales ranging from small (large eddy) scales to large (synoptic) scales.

To assess the performance of our retrieval technique we used data from one of the realization of meso-NH model which is a Large Eddy Simulation (LES) of Stratocumulus with a bulk microphysical parameterization. The microphysics is calculated with the bulk scheme of Khairoutdinov and Kogan (1999). In that scheme liquid water is divided into two categories, cloud droplets (with negligible velocity) and drizzle droplets (starting with a diameter D=40μm), similar to the Kessler-type parameterization (Kessler et al., 1969). The cloud/drizzle water mixing ratios and cloud/drizzle drop concentrations are predicted in new scheme. In our analysis we used simulated data with a domain size of 2.5km in horizontal and 1.2km in vertical direction, whereas the grid spacing in the horizontal is 50m and in the vertical is 10m.

In order to simulate radar signals for each grid box a droplet size distribution needs to be chosen. One of the common proposed distribution is a generalized gamma distribution with 4 parameters λ, N_c, α, ν, (Cohard et al., 2000):

$$n_c\left(D\right) = N_c\frac{\alpha}{\Gamma\left(\nu\right)}\lambda^{\alpha\nu}D^{\alpha\nu-1}exp\left(-\left(\lambda D\right)^{\alpha}\right) \qquad (6)$$

where D - diameter, N_c - droplet concentration, $\Gamma(\nu)$ - gamma function, $\lambda = \frac{1}{D_v}\left(\frac{\Gamma\left(\nu+\frac{3}{\alpha}\right)}{\Gamma(\nu)}\right)^{\frac{1}{3}}$ - slope parameter, D_v - mean volume diameter, α, ν - dispersion parameters set to the value of 3 (Olivier Geoffroy - private communication).

The formula for the *n*th moment of distribution is written as follows:

$$M_n = \frac{1}{\lambda^n}\frac{\Gamma\left(\nu+\frac{n}{\alpha}\right)}{\Gamma\left(n\right)} \qquad (7)$$

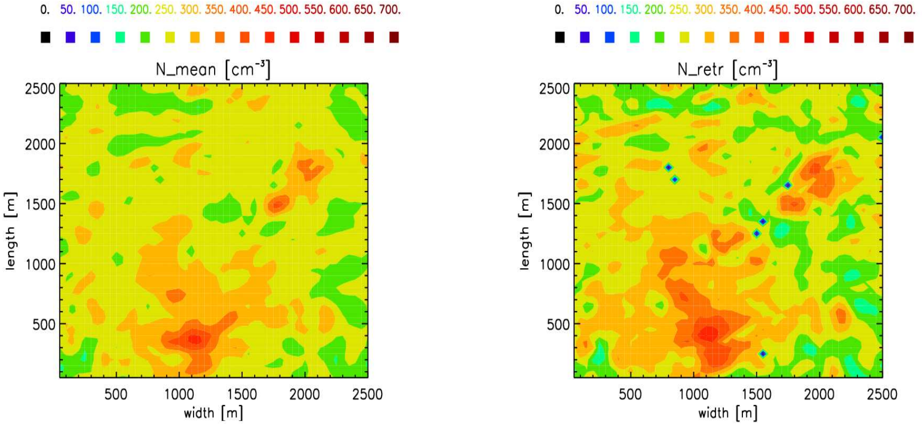

Fig. 2: Model mean droplet concentration derived in each vertical column of the model domain (N_{mean}) is compared against the retrieved values (N_{retr}).

Simulated radar signals from LES-microphysical output were used to derive a 2D field of droplet concentration. Figure 2 compares the retrieved droplet concentration for the entire domain (for simulated radar signals, integrated liquid water content and estimated cloud base height and cloud top height from the LES model we apply our method to retrieve droplet concentration) against the original LES output (mean droplet concentration for each vertical column). Figure 2 shows similar pattern and that illustrates the fact that our retrieval works reasonably well. The small, blue fields on the right figure suggest the presence of small cumulus clouds underlying stratocumulus. The LWC of these cumulus clouds is sufficient to cause the lower cloud base estimation in the algorithm and creates nonlinear LWC profile typical for double layer clouds.

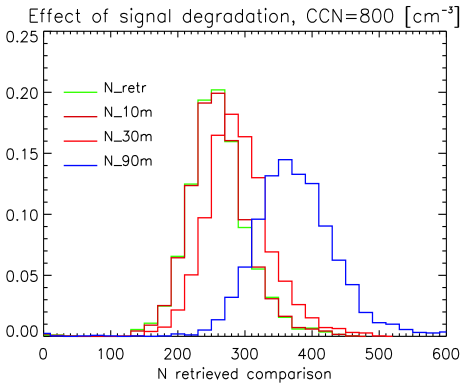

Fig. 3: Histogram of the retrieved droplet concentration numbers using reflectivity profiles from model (N_{retr}) and coarsened reflectivity profiles with different digitization rates (10m, 30m, 90m).

To simulate normal operating conditions for radar the LES reflectivity profiles were coarsened (Baedi et al., 2002) by applying the following steps: 1) convolution of Z with Gaussian shape signal function 2) digitization of the convoluted signal with a defined radar resolution (10m, 30m, 90m).

The retrieval method described in section 2 was reapplied. Figure 3 illustrates the radar signal analysis. The figure 3 presents comparison of histograms for droplet concentration which were retrieved with different rate of signal degradation. We observe that the droplet concentration retrieved from coarsened signal resulted in a larger overestimation of than the retrievals from original signal.

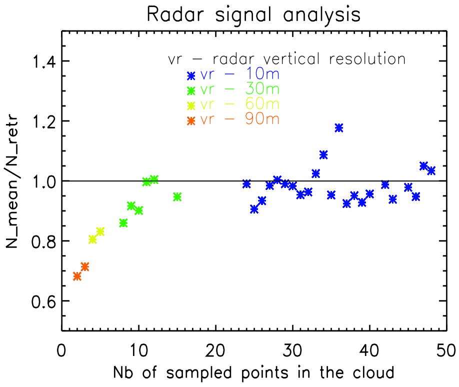

Fig. 4: Averaged ratio of the mean to the retrieved droplet concentration values for each number of sampled points. Typically for Scu of 300m N_{retr} exceeds N_{mean} of 10%.

Figure 4 presents the ratio of mean to retrieved droplet concentration for different radar resolution versus the number of sampled point in the cloud. The figure shows that a radar with vertical resolution of 10m would provide reasonably good data input data for our algorithm. The retrieval simulations demonstrate that the available data from radar of 30m resolution for typical Scu clouds causes in the technique about 10% of overestimation.

4. THE REAL WORLD APPLICATION

In this section we present results from the retrievals using data from Baltex Bridge Cloud (BBC) campaign at Cabauw (Homepage of the Cloud Liquid Water Network project). Our technique was applied to a sample of data from 13 August 2001. Ceilometer CT75 with spatial resolution of 15m and temporal resolution of 30s was used to estimate cloud base. The radar data used comes from KNMI 35GHz radar with vertical resolution of 90m and temporal resolution of 20s to 30s. The liquid water path was measured every 1s by microwave radiometer - MICCY. The retrieval method was tested for observations with homogeneous, non-precipitating stratocumulus cloud. The remote sensing data were averaged over the smallest temporal resolution, 30s.

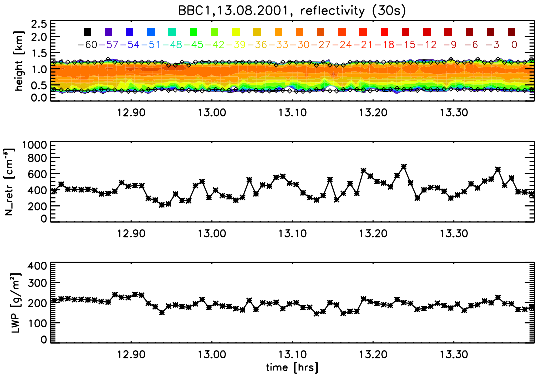

Fig. 5: Time series of 1) reflectivity factor with indicated cloud top and cloud base height; 2) retrieved droplet concentration numbers; 3) LWP measured by microwave radiometer.

Figure 5 shows for 13 August 2001 the measured reflectivity (first panel), the retrieved droplet concentration number (second panel), the liquid water path (third panel) and the cloud geometry using 30s ground based remote sensing data. Unfortunately, no research flight was performed during that day. Hence, the results were not compared with in situ data.

5. SUMMARY

Our retrieval technique was applied in non-drizzling one-layer water clouds. The method is sensitive to several issues: cloud base estimation, coarseness of signal (by decreasing the digitization rate the retrieved values increase), adiabaticity (only in clouds with liquid water content close to adiabatic values the algorithm perform with reasonably results).

Acknowledgments

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