Comparing ice-cloud microphysical properties using CloudNET and ARM data

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1. INTRODUCTION

The importance of ice clouds in the Earth's radiation budget is well recognized (Arking 1991). Depending on their optical thickness, altitude and microphysical properties, ice clouds can either cause warming (greenhouse effect) or cooling (albedo effect) at the Earth's surface. Cirrus clouds cover more than 20% of the globe (Wylie and Menzel 1999) making it an important issue to know what the balance between these two processes turns out to be.

Because of uncertainties concerning the properties of ice clouds and the complex interactions between microphysics and radiation in these clouds, as well as the dynamics of the environment (Quante and Starr 2002), ice clouds are not well treated in climate and forecasting models.

An important parameter for determining the radiative characteristics of a cloud is the effective radius ($R_{\rm eff}$) of its particles. For a given cloud volume, $R_{\rm eff}$ determines the relationship between the total mass and optical depth and influences the associated phase function and single-scattering albedo. For ice particles we may define

$$R_{\rm eff} = \frac{3}{4}\frac{\langle M(D)/\rho_i\rangle}{\langle A_c(D)\rangle}, \quad (1)$$

where the braces denote averaging over a particle size distribution, D is the particle maximum dimension, M the mass, A_c the cross-section area and, ρ_i the density of solid ice.

Since the explicit treatment of ice cloud microphysics is beyond the capabilities of large scale atmospheric models, it is necessary to parameterize their microphysical properties. Previous parameterizations of ice cloud $R_{\rm eff}$ have been formulated using in sit observations using aircraft mounted instrumentation. In situ approaches more-or-less directly measure the particle size distribution. However, it is difficult to obtain large in situ data sets. In contrast, lidars and radars sample entire cloud profiles instantaneously and may operate continuously for long periods of time.

In this paper, we compare long time-series of ice cloud effective radii and ice water content (IWC) derived from combined lidar and radar observations. The measurements were made at the Atmospheric Radiation Measurement Program's Southern Great Plains (ARM-SGP) site and the Cabauw site (the Netherlands, part of CloudNET).

In this work, the differences seen at the two sites are discussed. In addition, the possibility that particle size may be parameterized according to geometrical depth into the cloud seen from cloud-top is presented. A more detailed comparison can be found in van Zadelhoff and Donovan (2004).

2. ALGORITHM FOR LIDAR/RADAR REMOTE SENSING

The cloud microphysical properties used in this work have been derived using both lidar and radar signals. The procedure used to calculate the microphysical properties has been extensively described in Donovan et al. (2001) and Donovan and van Lammeren (2002). In this section a short summary on the procedure is given.

The lidar/radar effective radius is defined as

$$R'^4_{\rm eff} = \frac{9}{16\pi\rho_i^2}\frac{\langle M^2(D)\rangle}{\langle A_c(D)\rangle} = R_{\rm eff}\frac{3}{4\pi\rho_i}\frac{\langle M^2(D)\rangle}{\langle M(D)\rangle}, \quad (2)$$

which can be directly linked to the radar reflectivity ($Z_e \propto N_o\langle M^2(D)\rangle$) and optical extinction ($\alpha_{\rm lid} \propto N_o\langle A_c(D)\rangle$). The last term is obtained when inserting Equation 1 in Equation 2.

For lidar cloud measurements, multiple scattering can significantly contribute to the observed signal. A treatment of the multiple-scattering effects has been incorporated into the inversion process. The procedure has been found to be stable with respect to variations in the cloud backscatter-to-extinction ratio profile as well as measurement errors.

$R'_{\rm eff}$ can be looked at as the second moment of $R_{\rm eff}$ (Equation 1). The advantage of using $R'_{\rm eff}$ is its direct link to the observations, however it lacks

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a direct link to the calculation of the radiative influence due to ice particles. For this, a suitable particle habit (shape, orientation) and particle size distribution has to be adopted in order to estimate R_{eff} based on R'_{eff}.

In this paper all the particle sizes are given as the lidar/radar radius (R'_{eff}) and lidar/radar effective ice water content ($IWC' = IWC \times R'_{eff}/R_{eff}$).

3. USING THE ARM AND CLOUDNET DATA

In this comparison we make use of data from two facilities. The first is the U.S. Southern Great Plains Site established by the Atmospheric Radiation Measurement (ARM) Program, from here on referred to as the ARM site.

The second site is Cabauw (the Netherlands), which participates in the EU funded CloudNET research project. In all cases presented below the results for Cabauw and Chilbolton (another site within the CloudNET project) are the same within the error-bars.

In order to give a fair comparison of all the data, the similarities and differences in instruments at each of the sites have to be recognized and taken into account. The two instruments used for this comparison are a lidar and radar. In the case of the radar both the sites have a 35 GHz doppler-radar with similar sensitivities. In comparison, the lidars have different performance characteristics, where a CT-75K Ceilometer is placed at Cabauw, the ARM site uses the Multi-Pulse Lidar (MPL). The latter has a higher sensitivity compared to the CT-75K.

To make it possible to compare the data-sets a subset is defined for the sites. The subset is limited to those clouds which are fully visible in both the lidar and radar simultaneously, e.g. the cloud-top height seen by both the radar and lidar should be similar. The clouds fulfilling the criteria can reach optical depths up to $\tau \sim 4$.

4. COMPARING ARM AND CLOUDNET DATA

In the literature there has been much emphasize on finding particle size to temperature relationships (e.g. Boudala et al. 2002, Garrett et al. 2003) or a combination of temperature and IWC (e.g. McFarquhar et al. 2003, Donovan 2003). It is therefore of interest to see if these two different sites can be described by a same parameterization. First, however the effective particle sizes are correlated to their measured Doppler velocity (Figure 1). For ice particles, with a single habit and particle size distribution, it is expected that the fall velocity depends on its size only (e.g. Heymsfield and Iaquinta 2000, Khvorostyanov and Curry 2002).

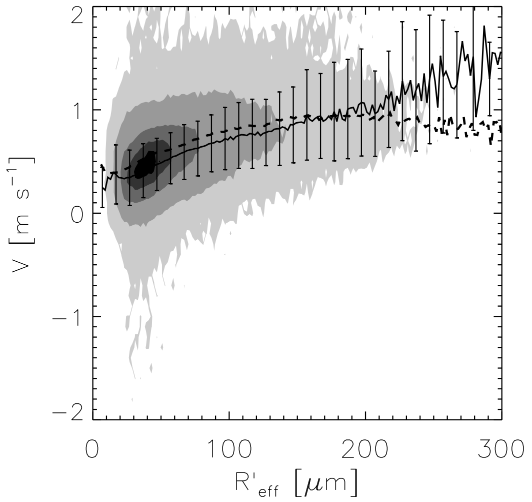

Figure 1: *Cumulative probability density plot of the occurrence of the Doppler velocity as measured by the radar to the calculated R'_{eff}. The greyscales, from dark to light, show the 10, 30, 60, 90 and 99 % probability of occurrence. The solid line shows the mean particle size at each temperature with the error-bars indicating the 1 σ level of the distribution. The dashed line shows the mean particle size as deduced from the ARM data.*

The distributions plotted in Figure 1 are wide but the mean doppler velocities for each effective particle size found at both the ARM site and the Cabauw site show a remarkable similarity. The same relation is observed at the Chilbolton site (not shown). As this is based solely on the observed quantities and no habit information or particle size distribution has been adopted, this suggests that a common mean ice particle habit, or habit combination, and size distribution at these sites dominates the statistics. More importantly the observed similarity implies that no large technical problems (such as radar calibration errors) are present that would prevent a meaningful comparison between each other.

In Figure 2 a correlation of the particle sizes and temperatures is made. The sizes of the distributions are comparable for the two sites, where it is clearly seen that the mean particle size at each temperature is higher at the ARM site. Secondly, it becomes clear that there are particles observed at lower temperatures at the latter site. This is due to the observed height of the cloud-tops within

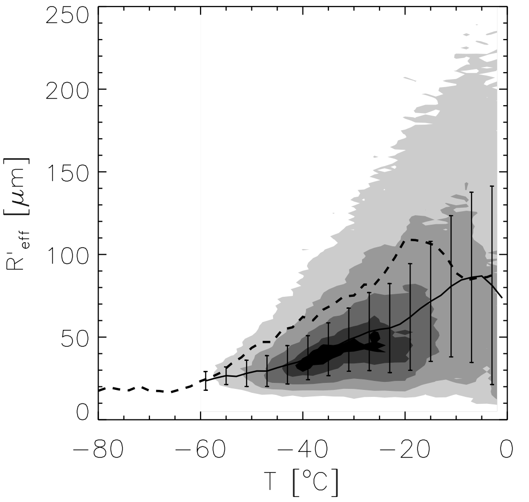

Figure 2: *Cumulative probability of occurrence of R'_{eff} as a function of temperature for optically thin ($\tau_{\text{vis}} \leq 4$) clouds at Cabauw. The contours and annotations follow the same scheme as in Figure 1.*

the sample; the ARM site has clouds reaching up to heights of 16 km, whereas the maximum cloud heights observed at the Cabauw site is 12 km. This comparison implies that the particle size-temperature relationships exist locally but that it is not possible to construct a simple global parameterization based on temperature only.

For a parameterization based on combination of IWC′ and T, the temperature versus IWC′ correlation should be different for the two sites to compensate for the differences seen in Figure 2. In Figure 3, the IWC′ is related to temperature for the Cabauw and ARM site. The two means overlap each other with a similar width of the distributions. The slope of the two means is slightly different, with hardly any temperature dependence at Cabauw and a small slope at the ARM site. Combining this with the previous results, the R'_{eff}(T) differences observed do not seem to be related to IWC′ differences.

When plotting R'_{eff} versus temperature (Figure 2), effectively one compares R'_{eff} to the height of the clouds at the different sites and not directly to the influence of the temperature on the microphysics, e.g. coagulation of particles or freezing onto particle seeds. Therefore the R'_{eff} is related to the depth into the cloud seen from cloud-top ($Z_t - Z = \Delta Z_t$) in order to use a cloud related criteria (Figure 4), for all observed cloud thicknesses.

Even though the distribution is wide, the mean values for the two sites are very similar for depths up to 3 km. The two curves diverge for clouds with a depth greater than 3 km, which has to do with the differences in observed clouds statistics, especially total cloud thicknesses. Also here the results obtained at the Cabauw, ARM and

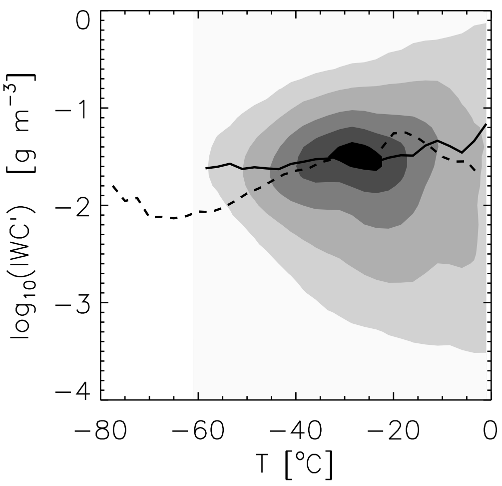

Figure 3: *Cumulative probability of occurrences of the ice water content (IWC′) as a function of temperature (T). The contours and annotations follow the same scheme as in Figure 1.*

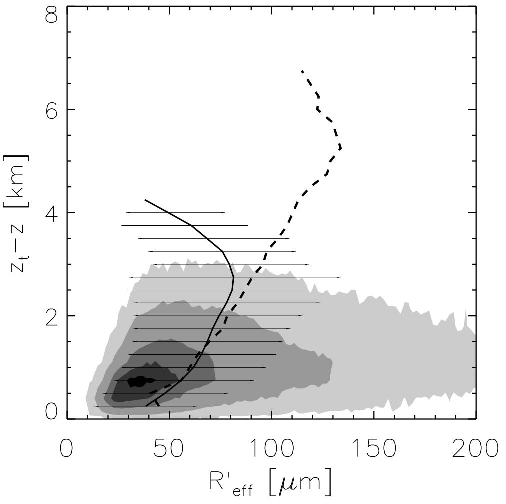

Figure 4: *Cumulative probability of occurrence of the particle size (R'_{eff}) to the depth in the cloud seen from cloud-top is made, where 0.0 stands for cloud-top. The contours and annotations follow the same scheme as in Figure 1.*

Chilbolton sites are the same, within the error bars (for more information, see van Zadelhoff and Donovan 2004).

If this feature can be observed on more points on Earth, using the CloudSAT and Calipso combination, a parameterization of particle sizes may be constructed depending on the depth into the cloud(ΔZ_t) and total thickness(H) of the cloud.

5. CONCLUSION

In this work a comparison on the microphysical properties of ice is presented for the ARM-SGP site and the Cabauw site. The main conclusions can be summarized as follows:

- The mean Doppler velocity at each of the mean derived particle sizes ($R'_{\rm eff}$) is the same for all three sites. This suggests that the statistics at each of the sites is dominated by a common ice-habit and particle size distribution. For individual clouds, the habits may be quit different.
- The ice water content (IWC')-temperature relation is similar at the two sites. The IWC' seems not to depend on temperature at the Cabauw site and has a small slope at the ARM-site.
- It does not seem possible to construct a global $R'_{\rm eff}(T)$ or $R'_{\rm eff}(T,IWC)$ parameterization.
- The particle size ($R'_{\rm eff}$) versus depth into cloud from cloud top (Z_t-Z=ΔZ_t) shows very similar results for the three sites. The $R'_{\rm eff}(\Delta Z_t)$ profiles show increasing particle sizes for thicker(H) clouds. This can lead to a global parameterization of ice microphysical properties to include in GCMs.

The Cloudsat/Calipso combination should be able to confirm these results and make a global effective radius parameterization possible.

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