IMPACT OF DRIZZLE AND 3D CLOUD STRUCTURE ON REMOTE SENSING OF CLOUD EFFECTIVE RADIUS

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Abstract

Remote sensing of cloud particle size with passive sensors like MODIS is an important tool for cloud microphysical studies. As a measure of the radiatively relevant droplet size, effective radius can be retrieved with different combinations of visible through shortwave infrared channels. The resulting effective radii are often quite different, indicative of different penetration depths for the spectral radiances used. Operational liquid water cloud retrievals are based on the assumption of a relatively narrow distribution of droplet sizes; the potential impact of precipitation on these distributions is neglected. MODIS observations sometimes show significantly larger effective radii in marine boundary layer fields derived from the 1.6 and 2.1 µm channel observations than for 3.7 µm retrievals.

Possible explanations range from 3D radiative transport effects and sub-pixel cloud inhomogeneity aspects to the impact of drizzle formation. To investigate possible factors of influence, we use LES simulated boundary layer cloud situations in combination with 3D Monte Carlo simulations of MODIS observations. LES simulations of warm cloud spectral microphysics for cases of marine stratus and broken cumulus produce cloud structures comprising droplet size distributions with and without drizzle size drops. From 3D radiative transport simulations considering individual droplet size distributions synthetic MODIS observations are obtained. On these scenes the operational MODIS effective radius retrievals are applied and the results are compared to the given LES microphysics.

INTRODUCTION

Standard passive cloud remote sensing retrievals are based on a few simplifying assumptions: (1) clouds are assumed to be plane-parallel homogeneous within each pixel, (2) pixels are independent, and (3) clouds consist of small cloud droplets only. The impact of real cloud situations not fulfilling the first two assumptions has been investigated in several studies (e.g., Marshak et al., 2006; Zinner and Mayer, 2006). The consequence of the last assumption has hardly been addressed in detail so far (e.g., Minnis et al, 2004).

The typical size distribution of cloud droplets used in the radiative transfer simulations to create the forward libraries of plane-parallel cloud properties and correlated reflected radiance is narrow. It is often approximated by Gamma functions defined by effective radii r_{eff} between 5 and 25 µm, and by dimensionless effective variances ν_{eff} of 0.05 or 0.1, e.g., in the MODIS cloud retrieval MOD06 (King et al., 1997; r_{eff}=5-25 µm, ν_{eff}=0.1). The thick red line in Figure 5 shows the Gamma function with an effective radius of 15 µm and effective variance of 0.1. From such narrow drop size distributions (DSD) optical properties are derived using Mie calculations. Narrow DSD are realistic as long as clouds do not start to develop precipitation. Usually the presence of a few large precipitation size drops is regarded negligible in radiative transport simulation and cloud remote sensing, because they do not contribute much to the overall cross section and volume which define the extinction.

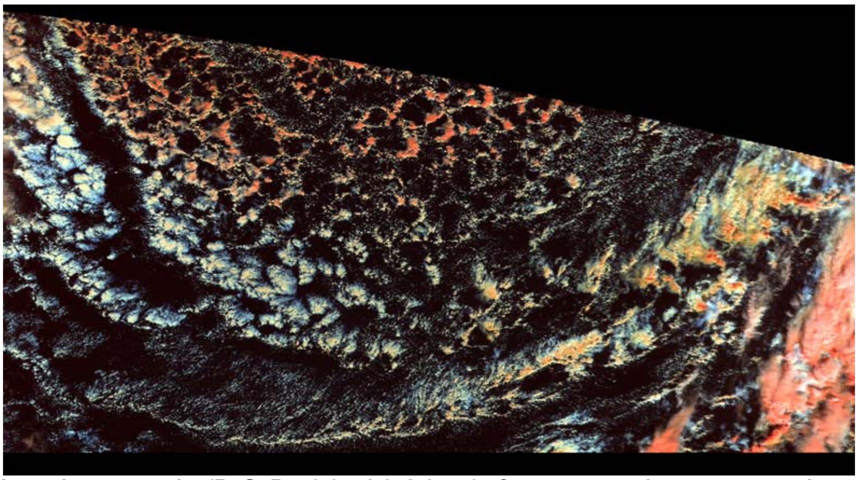

Figure 1: **SWIR false color composite (R, G, B = 0.65, 1.6, 2.1 µm) of a stratocumulus scene over the northern subtropical Atlantic, 21 Nov 2004, 1430 UTC, 1 km level 1B data.**

For rain drops at sizes of much more than 1 mm this is probably correct, but precipitation, especially in a marine environment with low cloud condensation nuclei numbers often develops drizzle. Drizzle droplets in the size range just above the typical cloud droplet sizes around 10-20 µm are much more numerous than larger rain drops. This is why some studies suspect that drizzle formation might be visible in passive remote sensing observations (Minnis et al., 1997, Chang et al., 2003).

At the same time, MODIS observations of cloud morphology which is usually linked to drizzle processes often show interesting features. Figure 1 shows marine stratocumulus clouds of the so called open and closed cells type. Obvious is the difference in color of the area of open cells, usually linked to drizzle formation, in the upper left half of the image compared to the closed cells just south of them in the left central part of the image. In this false color image red color stands for reduced near-infra red (NIR) contributions compared to the visible reflectance of the clouds. This can be due to large strongly absorbing ice particles (cf. the cirrus clouds in the lower right corner) or to large droplets. Figure 2 shows a further feature of the Figure 1 cloud scene which might hint to drizzle formation in this area. The evaluation of the MODIS effective radius retrievals for the open cell area in the upper left of Figure 1 reveals that the r_{eff} retrievals from the 0.8 µm /3.7 µm channel combination shows smaller droplets than the retrieval from 0.8 µm /2.1 µm. This is consistent with the picture that the wavelength less absorbed by liquid water droplets 2.1 µm can see the increasing influence of drizzle formation on the particle size deeper down in the cloud while the 3.7 µm signal is only affected by the particles from a thin layer at the top of the clouds where drizzle formation does not take place.

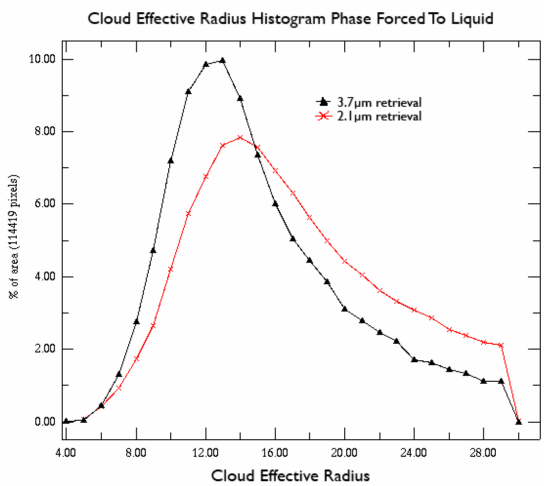

Figure 2: Histogram of two MOD06 effective radius retrievals for the area of open cells in the upper left part of Figure 1.

Other candidate sources for this type of difference are shadow effects or cloud masking deficiencies affecting the MODIS retrieval. Both are not unlikely to appear in such a complex cloud scene. Cloud top height variations are large in this cloud area causing sharp shadows; cloud masking is not easy in this type of cloud with strong small scale contrasts of illuminated and shadowed cloud areas and cloud free areas. Both effects have the potential of reducing NIR reflectances (and thereby mimicking large r_{eff} retrievals, Marshak et al., 2006). All these effects have in common that there is no direct way to separate them and no easy way to validate any of the conclusions one might reach by analyzing the satellite observational perspective alone. This brings us to the approach of synthetic satellite data based on realistic cloud simulations, the application of retrievals to be tested on these synthetic observations, and the subsequent comparison of retrieved properties to the given cloud properties. This approach has the further advantage that radiative transport as well as cloud input data can be modified in a targeted manner to test the sensitivity of retrievals to the modified characteristic. The retrieval is put in a closed fully controlled "simulation laboratory".

We will introduce the cloud data sets from LES with spectral cloud microphysics used for this experiment and then show how this complex cloud data is prepared to serve as input to a 3D radiative transfer model. Finally, we present first examples of the application of a slightly modified MODIS cloud property retrieval to the simulated MODIS observations in 4 channels.

CLOUD DATA

Figure 3 introduces the cloud data used in the simulated environment. It is data from an LES cloud model (Ackerman et al., 2003). The cases were simulated for the RICO (Rain In Cumulus over the Ocean, unpublished manuscript by M. van Zanten et al.) and FIRE-I campaigns (First ISCCP Regional Experiment, Ackerman et al., 2004). The model uses a spectral microphysics setup for the liquid phase with 25 and 20 droplet size bins, respectively. Both simulations, the highly complex cumulus and the almost plane-parallel stratus, show drizzle formation (red and grey areas in Figure 3). In the stratus case almost no drizzle sized drops can be found at the top of the cloud, while the situation is less clear for the cumulus case. This is clearly visible in the effective radius cross sections presented in Figure 4 as well. In the stratus case precipitation dominated size distributions (r_{eff} > 35 μm) are generally at the bottom or below the cloud layer while the cloud layer itself shows, at least on average, the layering typical for marine stratocumulus with smaller droplets at the bottom of the cloud and larger droplets at the top. For a single convective cell the situation is similar for the cumulus case, but here large effective radii, i.e., drizzle is all over the place, sometimes even on top of the cloud cells.

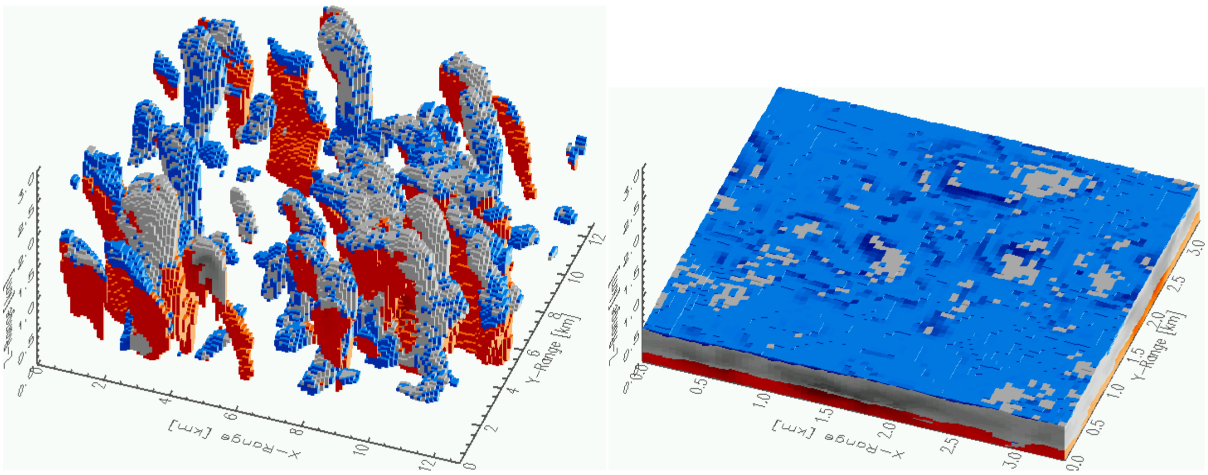

Figure 3: **Cloud data sets from LES simulations: (Left) trade wind cumulus, 128 x 128 x 100 boxes, 100 x 100 m horizontal resolution (RICO campaign, unpublished manuscript by M van Zanten et al.), (Right) marine stratus, 64 x 64 x 64 boxes, 52.5 x 52.5 m horizontal resolution (FIRE-I experiment, Ackerman et al. 2004). Plotted are 3D surfaces of each box containing water. Darker colors show larger water content. The cloud droplet liquid water is depicted in blue, drizzle drop water in red, and mixed areas in grey.**

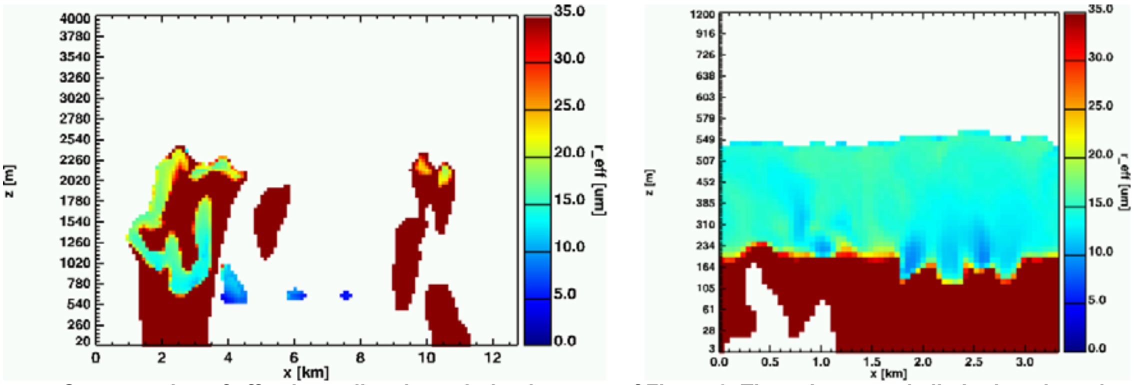

Figure 4: **Cross section of effective radius through the data sets of Figure 3. The color range is limited to show details of small cloud droplet sized r_{eff}.**

Figure 5 shows drop size distributions from the cumulus case. All these distributions have in common an effective radius of 15 µm. The standard assumption of cloud property remote sensing is the narrow DSD not considering any drizzle for simplicity reasons. This distribution is represented by the thick red line in Figure 5, a Gamma distribution with ν_{eff}=0.1. All other lines show 12 random distribution examples from the LES. It is obvious that distributions in this drizzling case are generally wider than the assumed Gamma DSD.

One of the reasons why narrow analytic functions (e.g. Gamma with fixed variance) are widely used to derive cloud optical properties for radiative transfer simulations is that this way it becomes possible to cover a realistic range of (non-drizzling) drop size distributions by just modifying one parameter – the effective radius. Thus, RT simulations do not consider the full variety of realistic DSD (Figure 5), but can use a simple table of optical properties as a function of effective radius. Once the broadening of the DSD due to precipitation should be included, the table of optical properties and of forward RT solutions had to include another dimension – the width of DSD. For the backward RT problem – the retrieval – this would in turn increase the number of solutions to choose from, most likely exceeding the information content in a few channel's observation.

In this experiment at least the width of the distribution has to be considered as the second variable on which the optical properties in an RT model depend. We decided to reduce the variety of real drop size distributions from the cloud model for the RT simulation of synthetic MODIS observations by separating a narrow cloud droplet mode from a wider drizzle droplet mode. Although we do not cover all possible DSD, we are able to approximate size distributions like the ones shown in Figure 5a. Figure 5b shows an example of this approximation. Two Gamma functions – one with ν_{eff}=0.1 representing the cloud mode and one with ν_{eff}=0.175 representing the drizzle mode – are fitted (cross section weighted) to each distribution from the cloud model. Total cross sectional area and total LWC are held constant in the process.

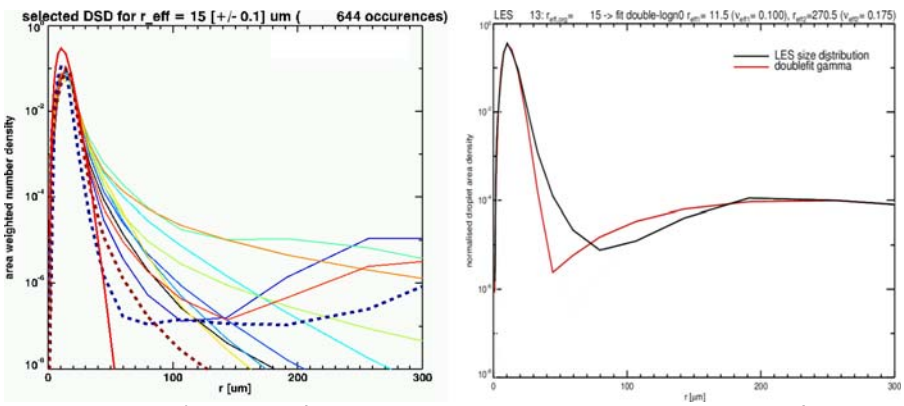

Figure 5: **Drop size distributions from the LES cloud model compared to the classical narrow Gamma distribution (thick red line). All DSD have the effective radius 15 µm.**

In the example shown, a simulated DSD with an effective radius of 15 µm is approximated by a cloud effective radius of 11.5 µm and a drizzle effective radius of 270.5 µm. This way, not only distributions with distinct second precipitation mode (as in Fig. 5b), but also the many “wide tail” DSD (Fig. 5a) are approximated well (in terms of the optical properties of the fit compared to the full distribution – not shown).

For each LES cloud model box, the liquid water content is divided into its cloud water and the drizzle water content according to this separation of modes of the drop size distribution. Thus two 3D fields each with water content and effective radius define the optical properties for the drizzling cloud scene (see Fig. 3).

RADIATIVE TRANSFER

For all radiative transfer purposes the package libRadtran is used (Mayer and Kylling, 2005). Optical properties are calculated as a function of effective radius for the narrow DSD cloud droplet mode and the wide DSD drizzle droplet mode separately using a Mie code. For the simulation of the synthetic MODIS observations the 3D Monte Carlo code MYSTIC is used (Mayer, 2000). MYSTIC accepts two 3D fields of cloud properties and related optical properties tables usually used to provide ice and water cloud input. This feature is used to set up the separate cloud and drizzle 3D fields. For these data sets different simulations of satellite reflectance are conducted with the aim to separate the different effects for later analysis: full 3D simulations and 1D independent column simulations to exclude 3D effects (not shown in this paper) as well as simulations with and without the drizzle field. A band model of the MODIS channels 2 (centered at 0.87 µm wavelength), 6 (1.6 µm), 7 (2.1 µm), and 20 (3.7 µm) is used to simulate the radiance at top of atmosphere for a nadir view and solar zenith angles of 10° and 45°. To limit the number of possible effects on the retrieval algorithm to a minimum, absorption and scattering by other atmospheric constituents and the surface are neglected. For the same reason, only the solar part of the radiance is simulated for channel 20. Instead of using the available 1D radiance libraries of the MODIS MOD06 retrieval, these libraries were re-generated using the libRadtran package to eliminate effects due to RT model inconsistencies.

Examples of the 3D simulations are shown in Figure 6. The simulation is done on the full cloud model resolution and the reflectance results are then averaged to MODIS spatial resolution.

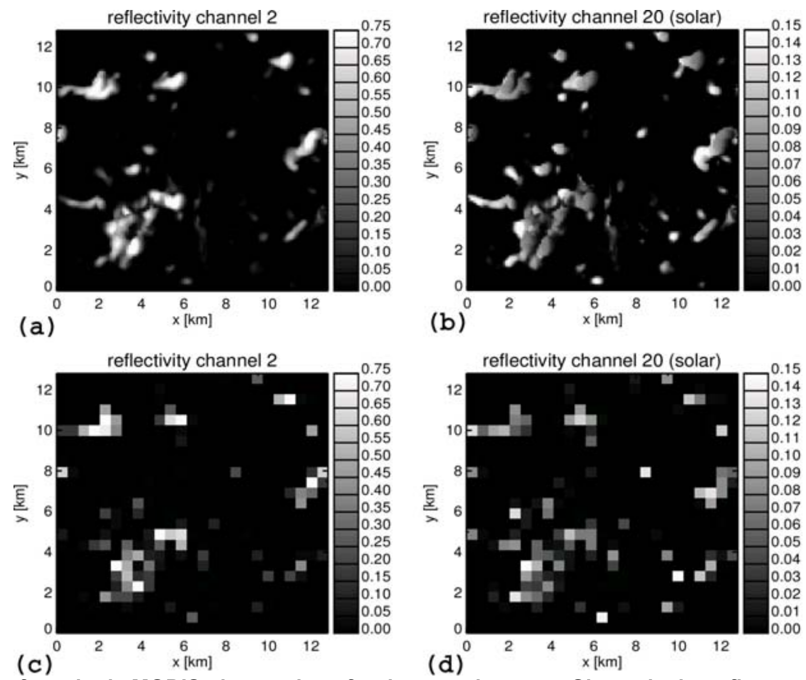

Figure 6: **Examples of synthetic MODIS observations for the cumulus case. Shown is the reflectance in channels 2 (a, c) and 20 (b, d, solar only) at 100 m resolution and 500 m (c, d) resolution. The solar zenith angle is 45° (sun to the left), the viewing zenith angle 0° (nadir).**

In the following we investigate a 500 m resolution only, because the cloud cover in cumulus case is so small that hardly any fully cloud covered pixel would be left to analyze at the 1000 m MODIS resolution. Clear differences are visible in the two results shown in Figure 6. While the visible channel (Fig. 6a,c) shows generally high reflectance where the cloud is optically thick, especially at the illuminated cloud sides close to the cloud tops, the near infra-red channel (Fig. 6b,d) shows much smaller reflectances, especially around the cloud tops. This is the obvious impact of the absorption by liquid water droplets in channel 20 which is especially large for the largest droplets near the cloud tops.

PARTICLE SIZE RETRIEVAL

All operational retrievals use the different sensitivities to cloud optical thickness and droplet effective radius at predominantly scattering wavelengths in the visible and more absorbing near infra-red wavelengths, respectively (e.g., MODIS MOD06, King et al., 1997). Part of MOD06 are several retrievals for the effective radius using different combinations of the “visible” scattering channel 2 at 0.87 μm and the channels 6, 7, and 20 where liquid water absorption becomes increasingly important.

Figure 7 shows the results of the retrievals applied to the simulated MODIS observations. From the cumulus cloud case only those 500 m pixel are analyzed for which at least 95% of all sub-pixels are cloud covered (optical thickness > 0.25). Some further pixels are excluded, if the observed reflectance values lie outside the reflectance space covered by the retrieval libraries. The retrievals are compared to effective radius values from the LES cloud data set.

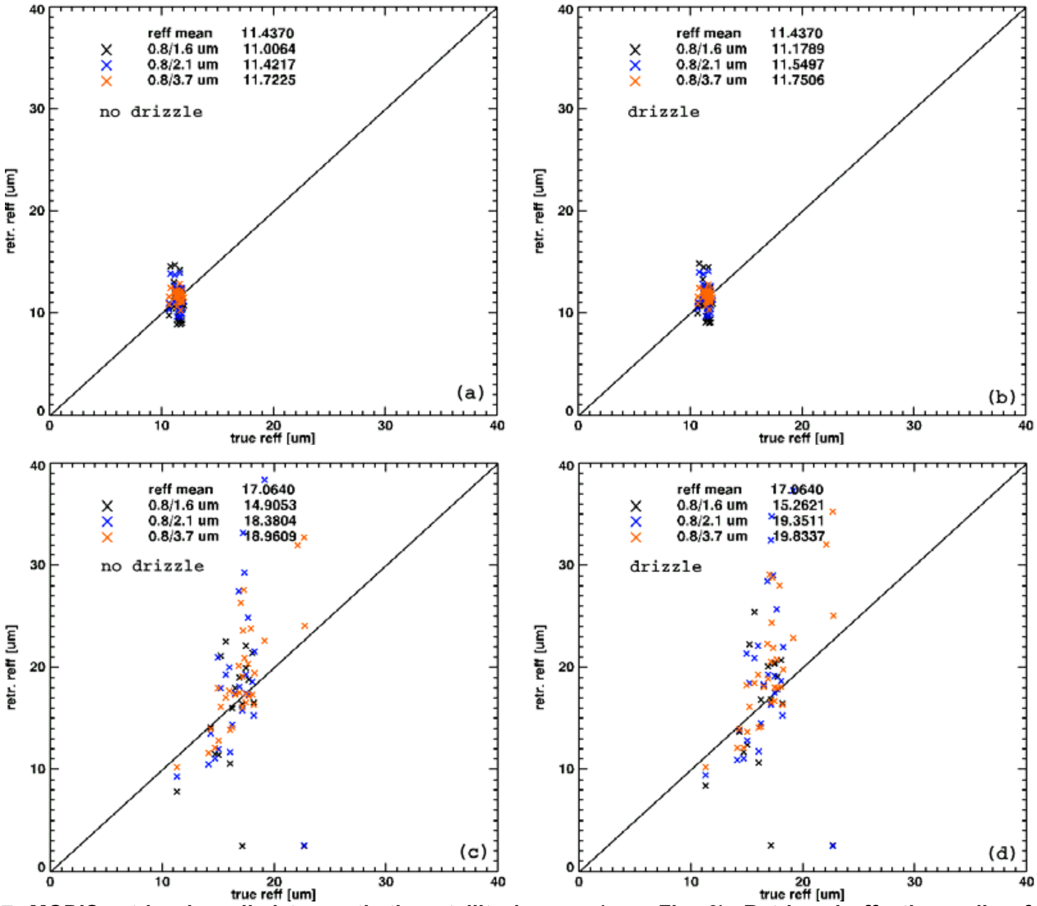

Figure 7: **MODIS retrieval applied to synthetic satellite images (e.g., Fig. 6): Retrieved effective radius from three different channel combinations compared to “real” effective radius. (a) and (b) give the results for the stratus case, (c) and (d) for the cumulus case. (a) and (c) stand for the respective cloud cases without the drizzle mode, (b) and (d) for the cases including the drizzle impact. Each cross symbolizes a 500 m pixel with a successful MODIS retrieval. Numbers in the legend give the domain averages of the “truth” (reff mean, details see text) and the average values for all three retrievals.**

It is not straight forward to define the truth to compare effective radius retrievals to, because effective radius in realistic clouds varies with height and each of the MODIS retrievals has a certain penetration depth. From cloud top down to this optical depth the reflectance in a near infra-red channel is sensitive to particle size. Thus the "truth" value which is defined in the following should give only an approximate idea of what could be expected from the retrieval. "Real" or "true" values of effective radius are obtained only from the cloud droplet mode as this is the parameter which is generally desired. Over a cloud layer at cloud top down to a penetration optical thickness of 5, effective radius from each cloud model column is averaged (weighted with LWC).

As expected all effective radius retrievals nicely work for the stratus cloud case without any drizzle (Fig.7a) due to the fact that this cloud scene is very close to the plane-parallel homogeneous situation used to generate the retrieval database. The remaining deviation of realistic cloud decks from the ideal PPH situation becomes visible comparing the domain averaged retrievals (given as numbers in the legend part of Fig.7a). The stratus cloud deck is not homogenous but has increasing droplet effective radii with height. Thus retrievals having a deeper optical penetration depth show decreasing average effective radius which is characteristic for of values deeper in the cloud deck. Our definition of the "true" value is obviously relevant for the penetration depth of the 0.8/2.1 µm retrieval while the retrieval with 1.6 µm shows smaller values and the one with 3.7 µm shows larger values – a picture in agreement with, e.g., Chang et al. (2003) who try to obtain some vertical droplet profile information from the three different MODIS channel retrievals. The scatter of retrieved values around the "truth" is small as the situation is very homogeneous. Interestingly the scatter is the smaller the longer the wavelength of the absorbing channel, i.e., the more absorbing the channel is. This is an effect of the decreasing sensitivity of absorbing channels to 3D effects due to reduced mean free path lengths. Adding the drizzle droplet mode (Fig. 7b) to the underlying cloud data set hardly changes the simulated MODIS reflectances and accordingly the results.

The situation for the cumulus case is different. Generally the scatter is much larger due to 3D effects in this much more inhomogeneous cloud scene. Bright slopes lead to an underestimation of droplet size, shadows to an overestimation. On average the retrieved values are again in the range of the "truth" value although over and underestimations of some retrievals are up to 100%. The "droplet profile" from the three retrievals again shows largest effective radius (larger than "truth") at the longest wavelength and the smallest (smaller than "truth") at the shortest wavelength. For this case the introduction of drizzle into the cloud scene leads to a visible effect in the average effective radius retrievals, most likely because zones of drizzle development are not covered by an optically thick layer where cloud sized droplets dominate as in the stratus case. Its impact is stronger for the retrievals using the 2.1 and 3.7 µm channels ($\Delta r_{eff} \approx 1$ µm), for the 1.6 µm channel retrievals it is smaller ($\Delta r_{eff} \approx 0.35$ µm).This is opposed to the expectation that low level drizzle would especially lead to larger 1.6 µm retrievals. Reason might be that drizzle is directly visible on top of the small cloud cells and through the cloud gaps (cf. Fig 4a).

DISCUSSIONS AND OUTLOOK

We have shown first results of a study on the sensitivity of the MODIS operational cloud effective radius retrievals to the formation of drizzle in the observed cloud. This was done using two LES cloud data sets and simulating synthetic MODIS images with a Monte Carlo model before the application of the MODIS retrieval to the simulated observations. Therefore it is possible to isolate impacts of drizzle and 3D radiative transfer by systematic modification of certain parts of our setup (no drizzle, 1D instead of 3D RT). In this paper only the analysis of the effects of drizzle was presented in detail.

For the given setup of our "laboratory" (two specific cloud cases) the impact of drizzle formation on the MODIS retrieval was negligible for the overcast stratus case. The reason for this is most likely the relatively large optical thickness of this case. For the broken cloud case the impact of drizzle is more obvious in the range of a 5% change of retrieved effective radii, especially for the retrievals using the less absorbing wavelengths. In this case regions of drizzle formation are often directly visible for the satellite, at cloud top and through the cloud gaps.

Beside the drizzle a further outcome is the further support for the concept to retrieve a “droplet profile” from the three retrievals using differently absorbing channels (Chang et al., 2003). The effective radius from the 3.7 µm retrieval is representative of cloud droplets at less than optical depth 5 (from cloud top), the 2.1 µm retrieval for an optical depth around this value, and the 1.6 µm retrieval for droplet size at lower altitude regions. Drizzle formation is not directly visible in this profile of droplet sizes (as also proposed by Chang et al., 2003). 3D effects definitely have the potential to generate effects as large as the ones seen in the examples (Fig. 1 and 2), but are not as systematic as seen in Figure 1.

The next step in this analysis has to be the isolation of 3D effects by using 1D RT to simulate the synthetic MODIS images. This way, 3D effects can be separated and quantified in the same way. As the optical depth of the overcast stratus case seemed to be too large for the retrieval to sense drizzle formation, it is planned to analyze other less opaque stratocumulus cloud examples. Successively the analysis will be extended to investigate the impact of yet neglected MODIS retrieval algorithm steps as the correction of the thermal contribution to the 3.7 µm channel using the 10.8 µm channel, the atmospheric correction, and the cloud masking.

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