Universität Leipzig
Fakultät für Physik und Geowissenschaften
Leipziger Institut für Meteorologie

Bachelorarbeit

Fehleruntersuchung für Wolkeneigenschaften aus Satellitenfernerkundung
(Uncertainties in the Retrieval of Cloud Properties from Satellite Remote Sensing)

vorgelegt von Friederike Hemmer
Matrikelnummer: 2509879

Erstgutachter: Prof. Dr. Johannes Quaas
Zweitgutachter: Dr. Odran Sourdeval

Leipzig, 02.08.2013
Abstract

The cloud droplet effective radius and the cloud optical thickness belong to the most important parameters, which specify the radiative properties of clouds. These parameters can be retrieved from satellite measurements. In this study, retrievals of the effective radius and the optical thickness from different instruments aboard the satellites of the A-Train constellation were compared in order to assess the uncertainties of the different retrieval methods. The A-Train provides various measurements of both, active and passive sensors. The advantage is, that the satellites fly in short time intervals behind each other. Thus, they observe the same situation of the atmosphere and provide comparable measurements.

For the droplet effective radius a comparison of the retrievals from the Moderate Resolution Imaging Spectroradiometer (MODIS) and from the Cloud Profiling Radar (CPR) was performed. Low-level, liquid water clouds were investigated and it was revealed, that CloudSat is not able to detect these clouds.

Furthermore, the cloud optical thickness retrieved from MODIS was compared to the one retrieved from the Polarization and Directionality of the Earth’s Reflectances (POLDER) instrument. The comparison showed, that the POLDER retrieved optical thickness is generally smaller than the MODIS derived optical thickness. The linear correlations between the retrievals of the two passive sensors were investigated. The results showed a better correlation for ice clouds than for water clouds. For water clouds the correlations found here were not as good as expected.
# Contents

1 Introduction  

2 Basics  
2.1 Clouds  
2.1.1 Definition, Formation and Classification  
2.1.2 Microphysical and Radiative Properties of Clouds  
2.2 Satellites and Instruments  
2.2.1 A-Train  
2.2.2 Aqua  
2.2.3 CALIPSO and CloudSat  
2.2.4 PARASOL  
2.3 Retrieval algorithm for MODIS  

3 Effective Radius from MODIS and CloudSat  
3.1 CCCM Dataset  
3.2 Considered Quantities  
3.2.1 MODIS: SSF variables  
3.2.2 CloudSat: CCCM variables  
3.3 Comparison of the Effective Radii from MODIS and CloudSat  

4 Optical Thickness from MODIS and POLDER  
4.1 POLDER Retrieval Algorithm  
4.2 Calxtract Dataset  
4.3 Comparison of the Optical Thickness from MODIS and POLDER  

5 Summary and Outlook  

Bibliography
Contents

List of Figures  38
List of Tables  40
1 Introduction

Clouds are of overriding significance for our planet. They are an important component of the Earth’s hydrological cycle. One of their main functions is the vertical and horizontal transport of water within the atmosphere and to the Earth’s surface. Clouds form precipitation, that reaches the ground and gets to the ground water, rivers and oceans. The water evaporates again and is transferred back to the atmosphere as water vapor, where it acts on the formation of new clouds.

However, the most striking thing about clouds is their strong effect on the Earth’s energy balance (Wielicki et al., 1995; Stephens, 2005). On the one hand, this concerns latent heating and cooling due to phase changes, which occur in clouds. All of the three different phases of water are present in the atmosphere. On the other hand, clouds transfer solar energy to terrestrial energy by absorption of solar radiation and emission of terrestrial radiation. This strongly affects the flow of energy within the atmosphere and to the Earth’s surface.

Different cloud types have different effects on the energy budget. Clouds reflect a large amount of sunlight back to space, which results in a cooling effect. This is mainly due to low and optically thick clouds. Clouds also contribute to the greenhouse effect, which means warming. This is the main effect of high and optically thin clouds. Considering all clouds, which are present in the atmosphere, their net effect on the global climate is a cooling effect. Wielicki et al. (1995) quantified it to be 20 W m\(^{-2}\).

The cloud feedback is very important for the global climate change. Clouds are the largest uncertainty factor in global climate models (Solomon et al., 2007; Cess et al., 1990; Senior and Mitchell, 1993). Changes in cloud cover and in the microphysical properties of clouds affect the global climate. They need to be further investigated, to reduce this uncertainty factor. The understanding of the relevant microphysical processes in clouds is still at an early stage. To quantify the cloud radiative forcing, important factors are, among others, the cloud optical thickness and the particle effective radius. These parameters characterize the radiative properties of clouds and are thus crucial for the parameterization of clouds in climate models (Slingo, 1990; Wielicki et al., 1995; Kristiansen and Kristjansson, 1999).

Retrievals of the optical thickness and the particle effective radius are available from

1
spaceborne measurements from various satellite instruments. In particular, the A-Train satellites offer different retrievals of the microphysical properties from both, active and passive sensors (Stephens et al., 2002). The advantage of the A-Train observations is, that several different sensors provide information about the same situation of the atmosphere, because the A-Train satellites fly in constellation within a few minutes.

The aim of this bachelor’s project is to make a statement about the quality of satellite retrievals of the optical thickness and the particle effective radius from different measurement instruments. Estimates of the uncertainties for these retrievals are rare. However, knowledge of the uncertainties is very important for the assessment of the cloud radiative forcing, which depends on the microphysical properties of clouds. In this context, especially the radiative forcing because of the ”indirect aerosol effect” is of big interest. Aerosol particles strongly influence the microphysical properties of clouds. They impact on the formation of clouds, because they serve as cloud condensation nuclei (CCN) (Twomey, 1974). If many aerosol particles are available, many cloud droplets are formed. These are smaller than in regions with less aerosol particles, because more CCN compete for the available water vapor in the air parcel. Clouds with small droplets last longer and have a larger vertical extension. Furthermore, their surface is larger and hence they reflect more sunlight. Thus, the indirect aerosol effect strongly affects the energy budget of the Earth.

This thesis is divided as follows. In chapter 2 the foundations of clouds and their microphysical properties are summarized, which are necessary for understanding the following chapters. Furthermore, the A-Train satellites and their instruments are introduced and the retrieval algorithm for the optical thickness and the particle effective radius for measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Aqua satellite is explained (Platnick et al., 2003). This algorithm also forms the basis for the retrievals from the Polarization and Directionality of the Earth’s Reflectances instrument (POLDER)(Buriez et al., 1997). Chapter 3 deals with comparisons of the retrievals and algorithms for the effective radius derived from MODIS and the Cloud Profiling Radar (CPR). The CPR is located on the CloudSat satellite (Stephens et al., 2002, 2008).

In chapter 4, comparisons of the cloud optical thickness retrieved from MODIS and from POLDER aboard the Polarization and Anisotropy of Reflectances for Atmospheric Sciences with Observations from a Lidar mission (PARASOL) are presented. Finally, chapter 5 gives a summary of the results, draws conclusions and presents a short outlook.
2 Basics

This chapter deals with the foundations and basic principles, which are necessary for understanding the following chapters. First, an overview of cloud formation and the different cloud types is given. Afterwards, the optical and microphysical properties of clouds, that are analyzed in chapters 3 and 4 are defined. Furthermore, the A-Train satellites and their instruments are introduced, which provide the analyzed data. Finally, in section 2.3 the algorithm for the retrievals of the cloud optical thickness and the particle effective radius from MODIS is described. This algorithm also builds the basis for retrievals of the optical thickness from PARASOL, which are compared to MODIS retrievals in chapter 4.

2.1 Clouds

2.1.1 Definition, Formation and Classification

According to Wendisch (2013) (Lecture Notes: Fundamentals of Cloud Physics), a cloud can be defined as an airborne suspension of hydrometeors (e.g. droplets or ice crystals), aerosol particles (e.g. sulfate, sea salt or soot) and gases (e.g. water vapor or carbon dioxide).

Clouds can occur in every air mass, that becomes supersaturated and contains aerosol particles, which serve as cloud condensation nuclei (CCN). Supersaturation, which means that the relative humidity exceeds 100%, can be reached when air is cooled by different atmospheric lifting mechanisms, for example convergence lifting, frontal lifting or orographic lifting. The lifted air contains water vapor. If the air is cooled below the dew point, condensation or sublimation processes start on the CCN. During the condensation and sublimation processes, latent heat energy is released. This energy can increase the vertical motion in clouds, especially in convective clouds.

Once a droplet or ice crystal is formed, it can grow further by condensation or sublimation and by coalescence. Coalescence is the fusion of colliding droplets.

The phase of water can change during the developing process of the cloud between
liquid water, ice and water vapor. However, freezing is complex and there are several different freezing processes which occur in clouds. Supercooled liquid water can exist up to -38°C (Wendisch, 2013).

In general, there are two different characters of clouds: stratiform and convective. One can distinguish between three main types of clouds: cirrus, stratus and cumulus. From this, ten different cloud genera are derived, which are sorted by altitude. They are listed in Table 2.1 and illustrated in Figure 2.1.

**Table 2.1:** Cloud Genera, according to the *International Cloud Atlas* (WMO, 1956)

<table>
<thead>
<tr>
<th>Level</th>
<th>Altitude</th>
<th>Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>high-level</td>
<td>5-13 km</td>
<td>cirrus, cirrostratus, cirrocumulus</td>
</tr>
<tr>
<td>mid-level</td>
<td>2-7 km</td>
<td>altostratus, altocumulus</td>
</tr>
<tr>
<td>low-level</td>
<td>0-2 km</td>
<td>stratocumulus, stratus</td>
</tr>
<tr>
<td>large vertical extension</td>
<td>0-13 km</td>
<td>cumulus, cumulonimbus, nimbostratus</td>
</tr>
</tbody>
</table>

**Figure 2.1:** Main Cloud Types, source: www.dwd.de.

Depending on their different characteristics, clouds can have different impact on the radiation budget of the Earth. The influence of cirrus clouds is complex and
not completely understood nowadays. Zhang et al. (1999) showed, that the cloud radiative forcing of cirrus clouds is extremely sensitive to crystal shape and crystal size distribution. However, in general high-level cirrus clouds are optically thin and therefore transmit a large quantity of the incoming solar radiation, while they reflect only a small part back to space. Because of their high altitude, there is a large temperature difference between the Earth’s surface and the cirrus cloud. The cloud absorbs the terrestrial radiation and re-emits at low temperatures. Therefore, cirrus clouds mostly have a significant greenhouse effect. In summation, high, optically thin clouds have a moderate warming effect. Nevertheless, Zhang et al. (1999) showed that especially contrail-induced cirrus clouds with large numbers of small ice particles produce negative cloud radiative forcing and therefore have a cooling effect on the atmosphere.

Low, optically thick clouds reflect a large amount of the incoming solar radiation and transmit only a small part. They have a cooling effect. Globally, this cooling effect of low, optically thick clouds is stronger than the warming effect of high, optically thin clouds, so altogether clouds have a cooling effect on climate (Wielicki et al., 1995).

The radiative forcing of clouds strongly depends on their microphysical properties. These will be introduced in the next section.

2.1.2 Microphysical and Radiative Properties of Clouds

The most important parameters which characterize the radiative properties of clouds, are the optical thickness, the particle size and concentration, and the liquid water content (LWC).

The optical thickness (τ) is a dimensionless measure of transparency of an atmospheric layer. It can be defined with the help of the Bouguer-Lambert-Beer law. This law describes the extinction of the spectral radiance \( I_\lambda \) along a path of length \( s \) through a medium without taking emission and multiple scattering processes into account. It shows the variation of the intensity of a light beam when crossing an atmospheric layer:

\[
dI_\lambda = -b_{\text{ext},\lambda}(s) \cdot I_\lambda \, ds,
\]  

(2.1)

where \( b_{\text{ext},\lambda}(s) \) is the extinction coefficient with the unit m\(^{-1}\). Extinction is the sum of scattering and absorption.

Equation 2.1 gives the differential form of the Bouguer-Lambert-Beer law. Integra-
tion of this equation yields the attenuation of the initial radiance $I_{\lambda,0}$ after the path $ds$, without considering the contributions of multiple scattering and emission.

$$I_{\lambda}(s) = I_{\lambda,0} \cdot e^{-\int_0^s b_{\text{ext},\lambda}(s')ds'}.$$  (2.2)

In case of attenuation of radiation on a path through a cloud, the boundaries of the integral would be the clouds base and top heights. The optical thickness of the cloud layer is then defined as:

$$\tau_{\lambda} = \int_{z_{\text{base}}}^{z_{\text{top}}} b_{\text{ext},\lambda}(z)dz.$$  (2.3)

The extinction coefficient can be written as:

$$b_{\text{ext},\lambda} = \int_0^\infty Q_{\text{ext},\lambda}A(r)N(r)dr.$$  (2.4)

In Equation 2.4, $Q_{\text{ext},\lambda}$ is the efficiency factor for extinction, $N(r)$ is the particle size distribution and $A(r)$ the projected area. In case of water droplets with the radius $r$, the expression $A(r) = \pi r^2$ is valid for the projected area. In the geometrical optics for the condition, that the particle sizes are much larger than the wavelengths, $Q_{\text{ext},\lambda}$ can be assumed to be a value of approximately two. This is true for wavelengths smaller than 4 $\mu$m. In this case the extinction coefficient may be described as:

$$b_{\text{ext},\lambda} = 2\pi \int_0^\infty r^2 N(r)dr.$$  (2.5)

From this, the following expression for the optical thickness of a cloud layer in case of water droplets and under the condition of geometrical optics can be obtained:

$$\tau_{\lambda} = \int_{z_{\text{base}}}^{z_{\text{top}}} 2\pi \left[ \int_0^\infty r^2 N(r)dr \right]dz.$$  (2.6)

The **particle effective radius** $r_e$ summarizes the particle size and concentration. It is a an area weighted mean radius of the particle size distribution and its unit is given in microns ($\mu$m). It was defined by Hansen and Travis (1974) as the ratio of the third to the second moment of the droplet size distribution:

$$r_e = \frac{\int_0^\infty \pi r^3 N(r)dr}{\int_0^\infty \pi r^2 N(r)dr}.$$  (2.7)
A further microphysical property is the **liquid water content** (LWC). The LWC is a measure of the mass of liquid water in a specified amount of dry air. It is usually given in g cm$^{-3}$ or g kg$^{-1}$. The LWC can be described as:

$$\text{LWC} = \int_0^\infty m(r)N(r)dr,$$  \hspace{1cm} (2.8)

where $m(r)$ is the particle mass. The mass can be written as $m(r) = \rho_w V$ with $\rho_w$ the density of water and the volume $V$, which is $V = \frac{4}{3}\pi r^3$ for spheres. Thus, the LWC can also be expressed as:

$$\text{LWC} = \int_0^\infty \frac{4}{3}\pi \rho_w r^3 N(r)dr.$$  \hspace{1cm} (2.9)

In case of geometrical optics, a relationship between the droplet effective radius and the optical thickness of a cloud layer can then be derived from Equations 2.6, 2.7 and 2.9:

$$\tau = \int_0^\Delta z \frac{3}{2} \frac{\text{LWC}}{\rho_w r_e} dz.$$  \hspace{1cm} (2.10)

The **liquid water path** (LWP) is the vertical integral of the LWC, so it gives the total amount of liquid water between two levels in the atmosphere. Its unit is given in g m$^{-2}$.

$$\text{LWP} = \int_0^{\Delta z} (\text{LWC}) dz.$$  \hspace{1cm} (2.11)

By inserting Equation 2.11 into 2.10, the relationship between the optical thickness and the droplet effective radius can be expressed as:

$$\tau = 3 \frac{\text{LWP}}{\rho_w r_e}.$$  \hspace{1cm} (2.12)

The effective radius is not constant with height, so in Equation 2.12 a vertical range of $r_e$ must be taken into account.

Equation 2.12 was used in section 3.3 for calculating the optical thickness from the effective radius and the LWP measured from CloudSat. CloudSat and the other A-Train satellites, that provide all data used in this evaluation, are introduced in the next section.
2.2 Satellites and Instruments

2.2.1 A-Train

The A-Train is a satellite constellation operated by the *U.S. National Aeronautics and Space Administration* (NASA) in cooperation with the French space agency, the *Centre National d’Etudes Spatiales* (CNES), which is responsible for the PARASOL mission. The "A" stands for "Afternoon", because the satellites pass the equator from south to north at a local time of 1:30 p.m.. They fly in a near-polar, sun-synchronous orbit at the altitude of 705 km, which means a cycle time of 100 minutes, so the satellites achieve 14 rotations around the Earth per day. As illustrated in Fig. 2.2, the A-Train currently consists of five satellites (Aura, PARASOL, CALIPSO, CloudSat and Aqua), which fly behind each other at short time intervals (Stephens et al., 2002). This provides the opportunity of measurements of the same situation of the atmosphere with several different passive and active sensors. The data used here originate from the satellites Aqua, CloudSat, CALIPSO and PARASOL. These satellites are further introduced in the following sections.

![A-Train Constellation](image)

*Figure 2.2: A-Train Constellation, Stephens et al. (2002), Bull. Amer. Meteorol. Soc.*
2.2.2 Aqua

Aqua is the oldest member of the A-Train and flies in the leading position. It was launched in 2002 as part of the NASA’s Earth Observing System (EOS). It carries six different measurement instruments, but here only the Clouds and the Earth’s Radiant Energy System (CERES) and MODIS are focused.

CERES is a cross-track scanning radiometer, which means that it scans perpendicular to the direction of movement. The horizontal length of its field of view is 20 km. CERES provides radiometric measurements from three channels. One channel measures the reflected shortwave solar radiance at wavelengths between 0.3 and 5 \( \mu \text{m} \), one channel the thermal radiance emitted by the Earth in the infrared window at 8 to 12 \( \mu \text{m} \) and the last channel the total radiance at all wavelengths between 0.3 and 100 \( \mu \text{m} \). The longwave radiance at the top of atmosphere (TOA) is not measured directly, but calculated by using the total radiance minus the shortwave radiance. The measurements only affect TOA, values in the atmosphere and at the Earth’s surface are calculated using additional information from other instruments like MODIS, which are provided simultaneously. These are for example information about clouds and aerosols, which are necessary input parameters for radiative transfer calculations.

MODIS is a spectroradiometer with 36 spectral bands at wavelength between 0.415 and 14.235 \( \mu \text{m} \), which have three different spatial resolutions at nadir (King et al., 1992). Two channels (0.65 and 0.86 \( \mu \text{m} \)) have a spatial resolution of 250 m, five channels (0.47, 0.56, 1.24, 1.63 and 2.13 \( \mu \text{m} \)) a resolution of 500 m and the remaining 29 channels a resolution of 1 000 m. MODIS scans cross-track on both sides of nadir up to 55\(^\circ\). Its swath is 2 330 km wide for an along track distance of 10 km. The instrument covers the entire globe in two days (Platnick et al., 2003).

MODIS provides information about cloud and aerosol properties, cloud boundaries and water and ice content in the atmosphere.

2.2.3 CALIPSO and CloudSat

In 2006, the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation mission (CALIPSO) and CloudSat were integrated into the A-Train. For the first time, these satellites carry active measurement instruments. They were launched at the same time. CALIPSO flies just 15 seconds behind CloudSat.

CloudSat carries the CPR (Stephens et al., 2002). It uses microwaves at a frequency
of 94 GHz like common weather satellites and it measures the power backscattered by clouds as a function of distance from the radar. Its horizontal resolution is approximately 1.7 km along-track and 1.3 km cross-track. The vertical profiles consist of 125 bins where each bin is 240 m thick. The observations are only nadir view. CloudSat provides vertical profiles of the ice and water content of clouds and information about cloud boundaries. It can observe clouds and precipitation simultaneously. In this ability it is unique. Its signal is sensitive to clouds with an optical thickness greater than 0.1 (Stephens et al., 2002).

Aboard CALIPSO there is a lidar located, the Cloud and Aerosol Lidar with Orthogonal Polarization (CALIOP) (Winker et al., 2009). It also provides only nadir view observations. CALIOP measures at two wavelengths, 1064 nm and 532 nm. Its horizontal and vertical resolutions depend on the observed altitude and on the channel. They are summarized in Table 2.2.

**Table 2.2:** Spatial Resolution of CALIOP, Winker et al. (2009), *J. Atmos. Oceanic Technol.*

<table>
<thead>
<tr>
<th>Altitude range (km)</th>
<th>Horizontal resolution (km)</th>
<th>532-nm vertical resolution (m)</th>
<th>1064-nm vertical resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.1–40.0</td>
<td>5.0</td>
<td>300</td>
<td>—</td>
</tr>
<tr>
<td>20.2–30.1</td>
<td>1.67</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>8.2–20.2</td>
<td>1.0</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>−0.5 to 8.2</td>
<td>0.33</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>−2.0 to −0.5</td>
<td>0.33</td>
<td>300</td>
<td>300</td>
</tr>
</tbody>
</table>

CALIOP provides vertical profiles of clouds and aerosols. Furthermore, because of its high sensitivity, it is able to detect sub-visible cirrus clouds, but its beam only reaches the cloud base for clouds with an optical thickness less than three. If the optical thickness is larger than three, the CPR is still capable to detect the cloud base (Stephens et al., 2002).

Although CALIPSO and CloudSat provide only nadir view observations and therefore have a poor global sampling, their high vertical resolution yields useful information about the vertical structure of the atmosphere. Collocated with the passive observations from the other A-Train satellites, they are nevertheless useful to better study the vertical structure of different cloud types.
2.2.4 PARASOL

The PARASOL mission was launched in 2004. The French space agency CNES is responsible for this mission. PARASOL was a member of the A-Train until December 2009, but was lowered to an orbit 3.9 km beneath the A-Train then. As a consequence, it is slowly leaving the A-Train environment. PARASOL was originally designed to be a 2-year mission, but has flown within the A-Train for five years. In spring 2009, the other A-Train satellites performed an inclination maneuver, but PARASOL could not be part of it because of insufficient fuel supplies. That was the reason for lowering its orbit. The Glory satellite was supposed to fill the data gap that PARASOL leaves, but its launch in 2011 failed. However, PARASOL is still fully operational and it keeps on sharing data with the A-Train satellites periodically.

The instrument aboard PARASOL is POLDER-3. Its mission is to improve the knowledge of radiative and microphysical properties of clouds and aerosols and their impact on climate. It is not the first of its kind in space. POLDER instruments have been flown aboard the Japanese Advanced Earth Observing Satellite 1 (ADEOS I), launched in 1996 and aboard its successor mission ADEOS II, launched in 2002. POLDER is the only satellite instrument, which provides measurements in polarized radiation. It measures the spectral, directional and polarized characteristics of solar radiation reflected by the Earth-atmosphere system. Therefor it uses nine spectral bands between 443 and 910 nm. Polarizers are added at three different wavelengths of 443, 670 and 865 nm (Deschamps et al., 1994). Altogether, POLDER has 15 channels, because for each polarized wavelength three filters measure the linear polarization of the incoming radiation in three directions separated by 120°. Solar radiation is unpolarized, but interactions with aerosols change the polarization properties. Therefore, properties of aerosols can be derived from measurements of the polarized characteristics of solar radiation. Because POLDER measures solar radiation, it can provide only daytime observations.

It consists of a Charged Coupled Device (CCD) matrix array detector, a rotating wheel, that carries the spectral filters and polarizers, and a wide field of view telecentric optics for both, along-track (1 800 km) and cross-track (2 400 km) directions. The CCD detector induces a spatial resolution at ground of 6 km x 7 km at nadir. POLDER requires a series of images every 19.6 s. It can observe the same ground site up to 16 times from different angles (Deschamps et al., 1994).
2.3 Retrieval algorithm for MODIS

This section describes the MODIS retrieval algorithm. It is shown how the optical thickness and the particle effective radius can be derived from multiwavelength radiometer measurements from satellites. The algorithms for MODIS and PARASOL are both based on the principles explained below, although there are a few differences. These are discussed in section 4.1.

The retrieval algorithm for MODIS is based on the Nakajima and King method, which is a method to retrieve the effective radius and the optical thickness simultaneously. It was developed by Nakajima and King (1990) for determining these two parameters of liquid water clouds from reflected solar radiation measurements. It is based on the fact that on the one hand, the reflection function of clouds in the visible wavelength region at a non-absorbing channel is sensitive to the cloud optical thickness ($\tau_c$), whereas on the other hand, the reflection function at water absorbing wavelengths in the near infrared region is sensitive to the effective radius ($r_e$).

In order to retrieve the optical thickness and the effective radius, the first step is to find the reflection function. Figure 2.3 shows the processing line for calculating the reflection function. There are two codes included, the scattering code (Mie code) and the radiative transfer code.

The scattering code determines the optical parameters. These are the efficiency factor for extinction $Q_{\text{ext}}$ and the single scattering albedo $\omega_0$, which is defined as the ratio of the scattering efficiency factor ($Q_{\text{scat}}$) to the extinction efficiency factor:

$$\omega_0 = \frac{Q_{\text{scat}}}{Q_{\text{ext}}}.$$  \hspace{1cm} (2.13)

The asymmetry parameter $g$ also belongs to the optical parameters. It is a measure of the angular distribution of the radiation, which is scattered by the particle. It gives the preferred direction of radiation after interacting with a particle and ranges between -1 and 1. A value of 1 means pure forward scattering as if there was no particle. If $g$ is equal to -1, the radiation is totally scattered into the backward direction. The case $g=0$ implies, that the scattered amount of radiation in the forward hemisphere is the same as that in the backward hemisphere. The radiation is sent into all directions, so in this case there is isotropic scattering.

The scattering code uses the Lorenz-Mie theory, which is suitable for liquid water droplets with sizes comparable to wavelengths in the visible range and which can be considered as spheres. For ice clouds more complex theory is necessary, because ice crystals can have several different shapes. Thus, they cannot be assumed to be
2.3. Retrieval algorithm for MODIS

The second code for the calculation of the reflection function is the radiative transfer code. This code describes how the radiation interacts with the atmosphere and determines the reflection function. The particle effective radius and the optical thickness can be retrieved by comparing the measured reflection functions at an absorbing and a non-absorbing wavelength to the calculated theoretical relationship between two reflection functions of the same wavelengths.

A quantity, that represents the sensitivity of the different wavelengths to the effective radius and the optical thickness well, is the similarity parameter \( s \). It is defined as:

\[
s = \left( \frac{1 - \omega_0}{1 - \omega_0g} \right)^{\frac{1}{2}}.
\]  

(2.14)

Figure 2.4 shows the similarity parameter as a function of wavelength for several different effective radii. In the water vapor windows at wavelengths smaller 1.0 \( \mu \)m, the similarity parameter is equal to zero. Hence, according to Equation 2.14, the single scattering albedo must be equal to one. That means, there is no absorption. The optical thickness is sensitive to the reflectance at these wavelengths. Thus,
it can be derived from reflection function measurements in this wavelength region. At non-absorbing wavelengths near 1.65 and 2.16 $\mu$m, the similarity parameter is sensitive to particle size, so the effective radius can be derived from reflection measurements at these wavelengths. This forms the basis of the retrievals of the effective radius and the optical thickness from solar reflection measurements from satellites. Figure 2.5 shows calculations, which relate the reflection functions at 0.75 and 2.16 $\mu$m for different values of the optical thickness and the effective radius. The dashed curves show the reflection functions for specified values of the cloud optical thickness at 0.75 $\mu$m and the solid curves represent the reflection functions at specified values of the effective radius.

With increasing optical thickness, the dashed and solid curves are nearly orthogonal. That shows that the determination of the optical thickness and the effective radius is nearly independent of each other, so measurement errors in one channel have little impact on the retrieval of the property from the other channel. Furthermore, Figure 2.5 shows, that multiple solutions of the optical thickness and the effective radius are possible from the measurements of the reflection functions at 0.75 and 2.16 $\mu$m, especially for small values of the optical thickness and the effective radius.

In a practical sense, to simplify the calculations and limit calculation time for the retrieval of the effective radius and the optical thickness, pre-calculated look-up tables (LUT) exist for different spectral bands, microphysical models and viewing geometries. These tables are calculated using a forward radiative transfer model.
The effective radius and the optical thickness are finally retrieved by matching the measured reflection with the LUT. Therefore, pairs of spectral bands are used. One band in the visible region is paired with an appropriate near-infrared band (1.64, 2.13 or 3.75 μm). The bands in the visible region vary with surface type. They are chosen to minimize the reflectance of the underlying surface. Over land surfaces the 0.65 μm channel is used, over ocean 0.86 μm and over snow or sea ice 1.24 μm (Platnick et al., 2003).

As discussed by Platnick (2000), the three different near-infrared channels yield three different retrievals of the effective radius. The longer the wavelength is, the larger is the absorption. That means, the different retrievals sample different portions of the cloud. The retrieval from the 1.64 μm channel is at least affected by absorption, so it can contain information of relatively deep cloud layers. At wavelengths of 2.13 and 3.75 μm, there is progressively more absorption. That means, the retrievals from the 2.13 and 3.75 μm channels belong closer to the cloud top. From the theory, it might then be expected that the water droplet sizes retrieved from the 3.75 μm channel are larger than those from the 2.13 and 1.64 μm channels, because generally the droplet size increases in non-precipitating water clouds from the bottom to the top. However, in reality it is not so simple and studies of Nakajima et al. (2010) and Suzuki et al. (2010) show, that the water droplets retrieved from the 2.13 and 1.64 μm channels are larger than those retrieved from the 3.75 μm channel.
3 Effective Radius from MODIS and CloudSat

This chapter deals with a comparison of the droplet effective radius derived from MODIS and CloudSat. Initially, the aim was to compare the effective radii derived from the three MODIS channels at 1.6, 2.1 and 3.7 \( \mu \text{m} \) to each other and to the effective radius derived from CloudSat. However, the 1.6 and 2.1 \( \mu \text{m} \) channels do not contain retrievals of the effective radius for the regarded months of July 2007 to December 2007. Therefore, only the retrievals from the 3.7 \( \mu \text{m} \) channel were considered. The data used for this evaluation originate from the CCCM dataset, which is described in the following section. Afterwards, the considered quantities are introduced and the retrieval algorithm for the CloudSat retrievals is summarized. Finally, the results of the comparison are presented.

3.1 CCCM Dataset

The A-Train integrated CALIPSO, CloudSat, CERES and MODIS merged product (CCCM) merges retrievals of cloud and aerosol properties derived from measurements of the various instruments aboard the A-Train satellites. A description of the dataset is given in the documentation Variable Descriptions of the A-train Integrated CALIPSO, CloudSat, CERES, and MODIS merged product (CCCM (C3M)) by Kato et al. (2010a). The dataset includes cloud and aerosol properties derived from the active lidar and radar aboard CALIPSO and CloudSat, as well as those derived from the passive CERES and MODIS measurements.

The instruments have different spatial resolutions. This must be considered when the observations are collocated. At first, three profiles with a resolution of 333 m from the CALIOP lidar aboard CALIPSO and one profile with 1.3 km horizontal resolution from the CPR aboard CloudSat are collocated with 1 km MODIS imager pixels. Afterwards, these 1 km pixels are collocated with the CERES field of view of 20 km resolution. All data in the CCCM product are stored in the grid of the 20 km CERES footprints.
CALIPSO and CloudSat profiles are merged as follows: If either CALIPSO or CloudSat detects a cloud layer, it is used. If both detect a cloud layer, for the cloud top the higher observed top height is kept. For the cloud base it depends on whether the CALIPSO signal is completely attenuated or not. If the signal is not completely attenuated, the cloud base from CALIPSO is kept. If the signal is completely attenuated, the cloud base from CloudSat is used, if CloudSat detects a cloud below the attenuation level of CALIPSO. If CloudSat missed the cloud, the complete attenuation level from CALIPSO is used as cloud base height (Kato et al., 2010a).

Within a CERES footprint, the retrieved cloud properties vary, so a cloud grouping process is implemented. Cloud profiles with the same vertical structure, which means they have the same cloud top and base height and the same number of overlapping cloud layers, are grouped together. The maximum number of cloud groups within a CERES footprint is 16 and each cloud group can consist of up to six overlapping layers (Kato et al., 2010b).

The CCCM dataset merges variables originating from the CERES standard product Single Scanner Footprint TOA/Surface Fluxes and Clouds (SSF) with retrievals derived from CALIPSO and CloudSat measurements. The SSF product combines CERES measurements with information from a high-resolution imager. In case of the Aqua satellite this is MODIS. However, in contrast to the standard SSF product, the CCCM data set contains four different sets of MODIS derived cloud properties for each CERES footprint (Kato et al., 2010a):

1. cloud and aerosol properties derived from MODIS radiances by the CERES standard cloud algorithm, averaged over the entire CERES footprint
2. cloud and aerosol properties derived from the standard algorithm, but only MODIS pixels along the CALIPSO and CloudSat ground track are considered
3. only MODIS pixels along the CALIPSO and CloudSat ground track, but for the derivation of cloud and aerosol properties, cloud heights from CALIPSO and CloudSat are implemented in the retrieval algorithm (enhanced algorithm)
4. use of enhanced algorithm for all MODIS pixels in the CERES footprint, but this is under development and currently the data set contains a default value

The enhanced algorithm uses the information of cloud heights provided by the active instruments of the A-Train members in order to improve the cloud properties derived
from MODIS. This set of MODIS derived cloud properties was used here for the comparison of the droplet effective radius from MODIS and CloudSat measurements.

3.2 Considered Quantities

3.2.1 MODIS: SSF variables

The considered droplet effective radius from MODIS measurements originates from the SSF product, described in the documentation *Single Satellite Footprint TOA/ Surface Fluxes and Clouds (SSF) Collection Document* by Geier et al. (2003). The droplet effective radius was retrieved using the MODIS algorithm described in section 2.3. Its name is *Mean Water Particle Radius for Cloud Layer 3.7*, so the effective radius retrieved from the 3.7 µm channel is used here. As already mentioned, the data set does not contain any retrievals of the effective radius from the 1.6 and 2.1 µm channels for the regarded time span. Therefore, further comparisons between the different MODIS channels and CloudSat were not possible.

The comparison was performed for liquid water clouds, so another variable that was used in this evaluation is the *Mean Cloud Particle Phase for Cloud Layer 3.7*. This quantity is also derived from measurements of the 3.7 µm channel. Additionally, the algorithm for determining the cloud phase uses measurements from the 10.8 and 12.0 µm channels. A couple of different tests are implemented in this algorithm to distinguish between water and ice clouds. These tests refer to different cloud properties, for example the effective temperature of the cloud. The effective temperature is the temperature a black body would have, which emits the same total amount of electromagnetic radiation. If the effective temperature is larger than 273 K, no cloud in the corresponding pixel can be designated as an ice cloud. In the same way, no clouds with an effective temperature below 233 K can be designated as water clouds (Geier et al., 2003).

3.2.2 CloudSat: CCCM variables

The droplet effective radius from CloudSat is called *Mean CloudSat Radar Only Liquid Effective Radius*. It originates from the 2B-CWC-RO (Radar Only Combined Water Content) CloudSat product. The *Mean CloudSat Radar Only Liquid Water Content*, which was used here as well for computations of the optical thickness, orig-
3.2. Considered Quantities

inates from the same product and is derived with the same retrieval algorithm. The algorithm was developed by Austin and Stephens (2001) for the retrieval of microphysical parameters of stratus clouds from radar measurements in preparation for the CloudSat mission. The retrieval uses active remote sensing data together with a priori data to estimate the parameters of the particle size distribution. It uses other CloudSat products as input. First, the 2B-GEOPROF (Cloud Geographical Profile) product is used to determine cloudy bins. The 2B-CLDCLASS (Cloud Classification) product is used to examine the cloud type and thermodynamical phase. Afterwards, a priori values for liquid and ice particle size distribution parameters are assigned to the cloudy bins. These a priori values are based on collections of microphysical measurements in a database. The effective radius and the liquid water content is then derived from the retrieved size distributions. Additionally, uncertainties and covariance matrices are calculated for every estimate (Austin and Stephens, 2001).

The algorithm is described in the Level 2B Radar-only Cloud Water Content (2B-CWC-RO) Process Description Document by Austin (2007). The forward model, which was developed for the retrieval, assumes a log-normal particle size distribution of the form

\[ N(r) = \frac{N_T}{\sqrt{2\pi}\sigma_{\log}r} \exp \left[ -\frac{\ln^2 \left( \frac{r}{r_g} \right)}{2\sigma_{\log}^2} \right], \tag{3.1} \]

where \( N_T \) is the droplet number density and \( r \) is the droplet radius. \( r_g, \sigma_{\log} \) and \( \sigma_g \) are defined as follows:

\[ \ln r_g = \overline{\ln r}, \tag{3.2} \]
\[ \sigma_{\log} = \ln \sigma_g, \tag{3.3} \]
\[ \sigma_g^2 = (\ln r - \ln r_g)^2. \tag{3.4} \]

\( r_g \) is the geometric mean radius and \( \sigma_g \) the geometric standard deviation. The overbar indicates the arithmetic mean.

The particle size distribution in Equation 3.1 is completely determined by \( N_T, \sigma_{\log} \) and \( r_g \). Thus, the retrieval algorithm seeks to find these three size distribution
3.2. Considered Quantities

parameters. If they are known, the LWC and the effective radius can be calculated with the following expressions derived by Austin and Stephens (2001):

\[
\text{LWC} = \frac{4\pi}{3} N_T \rho_w r_g^3 \exp \left( \frac{9}{2} \sigma_{\text{log}} \right),
\]

\[
\text{r}_e = r_g \exp \left( \frac{5}{2} \sigma_{\text{log}} \right),
\]

where \( \rho_w \) is the density of water. In order to retrieve the three size distribution parameters, an approach described by Rodgers (1976) is used in the retrieval algorithm, which relates a vector of measured quantities \( y \) to a state vector of unknowns \( x \) by the forward model \( F \):

\[
y = F(x) + \epsilon,
\]

where \( \epsilon \) represents measurement errors. The state vector

\[
x = \begin{pmatrix}
r_g(z_1) \\
\vdots \\
r_g(z_n) \\
N_T(z_1) \\
\vdots \\
N_T(z_n) \\
\sigma_{\text{log}}(z_1) \\
\vdots \\
\sigma_{\text{log}}(z_n)
\end{pmatrix},
\]

contains the quantities, which are desired to be retrieved, and the measurement vector

\[
y = \begin{pmatrix}
Z'_{\text{dB}}(z_1) \\
\vdots \\
Z'_{\text{dB}}(z_n)
\end{pmatrix},
\]

consists of the measured radar reflectivity factors \( Z'_{\text{dB}} \) in every height \( z_i \) of the vertical profile. The radar reflectivity \( Z \) is given in units of \( \text{mm}^6 \text{m}^{-3} \). In order to make the model more linear, \( Z \) is converted to a logarithmic variable \( Z'_{\text{dB}} = 10 \log Z \) with the unit dBZ.

The forward model \( F(x) \) has the same dimension as \( y \), because it relates the mea-
3.3. Comparison of the Effective Radii from MODIS and CloudSat

Measurement vector $y$ to the state vector $x$. $F(x)$ consists of quantities, which are calculated from the elements of $x$ by using a forward model for radiative transfer.

$$F(x) = \begin{pmatrix} Z_{dB_FM}(z_1) \\ \vdots \\ Z'_{dB_FM}(z_n) \end{pmatrix}.$$ (3.10)

The subscript FM indicates, that these values are calculated with the forward model and not measured like the values of $y$.

With these vectors and an additional vector $x_a$ for the a priori data, which contains a priori values for the same quantities like $x$, the LWC and the effective radius can be retrieved.

Furthermore, there are two more variables from CloudSat used in this evaluation. These are the Level Height Profile Clouds and Aerosols to gain height information of the vertical profiles and the Precipitation Flag CloudSat. The precipitation flag originates from the 2B-CLDCLASS product and was used to distinguish between precipitating and non-precipitating clouds. Finally, the CALIPSO Cloud Layer Type profile from the CALIPSO Vertical Feature Mask (VFM) product was used to select specific cloud types.

3.3 Comparison of the Effective Radii from MODIS and CloudSat

The comparison of the droplet effective radius retrieved from MODIS and CloudSat measurements was performed for a six month time series from July 2007 to December 2007. In a first step, the uppermost value for the effective radius from the vertical CloudSat profile was compared to the MODIS retrieved effective radius without any further restrictions.

Figure 3.1 shows the average difference of the effective radii derived from MODIS minus the effective radii from CloudSat for the regarded six months. One can easily see that the differences between MODIS and CloudSat retrievals are large over the entire globe. The MODIS retrieved values are almost everywhere quite larger than the CloudSat retrieved values.

To find out where these discrepancies arise from, a couple of restrictions for the regarded clouds were implemented in the comparison. The CloudSat precipitation flag was used to select only non-precipitating clouds and the CALIPSO cloud layer.
type profile to choose only low water clouds. The MODIS cloud phase was used to confirm that only liquid water clouds are selected. Furthermore, only single layer cases were regarded.

For CloudSat one further condition concerning the optical thickness was inserted. Not the uppermost layer of the vertical profile was selected anymore, but the layer where the optical thickness exceeds a threshold of two. Only high, cold cirrus clouds can have optical thicknesses smaller than two. These were ought to be excluded, because only liquid water clouds were considered. The computation of the optical thickness was realized following Equation 2.12.

After inserting all these restrictions, the average droplet effective radius from MODIS measurements for the regarded six months was plotted in Figure 3.2. This figure show the droplet effective radii for low, non-precipitating water clouds for only single-layer cases. It can be seen, that the droplet effective radii over the oceans are larger than those over land surfaces. This is due to a larger amount of aerosol particles over land surfaces. Aerosol particles strongly influence the cloud formation, because they serve as CCN. If more CCN are available, the cloud droplets are smaller, because more CCN compete for the water vapor in the air parcel. The air over oceans is clearer than that over land surfaces, so the droplets formed over oceans can grow larger.
3.3. Comparison of the Effective Radii from MODIS and CloudSat

Figure 3.2: Six months average of the droplet effective radius derived from MODIS measurements for low, non-precipitating water clouds.

The chart for the droplet effective radius from CloudSat for low-level water clouds becomes almost empty. After all, it was concluded that CloudSat does not detect low-level liquid water clouds. This was already feared by Stephens et al. (2002), who stated that CloudSat may have problems with detecting shallow boundary layer clouds. The minimum detectable signal the CPR was expected to be approximately -28 dBZ. Figure 3.3 shows cumulative distribution functions of the minimum radar reflectivity from many hours of aircraft and surface radar measurements for stratus and stratocumulus clouds. This figure indicates, that a minimum detectable signal of -28 dBZ means, that only approximately 70% of the low-level water clouds over ocean and only approximately 40% of these clouds over land are detected by radars. Therefore, Stephens et al. (2002) supposed that the CPR aboard CloudSat may also not sufficiently detect low-level water clouds.

Stephens et al. (2008) presented results from CloudSat measurements after the first year of operation. They confirmed that low-level clouds with tops below 1 km and small cumulus (e.g. fair weather cumulus) are not well represented in the CloudSat data. They argued that this is due to reflection of the underlying surface, which contaminates the reflection of the bins near the surface. In comparison to the underlying surface, clouds are weaker scatterers of microwave radiation at the radar frequency of 94 GHz. This causes problems in the detection of low clouds.

As a conclusion, the differences of the droplet effective radii derived from MODIS and CloudSat presented in Figure 3.1 are not representative, because different cloud
3.3. *Comparison of the Effective Radii from MODIS and CloudSat*

types are compared. CloudSat does not detect low-level liquid water clouds. This shows, that additional measurements from the other sensors on the A-Train satellites are essential to gain information of all clouds, that are present in the atmosphere.

![Cumulative distribution functions of the minimum radar reflectivity](image)

**Figure 3.3:** Cumulative distribution functions of the minimum radar reflectivity, constructed from approximately 30,000 reflectivity profiles of marine stratus and stratocumulus clouds observed off the coast of California (CAVEX) and over the southern Pacific Ocean in the vicinity of New Zealand (PACRIM). For comparison, a similar cumulative distribution function from more than 17,000 profiles over continent from Millimeter Wavelength Cloud Radar (MMCR) measurements is included. Stephens et al. (2002), *Bull. Amer. Meteorol. Soc.*
4 Optical Thickness from MODIS and POLDER

This chapter shows comparisons of the cloud optical thickness of both, water and ice clouds, retrieved from measurements of MODIS and POLDER. First, the POLDER retrieval algorithm is introduced and differences between this one and the MODIS algorithm are explained. Afterwards, a short introduction of the Calxtract dataset, where the POLDER data originate from, is given. Finally, the results of the comparison of the optical thickness derived from the two different measurement instruments are presented.

4.1 POLDER Retrieval Algorithm

Both, MODIS and POLDER algorithms use the solar reflective method for assumed plane parallel geometry from Nakajima and King (1990), which is introduced in section 2.3. Nevertheless, there are differences in the determination of the cloud optical thickness from the two different sensors. The algorithms use different channels for the visible wavelength region. As already mentioned in section 2.3, the MODIS algorithm uses the 0.645 \( \mu \text{m} \) band over land surfaces and the 0.858 \( \mu \text{m} \) band over ocean (Platnick et al., 2003). In contrast, the POLDER algorithm uses the 0.67 \( \mu \text{m} \) channel over land and the 0.865 \( \mu \text{m} \) channel over ocean instead (Buriez et al., 1997). Furthermore, concerning liquid clouds, the POLDER algorithm assumes a gamma distribution of particle sizes with an effective variance of \( \nu_{\text{eff}}=0.15 \) (Buriez et al., 1997), whereas the MODIS algorithm assumes a natural log-normal size distribution with an effective variance of \( \nu_{\text{eff}}=0.13 \) (Nakajima and King, 1990).

Another significant difference between the two algorithms is the fact, that the effective radius varies in the MODIS algorithm, because MODIS disposes of additional information about the particle size, which is retrieved from measurements of its water absorbing channels in the near-infrared region. POLDER cannot make use of particle size information from simultaneous retrievals of the particle effective radius, so in the POLDER algorithm fixed particle radii for liquid water clouds of 9 \( \mu \text{m} \) over
land and 11 µm over ocean are assumed (Buriez et al., 1997).

The retrieval of the optical thickness of ice clouds is more complex than the retrieval of the optical thickness of water clouds, because of the large diversity in shape and size of the ice crystals. Ice crystals cannot be assumed as spheres, so the Lorenz-Mie theory is not suitable here. POLDER and MODIS use different strategies in the retrieval of ice clouds (Zhang et al., 2009). Among others, one significant difference is, that the POLDER retrieval algorithm assumes a constant phase function for ice clouds with an asymmetry parameter of \( g = 0.766 \). In contrast, the MODIS algorithm uses different ice cloud models, which depend on the ice particle size distributions determined by its infrared channels. The asymmetry parameter thus ranges between 0.775 and 0.8808 and is not constant (Zeng et al., 2012).

Additionally, the different initial spatial resolution, which is 6x7 km\(^2\) for POLDER and 1x1 km\(^2\) for MODIS, may cause differences in the retrievals of the optical thickness.

### 4.2 Calxtract Dataset

The data used in this evaluation for the comparison of the optical thickness from MODIS and PARASOL was provided from the ICARE Thematic Center (Interactions Clouds Aerosols Radiations Etc.).

ICARE is a data center for atmospheric research. Its aim is to produce and distribute remote sensing data derived from Earth Observation missions of NASA, CNES and EUMETSAT. This includes in particular products from A-Train satellites, but also previous missions like POLDER I and II and weather satellites like METEOSAT. ICARE was set up in 2003 by CNES, CNRS (Centre National de Recherche Scientifique), INSU (Institut National des Sciences de l’Univers) and the University of Lille. The Data and Services Center is located at the University of Lille. It develops science algorithms and production codes and distributes the products to the users. One of these products is Calxtract, which extracts variables from different sensors (MODIS, PARASOL, CloudSat, CALIOP and the Imaging Infrared Radiometer (IIR)). These measurements are aligned with CALIOP observations either at 333 m (level 1) or 5 km (level 2) horizontal resolution. For this evaluation level 2 products were used. For PARASOL the Earth Radiation Budget, Water Vapor and Cloud level 2 Product (PARASOL RB 2) was used, which contains information about cloud and
4.3. Comparison of the Optical Thickness from MODIS and POLDER

The comparison of the optical thickness from MODIS and POLDER was performed using the P3L2TRGB Cloud Optical Thickness and P3L2TRGB Cloud Phase from PARASOL RB2 for POLDER. For MODIS the MYD06 Cloud Optical Thickness and the MYD06 Cloud Phase Optical Properties were used.

To analyze the data, two-dimensional histograms were created, where the optical thickness retrieved from MODIS builds the x-axis and the optical thickness from POLDER the y-axis. The results for liquid water clouds and ice clouds are shown in Figure 4.1. The considered data comprises single satellite orbits only over ocean, one orbit per day for two months. The dashed curves in Figure 4.1 represent the one-to-one lines and the solid curves represent the regression lines. The slope of the regression line and the correlation coefficient, which is given in the upper left corner of the graphics, give a measure of the pertinence of the linear relationship between the two optical thicknesses. For a perfect linear relationship, these parameters should be equal to one.

In Figure 4.1 only the pixels, where MODIS and POLDER retrieve the same cloud phase are considered. For both, water and ice clouds, the slopes of the regression lines are less than one. That means, the MODIS derived cloud optical thicknesses are larger than those derived from POLDER for liquid water clouds as well as for ice clouds.

For liquid water clouds 30 701 pixels were considered and for ice clouds 11 068 pixels. The linear correlation for ice clouds with a correlation coefficient of 0.86 is stronger than the correlation for liquid water clouds (correlation coefficient 0.73).

The slope of the regression line is 0.73 for ice clouds. This confirms the results from Zeng et al. (2012), who found a slope of 0.74 for ice clouds for overcast pixels. Zeng et al. (2012) examined the optical thickness retrieved from MODIS and POLDER in the same way like it was done in this evaluation, but they considered much more data points. They explained the smaller optical thickness from POLDER for ice clouds with the different strategies in the retrieval algorithms of the two sensors for ice clouds, which were introduced in section 4.1. The fixed ice cloud model
Figure 4.1: Two-dimensional histograms of the cloud optical thickness from MODIS (x-axis) and POLDER (y-axis) for a) liquid water clouds and b) ice clouds. The dashed lines are one-to-one lines and the solid lines are the computed linear regression lines. The color scales represent the number of pixels in percent.
in the POLDER retrieval algorithm assumes a constant phase function with an asymmetry parameter of \( g = 0.766 \). In contrast, the asymmetry parameter in the MODIS algorithm, which uses different ice cloud models, ranges between 0.775 and 0.8808. Thus, in the POLDER algorithm the asymmetry parameter is smaller than in the MODIS algorithm. This means, that more energy is assumed to be returned backward in the POLDER algorithm. Therefore, the retrieved values of the optical thickness are smaller for POLDER.

For liquid water clouds, Zeng et al. (2012) found a good linear correlation between the two sensors with a slope of the regression line of almost one for overcast pixels. The large difference to the slope of 0.63 in this evaluation may be due to the fact, that it was not distinguished between broken and overcast pixels here. Zeng et al. (2012) showed, that the strong linear correlation belongs to overcast cases, but breaks down for broken clouds. Regardless of the thermodynamical phase, they found correlation coefficients less than 0.7 for broken clouds. Furthermore it must be stressed, that in this evaluation much less pixels were considered.

To investigate the quality of the considered retrievals, the standard deviation for the optical thickness from POLDER, which is also contained in the PARASOL RB2 product (\textit{P3L2TRGB Cloud Optical Thickness Stddev}), was consulted. This quantity gives the relative standard deviation, which is a measure of the variation from the average value. It is defined as

\[
\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2},
\]

where \( \bar{x} \) is the mean value

\[
\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i.
\]

Table 4.1 shows the correlation coefficients and slopes of the regression lines for different standard deviations for liquid water clouds. It also gives the number of pixels that apply to the different standard deviations. One can easily see that only approximately 10% of all retrievals of the optical thickness from POLDER have a relative standard deviation of less than 10%. For these retrievals the linear correlation between the optical thickness from MODIS and POLDER is quite good with a correlation coefficient of 0.92. As illustrated in Figure 4.2, the slope of the regression line is 0.88 for these pixels. Thus, if only retrievals with high quality are taken into account, the slope is much closer to one.
Table 4.1: Statistics for Liquid Water Clouds

<table>
<thead>
<tr>
<th>Standard deviation</th>
<th>Correlation coeff.</th>
<th>slope</th>
<th>number of pixels</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 10 %</td>
<td>0.92</td>
<td>0.88</td>
<td>3013</td>
</tr>
<tr>
<td>≤ 20 %</td>
<td>0.88</td>
<td>0.81</td>
<td>10569</td>
</tr>
<tr>
<td>≤ 30 %</td>
<td>0.84</td>
<td>0.76</td>
<td>17486</td>
</tr>
<tr>
<td>≤ 40 %</td>
<td>0.81</td>
<td>0.72</td>
<td>22629</td>
</tr>
<tr>
<td>≤ 50 %</td>
<td>0.78</td>
<td>0.68</td>
<td>26466</td>
</tr>
<tr>
<td>≤ 60 %</td>
<td>0.76</td>
<td>0.66</td>
<td>28653</td>
</tr>
<tr>
<td>≤ 70 %</td>
<td>0.75</td>
<td>0.65</td>
<td>29658</td>
</tr>
<tr>
<td>≤ 80 %</td>
<td>0.74</td>
<td>0.64</td>
<td>30207</td>
</tr>
<tr>
<td>≤ 90 %</td>
<td>0.74</td>
<td>0.63</td>
<td>30428</td>
</tr>
<tr>
<td>≤ 100 %</td>
<td>0.73</td>
<td>0.63</td>
<td>30701</td>
</tr>
</tbody>
</table>

Figure 4.2: Two-dimensional histogram for liquid water clouds for the optical thickness from MODIS and PARASOL with a standard deviation less than 10% for the PARASOL optical thickness.
4.3. *Comparison of the Optical Thickness from MODIS and POLDER*

The slope decreases fast when larger values for the standard deviation are permitted. Roughly 86% of all values fall in the range of a standard deviation less than 50%. For these retrievals the slope of the regression line is 0.68. When all pixels are considered, the slope is just 0.63. It can be supposed, that if more data were considered in this evaluation, the slope and the correlation coefficient would be much better.

**Table 4.2: Statistics for Ice Clouds**

<table>
<thead>
<tr>
<th>Standard deviation</th>
<th>Correlation coeff.</th>
<th>slope</th>
<th>number of pixels</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 10 %</td>
<td>0.94</td>
<td>0.73</td>
<td>3179</td>
</tr>
<tr>
<td>≤ 20 %</td>
<td>0.91</td>
<td>0.73</td>
<td>7763</td>
</tr>
<tr>
<td>≤ 30 %</td>
<td>0.89</td>
<td>0.74</td>
<td>9745</td>
</tr>
<tr>
<td>≤ 40 %</td>
<td>0.88</td>
<td>0.74</td>
<td>10542</td>
</tr>
<tr>
<td>≤ 50 %</td>
<td>0.87</td>
<td>0.74</td>
<td>10837</td>
</tr>
<tr>
<td>≤ 60 %</td>
<td>0.87</td>
<td>0.73</td>
<td>10939</td>
</tr>
<tr>
<td>≤ 70 %</td>
<td>0.86</td>
<td>0.73</td>
<td>10993</td>
</tr>
<tr>
<td>≤ 80 %</td>
<td>0.86</td>
<td>0.73</td>
<td>11023</td>
</tr>
<tr>
<td>≤ 90 %</td>
<td>0.86</td>
<td>0.73</td>
<td>11038</td>
</tr>
<tr>
<td>≤ 100 %</td>
<td>0.86</td>
<td>0.73</td>
<td>11068</td>
</tr>
</tbody>
</table>

Table 4.2 shows the same statistics for ice clouds. One can easily see, that the slope of the regression line does not vary for the different ranges of the standard deviation. The slope is almost constant with values between 0.73 and 0.74. This confirms the results of Zeng et al. (2012), who found a slope of 0.74.

For standard deviations of the POLDER optical thickness of less than 10%, the correlation coefficient is 0.94. It does not decrease as drastically as for liquid water clouds when larger standard deviations are allowed. For all ice cloud retrievals, the correlation coefficient is still 0.86. Furthermore, almost 29% of all ice cloud retrievals from POLDER fall in the range of a standard deviation less than 10%. Contrary to this, for liquid clouds only approximately 10% of the retrievals belong to this range. For roughly 90% of all ice cloud retrievals the standard deviation of the optical thickness derived from POLDER is less than 30%. This shows, that the regarded retrievals for ice clouds are better than those for water clouds.

To sum up, it can be recorded, that the comparisons of the optical thickness retrieved from MODIS and POLDER show a better linear correlation for ice clouds than for water clouds. If only retrievals with a standard deviation of the optical thickness of less than 10% are considered, for water clouds the slope of the regression line is 0.88. For these high quality retrievals, the linear correlations are quite good.
The slope was expected to be close to one for water clouds and Zeng et al. (2012) were able to prove that for overcast pixels. This evaluation does not distinguish between overcast and broken clouds. Furthermore, it must be emphasized again, that in this evaluation only a small fraction of the number of pixels, that were used by Zeng et al. (2012), was considered. This may be a possible explanation for the discrepancies in the slopes and correlation coefficients for water clouds. For ice clouds, the slope found here agrees better with the results from Zeng et al. (2012).
5 Summary and Outlook

Currently, there are a lot of different measurements from the various instruments of the A-Train satellites available. In general, this means a good chance to determine cloud and aerosol properties more precisely by the use of a combination of active and passive sensors. From this, a better estimate of the influence of clouds and aerosols on the energy budget of the Earth can be received. But before this can be done, the quality of the retrievals from the different sensors must be investigated to better assess the advantages and disadvantages of the different instruments.

The performed comparison of the droplet effective radius from MODIS and CloudSat showed, that CloudSat is not able to detect low water clouds. That means, that CloudSat alone cannot sufficiently provide observations of all clouds, that are present in the atmosphere. Furthermore, CloudSat only provides nadir view observations, that means, it does not cover the entire globe. The combination with the passive measurements from the other A-Train members is therefore essential.

In the second part of this evaluation comparisons of the two passive sensors MODIS and POLDER were discussed. The linear correlations between the two sensors for measurements of the cloud optical thickness were investigated. The results show better correlations for ice clouds than for water clouds. For ice clouds, the results from Zeng et al. (2012) could be confirmed, who found a slope of the regression line of 0.74. For water clouds the correlations found here are not as good as expected. This may be due to the fact, that not enough pixels were regarded here. Nevertheless, consulting the standard deviations for the POLDER retrievals, for standard deviations of less than 10% the linear correlation is quite good with a correlation coefficient of 0.92 and a slope of the regression line of 0.88. For standard deviations greater than 10% the linear correlation is much weaker. In general, the POLDER retrieved values for the cloud optical thickness are smaller than the MODIS retrieved values.

In the future, further comparisons of the different instruments are of big interest for uncertainty calculations of satellite retrieved cloud properties. This may also include comparisons of the effective radius from the 1.6 and 2.1 $\mu$m channels from MODIS, that were unfortunately not available for the regarded time span. The CCCM dataset merges retrievals from all of the A-Train members. Thus, it pro-
vides a lot of relevant information needed for the uncertainty estimations. Therefore, new findings of the uncertainties of the different satellite retrievals may result from a further investigation of this dataset.

The optical and microphysical properties of clouds define the radiative properties and are thus crucial for the parameterizations of clouds in global climate models. Especially, the indirect aerosol effect plays a significant role, because the number of aerosol particles in the air parcel strongly influences the optical and microphysical properties of clouds. Hence, it affects the energy budget of the Earth. Uncertainty estimates of the optical and microphysical properties are essential to quantify the radiative forcing of clouds, especially the radiative forcing due to the indirect aerosol effect.
Bibliography


List of Figures

2.1 Main Cloud Types, source: www.dwd.de .......................... 4
2.2 A-Train Constellation, Stephens et al. (2002), Bull. Amer. Meteorol. Soc. ........................................ 8
2.4 Cloud similarity parameter as a function of wavelength for selected values of the effective radius, Nakajima and King (1990), J. Atmos. Sci. .......................................................... 14
2.5 Theoretical relationships between the reflection function at 0.75 and 2.16 µm for various values of the cloud optical thickness and particle effective radius. Data from measurements above marine stratocumulus clouds during FIRE are superimposed on the figure (10 July 1987). Nakajima and King (1990), J. Atmos. Sci. .......................................................... 15
3.1 Difference between MODIS and CloudSat retrieved droplet effective radius averaged over six months from July 2007 to December 2007. The Difference is defined as MODIS minus CloudSat. Black corresponds to missing data. .................................................. 22
3.2 Six months average of the droplet effective radius derived from MODIS measurements for low, non-precipitating water clouds. .................. 23
3.3 Cumulative distribution functions of the minimum radar reflectivity, constructed from approximately 30 000 reflectivity profiles of marine stratus and stratocumulus clouds observed off the coast of California (CAVEX) and over the southern Pacific Ocean in the vicinity of New Zealand (PACRIM). For comparison, a similar cumulative distribution function from more than 17 000 profiles over continent from Millimeter Wavelength Cloud Radar (MMCR) measurements is included. Stephens et al. (2002), Bull. Amer. Meteorol. Soc. ........ 24
List of Figures

4.1 Two-dimensional histograms of the cloud optical thickness from MODIS (x-axis) and POLDER (y-axis) for a) liquid water clouds and b) ice clouds. The dashed lines are one-to-one lines and the solid lines are the computed linear regression lines. The color scales represent the number of pixels in percent. ................................. 28

4.2 Two-dimensional histogram for liquid water clouds for the optical thickness from MODIS and PARASOL with a standard deviation less than 10\% for the PARASOL optical thickness. ............................... 30
List of Tables

2.1 Cloud Genera, according to the *International Cloud Atlas* (WMO, 1956) ............................................................ 4

2.2 Spatial Resolution of CALIOP, Winker et al. (2009), *J. Atmos. Oceanic Technol.* ............................................... 10

4.1 Statistics for Liquid Water Clouds ........................................ 30

4.2 Statistics for Ice Clouds ................................................... 31
Erklärung

Ich versichere, dass ich die vorliegende Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

Alle Stellen, die wörtlich oder sinngemäß aus veröffentlichten oder noch nicht veröffentlichten Quellen entnommen sind, sind als solche kenntlich gemacht.

Die Zeichnungen oder Abbildungen in dieser Arbeit sind von mir selbst erstellt worden oder mit einem entsprechenden Quellennachweis versehen.

Diese Arbeit ist in gleicher oder ähnlicher Form noch bei keiner anderen Prüfungsbehörde eingereicht worden.

Leipzig, 02.08.2013