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MASTER THESIS

Evaluation and possible improvement of the Wegener-Bergeron-Findeisen Process in the ECHAM6 model

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Abstract

The Wegener-Bergeron-Findeisen process (WBF) is a central process in mixed phase clouds. Ice crystals grow rapidly at the expense of liquid water droplets due to water vapour deposition. The global climate model ECHAM6, developed by the Max-Planck-Institute (MPI) in Hamburg, uses a simple assumption of the WBF. Therefore, for this master thesis a much more complex scheme described by Rotstayn et al. (2000) is implemented and replaces the old WBF. This Rotstayn parametrization describes the ice crystal growth due to vapour deposition and specifications with regards to spatial distribution, ice crystal number concentration and ice crystal habits are included, too.

After removing the old WBF strong changes in the cloud water and cloud ice content develop. By adding different modifications of the Rotstayn parametrization the cloud water was reduced. However, the cloud water amount still does not seem to be correct. The best results of the Rotstayn versions compared to the standard version of ECHAM6 show a low variability of ice fraction with respect to temperature. This does not agree with observations. The additionally adding of the Rotstayn parametrization after the detrainment allocation produces a larger variability of the ice fraction and therefore, shows better results compared with observations. However, this case produces less cloud ice in the lower cloud layers and generates many differences in comparison to the base run.
1 Introduction

The precise modelling of clouds in climate models plays a crucial role due to the importance and big influence of clouds on the radiation budget and consequential on the climate change (IPCC, 2013). Due to the difficulty of simulating the complex cloud processes, clouds are a major source of uncertainty in climate models (Soden and Held, 2006). Some clouds consist of a mixture of liquid water droplets and ice crystals which occurs between 0°C and -40°C (Korolev et al., 2003). These clouds are called mixed-phase clouds and cover 20-30% of the globe (Warren et al., 1988). Therefore, the cloud ice fraction or cloud liquid fraction as function of temperature serves as an indicator for the cloud phase. Satellite observations of the supercooled cloud fraction provided by Tan et al. (2014) also show an occurrence of liquid water droplets down to -40°C. Due to the different distribution of liquid water droplets and ice crystals within the clouds different radiative effects are developed because liquid water droplets and ice crystals have different radiative properties and herewith affect the global radiation budget (Curry et al., 1996). High-level ice clouds are nearly transparent for incoming solar radiation whereas low-level liquid clouds reflect most of the solar radiation. Thus, it is important to know the distribution of the phase composition. Mixed phase clouds are also important for the precipitation (Mühlstädt et al., 2015), because precipitation can also be generated via the ice phase.

One of the most important processes in mixed phase clouds is the Wegener-Bergeron-Findeisen (WBF) process which describes the fast growth of ice particles due to water vapour deposition (Bergeron, 1928; Findeisen, 1938; Wegener, 1911). Korolev et al. (2003) shows with the help of aircraft measurements that the clouds tend to be either liquid or glaciated which is caused by the WBF. Komurcu et al. (2014) highlighted the importance of the WBF in climate simulations compared to the heterogenous ice nucleation processes. Also Storelvmo and Tan (2015) extract the WBF as one of the most important processes in the cloud microphysics with regard to the radiation budget and show the different treatments of the WBF which are used in different climate models. The two mainly used approaches use a prescribed threshold for activation of the WBF and a physically complex method. The different types of WBF treatments and its comparison with model data are also shown in Hörning (2015). One of the complex methods to parametrize the WBF is described by Rotstain et al. (2000). Here, the ice crystal growth due to water vapour deposition is represented. For this scheme different specifications of spatial distribution of cloud ice and cloud water, ice crystal number concentrations and ice crystal habits are given. The exact description can be found in section 2.4.

This master thesis is a continuative work of Schacht (2016). He implemented the Rotstain parametrization into the global climate model ECHAM6 from the Max-Planck-Institute (MPI) of Hamburg successfully. The process was imple-
1. **INTRODUCTION**

implemented instead of the freezing processes. However, the ECHAM6 uses one of the simple assumptions with a prescribed threshold of cloud ice mixing ratio in its standard version. If this threshold is exceeded the WBF occurs. The descriptions of the current ECHAM6 parametrizations of the freezing processes as well as the WBF are given in section 2.3. In this master thesis, the original WBF process is removed and the Rotstayn parametrization is implemented and switched on first. The results (section 3) are shown for the cloud ice and cloud water content of the different model runs in comparison with the basic ECHAM6 run and are separated in different run groups. These groups include some basic tests (section 3.1), the Rotstayn specifications (section 3.2) and tests with different ice crystal number concentration assumptions (section 3.3). Additionally, an evaluation for the main results with satellite data of CloudSat, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) and Moderate-resolution Imaging Spectroradiometer (MODIS) and measurements from Korolev et al. (2003) is done to evaluate the quality of the generated model data. Furthermore the net top radiation which is the difference between the incoming solar radiation and the outgoing terrestrial radiation at the top of the atmosphere (TOA). This will show the sensitivity of the model with respect to changes in the WBF process. Goals of this work are the replacement of the simple WBF assumption in the ECHAM6 by the more physical correct Rotstayn scheme and its evaluation with the help of observations. This will also show the relevance of the WBF in climate models.
2 Fundamentals and Methods

2.1 Ice nucleation

At temperatures below 0°C clouds may consist with ice crystals. The ice nucleation is the process of ice crystal formation which is possible in a homogeneous and heterogeneous way (Rogers and Yau, 1996). Homogeneous nucleation is a pure freezing process at temperatures below -40°C. Thus, below this temperature only pure ice clouds exist (Heymsfield and Sabin, 1989). Four different heterogeneous ice nucleation mechanisms are possible at temperatures higher than -40°C which are illustrated schematically in Figure 2.1 (Rogers and Yau, 1996). Depositional freezing occurs if ice crystals are formed due to water vapour deposition on an active ice nuclei. At condensational freezing a nuclei first acts as a condensation nuclei and afterwards as a freezing nuclei. Therefore the supercooled droplet is formed due to supersaturation with respect to water phase first. During the condensation process the freezing process starts and the droplet turns into an ice crystal. Contact freezing takes place if a supercooled liquid water droplet comes into contact with a freezing nuclei. This causes an instantaneously freezing of the water droplet. If an ice nuclei becomes embedded in a water droplet and the water droplet freezes, the immersion freezing occurs (Rogers and Yau, 1996). The different nucleation types depend on temperature. Contact freezing occurs at higher temperatures while deposition freezing takes place at lower temperatures (Hoose and Möhler, 2012). Additionally, all types depend on the quality of aerosol which is acting as ice nuclei.

![Figure 2.1: Different versions of heterogeneous ice nucleation after Rogers and Yau (1996)](image-url)
2. FUNDAMENTALS AND METHODS

2.2 Wegener-Bergeron-Findeisen process

The Wegener-Bergeron-Findeisen process (WBF), discovered by Wegener (1911); Findeisen (1938); Bergeron (1928) is the most important process of ice crystal growth. Ice crystals grow at the expense of liquid water because the equilibrium vapour pressure over ice ($e_{s,i}$) is lower than over liquid water ($e_{s,l}$) at temperatures ($\vartheta$ in °C) below 0°C. Here the empirical Magnus approximation for $e_{s}$ after Jarraud (2008) is used:

$$e_{s,i} = 6.112 \cdot \exp\left(\frac{22.46 \cdot \vartheta}{272.62 + \vartheta}\right) \text{hPa}$$  \hspace{1cm} (2.1)

$$e_{s,l} = 6.112 \cdot \exp\left(\frac{17.62 \cdot \vartheta}{243.12 + \vartheta}\right) \text{hPa}$$  \hspace{1cm} (2.2)

Korolev (2007) shows two different situations where ice crystals will grow and gain mass. The first one is that the actual in-cloud water vapour pressure ($e$) is higher than $e_{s,l}$ but below $e_{s,i}$ and occurs in updraft regions:

$$e_{s,i} < e < e_{s,l}$$  \hspace{1cm} (2.3)

In this state ice crystals can grow due to water vapour deposition at expense of the surrounding liquid water droplets so that these liquid water droplets are diminished by evaporation. It results in a completely glaciation of the cloud.

For the second condition $e$ exceeds both $e_{s,l}$ and $e_{s,i}$:

$$e_{s,i} < e_{s,l} < e$$  \hspace{1cm} (2.4)

Thus the air is saturated with respect to ice and water. Therefore both ice crystals and liquid water droplets gain mass and grow. This process maintains the mixed phase within the cloud because the cloud can not be glaciated completely. (Korolev, 2007).

In case that $e$ shows lower values than both $e_{s,l}$ and $e_{s,i}$:

$$e < e_{s,i} < e_{s,l}$$  \hspace{1cm} (2.5)

ice crystals and liquid water droplets will shrink because the air is not saturated neither with respect to ice nor to liquid water. This state takes place in down-draft regions of the cloud.

Figure 2.2 shows both of the equilibrium water vapour pressure equations depending on temperature on the left hand side and the difference between ice and liquid water on the right hand side. Additionally, Figure 2.2a depicts all three different states mentioned before. The blue area depicts state one which is mentioned in Equation 2.3. In this region the growth of ice crystals and liquid water droplets is possible. The orange region shows case two (Equation 2.4). Ice crystals grow at the expense of water droplets. The white area demonstrates the last case (Equation 2.5).
2. **Fundamentals and Methods**

2.3 **ECHAM6**

ECHAM6 is an atmospheric general circulation model in the sixth generation developed by the Max Planck Institute (MPI) for Meteorology in Hamburg and describes the atmospheric component of the earth system model MPI-ESM (Stevens et al., 2013). The Model is able to run with 47 or 97 vertical levels and with a horizontal resolution range from T31 (96x48 grid) to T255 (786x384 grid) (Giorgetta et al., 2013). For this master thesis the lowest resolution T31 is used for computing time reasons.

There is a different treatment of cumulus convection based on mass fluxes (Tiedtke, 1989) and stratiform clouds including cloud microphysics. For the stratiform cloud scheme Lohmann and Roeckner (1996) give an approach for the prognostic equations of cloud ice and cloud liquid water.

2.3.1 **Freezing parametrization**

Homogeneous freezing of cloud water occurs at temperatures below -35°C. Therefore, cloud water freezes during one time step instantaneously (Giorgetta et al., 2013).

Heterogeneous freezing takes place within the mixed phase temperature range -35°C < T < 0°C. The ECHAM6 treats three different types of heterogeneous freezing.
freezing. The first two, the stochastical and heterogeneous freezing \((Q_{frs})\), developed by Bigg (1953) are for bigger droplets and is extrapolated down to cloud droplet size:

\[
Q_{frs} = C a_1 \left\{ \exp[b_1(T_0 - T)] - 1 \right\} \frac{\rho_{cl}^2}{\rho_w N_l} \tag{2.6}
\]

with constants \(a_1 = 100 \text{ m}^3 \text{s}^{-1}\), \(b_1 = 0.66 \text{ K}^{-1}\) from laboratory experiments, the freezing point \(T_0 = 273.15 \text{ K}\) and \(\rho_w = 1000 \text{ kg m}^{-3}\) the water density. \(C\) indicates the fractional cloud cover, \(T\) the mean temperature of the grid cell, \(\rho\) the air density, \(q_{cl}\) the in-cloud water mixing ratio and \(N_l\) the cloud droplet number concentration, which is prescribed for the boundary layer over land with \(N_l = 220 \cdot 10^6 \text{ m}^{-3}\) and over sea with \(80 \cdot 10^6 \text{ m}^{-3}\) (Giorgetta et al., 2013).

Contact freezing, shown in equation 2.7, is described by random collisions of aerosols with supercooled cloud droplets due to Brownian motion (Giorgetta et al., 2013; Levkov et al., 1992).

\[
Q_{frc} = C m_{io} F_1 DF_{ar} \tag{2.7}
\]

\(m_{io}\) is the initial mass of an ice crystal and \(DF_{ar}\) is the aerosol diffusivity with \(DF_{ar} = 1.4 \cdot 10^{-8} \text{ m}^2 \text{s}^{-2}\) (Pruppacher and Klett, 1997). \(F_1\) is defined by

\[
F_1 = \frac{4\pi R_{vl} N_l N_{a}}{\rho} \tag{2.8}
\]

where \(N_{a}\) is the concentration of active contact nuclei and may be written as

\[
N_{a} = \max[N_{a0}(T_0 - T - 3), 0], \quad \text{with} \quad N_{a0} = 2 \cdot 10^5 \text{ m}^3 \tag{2.9}
\]

The mean volume droplet radius \(R_{vl}\) is given by (Giorgetta et al., 2013)

\[
R_{vl} = \sqrt[3]{\frac{1}{3\pi N_1 \rho_w} \frac{q_{cl} \rho}{\frac{3}{16} \pi N_{a}}} \tag{2.10}
\]

### 2.3.2 Current parametrization of WBF

Depositional growth of cloud ice takes place if one of the following conditions is true:

1. \(T < -35^\circ \text{C}\)

2. \(T < 0^\circ \text{C}\) and the in-cloud ice mixing ratio \(q_{i} > 5 \cdot 10^7 \text{ kg kg}^{-1}\)

The second condition can be seen as a simple parametrization of the WBF (Giorgetta et al., 2013). A schematic overview of the effect of the WBF within the ECHAM6 code is given in Figure 2.3. As shown, the WBF takes place at two different places. First the WBF is used for the detrainment. For checking the
threshold of \( q_i \), the mixing ratio of falling ice is used given by a weighted function of fall velocity \( W(-v_i) \):

\[
q_{i,\text{sed}} = q_i \cdot \exp\{W(-v_i)\} + q_{i,\text{sed}} \cdot [1 - \exp\{W(-v_i)\}] \tag{2.11}
\]

So positive fall velocities result mainly in \( q_{i,\text{sed}} \). Due to checking the conditions mentioned above the convective detrainment is allocated to cloud water or cloud ice. If one of the conditions is true the convective detrainment is set to cloud ice otherwise to cloud water. This part is the link between convective cloud parametrization to the large scale cloud microphysics. By using the same variable \( q_{i,\text{sed}} \) the condition check results in depositional or condensational growth. The second time the WBF is used for saturation adjustment. Therefore \( q_i \) including the mentioned depositional or condensational growth is utilized for comparison with the conditions. If one of the conditions is true the equilibrium water vapour pressure of the mixed phase case is utilized, otherwise the water phase case is used. Afterwards, deposition and condensation get an update for the new saturation adjustment.

**Figure 2.3:** Schematic overview of the effect of the WBF within the ECHAM6
2.4 Rotstayn parametrization

A much more complex and more physical based parametrization of the WBF gives Rotstayn et al. (2000). In Rotstayn et al. (2000) the WBF parametrization is implemented in the global climate model of Commonwealth Scientific and Industrial Research Organisation (CSIRO). The cloud scheme of this model is described by Rotstayn (1997). Coexisting liquid water droplets and ice crystals can occur in temperature ranges of 0°C to -40°C. Thus, below -40°C only pure ice clouds exist. At temperatures above 0°C the whole cloud ice melts to liquid water within one time step. This two processes give the boundaries for mixed phase calculations in the cloud.

Water vapour deposition

Within the mixed phase temperature range Rotstayn et al. (2000) describes the growth of cloud ice crystals due to water vapour deposition at the expense of liquid water droplets. Pruppacher and Klett (1997) give a formulation for the growth of ice mass $dM_i$ per time step $dt$

$$\frac{dM_i}{dt} = \frac{4\pi C(S_i - 1)}{A'' + B''}$$

(2.12)

where $(S_i - 1)$ gives the supersaturation with respect to ice and $C$ the different ice crystal shapes which will be described in section 2.4.2. $A''$ represents the heat conductivity with

$$A'' = \frac{L_s}{K_a T} \left( \frac{L_s}{R_v T} - 1 \right)$$

(2.13)

and $B''$ the water vapour diffusion with

$$B'' = \frac{R_v T}{\chi e_{s,i}}$$

(2.14)

Here $L_s = 2.834 \cdot 10^6$ J kg$^{-1}$ is the latent heat of water sublimation, $K_a$ the heat conductivity of air, $R_v = 416$ J kg$^{-1}$ the specific gas constant of water vapour, $T$ the air temperature, $\chi = 2.21$ the diffusivity of water vapour in air and $e_{s,i}$ gives the equilibrium vapour pressure over ice. If the air is saturated with respect to water, so that $(S_i - 1) = \frac{e_{s,l} - e_{s,i}}{e_{s,i}}$, Equation 2.12 may be written for the cloud ice mixing ratio $\tilde{q}_i$ as

$$\frac{d\tilde{q}_i}{dt} = \frac{N_i 4\pi C e_{s,i} - e_{s,i}}{p (A'' + B'')}$$

(2.15)

with the ice crystal number concentration $N_i$ and the pressure $p$. After describing all of the specifications in spatial distribution, ice crystal shape and ice crystal number concentration formula 2.17 gives a general form for the change of $\tilde{q}_i$ depending on these specifications.
2.4.1 Spatial distribution

Rotstayn et al. (2000) uses two different forms of spatial distributions for cloud ice and cloud water. Figure 2.4 illustrates these two cases. On the left hand side the 'horizontally adjacent' case is shown where cloud ice and cloud water is separated. However, water vapour deposition only takes place in the liquid water part. Therefore, small ice crystals are built in every time step and gain more mass by water vapour deposition. For the calculation of liquid cloud fraction $C_l$ cloud liquid water mixing ratio $q_l$ and cloud ice mixing ratio $q_i$ are used.

$$C_l = C \frac{q_l}{q_l + q_i}$$  \hspace{1cm} (2.16)

$C$ describes the entire cloud fraction and $f_l$ the liquid water fraction. Analogously, the ice cloud fraction is described by $C_i = 1 - C_l$.

In the 'uniformly mixed' case liquid water and ice are mixed in the cloud. Therefore, water vapour deposition can occur within the entire cloudy part $C$.

![Figure 2.4: Spatial distributions for cloud ice and cloud water treated in Rotstayn et al. (2000)](image)

2.4.2 Ice crystal habit

Many observations show that ice crystal habits have complex structures which differ with temperature and ice supersaturation (Pruppacher and Klett, 1997). The different shapes of ice crystals affect their growth, density, terminal velocities and radiative properties (Korolev et al., 1999). Thus, they influence the glaciation process of the cloud. Figure 2.5 gives an overview about different ice crystal habits as function of ice supersaturation and temperature. The solid line indicates the water saturation. With decreasing temperatures the ice crystal shape
Figure 2.5: Variation of ice crystal habit with temperature and ice supersaturation \((S_i - 1)\) based on laboratory observations (Pruppacher and Klett, 1997)

Changes from a plate to a column back to plates and columns. However, there are specifications of plates and columns and some other shapes as needles, sheath and dendrites at higher ice supersaturations. In Rotstayn et al. (2000) three different habits of ice crystals are assumed. From Equation 2.4 the capacitance \(C\) is replaced by the different formulations from Pruppacher and Klett (1997). Table 2.1 gives the equations for \(C\) in Equation 2.12 for the different ice crystal habits. Spherical ice crystals is the idealized case of an ice crystal with a ball diameter \(D_i = \left(\frac{6M_i}{\pi \rho_i}\right)^{1/3}\) and with a constant density \(\rho_i\) and ice crystal mass \(M_i\). Hexagonal plates are assumed to be a circular disk with diameter \(D_i\). The modelling of

<table>
<thead>
<tr>
<th>Ice crystal habits</th>
<th>Equations</th>
<th>Constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere</td>
<td>(C = \frac{D_i}{2})</td>
<td>(D_i)...ball diameter</td>
</tr>
<tr>
<td>Hexagonal plates</td>
<td>(C = \frac{D_i}{\pi})</td>
<td>(D_i)...disk diameter</td>
</tr>
<tr>
<td>Columns</td>
<td>(C = \frac{A}{ln\left(\frac{a+b}{a-b}\right)})</td>
<td>(a, b)...semi-axis of a prolate spheroid (A = \sqrt{a^2 - b^2})</td>
</tr>
</tbody>
</table>
columnar ice crystals is described as prolate spheroids of semi-axes $a$ and $b$. Related to the ice crystal growth these three crystal habits have different growth rates. Hexagonal plates grow much faster than spheres and columns. However, the difference between columnar and spherical crystals is not that significant (Rotstayn et al., 2000). Figure 2.6 shows the change of ice crystal mass for the three crystal habits and summarizes the facts mentioned before.

2.4.3 Ice crystal number concentration

The ice crystal number concentration $N_i$ plays an important role within the Rotstayn Parametrization. $N_i$ is only a function of temperature and does not include the actual cloud ice content. Rotstayn et al. (2000) presents two different $N_i$ formulations. In the standard version of the Rotstayn scheme a function of equilibrium water vapour pressure (Equation (2) of Table 2.2) is used and is described by Meyers et al. (1992) with the condition that air is water saturated, so that $S_i - 1 = (e_{sl} - e_{si})/e_{si}$. An earlier assumption was provided by Fletcher (1962). He describes $N_i$ as a function of temperature (Equation (2) Table 2.2). A third version by Rogers et al. (1996) is added for this master thesis which gives the best agreement with observations after Gultepe et al. (2001). Rogers et al. (1996) describes it also a function of temperature which can be seen in Table

Figure 2.6: Mass of capacitance of spheres, hexagonal plates and columns according to Rotstayn et al. (2000)
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Table 2.2: Different parametrizations for $N_i$ based on Gultepe et al. (2001)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Calculation of $N_i$ in (L$^{-1}$)</th>
<th>Constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Fletcher, 1962)</td>
<td>$N_i = 10^{-5} exp[a(T_0 - T)]$</td>
<td>$(1) a = 0.6 K^{-1}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T_0 = 273.15 K$</td>
</tr>
<tr>
<td>(Meyers et al., 1992)</td>
<td>$N_i = exp[a(S_i - 1) - b]$</td>
<td>$(2) a = 12.96$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$b = 0.639$</td>
</tr>
<tr>
<td>(Rogers et al., 1996)</td>
<td>$N_i = 0.0063 \cdot exp(-0.281 \cdot T)$</td>
<td>$(3)$</td>
</tr>
</tbody>
</table>

2.2, Equation (3). In Figure 2.7a all three $N_i$ parametrizations are plotted as a function of temperature. Meyers equation produces the most ice crystals at higher temperatures. Compared to Meyers relation Fletcher and Rogers create less values of $N_i$ up to -23$^\circ$C in which Fletcher gives the lowest values. However, Fletcher’s relation has the largest slope and therefore produces the largest difference of $N_i$ regarding to the temperature.

Figure 2.7b shows variations of Meyers relation (2.5-fold, 5-fold and 10-fold multiplication) which are used for sensitivity tests in this master thesis. Compared to Figure 2.7a the difference of $N_i$ values within the temperature range 0 to -20$^\circ$C between Meyers and Fletchers parametrization is much larger than between Mey-

![Figure 2.7](image-url)  

(a) Different versions for $N_i$ (Table 2.2)  
(b) Variations of Meyers et al. (1992) $N_i$

**Figure 2.7:** Ice crystal number concentrations $N_i$ used for the Rotstayn parametrization
2. FUNDAMENTALS AND METHODS

ers original relation and its 10-fold. The result chapter 3 shows the impact of the different treatments of \( N_i \). To give a comparison with observational data several data points are taken due to digitalization from DeMott et al. (2010). All these observations originate from aircraft measurements over different regions (more informations about the observation data can be found at http://www.pnas.org). The data shows large variations of \( N_i \) with temperature. For example, at -32°C the ice crystal number concentration varies from 0.5 to 500 L\(^{-1}\).

**General form of all different specifications**

Equation 2.17 gives the general form of the change in cloud ice mixing ratio \( \Delta \tilde{q}_i \) for each time step \( \Delta t \) with all different specifications.

\[
\Delta \tilde{q}_i = \max \left[ q_i, \tilde{C} \left( (1 - \alpha) c_{ed}^{s,p,c} \Delta t + q_{i,0}^{1-\alpha} - q_i^* \right) \right]
\]  

(2.17)

Here \( \tilde{C} \) gives the cloud fraction where the WBF is assumed and \( q_{i,0} \) the initial cloud ice mixing ratio in the supercooled liquid cloud part. \( c_{ed}^{s,p,c} \) is the rate constant which differs with each ice crystal shape and \( \alpha \) is a constant for each crystal habit. The explicit formulations for each of these variables are listed in Table 2.3.

**Table 2.3: Variables for Equation 2.17 based on Schacht (2016)**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontally adjacent</td>
<td>( q_i^* = 0 ) &lt;br&gt; ( \tilde{q}_{i,0} = \frac{10^{-12} N_i}{\rho} ) &lt;br&gt; ( \tilde{C} = C \frac{q_i}{q_i + q_i} )</td>
</tr>
<tr>
<td>Uniformly mixed</td>
<td>( q_i^* = q_i ) &lt;br&gt; ( \tilde{q}_{i,0} = \max \left[ \frac{10^{-12} N_i}{\rho} q_i, C \right] ) &lt;br&gt; ( \tilde{C} = C )</td>
</tr>
<tr>
<td>Spheres</td>
<td>( c_{ed}^{s} = 7.8 \frac{(N_i/\rho)^{2/3}(e_{s,l}-e_{s,i})}{\rho^{1/3}(A^{e}+B^{e})e_i} ) &lt;br&gt; ( \alpha = \frac{1}{3} )</td>
</tr>
<tr>
<td>Hexagonal plates</td>
<td>( c_{ed}^{p} = 65.2 \frac{(N_i/\rho)^{1/2}(e_{s,l}-e_{s,i})}{\rho^{1/2}(A^{e}+B^{e})e_i} ) &lt;br&gt; ( \alpha = \frac{1}{2} )</td>
</tr>
<tr>
<td>Columns</td>
<td>( c_{ed}^{c} = 0.839 \left( \frac{N_i}{\rho} \right)^{0.661} \frac{e_{s,l}-e_{s,i}}{(A^{e}+B^{e})e_{s,i}} ) &lt;br&gt; ( \alpha = 0.339 )</td>
</tr>
</tbody>
</table>
2.5 Model data

All model data are produced with the T31 ECHAM6 climate model version for monthly, daily and six-hour mean values for the years 1990 and 1991. The calculation of cloud ice fraction \( f_i \) can be written as

\[
   f_i = \frac{q_i}{q_i + q_l}
\]

with cloud ice \( q_i \) and cloud water \( q_l \). For this relation only six time steps of six-hourly data sets of the entire global grid and a height range from 0 to 400 hPa is used to give a better representation of the temperature dependency. For illustration of single variables a global average of monthly data for two years is produced.

The cloud top phase is calculated with help of a prescribed threshold for the total cloud condensate. There is a dependency of this threshold which is shown in the appendix. To have more input points the daily data instead of the monthly data are used to provide the annual mean.

2.6 DARDAR-Mask data set

The DARDAR-MASK (RaDAR/LiDAR) data set consists of satellite products from CALIPSO, CloudSat and MODIS to study the ice phase properties (Huang et al., 2012). CALIPSO, CloudSat and MODIS, stationed on Aqua, are part of the A-Train constellation (L’Ecuyer and Jiang, 2010).

CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) was launched together with CloudSat in April 2006 (Winker et al., 2009). On board on the CALIPSO satellite is the Cloud-Aerosol Lidar with Orthogonal Polarization (Caliop). It has a two-channel transmitter, which produces light pulses at 532 nm and 1024 nm (Winker et al., 2003). The backscattered signal is collected by a 1-m diameter telescope and is send to a three-channel receiver system. This system measures the 1024 nm signal and the 532 nm signal which is separate by a polarization beam-splitter in an orthogonal and parallel component (Winker et al., 2009). Caliop produces vertical profiles of the clouds and aerosol layers. With the help of computer algorithms different aerosol types and cloud phases can be determined (Winker et al., 2003). Because of the optical measuring method Caliop is suitable for detecting optical thin clouds and aerosol layers.

CloudSat flies the first spaceborne 94 GHz-millimetre wavelength cloud profiling radar (CPR) 15 s in front of CALIPSO with a vertical resolution of 500 m (Stephens et al., 2002). The CPR emits monochromatic pulses and also provides vertical profiles of clouds. Compared to Caliop the CPR detects optical thick clouds and precipitation. Therefore, the combination of Caliop, which detects the upper troposphere thin clouds and aerosols, and CPR, which provides the profiles of optical thick clouds, is very useful to get more informations about
cloud properties as they are complementary. The Moderate Resolution Imaging Spectroradiometer (MODIS) is a spectroradiometer with 36 spectral bands between 0.415 and 14.235 µm that flies on the Aqua satellite (King et al., 2003). For the DARDAR-MASK only three infrared channels 8.5 µm, 11 µm, 12 µm are used (Huang et al., 2012). MODIS provides informations about land, ocean, and atmospheric properties. A summarized table of all three instruments is given in table 2.4. For this master thesis the DARDAR-Mask Data set is used for comparison of cloud top phase in section 3.4.3.

Table 2.4: Overview of the used instruments of the DARDAR-MASK data set

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Payload</th>
<th>Description</th>
<th>Output products</th>
</tr>
</thead>
<tbody>
<tr>
<td>CALIPSO</td>
<td>Caliop (Lidar)</td>
<td>two-channel transmitter with 532 nm and 1024 nm light pulses, three-channel receiver for 1024 nm and 532 nm, splitted in an orthogonal and parallel component</td>
<td>vertical profiles for optical thin clouds, computer algorithms for detecting different aerosol types and cloud phases</td>
</tr>
<tr>
<td>CloudSat</td>
<td>CPR(Radar)</td>
<td>500 m vertical resolution, 94-GHz radar emits monochromatic pulses</td>
<td>vertical profiles of optical thick clouds and precipitation</td>
</tr>
<tr>
<td>Aqua</td>
<td>MODIS</td>
<td>imaging spectroradiometer with 36 spectral bands</td>
<td>informations about land, ocean and atmospheric properties (aerosol and clouds)</td>
</tr>
</tbody>
</table>
3. RESULTS

The results are presented by sorting them into different experiment groups which are compared among each other. These groups are additionally sorted by different parameters to compare different aspects like cloud water and ice content. The sorting of the following sections is based on the time flow of finding the results. Following, each experiment is shortly described. First of all the WBF was removed which is marked with no WBF. Therefore, the second condition of depositional growth (see section 2.3.2) was turned off. Thus, depositional growth occurs only at temperatures below -35\degree C. For the following runs the state of removed WBF is kept up. After removing the current WBF from the ECHAM6 the standard version of the Rotstayn parametrization, which includes spherical ice crystals, a horizontal adjacent spatial distribution and Meyers et al. (1992) assumption of \( N_i \), was turned on. Therefore, the Rotstayn parametrization were applied after the droplet freezing processes. This experiment run is named Rotstayn. Specifications of the Rotstayn parametrization (see Table 2.3) are additionally indicated. As a first try to adjust the results the droplet freezing and the Rotstayn parametrization were applied directly after the detrainment allocation (see the left block of Figure 2.3), because the cloud ice and cloud water from convective cloud calculations appears here for the first time in the stratiform cloud and is still unchanged. This is described with on detrained. Other tests were made within the Rotstayn parametrization, especially for \( N_i \) which are indicated with \( N_i \). Multiplications of \( N_i \) are related to Meyers’ formulation unless other authors are mentioned. Table 3.1 presents the experiment constellations in which the results are represented. After the representation of the grouped experiments the main results are summarized for a comparison with observation data and the representing net radiation flux at the top of the atmosphere.

<table>
<thead>
<tr>
<th>Abbrevation</th>
<th>Section</th>
<th>full name</th>
<th>Includes experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASIC</td>
<td>3.1</td>
<td>Basic tests</td>
<td>no WBF, Rotstayn, on detrained</td>
</tr>
<tr>
<td>ROTSTAYNmod</td>
<td>3.2</td>
<td>Rotstayn modifications</td>
<td>adjacent, spheres, adjacent, plates, adjacent, columns, uniformly, spheres, uniformly, plates, uniformly, columns</td>
</tr>
<tr>
<td>NImod</td>
<td>3.3</td>
<td>( N_i ) modifications</td>
<td>2.5x( N_i ), 5x( N_i ), 10x( N_i ), ( N_i ) Fletcher, ( N_i ) Fletcher, ( N_i ) Rogers</td>
</tr>
</tbody>
</table>

Table 3.1: Experiment groups for presenting results
3. RESULTS

3.1 BASIC

3.1.1 Cloud water

Changes in cloud microphysic with respect to WBF cause changes in the cloud water content. Figure 3.1 shows the zonal average of cloud water for the total average over the two years 1990 and 1991 for the first experiment runs. Therefore, the right column shows the difference to the BASE run of the standard ECHAM6 (upper panel left). The BASE run shows increased cloud water values in lower layers up to 700 hPa in the midlatitudes. The second row depicts the no WBF modification. Due to the removing of the current WBF the cloud water generating processes are favoured. During the detrainment allocation most of the detrained convective cloud ice and water is transformed to cloud water. Further-

![Figure 3.1: Zonal average of cloud water (g/kg) for experiment setups no WBF, Rotstayn and on detrained; right column indicates the difference to the BASE run](image)

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more, condensational growth occurs more often than depositional growth. The only process which generates a cloud water loss is the droplet freezing process. Therefore, the cloud water in the no WBF run is much higher than in the BASE run. Especially in the mid and higher latitudes a lot of cloud water is generated up to a height of 400 hPa. The next row shows the results of using the Rotstayn scheme. It can be seen that there is much less cloud water than in no WBF but more than in BASE. The loss of cloud water within the Rotstayn parametrization is much higher compared to the droplet freezing. This can be seen in comparison with no WBF, because in no WBF only the droplet freezing occurs whereas in Rotstayn both the droplet freezing and the Rotstayn parametrization are applied. However, the Rotstayn parametrization is not able to balance the removing of the old WBF from the ECHAM6 because there is still too much cloud water. The next idea was to balance the cloud water excess by testing the Rotstayn parametrization directly after the detrainment allocation and so it acts directly on the new generated cloud water. The effect of this test can be seen in the bottom row of Figure 3.1. Compared to BASE there is still too much cloud water in the mid latitudes but in comparison to Rotstayn the cloud water is slightly reduced, because the Rotstayn parametrization acts additionally at an earlier place. However, the effect of the water generation due to the detrainment allocation is much lower as the condensation and deposition process within the standard ECHAM6, which is shown in the appendix Figure A.2. The area of cloud water gain is larger compared to the Rotstayn case. As an additionally parameter of cloud water the liquid water path (LWP), which indicates the total amount of cloud water within a vertical column, is shown in the appendix, Figure A.1.

### 3.1.2 Cloud ice

Another important parameter is shown in Figure 3.2. Here, the results for the zonal average of cloud ice for the BASIC runs are depicted. The BASE run shows an increased cloud water content in the higher cloud layers. In the midlatitudes the cloud ice content is increased down to 900 hPa. The second row shows the no WBF case. Due to the removal of the WBF much of the ice is not generated in the lower atmospheric layers. In comparison to the cloud water (Figure 3.1) it becomes clear, that the absent cloud ice turned into cloud water. This is due to the decision whether condensation or deposition and the detrainment goes into cloud water or cloud ice, respectively. Additionally, much more cloud ice compared to the BASE run exists in the upper atmospheric layers. Due to the removing of the old WBF depositional growth only occurs at a temperature below -35°C which is the temperature of starting homogeneous freezing. The cloud ice in the upper layer is only formed because of this temperature condition. The ice formation process acts stronger at lower temperatures and therefore at higher cloud layers, because in the lower, warmer layers no cloud ice is generated.
For a better understanding see Figure 3.3. In the second row the Rotstyn run shows a good agreement with the BASE run of the ECHAM6. In the upper cloud layer slightly too much cloud ice is present. The reason can be seen in Figure 3.3 and will be described in the next section. In the lowermost row the results are shown for on detrained. The panel on the right hand side shows a big cloud ice loss compared to BASE in the lower layers. Only an iced cloud layer at higher altitudes can be seen. The pattern is similar to no WBF with the difference that the cloud ice layer in higher altitudes is not that extremely distinct. Compared to Rotstyn the cloud ice loss is very significant because the same parametrization is used on two different places. Explanations gives the analysis of ice fraction in section 3.1.3. However, the additionally placement after the detrainment allocation disturbs the second placement of the Rotstyn parametrization, so that the Rotstyn scheme is not able to produce cloud ice in the lower cloud layers which is not just yet clear why.
3. RESULTS

3.1.3 Cloud ice fraction

In this section the cloud ice fraction is presented as a function of temperature, shown in Figure 3.3. All points were captured over the entire globe and up to 400 hPa. An ice fraction of 0.0 indicates that the whole cloud consists of liquid water droplets and 1.0 represents a completely glaciated cloud. In the BASE run a big variability of ice fraction for each temperature is noticeable. This reveals that there is no pure temperature dependency which is caused by the complex microphysic. However, the variability of ice fraction is created by using the threshold for cloud ice mixing ratio. Mainly the points either close to an ice fraction of 0.0 or 1.0 so that clouds tend to be either full of liquid water or ice. Pithan et al. (2014) also show the ice fraction of the ECHAM6 but in comparison with much more simple mixed phase treatments, which underlines the complexity due to the use of complex microphysics. A big difference can be seen in comparison to no WBF. As mentioned before a lot of cloud water is generated. Down to a temperature of -30°C the ice fraction varies within a range between 0.0 to 0.2. Below -30°C the main cloud ice generation would occur. But this temperature is generally too low for starting the cloud ice production and the water expense is too high at higher temperatures. For the Rotstagn run the temperature interval for the mixed phase ranges from 0°C to -20°C so below -20°C a pure ice cloud exists. At temperatures between 0°C and -10°C the most ice fraction points are located between 0.0 and 0.1. This explains the cloud water expense in figure 3.1. The last case is the on detrained run. In comparison to Rotstagn the mixed phase occurs within a larger temperature interval, which is the reason why cloud water occurs also at temperatures from -20°C down to -35°C. Between 0°C and -5°C nearly only ice fraction values lower than 0.1 with few exceptions. Below -5°C the liquid water transformation to cloud ice takes place. The variability pattern is more similar to the BASE run because the variability of ice fraction from 0°C to -35°C is better developed compared to Rotstagn.
3. RESULTS

3.2 ROTSTAYNmod

3.2.1 Ice fraction

For the ROTSTAYNmod run group firstly the ice fraction is shown. Figure 3.4 shows all of the Rotstayn modifications in comparison. The left panel in the upper row gives the Rotstayn standard case, described in section 3.1.3. It can be seen that some panels look very similar. Especially the horizontal adjacent (upper row) and the uniformly mixed (lower row) runs are very similar with only a few differences. The main difference exists between the ice crystal shape plates (middle column) and spheres or columns, because columns and spheres look also very similar. As mentioned in section 2.4.2 plates have the biggest growth rate compared to the other two ice crystal habits. Thus the ice crystal growth is more efficient and the transformation from cloud water to cloud ice is much faster. Therefore, the mixed phase temperature interval ranges only from 0°C to -10°C. Because only plates differ from the remaining modifications this ice crystal shape is used for the next sections as comparison for the following parameters. Additionally, changes in liquid water fraction are small as well which is shown in Figure A.3 in the appendix.

3.2.2 Cloud water

The standard Rotstayn scheme and the modification with plates instead of spherical ice crystals for the cloud water is shown in Figure 3.5. As shown before the Rotstayn scheme produces to much cloud water in the midlatitudes. The plate
specification gives a reduction of cloud water. In the difference plot of the Rotstayn, plates run near 60° North (N) and South (S) a border between cloud water expense and absence is visible. In the poleward direction there is too little cloud water while in direction to the equator up to 40° N/S there is too much cloud ice. That means that the region of higher cloud water is shifted towards the equator. The border of negative and positive difference is within the temperature interval from -10°C to 0°C. Figure 3.4 shows that the ice generation is very fast and occurs in the mentioned temperature interval. Thus, the reduction of cloud water is due to the strong growth rate of ice crystals. But it has to be considered how realistic the assumption of using platelike ice crystals is, because they are not everywhere represented (e.g. see Figure 2.5). However, in general it is an improvement compared to Rotstayn. On the southern hemisphere the border in the difference is stronger distinct. This described region is the southern storm track region which reacts very sensitive to changes in the Rotstayn parametrization.

3.2.3 Cloud ice

Figure 3.6 shows the same two experiments as in Figure 3.5 in comparison. The middle row gives again the Rotstayn run. As mentioned before the results look very similar compared to BASE with the difference that the upper cloud layer
Figure 3.6: Cloud ice (g/kg) same as in Figure 3.5

includes slightly more ice than the BASE case. In the upper panels the Rotstayn, plates run is shown. A significant difference occurs in the lower south-midlatitudes up to 800 hPa where the cloud ice content is much larger than in the Rotstayn run. This region is the same region with the difference border in cloud water difference as described in section 3.2.2. Due to the small temperature interval of mixed phase clouds more cloud ice is build within the cloud. The southern midlatitudes near to 60°S are a region of high cloud coverage (see Figure A.4 in the appendix). Because the cloud coverage is that high the modified cloud properties by using platelike instead of spherical ice crystals show stronger changes.

3.3 NImod

3.3.1 Cloud water

To show the importance of the $N_i$ parameter Figure 3.7 presents the difference of cloud water due to the multiplication of Meyers $N_i$ parametrization. For better interpretation of the results Figure 2.7b shows, as mentioned before, the different $N_i$ multiplications as function of temperature. It will be clear that the higher the multiplication factor the smaller is the cloud water content. By using a multiplication factor of 10 the water expense of the Rotstayn run is nearly removed
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Figure 3.7: Cloud water (g/kg) for the n-fold of Meyers $N_i$

and leads to a cloud water absence. Additionally, there is the same border in difference plots as in Figure 3.6. In comparison with Rotstyn, plates it can be noted that a fivefold $N_i$ looks very similar to Rotstyn, plates. In poleward direction there is too less cloud water and in the midlatitudes, especially in the southern midlatitudes, the cloud water content is too high, which causes a motion in direction to the equator. By using the 2.5-fold $N_i$ there is still too much cloud water compared to BASE. The reduction of cloud water is due to the increased $N_i$. More ice crystals lead to a better efficiency of the Rotstyn parametrization. Therefore, the mixed phase temperature interval becomes smaller and the glaciation of the cloud occurs more rapidly. Thus, at lower temperatures the cloud water reduction acts stronger. Therefore, in regions of higher latitudes the cloud water gets reduced. The best agreement with the BASE run gives the fivefold $N_i$ case. Figure 3.8 shows the different $N_i$ parametrizations which are given in Table
3. RESULTS

Figure 3.8: Cloud water (g/kg) for three different $N_i$ parametrizations (equations are given in Table 2.2)

2.2 and are illustrated in Figure 2.7a, respectively. The first one is Meyers $N_i$ which is implemented in the standard ECHAM6 and is described in the previous sections. This case is only shown for comparison with the other parametrizations. The second one is Fletcher’s $N_i$ formulation which produces much more cloud water than Meyers equation. Because this version of $N_i$ produces much less ice crystals at higher temperatures compared to Meyers’ $N_i$, the cloud water content exceeds the values of Meyers’ equation. Not until the temperature is below $-25^\circ C$ Fletcher’s formulation produces more ice crystals than Meyers’ relation. The important temperature interval for this process is from $0^\circ C$ to $-25^\circ C$. The last version is an equation provided by Rogers. After Gultepe et al. (2001) this formulation for $N_i$ gives the best results compared to observations. The bottom panels present the results of this version. It can be seen that the cloud water
content is still much higher than BASE and equals Fletcher’s version with only a few differences. Compared to Meyers $N_i$ version the ice crystal generation is too less at higher temperatures.

### 3.3.2 Cloud ice

Variations for cloud ice due to increasing $N_i$ are shown in Figure 3.9. The cloud ice pattern looks very similar with the main difference at circa 60°S in the lower layers. In upper cloud layers the cloud ice content is slightly too high. In this regions lower temperatures are present so the higher $N_i$ leads to higher concentrations of cloud ice in the upper layers. The main difference region increases with higher $N_i$ concentration. Close to the Rotstyan, plates run in Figure 3.6 the main difference region in the southern midlatitudes reacts very sensitive to

![Figure 3.9: Cloud ice (g/kg) for the n-fold of Meyers $N_i$](image)
3. RESULTS

changes in the Rotstayn parametrization. The increase in cloud ice is also visible in the northern pole regions but not as significant as in the southern midlatitudes. Compared to the BASE run the 2.5-fold $N_i$ gives the best results. The higher $N_i$ the larger the difference to BASE. With respect to the cloud water results the fivefold $N_i$ is still the best result and also looks similar to Rotstayn, plates. Figure 3.10 shows the different $N_i$ parametrizations. Due to the lower ice crystal production of Fletcher’s equation for $N_i$ the cloud ice content in the middle and lower layers is too low. The upper cloud layers are more iced than in the BASE run. For the last $N_i$ parametrization provided by Rogers a similar difference pattern like Fletcher’s $N_i$ can be seen. The lower cloud layers include too little cloud ice compared to the BASE run. Because at higher temperatures more ice crystals exist with Rogers’ equation the cloud ice loss in the lower layers is not as

Figure 3.10: Cloud ice (g/kg) for three different $N_i$ parametrizations (equations are given in Table 2.2)
3. RESULTS

strong as in Fletcher’s relation. In general it can be said that the higher \( N_i \) is at higher temperatures the better are the results but \( N_i \) at 0°C should not exceed a threshold of 10 L\(^{-1}\) because than the cloud ice production is too efficient.

3.3.3 Ice fraction

The different \( N_i \) variations lead to changes in the temperature dependency of the ice fraction. The first panel of Figure 3.11 shows the standard Rotstauyn parametrization for a better comparison again. By multiplication of this \( N_i \) version with five the temperature range for mixed phase gets smaller and is shifted in the direction of higher temperatures. Fletcher’s equation leads to small ice fractions (< 0.2) within the temperature interval from 0°C to -15°C. Below -15°C the main ice production occurs and as a result all cloud water is turned to cloud ice at a temperature of -25°C. With Rogers’ \( N_i \) the figure shows small ice fractions between 0°C and -10°C. But here, ice fractions above 0.2 occur at higher temperatures compared to \( N_i \) Fletcher. Because of this larger variability of ice fraction values with regard to temperature the cloud ice content is slightly higher compared to \( N_i \) Fletcher, which is mentioned previously in section 3.3.1.

![Figure 3.11: Ice fraction for different \( N_i \) variations](image)

Figure 3.11: Ice fraction for different \( N_i \) variations
3.4 Main results in comparison

In this section the main results, which are shown in previous sections, will be summarized for comparison. Here the probability density function (PDF), the net radiation flux at the TOA and the comparison with DARDAR data are presented.

3.4.1 PDF for ice fraction

In the sections above the different ice fraction plots for different runs are shown as function of temperature. For this section another representation is used. Korolev et al. (2003) gives the observation data collected from different aircraft measurements within stratiform clouds. These results are plotted in Figure 3.12. The vertical axis indicates the probability for the different ice fractions and the horizontal axis gives the different ice fractions where 0.0 stands for a complete liquid cloud and 1.0 for a pure ice cloud. The different lines show seven 5°C temperature intervals from -35°C minimum to 0°C maximum value. It is clearly visible that there is a high probability for a high liquid water fraction \(0 < \mu_3 < 0.15\), especially at higher temperatures. Here, the curves show a strong decrease. Probabilities between 0.15 and 0.7 are very low within all temperature ranges. At a probability of 0.7 the curves start to rise but not as strong as in the direction of lower ice fractions. Therefore, clouds tend to be either liquid or iced. Everything in between indicates the mixed phase, which is represented with low probabilities for each temperature interval. The increased probability between an ice fraction of 0.6 and 0.9 could be caused by measurement problems (Lohmann et al., 2007, based on A. Korolev, personal communication, 2006) This aircraft measurements are used for evaluation of the simulated model results, presented in Figure 3.13. Here, it has to be considered, that aircraft measurements are in situ measurements. Therefore, the comparison with the low-resolution (T31) model version should be treated carefully. The standard ECHAM6 shows a good agreement for low ice fractions. There is a low probability for the mixed phase between an ice fraction of 0.1 to 0.9. However, the increase of the curves at an ice fraction value of circa 0.9 is too strong compared to the observations because the cloud ice fraction variability at lower temperatures is too small. Usually the cloud ice fraction at temperatures below -25°C is above 0.9 with few exceptions. However, the standard ECHAM6 looks very similar to the observations. Due to the removal of the old WBF the no WBF run shows many differences compared to observations. At almost all temperatures there is a high probability for low ice fractions and therefore for much cloud water. Probabilities below 20% are prevalent for ice fractions higher than 0.3 which means there is too less cloud ice produced. Between the temperature range -30°C to -35°C the curve has a maximum value at an ice fraction value of 0.3. The presentation of the ice fraction of Figure 3.3 for the no WBF gives the reason for that curve progression: the most ice fraction
3. RESULTS

Figure 3.12: Probability density function for ice fraction within different temperature intervals by Korolev et al. (2003)

values are below 0.2 or above 0.9, therefore, for these values a higher probability is visible. Between -30°C and -40°C the ice fraction is nearly a linear function of temperature. Thus, the peak is in the middle of the ice fraction range of the linear curve at 0.3. Compared to the no WBF case the Rotstayn run gives much better results. Down to -15°C there are increased values of lower ice fractions. Below -15°C the probability of ice fractions below 0.2 is nearly zero. Therefore, at lower temperatures there is too much water compared to observations. There is also a strong rise at an ice fraction of 0.85 because the ice fraction varies not that strongly with temperature. For higher temperatures the probability for higher ice fractions is too low. As mentioned before Rotstayn, plates and 5xN_i generate very similar results, also for the PDF. In general both panels show only high probabilities for ice fractions lower than 0.15 within the temperature range 0°C to -5°C. The mixed phase between 0.2 and 0.8 is very unlikely so there are too few mixed phase cases. At the ice fraction value 0.85 strong rises of the curves up to temperatures of -5°C are registered. There is also to less variability for each temperature. The main difference between these two cases is the curve progression of the temperature range from -5°C to -10°C (red line), where 5xN_i creates a higher probability for the liquid phase than by using the platelike ice crystals and vice versa for higher ice fractions. Summarized it can be said that with the use of the new Rotstyn parametrization the mixed phase case is underrepresented. By using Rogers’ relation of N_i clouds tend to be more liquid or more iced, because the probabilities for iced or liquid clouds strongly increases. The mixed phase case in between with an ice fraction of 0.1 to 0.9 is fairly small. Below -25°C the probability of liquid clouds tends to be zero. The last panel shows the on detrained model run while it gives large deviations in cloud ice and cloud water mixing ratio compared to BASE. Figure 3.3 shows for the on detrained
Figure 3.13: Probability density function of ice fraction for different temperature intervals from -40°C to 0°C in 5°C steps, 0.0 indicates all liquid and 1.0 all iced.

case a large variability of ice fraction with temperature. Hence, the PDF gives a good agreement with the observational data, there is a high occurrence of lower (\(< 0.1\)) and higher (\(> 0.9\)) ice fractions. With decreasing temperature intervals down to -40°C the probability of liquid clouds decreases whereas the probability of ice clouds increases. Within the entire temperature interval from 0°C to -40°C the mixed phase case is represented. Thus, the probability for low ice fractions (\(< 0.2\)) is too high, especially for warmer temperatures. This model run looks very similar to observational data of Korolev et al. (2003).
3. RESULTS

3.4.2 Net top radiation

As an important parameter for each climate model the net top radiation is presented which is described by the difference of incoming solar radiation and outgoing terrestrial radiation at the top of the atmosphere (TOA). This parameter is plotted in Figure 3.14 where the upper left panel shows the BASE run and the other panels the difference between the modified run and the BASE run. The actual value of the global average for the net top radiation is between 0.5

Figure 3.14: Net top radiation for the main results; top panel: BASE run, other panels differences to BASE run
3. RESULTS

and 1.0 W m\(^{-2}\) (Trenberth et al., 2014). The actually value for the BASE run with circa 3.47 W m\(^{-2}\) is to high compared to the observed value. But is has to be considered that the used model resolution T31 is the lowest resolution of the ECHAM6 so the global average can be to high due to the low resolution. Furthermore, the T31 resolution was not tuned yet. The removal of the old WBF produces, as already mentioned, too much water which leads to a stronger cloud cover including much water. More incoming solar radiation is reflected by clouds and the net top radiation gets strongly negative. Especially in the midlatitudes the negative radiation flux is strongest because of the higher occurrence of clouds (see Figure A.4). With the included Rotstayn parametrization only a few differences in comparison with the BASE run can be seen. In the midlatitudes the net top radiation is more negative compared to BASE due to too much cloud water generation and in the tropics it tends to be more positive. So the net top radiation is balanced by the loss of energy in the midlatitudes and the gain in the tropics. By multiplication of \(N_i\) with the factor five the radiation imbalance increases by circa 2 W m\(^{-2}\). The cloud water loss in the midlatitudes leads to less reflected incoming solar radiation. Therefore, in this region the radiation imbalance gets more positive. The same pattern can be seen if platelike ice crystals are used. However, the same positive net top radiation regions of the \(5xN_i\) run are more intense developed because the cloud water loss in the midlatitudes is slightly higher. The next panel shows the results of Rogers’ \(N_i\) relation. In the \(N_i\) Rogers run the cloud water content is much higher and the cloud ice content much lower in lower layers compared to the standard Rotstayn case. But the cloud water gain is not as high as in no WBF. The net top radiation is higher than the no WBF case but lower than Rotstayn and produces a value of circa 0.2 W m\(^{-2}\) for the global time average. Also the on detrained run produces a reduction in net top radiation due to the high cloud water content. However, the decrease is not that strong compared to no WBF and \(N_i\) Rogers. In summary, it can be said that the higher the cloud water content the lower the net top radiation, and vice versa. Here the best results grants the \(N_i\) Rogers run but it shows more inaccuracies with respect to cloud water or cloud ice content. Here, the runs (Rotstayn, plates and \(5xN_i\)) which are closer to the BASE run of the sections above show the largest difference to the BASE run and give the highest global average of the net top radiation of up to 6.41 W m\(^{-2}\). Therefore, as a next step this value should be balanced with the help of model tuning.

3.4.3 Cloud top phase

Figure 3.15 shows the comparison of model runs with the DARDAR data set within the cloud top temperature range from -30\(^\circ\)C (uppermost panel) to -10\(^\circ\)C (lowermost panel) in 5\(^\circ\)C steps. Similar to the ice fractions plots 0.0 indicates that the entire cloud is liquid and 1.0 the entire cloud is iced. For production of the cloud top phase of the model data a prescribed threshold for detecting clouds
3. RESULTS

(a) DARDAR  
(b) BASE  
(c) no WBF

Figure 3.15: Cloud top phase at different temperatures for DARDAR-MASK, ECHAM6 BASE run and ECHAM6 without the current WBF; red is for more liquid and blue for more ice

is used. In Hörning (2015) the impact of using different thresholds is shown. Here the threshold of $1 \cdot 10^{-6}$ kg kg$^{-1}$ for cloud detection is used because in Hörning (2015) this value was expected to produce the best results. The plot also includes some missing points where no point with such a cloud top temperature could be found. On the left side the DARDAR-Mask data set, in the middle the BASE run and on the right side the no WBF case are plotted. The DARDAR-Mask data set provides for each cloud top temperature large regional differences with lower ice fractions in regions of higher latitudes and higher ice fractions in the midlatitudes. For the standard ECHAM6, similar differences can be seen but
3. RESULTS

(a) Rotstayn
(b) Rotstayn with $N_i \cdot 5$
(c) Rotstayn, plates

Figure 3.16: Same as in Figure 3.15 for Rotstayn, $5 \cdot N_i$ and Rotstayn, plates

the icing process occurs too fast. Additionally, at higher temperatures the ice fraction is too low compared to observations. The no WBF case shows a too low ice fraction for each temperature due to the intensive cloud water production what causes a nearly complete liquid cloud top layer at $-25^\circ C$. Furthermore only few differences can be seen: the tropics and subtropics show a more glaciated cloud top at lower temperatures than the higher midlatitudes. In addition, Figure 3.16 illustrates the Rotstayn, the $5xN_i$ and the Rotstayn, plates runs. All runs show a too fast icing at too low temperatures but due to the higher $N_i$ version in $5xN_i$ and due to the use of platelike ice crystals more ice at lower temperatures is produced and therefore the ice fraction is too high. Thus, the icing process occurs faster by using the platelike crystals instead to the fivefold
3. RESULTS

Figure 3.17: Same as in Figure 3.15 for $N_i$ Rogers and on detrained

$N_i$ version. The ice fraction of the standard Rotstayn scheme shows rarely regional differences in the higher latitudes up to 30° N/S. Between 30° N/S the ice fraction is significantly increased. So there is a border between the midlatitudes and subtropics which indicates the main regional difference. Generally, by using the Rotstayn parametrization the variability of ice fraction values for each temperature is missing, which also has been shown in the ice fraction plots. A too strong temperature dependency emerged. The left column of Figure 3.17 shows Rogers’ relation of $N_i$. For lower temperatures there is too much cloud ice and in the higher temperatures too little cloud ice. Here, also a strong temperature dependency and so a few regional differences for each temperature can be seen with the only exception of the subtropics-midlatitudes border where, in the di-
section of the equator, the ice fraction is increased. It seems that this border is not generated due to using the Rotstayn parametrization but due to the removal of the old WBF condition. Therefore, the depositional or condensational growth and the detrainment allocation depends only on temperature (above or below \(-35^\circ\text{C}\)). This could be a reason why this border developed. The right column of Figure 3.17 shows the on detrained model run. Due to the added implementation of the Rotstayn parametrization after the detrainment input the mentioned border between midlatitudes and subtropics is attenuated. The icing process occurs much more slowly compared to the other runs and the ice fractions vary more for the different cloud top temperatures. Therefore, the on detrained case shows the best results in comparison with the observations. It has to be kept in mind that the used model resolution is quite low leading to inaccuracies which are included and therefore missing data are generated.
4 Discussion

The removal of the old WBF as first step of this master thesis leads to an intense cloud water generation, while the cloud ice is too less produced. The major part of this cloud water is produced within the condensation scheme of the model. Only a minor part is generated through the detrainment allocation (see Figure A.2), which gives the connection between the convective cloud scheme and the stratiform microphysics. As described in section 2.3.2 the old WBF is only one condition for the depositional growth. Due to the removal of this condition only the first condition with \( T < -35^{\circ} \text{C} \) exists. Thus, the decision of condensational or depositional growth and the convective detrainment becomes cloud ice or cloud water, respectively, depends only on temperature. Presumably this is the reason why this border of the ice fraction between the midlatitudes and the subtropics in the cloud top phase figures develops. Below \(-35^{\circ}\text{C}\) the major part of the cloud ice is generated. So within \(30^{\circ}\text{S}\) and \(30^{\circ}\text{N}\) the cloud top is more iced than in other regions because of the higher convective clouds. Too much water generation due to condensation is the initial situation for the implementation of the Rotstayn scheme. This scheme is based on the cloud water removal to compensate the cloud water excess. As shown previously the Rotstayn parametrization decreases the cloud water and increases the cloud ice. However, the cloud water was still too high. Additionally, the Rotstayn parametrization led to a faster icing, so that the cloud is completely iced below \(-25^{\circ}\text{C}\). But observations show that liquid water may occur at temperatures down to \(-35^{\circ}\text{C}\) (Korolev et al., 2003). The specifications and sensitivity tests for the Rotstayn parametrization are made for adjusting the cloud water content. An important parameter within the parametrization is the ice crystal number concentration \(N_i\). For this master thesis only functions of temperature are used for calculating number of ice crystals. They do not keep in mind how much cloud ice actually exists which however could be very useful. Additionally, the ECHAM6 does not include an aerosol module, which makes the correct calculation of \(N_i\) much more difficult, because ice crystals are mainly formed with the help of aerosols (Rogers and Yau, 1996). The manual increase of \(N_i\) leads to a cloud water reduction but also to an increase of cloud ice in the southern storm track regions. Ceppi et al. (2012) found that a significant bias in short wave cloud forcing in the midlatitudes of the southern hemisphere, especially in this storm track region, exists. Therefore, they used 34 CMIP5 coupled general circulation models in comparison. Models have several problems with the treatment of this region with the result that this region is very sensitive to changes in different Rotstayn specifications. The use of platelike ice crystals instead of spherical ice crystals gives similar results compared to the fivemfold of \(N_i\). Platelike ice crystals have a high growth rate and lead to a fast cloud ice production. The multiplication of \(N_i\) generates more ice crystals, which are able to grow, at each temperature. This assumption was only made for the sensitivity
test and delivers too high values of $N_i$ compared to observations. Thus, these two cases lead to a reduction of cloud water and better agreements with the BASE run and the temperature range where mixed phase occurs decreases significantly. Thus, below -15°C the entire cloud is iced which represents a too fast icing process. This missing liquid water at lower temperatures can also be seen in Figure 3.16 which shows a lot of differences compared to observations. However, it has to be considered whether the permanent use of platelike ice crystals is a realistic assumption. An interesting case is the on detrained case. Compared to observations of cloud top phase (DARDAR) or ice fraction (aircraft measurements) this case provides the best results. The main problem is that too little cloud ice is generated in lower cloud layers and too much cloud water is produced. The on detrained run describes the additionally implementation of the Rotstayn parametrization directly after the convective detrainment allocation. This position of the Rotstayn parametrization causes a cloud water excess correction, so that the cloud water is reduced and ice is generated. Probably this causes this variability in the ice fraction with temperatures down to -35°C, see Figure 3.3. Further research are necessary to extract the reason why no cloud ice is generated in the lower levels.

The use of the Rotstayn parametrization instead of the old WBF illustrates the importance of the WBF as a cloud ice producing process. In comparison, the droplet freezing mechanisms are not able to compensate the loss of the old WBF condition. This agrees with the results of Komurcu et al. (2014) where research of heterogeneous freezing are made. They also extract the importance of the WBF in climate models. Storelvmo and Tan (2015) pointed out that the different treatments of the WBF has a big impact on the the radiation budget which agrees with the results of this master thesis. Changes in the WBF process lead to strong net top radiation decreases (down to -7.2 W m$^{-2}$ due to removal of the WBF) or increases (up to 2.9 W m$^{-2}$ due to fast cloud glaciation) depending on the treatment of the WBF. This also highlights the importance of the process in climate models. Helpful for further evaluations may be the use of satellite data to compare the cloud ice and water content of each cloud layer. Additionally, a higher resolution of the ECHAM6 may produce much better results. This can be also helpful to figure out the current problems in detail.
5 Conclusion

Clouds are always a big source of uncertainties in global climate models. The treatment of the Wegener-Bergeron-Findeisen process (WBF) plays an essential role within the cloud microphysic. This process describes the growth of ice crystal at the expense of liquid water droplets due to saturation differences between the liquid and the ice phase. The treatment of the WBF differs remarkably between the climate models. Some use simple assumptions such as a prescribed threshold for cloud ice mixing ratios. If this threshold is exceeded the WBF occurs and leads to a fast cloud ice generation. Other models use much more complex and physically based version where the growth of ice crystals due to vapour deposition is calculated. Rotstyn et al. (2000) describe one of those complex deposition schemes.

In this master thesis the Rotstyn parametrization is implemented instead of the current WBF version in the global climate model ECHAM6 as an extension of previous research by Schacht (2016). He replaced the droplet freezing process but he did not replace the simple threshold formulation of the WBF of the ECHAM6. In the ECHAM6 one of those simple assumptions is used and therefore it should be replaced by the more physically correct version of Rotstyn et al. (2000). Initially, the removing of the old WBF of the standard ECHAM6 generates a lot of cloud water and too less cloud ice. After implementing the Rotstyn parametrization the cloud ice and cloud water content adapted to the standard ECHAM6, however, the cloud water content is still too high. Rotstyn et al. (2000) describe different specifications in spatial distribution, ice crystal number concentration and ice crystal habit. The use of platelike ice crystals provides results similar to the basic run with the main difference of cloud ice and cloud water content in the southern storm track region. However, the mixed phase occurs only within a temperature interval from 0°C to -15°C which does not agree with observational data. The cloud top phase depending on different cloud top temperatures shows a too fast icing process and too few regional differences. Other tests are made for different ice crystal number concentrations by using the n-fold of (Meyers et al., 1992) relation and formulations of Fletcher (1962) and (Rogers et al., 1996). Meyers’ calculation, which is the default version in the Rotstyn scheme, produces the most ice crystals followed by Rogers’ and Fletcher’s relation. The five-fold of Meyers’ version gives similar results to the use of platelike ice crystals. By testing all different Rotstyn modifications it can be said that the main problem is the missing variability of ice fraction values within the temperature range from 0°C to -35°C (see section 3.2.1). Therefore, large differences compared to the observational data developed. To correct this missing variability and as an idea to correct the cloud water excess the Rotstyn parametrization is applied additionally after the detrainment allocation. This detrainment is the link between the cumulus convection and the stratiform microphysic. The results of this
test deliver still too much cloud water and too less cloud ice in the lower cloud layers which has to be figured out in further research why this pattern developed. Thus, this run gives the best results in comparison with observations because the mixed phase occurs between $0^\circ$C and $-35^\circ$C. The net top radiation reacts very sensitive to changes of the different WBF treatments. More cloud water and less cloud ice leads to more reflected solar radiation at the top of the atmosphere. Due to all the different tests with new WBF parametrizations the importance of the WBF is highlighted. Some further research is necessary to improve the ECHAM6 with respect to the cloud phase. Therefore some more ideas need to be collected how the removal of the old WBF can be better replaced by the Rotstayn parametrization. As some ideas, the deposition and condensation, which currently are included in the ECHAM6, could be revised and the detrained case should be further investigated. More evaluations with observations are helpful to extract the main differences to the model simulations. Therefore, the scale of satellite data has to be taken into account, which is already done. It is planned to use this satellite observations for the comparison with the higher T63 model resolution simulations.
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### List of abbreviations and variables

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<tr>
<td>$A''$</td>
<td>Heat conductivity</td>
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<td>$C$</td>
<td>Capacitance</td>
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<td>$C$</td>
<td>Cloud fraction</td>
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<td>$\tilde{C}$</td>
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<td>$L_s$</td>
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