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Studying the Atmospheric Cloud Radiative Effect in Realistic High-Resolution Simulations

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Abstract

The interactions between clouds and radiation are complex and still subject of current research. To expand the understanding of cloud-radiation interactions previous studies performed idealized model simulations. However, a new generation of atmospheric circulation models, such as the ICOsahedral Nonhydrostatic (ICON) model, allows the study of cloud-radiation interactions in realistic, high-resolution model simulations. This study focuses on cloud-radiation interactions and the so-called atmospheric cloud radiative effect over the tropical Atlantic Ocean. The atmospheric cloud radiative effect (ACRE) is defined as the difference between all-sky and clear-sky heating rates. Previous studies have shown that the ACRE has two major effects on cloud layers, a radiative destabilization of the cloud layer due to radiative heating at cloud bottom and cooling at cloud top (direct effect) as well as a stabilizing effect due to cloud radiative heating of the atmospheric column (indirect effect). A new method with locally averaged ACRE profiles is proposed and tested to divide the ACRE into direct and indirect effect. This new method was applied in 48 hours of high-resolution model simulations.

The results show that the ACRE has the most significant influence on low clouds. In general, the indirect effect reduces low-level clouds and the direct effect increases low-level clouds. However, the ACRE also depends strongly on the cloud regime. In a shallow cumulus regime, the indirect and direct ACRE reduces cloud cover. In inversion topped stratocumulus cloud regimes, the indirect ACRE lifts the inversion due to the radiative cooling of the cloud top. This can lead to a spread of moisture in the lower troposphere, and at fewer points, saturation is reached, resulting in fewer clouds. In contrast, the results show that the direct effect enhances the formation of stratocumulus by strengthening the mesoscale convective circulation within stratocumulus clouds. However, it is possible that the setup of the simulations overestimates the direct effect on stratocumulus clouds.

Contents

List of Abbreviations

ACRE atmospheric cloud radiative effect

CRE cloud radiative effect

DKRZ German Climate Computing Center

ECHAM General circulation model, acronym from ECMWF and Hamburg

ECMWF European Center for Medium-Range Weather Forecasts

ICON ICOsahedral Nonhydrostatic

ITCZ Inner Tropical Convergence Zone

KIT Karlsruhe Institute of Technology

LES large eddy simulation

MBL marine boundary layer

MCC mesocale cellular convection

NARVAL Next-Generation Aircraft Remote Sensing for Validation

NWP numerical weather prediction

PSrad named because it is a postscript to the RRTMG package from which it descends

RRTM rapid radiation transfer model

RRTMG rapid radiation transfer model for GCM applications

SFC surface

TB Terabyte

TOA top of atmosphere

UTC Coordinated Universal Time

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1 Introduction

The sun is the powering component of our climate system and the key driver of atmospheric motion. Incoming solar radiation is reflected, absorbed and scattered by clouds. The interaction between clouds and radiation plays an important role in forming and maintaining clouds. Clouds have a major impact on the earth's radiation budget and among other things the presence of clouds doubles the planetary albedo approximately.

This thesis aims to study and atmospheric cloud radiative effect (ACRE) in realistic high-resolution model simulations with a new method to decouple the indirect and direct ACRE locally. While cloud radiative effect (CRE) describes the changes in fluxes at the top of atmosphere (TOA) due to clouds, the so-called ACRE is the difference between all-sky and clear-sky radiative heating profiles (Harrop and Hartmann, 2016b). In other words, the ACRE describes the change in radiative fluxes within the atmosphere due to interactions between clouds and radiation. Previous studies showed that the average overall net CRE is negative. This cooling is a result of longwave warming and short wave cooling which exceeds the long wave warming. However, in most parts of the atmosphere these effects can compensate each other (Ardanuy et al., 1991). Nevertheless, in tropical convective regions the CRE can also lead to a positive forcing (Slingo and Slingo, 1988).

However, not only short and long wave radiation have opposite effects by interacting with clouds, also the strength of CRE depends on the cloud height. Hartmann et al. (1992) showed in their study that high-level clouds in equatorial regions lead to a net positive CRE and low-level clouds have a net negative CRE. Because of the contrary effect of high and low clouds, the first part of this study will distinguish between ACRE at high altitudes and ACRE at low altitudes. This leads to the following research question: Which effect has ACRE in a realistic high-resolution model simulation at different altitudes and does ACRE effects the cloud formation and cloud cover? Is there any effect on low-level clouds when switching the ACRE at high altitudes off and vice versa? For this purpose high-resolution simulations with the ICOsahedral Nonhydrostatic (ICON) model are performed over an area covering the tropical Atlantic.

The second part of this study aims to investigate the direct and indirect ACRE. The so-called direct ACRE destabilizes the cloud layer due to radiative heating at the cloud bottom and radiative cooling at the cloud top. Webster and Stephens (1980) showed in their study that this effect can result in a difference of heating rates in thick anvil clouds of up to 35 K day^{-1} between the cloud bottom and the cloud top. Later Ackerman et al. (1988) showed that the difference in heating rates in thick anvil clouds can range from 30 K day^{-1} up to 200 K day^{-1}. Harrop and Hartmann (2016b) concentrated in their study on high cloud changes, they showed that the direct ACRE results in an increase of high clouds.

As already mentioned above, the CRE is positive in tropical convective regions therefore the ACRE warms the upper troposphere, Harrop and Hartmann (2016b) named this effect the "indirect" ACRE. They showed that the indirect ACRE stabilizes the atmosphere to deep convection and plays the dominant role in limited area simulations. They also showed that the indirect ACRE decreases the high cloud fraction. However, in their mock-Walker circulation experiment, which also includes large-scale circulation, the effect of the direct and indirect ACRE tend to cancel each other.

Most of the previous studies concentrated on high clouds in deep convective regions in idealized model simulations. However, this study will focus on regions within the tropical Atlantic. The model area covers about 30 Million square kilometers including the ITCZ and parts of the northern and southern trades in the Atlantic Ocean. Due to the large area covered by the model simulation and the dependency of ACRE on different cloud types, the simulation area is divided into different small areas for the evaluation. In these model simulations ACRE has the highest influence on low-level clouds. Therefore the main focus of this thesis will be on changes of low-level clouds due to ACRE. In a recent study Schneider et al. (2019) showed that stratocumulus cloud decks become unstable in a warmer climate. Due to the rise of CO_2 concentration in the atmosphere the cooling at the cloud top becomes more inefficient and the difference between heating rates at cloud bottom and cloud top weakens. This can lead to a break up of stratocumulus cloud decks.

To study the different effects of direct and indirect ACRE in this thesis, high-resolution simulations with only direct and indirect ACRE are performed. A new method is introduced to split ACRE in direct and indirect ACRE locally. Previous studies used a domain mean ACRE to perform simulations where only direct or indirect ACRE is active. However, this study will take a local averaged ACRE instead of the domain mean ACRE to perform these kind of simulations. The aim of this local averaged ACRE is to preserve regional effects of ACRE and make simulations more realistic. The following research questions will be discussed in the second part of this thesis: How does indirect and direct ACRE contribute to low-level cloud cover? How strong does ACRE depends on different cloud types?

Chapter 2 provides background information and a detailed description of the methodology and set up of the model simulations as well as introducing the new technique to divide ACRE in indirect and direct effects. Chapter 3 evaluates and discusses the results of the simulations with the main focus is on low-level clouds. Chapter 4 summarizes this thesis and will provide an outlook.

2 Model, Simulations and Methodology

This chapter introduces the ICON model which is used to perform the simulations for this thesis (see Section 2.1). The ICON model can be run with different physical packages, this study uses the numerical weather prediction (NWP)-Physics, which are explained in detail in Section 2.1.1 as well as the internal radiation transfer model in Section 2.1.2.
To study the ACRE with the ICON model some new options and implementations were necessary. Section 2.2 describes the changes in the ICON model code and gives an instruction on how to use the new implemented options to rerun the simulations.
The last part of this chapter is dedicated to describe the experiment setup of the ICON model simulations (Section 2.3). This section also includes a detailed description of the experiment setup.
In Section 2.4 different cloud regimes within the simulation area are introduced and described. These cloud regimes will be used for the evaluation process.

2.1 The ICON Model

The ICON model (Zängl et al., 2015) is a new generation of atmospheric general circulation models. The ICON model uses an unstructured icosahedral-triangular grid instead of the typical rectangular grid of weather and climate models. The unstructured icosahedral-triangular grid simplifies the scalability of the model resolution and improves the scaling on high-performance parallel computer platforms (Zängl et al., 2015). In non-hydrostatic models, it can not be guaranteed that pressure decreases monotonously with increasing altitude. Instead of the vertical pressure coordinates used in hydrostatic models, the ICON model expresses vertical coordinates in terrain-following geometric altitudes (Reinert et al., 2018).
One of the two major components of the model is the non-hydrostatic dynamical core, which solves the equation of atmospheric motion, temperature, density, concentrations of water vapor, cloud water, and cloud ice. The dynamical core of the model remains untouched for the simulations of this study. The other major component of the model are the physics, which compute changes in processes related to radiation, turbulence, and cloud condensation. The model physics and dynamics are closely linked to each other. The dynamical core of the model is forced by changes in the physics and changes in the physical part depend on the stage of the atmosphere computed by the dynamical core of the model (Giorgetta et al., 2018).

2.1.1 NWP-Physics

The ICON model comes with three different physical parametrization packages, ECHAM physics (Roeckner et al., 2003), large eddy simulation (LES) physics (Dipankar et al., 2015) and NWP physics. The NWP physics (Zängl et al., 2015) where used to perform Simulations

for this study.
The ICON model has different microphysic schemes. The microphysics are a set of closed equations in the physical core of the model, which calculates the formation and evaluation of condensed water in the atmosphere. In this experiments a single-moment scheme including graupel is applied to predict the mass of hydrometeors. The single-moment scheme predicts cloud water, rain water, cloud ice, snow and graupel (Seifert, 2008; Doms et al., 2002).

For the radiative transfer model optical cloud properties are one important component. The cloud cover for the radiative transfer model is calculated after the Köhler scheme (Giorgetta et al., 2018; Reinert et al., 2018). This diagnostic cloud cover scheme combines information of different parameterizations such as turbulence, convection and microphysics to calculate the cloud cover. The sub-grid variability of water is described by turbulent motion, the convection is used to detrain clouds into anvil and the microphysical scheme describes the distribution between vapor and ice.

2.1.2 Radiation Physics Implementation in the ICON Model

The PSrad (named because it is a postscript to the RRTMG package from which it descends) scheme is a radiation package introduced by Pincus and Stevens (2013) and it is used to parameterize solar and terrestrial radiation. The PSrad scheme implements the gas optics and solver of the rapid radiation transfer model (RRTM) described by Mlawer et al. (1997). The RRTM model consists of 30 spectral bands, 16 long wave and 14 short wave spectral bands respectively (Reinert et al., 2018). The RRTM is a rapid and accurate, correlated k-distribution band model (Mlawer et al., 1997), which is used to calculate short wave and long wave radiative fluxes as well as heating rates.

2.2 ICON Model Code Changes and Instructions

This section describes the ICON model code changes to run the ACRE experiments. It provides a guide for further usage of the ACRE experiment setup. Please note that all newly implemented experiment setups are only usable when running with NWP-physics.
The current version of the ICON model code including the change due to the ACRE experiments can be obtained from the Max-Planck-Institute for Meteorology ICON-LEM Git repository[1] and the branch name is `icon-hdcp2s6-2.1.00-extvar`. This branch originates from the `icon-hdcp2s6-2.1.00`. The `extvar` extend of this branch includes all changes needed to run the simulations for this study.
Some of the model code expansion for this study uses the ICON model internal definition of high and low clouds. High clouds are defined as clouds above a level of 400 hPa, and low clouds are defined as clouds up to a level of 800 hPa. Since the ICON model uses terrain-following geometric altitudes, a routine calculates the geometric level index corresponding to

[1] `https://code.mpimet.mpg.de/projects/icon-lem/`

the 400 hPa and 800 hPa level. The corresponding level index is calculated according to the definition of the US. Standard Atmosphere at the beginning of a simulation. The level index is fixed and does not adapt to pressure changes during a simulation.

2.2.1 Code Changes to Run with Clear-Sky Heating Rates Only

The ICON model of the `icon-hdcp2s6-2.1.00` branch Aiko Voigt[2] already implemented a new namelist parameter within the `nwp_phy_nml` namelist to run with clear-sky heating rates instead of all-sky heating rates. This can be done by setting the logical namelist parameter `lrad_cldfrc0` to `.TRUE.`. If the parameter is set to `.TRUE.`, the cloud cover passed to the RRTM routine of the ICON model is set to zero and clouds are removed for the RRTM routine.

From now on, the `icon-hdcp2s6-2.1.00` branch and `icon-hdcp2s6-2.1.00-extvar` branch differ. The following implementations are only within the `icon-hdcp2s6-2.1.00-extvar` branch. To run experiments where low clouds or high clouds are removed for the RRTM routine, two new namelist switches in the `nwp_phy_nml` are implemented: `lrad_cldfrc_high0` and `lrad_cldfrc_low0`. The `lrad_cldfrc_high0` sets the cloud cover above 400 hPa to zero for the RRTM routine and `lrad_cldfrc_low0` sets the cloud cover below 800 hPa to zero for the RRTM routine. These two switches use the ICON model internal definition of high and low clouds.

2.2.2 New Implementations in the ICON Model Code to Run with External ACRE

For the simulations in this study some new routines within the ICON model code were implemented. This includes a routine which makes it possible to read ACRE fields at runtime. This implementation was necessary since at every radiation time step of the model a new ACRE field must be read in. The difficulty is that the ACRE fields have to be read in at runtime and the ICON model does not provide an option to read fields from external files at runtime and replace fields calculated by the model. Fortunately, the ICON model already has an infrastructure to read lateral boundary data at runtime. This infrastructure is used as a template to read external ACRE fields at runtime. A copy of the `mo_sync_latbc.f90` has been changed that it can now prepare, allocate, read and deallocate external ACRE fields. This modified copy of the `mo_sync_latbc.f90` is available under the name `mo_sync_extrad.f90`. Furthermore two new arrays have been defined in which the current external short wave ACRE and long wave ACRE fields are stored.

In the subroutine `nwp_nh_interface` of the `mo_nh_interface_nwp.f90` script the external ACRE fields are either subtracted from the all-sky heating rates or added to the clear-sky heating rates depending on direct or indirect ACRE simulation. The new heating rates then

[2] Karlsruhe Institute of Technology (KIT)

replace the heating rates calculated by the ICON model. How to set up a direct or indirect ACRE simulation is described in Section 2.2.3.

2.2.3 Instructions to Run the ICON Model with External ACRE Fields

A new namelist is introduced to the model, which allows to specify parameters to read ACRE fields at runtime. The so-called `extrad_nml` namelist contains six parameters. By setting the logical parameter `luse_extrad` to `.TRUE.` the import of external ACRE fields is activated. If the `luse_extrad` is set to `.TRUE.` the user can choose between indirect and direct ACRE simulation by using a second namelist parameter called `indirect_direct`. If the `indirect_direct` namelist parameter is set to `1`, the model runs an indirect ACRE simulation. If the `indirect_direct` namelist parameter is set to `2`, the model runs a direct ACRE simulation. The `dtime_extrad` parameter define the read-in time step of the ACRE field. It is recommended that the read-in ACRE fields have the same time step as the radiation time step (parameter `dt_rad` in the `mwp_phy_nml`). With the namelist parameter `extrad_filename` the name of the external ACRE file is specified. One ACRE file should only contain one time step and the time step should be included in the file name. The naming convention of the file for date and time is in line with the `latbc_filename` of the `limarea_nml` namelist. With the namelist parameter `extrad_path` one should specify the path of the folder where the ACRE files are located. With the optional `extrad_varnames_map_file` a map file for the variable names can be specified if needed.

2.3 ICON Experiment Setup

2.3.1 General Model Setup

The ICON model simulations are inspired by the simulations of the Next-Generation Aircraft Remote Sensing for Validation (NARVAL) campaign in the region of the tropical Atlantic (Klepp et al., 2014). Each simulation covers the same area and reaches from about 15°E to 68°W and from 10°S to 20°N. Figure 1 shows the exact simulation area including the terrain, the nudging area of the boundary conditions (small boundary of colored terrain outside the red box) as well as the four different evaluation areas (a - d). Section 2.5 provides a detailed description of the evaluation areas. The resolution of the triangular grid-cells is 2.4 km. This results in a total number of about 4.9 million grid points. The vertical dimension consists of 75 full levels between 10 m and 30000 m.

All simulations run for 48 hours starting at midnight of the 20th of December 2013 until midnight 00:00 of the 22nd December 2013 and where performed on the German Climate Computing Center (DKRZ) supercomputer. Initial and boundary data are taken from the atmospheric analyses of the European Center for Medium-Range Weather Forecasts (ECMWF), with a horizontal resolution of 13 km, 137 vertical levels and a time resolution of three hours. The sea surface temperature is fixed and taken from the ECMWF data. The simulation out-

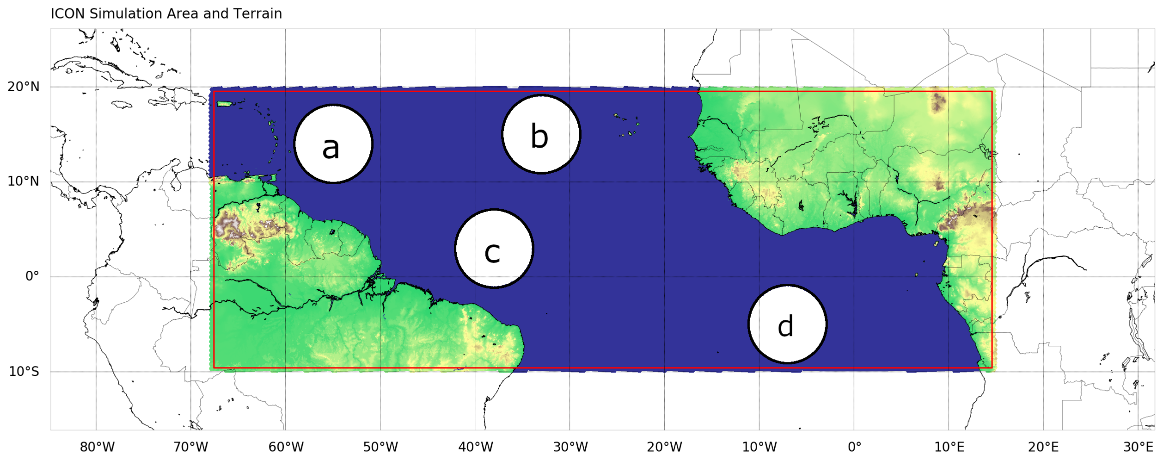

Figure 1: *Area and terrain of ICON simulations. The colored terrain is the area of the ICON simulation. The data inside the red square are used to perform the analysis in this study. The whites circles a - d show the four subgrouped evaluation areas*

put consists of two-dimensional and three-dimensional fields. The state of three-dimensional fields is saved every hour except for the radiative heating rates, which are saved every 12 minutes. The state of two-dimensional fields are saved every 30 minutes. Each simulation produces an output of about 3 TB.

The basic time step of the model is set to 24 seconds, which is used for numerical diffusion and fast-physics parameterizations. The dynamical core of the model is called five times within this time step (Reinert et al., 2018). The convection time step is set to 4 minutes and the radiation time step is set to 12 minutes.

To study the ACRE six different simulations were performed with the ICON model. The notations of the simulations follow the study of Harrop and Hartmann (2016b) but with slightly different calculations of ACRE in simulations where it is partly inactive or manipulated. The first simulation is a control simulation where clouds interact normally with radiation, this simulation is denoted as T1C1, where "T" stands for the atmospheric heating (indirect effect) and "C" stands for the radiation interactions within the cloud layer (direct effect). In the second simulation clouds do not interact with radiation (T0C0). In simulations with non-interactive clouds, the cloud cover is set to zero for the radiation transfer model, but for all other model routines clouds still exist. In a third simulation high clouds are removed for the radiation routine, which means that clouds are only removed above a level of 400 hPa ($T0C0_{high}$) The 400 hPa level is roughly equal to a height of 7800 meters. In a fourth simulation low-level clouds do not interact with radiation ($T0C0_{low}$). Low-level clouds are defined as clouds between the surface and a pressure level of 800 hPa. 800 hPa are roughly equal to a height of 2000 meters. The next simulation removes the direct ACRE and only the indirect ACRE heats the troposphere (T1C0). The last simulation runs with direct ACRE (T0C1) and the indirect ACRE is removed. A detailed description of each simulation is following in the next subchapters.

2.3.2 Non-Interactive Cloud Simulations

As mentioned above, three simulations were performed where all clouds or part of the clouds do not interact with radiation. This has been achieved by removing clouds within the RRTM routine. For the T0C0 simulation, the following heating rates $Q_{RAD}(n, h)$ are used:

$$Q_{RAD}(n, h) = Q_{RAD,CLR}(n, h) \tag{1}$$

$Q_{RAD,CLR}$ denotes the clear sky heating rates, n the cells and h the height levels.
In the next two simulations, clouds are removed for the radiation routine at different heights. In the so-called non-interactive high cloud simulation (T0C0$_{high}$), all clouds above the 400 hPa level are removed for the radiation routine. The heating rates are computed as follows:

$$Q_{RAD}(n : h) = \begin{cases} Q_{RAD,NO\ CLC}(n, h), & \text{for } h < 400\ hPa \\ Q_{RAD,ALL}(n, h), & \text{otherwise} \end{cases} \tag{2}$$

where $Q_{RAD,NO\ CLC}$ denotes heating rates without cloud cover. Above the height equal to the pressure level of 400 hPa, heating rates without cloud cover are calculated and applied. In all other levels the model runs with all sky heating rates $Q_{RAD,ALL}$.
In the fourth simulation, the so-called non-interactive low cloud simulation (T0C0$_{low}$), all clouds up to the 800 hPa level are removed for the radiation routine. The heating rates are computed as follows:

$$Q_{RAD}(n : h) = \begin{cases} Q_{RAD,NO\ CLC}(n, h), & \text{for } h \geqslant 800\ hPa \\ Q_{RAD,ALL}(n, h), & \text{otherwise} \end{cases} \tag{3}$$

Between the surface and a height equal to the pressure level of 800 hPa, heating rates without cloud cover are calculated and applied. In all other levels the model runs with all sky heating rates $Q_{RAD,ALL}$.

2.3.3 Indirect ACRE Simulation

The non-interactive simulations are a good approach to study the interactions of clouds and radiation, but these simulations have a decisive disadvantage: due to changes in the cloud cover inside the radiation routine, the radiative cloud forcing is partly or in total removed and the energy budget is heavily manipulated. To keep the energy budget realistic another simulation is performed.
In this simulation, a smoothed ACRE is used instead of the model calculated ACRE. The calculations of the smoothed ACRE is done outside the model simulation ("offline"). To smooth the ACRE, the ACRE of the control simulation is averaged for every time step and height level over an area with a radius of five degrees. Because of the unstructured grid points of the ICON model and for efficiency reasons, the original ACRE in the unstructured ICON

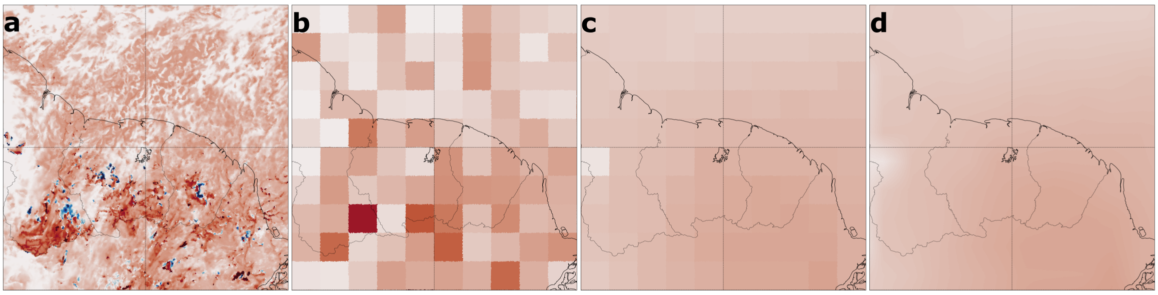

Figure 2: *Example of the ACRE smoothing process. Original ACRE (a), to a latitude-longitude grid regridded ACRE with a resolution of one degree (b), average ACRE over an area of five degrees with a resolution of one degree (c) and bilinear interpolated ACRE into the unstructured, triangular ICON grid.*

grid is regridded with area weighted averages to a latitude-longitude grid. The resolution of the latitude-longitude grid is one degree. After the regridding process, latitude-longitude ACRE fields are averaged over a five degree radius. The averaged ACRE in latitude-longitude coordinates are then regridded with a bilinear interpolation back to the original unstructured ICON grid format. An example of this smoothing process is illustrated in Figure 2.

The simulation which applies the smoothed (indirect) ACRE is called T1C0 and the heating rates are computed as follows:

$$Q_{RAD}(n,h) = Q_{RAD,CLR}(n,h) + [ACRE]_{r=5°,T1C1}(n,h) \tag{4}$$

The square brackets indicate the spacial average over an radius of $r = 5°$. This simulation differs from the simulation Harrop and Hartmann (2016b) performed to study the role of cloud radiative heating within the atmosphere. In their indirect ACRE simulation (T1C0) they used the domain mean time averaged ACRE profile of the control simulation, while in this study the horizontal smoothed ACRE profiles of the control simulation are applied.
Following Harrop and Hartmann (2016b) the effect of indirect ACRE can now be calculated as the difference between simulation T1C1 and T0C1 as well as the difference between T1C0 and T0C0.

2.3.4 Direct ACRE Simulation

The direct ACRE simulation excludes the indirect ACRE and runs only with the direct ACRE. To archive this, the smoothed ACRE of the control simulation is subtracted at each radiation time step from the model calculated all-sky radiative heating rates. As a result, the domain mean ACRE should be zero, while clouds still interact with radiation. This calculation of the heating rates ensures that the direct effect of the ACRE still exists. The computation of ACRE is shown in Equation 5.

$$Q_{RAD}(n,h) = Q_{RAD,ALL}(n,h) - [ACRE]_{r=5°,T1C1}(n,h) \tag{5}$$

This computation of the direct ACRE differs as well from the computation of Harrop and Hartmann (2016b). Each time the radiation routine is called, Harrop and Hartmann (2016b) subtracted the current domain mean ACRE from the all-sky heating rates directly during the simulation, while in this study the smoothed ACRE of the control simulation is subtracted from the all-sky heating rates.
Following Harrop and Hartmann (2016b) the effect of direct ACRE can now be calculated as the difference between simulation T1C1 and T1C0 as well as the difference between T0C1 and T0C0.

2.4 Low-Level Cloud Regimes

The interaction between clouds and radiation depends on the cloud type and cloud coverage. ACRE is one ingredient to trigger and maintain stratocumulus cloud decks and cell convection within the marine boundary layer (MBL) (Schneider et al., 2019). The self-organization of clouds to mesocale cellular convection (MCC) is very common (Wood and Hartmann, 2006) within the MBL. In the following section, four different mesoscale cloud regimes within the MBL are presented. These four cloud regimes are described using an example of the control (T1C1) simulation.

2.4.1 Shallow Cumulus Clouds

An open cloud cell regime is observed in the western tropical Atlantic (Figure 3a) consisting of shallow cumulus clouds. Single clouds do not have a visible connection to other clouds and every cloud is surrounded by a cloud-free area. However, the smallest shallow cumulus clouds can have a diameter of a few meters. These clouds are too small to be resolved in the model runs with a horizontal resolution of 2.4 km, which is why the amount of shallow cumulus clouds is likely to be underestimated (Nam et al., 2012).
In the control simulation (T1C1) the average cloud bottom height is observed at about 750 m. The cloud top of the shallow cumulus clouds is at a height of 1360 m.

2.4.2 Clouds within the ITCZ

Low-level cloud regimes within the ITCZ are mainly driven and formed by the large-scale circulation. In this area the low-level northeast and southeast trade winds converge and air masses are forced to ascend. Figure 3b shows in detail a section of low-level cloud cover within the ITCZ. Neither an open structure nor a closed structure cell structure can be assigned, since this clouds are mainly formed by the large-scale circulation and part of a deep convection.

2.4.3 Stratocumulus Clouds

Closed convective cell structures are typical stratocumulus clouds. Stratocumulus are the most common cloud type on our planet. These clouds cover on an annual mean 12 % of the land surface and 22 % of the sea surface (Wood, 2012). In general, stratocumulus clouds are characterized as a thin cloud layer within the upper planetary boundary layer with a cloud base height of about 600 meters (Hahn and Warren, 2007). The turbulent mixing within the planetary boundary layer ensure a constant moist supply in stratocumulus cloud decks (Wood, 2012). One source of turbulence and convective circulation in stratocumulus cloud decks is latent heating in the updrafts and evaporation in downdrafts (Moeng et al., 1992). Previous studies showed that stratocumulus clouds are coupled to the general circulation and mainly occur in large-scale subsidence regions like the subsidence regions of the Walker or Hadley circulation (Bretherton and Hartmann, 2009). Stratocumulus clouds reflect large amounts of incoming solar radiation back to space and therefore they reduce the CRE. However, the influence of stratocumulus clouds on the long wave CRE is small (Hartmann et al., 1992). One substantial driver for maintaining stratocumulus clouds is radiation, the strong thermal cooling at cloud top drives the convective instability and helps to sharpen the temperature inversion above the cloud. The longwave cooling is the main factor for the overturning convective circulation of stratocumulus clouds (Moeng et al., 1996). This cooling occurs within the upper few meters of the clouds.

Two different types of stratocumulus clouds can be observed in the snapshot of the control simulation in Figure 3. Figure 3c shows a stratocumulus cloud deck in the north-east tropical Atlantic. The cloud base is observed at 600 m high and the cloud top is observed at 1000 m high. At 1050 m a strong inversion above the MBL is observed which hinders air from rising higher.

The second stratocumulus cloud deck is located in the Eastern Atlantic, south of the ITCZ. (Figure 3d). This stratocumulus cloud deck is characteristic for closed cell convection. Closed convective cells have an organized structures with a cloudy center and a narrow cloud free border (EUMeTrain, 2014). The cloud bottom is on average at 440 m and the cloud top at about 980 m. An inversion above the stratocumulus clouds starting at 1000 m is observed. This type of cloud regime has typically strong MCC (Wood, 2012).

2.5 Evaluation Areas

The first evaluation area used to study the ACRE is the Atlantic Ocean within the simulation area. This area was chosen to exclude the influence of different surfaces on radiation.

ACRE strongly depends on the cloud type and cloud cover. The study also divides the evaluation areas according to different cloud types. Figure 1 shows the four additional evaluation areas. These areas are consistent with the cloud regimes introduced in Section 2.4 and shown in Figure 3 a-d.

All subgrouped evaluation areas are circular areas with a radius of 4°. Circular areas were

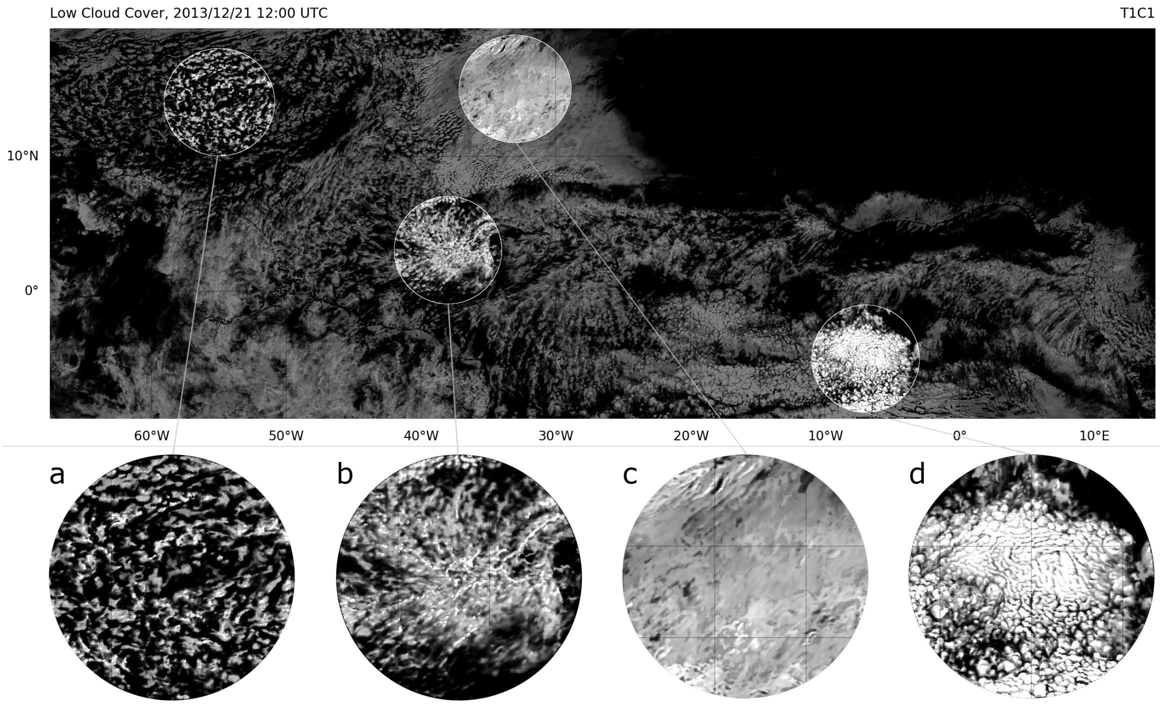

Figure 3: *Low-level cloud cover snapshot of the control simulation of the second simulation day (21st December 2013) at 12:00 UTC. Shallow cumulus clouds (a), deep convection at ITCZ (b), stratocumulus cloud deck (c) and closed convective cells (d)*

chosen as they allow to extract single cloud regimes very easy from the simulation.
The center of area a is at 14 ° north and 55 ° west. Area b has its center at 3 ° north and 38 ° west. Area c is placed at 15 ° north and 33 ° west and the center of area d is at 5 ° south and 4 ° west.

3 Results and Discussion

The results of this study are presented and discussed in the following sections of this chapter. The first part focuses on the response of clouds at different heights to the energy budget. The second part highlights general aspects of the ACRE. The third part presents and discusses the impact of indirect and direct ACRE in different cloud regimes over the Atlantic Ocean.

3.1 Energy Budget

This section evaluates and discusses the changes in the radiative fluxes and the energy budget of simulations where clouds in parts or the entire troposphere are invisible to radiation. The radiative fluxes and energy budget includes the model domain over the Atlantic Ocean only. Table 1 shows the radiative fluxes at the TOA and the surface for shortwave and longwave radiation. At the TOA net downward fluxes are positive, and net upward fluxes are negative. At the surface the reverse is true, net downward fluxes into the surface are negative, and net upward fluxes into the model domain are positive.
If clouds are partly or entirely invisible to radiation (T0C0, T0C0$_{high}$, T0C0$_{low}$), the TOA albedo decreases and therefore less incoming shortwave radiation is reflected to space. As a result, net shortwave TOA fluxes into the model domain increase. Due to the low albedo of

Table 1: *Top of atmosphere (TOA) and surface (SFC) radiative fluxes for shortwave and longwave radiation as well as sensible and latent heat fluxes over the Atlantic Ocean. Net fluxes into the model domain are positive. All fluxes are expressed in* Wm^{-2}.

Flux Type	Location	T1C1	T0C0	T0C0$_{high}$	T0C0$_{low}$
Shortwave	TOA	298.5	339.5	300.4	326.0
	SFC	-205.8	-250.1	-207.6	-236.7
	NET	92.7	89.4	92.8	89.3
Longwave	TOA	-275.2	-286.6	-279.2	-236.7
	SFC	50.2	68.2	50.6	64.0
	NET	-225.0	-218.4	-228.6	-214.3
Shortwave + Longwave	TOA	23.3	52.9	21.2	47.7
	SFC	-155.6	-181.9	-157.0	-172.7
	NET	-132.3	-129.0	-135.8	-125.0
Sensible	SFC	10.4	11.8	10.4	11.3
Latent	SFC	137.6	132.3	137.3	130.3
Total	TOA + SFC	15.7	15.1	11.9	16.6
Difference to T1C1	TOA + SFC	-	-0.6	-3.8	+0.9

the ocean surface, a more substantial amount of incoming shortwave radiation is absorbed by the Atlantic Ocean. Simulation T0C0 has with 41 Wm^{-2} the most substantial increase in net shortwave TOA fluxes, followed by simulation $T0C0_{low}$ with 27.5 Wm^{-2}. However, high clouds affect the net shortwave TOA fluxes with an increase of 1.9 Wm^{-2} very little compared to low clouds.
Clouds emit longwave radiation but also can trap longwave radiation between the surface and a cloud layer or between two cloud layers. The outgoing longwave TOA fluxes increase in all simulations where clouds are partly or entirely removed for the radiation routine. When ACRE is switched off for the entire troposphere outgoing longwave radiation at TOA has the highest increase mainly due to the increase of surface fluxes into the model domain. Since all clouds are invisible to radiation, longwave radiative fluxes can easier escape without distraction into space. Total net longwave radiative fluxes (TOA + SFC) of the T0C0 simulation are less negative (an increase of 3.3 Wm^{-2} compared to the T1C1 simulation). In simulation $T0C0_{high}$ the total net longwave radiation budget decreases due to missing high clouds, which usually trap outgoing longwave radiation from lower levels inside the troposphere. In the $T0C0_{low}$ simulation, more longwave radiation stays inside the atmosphere because high clouds trap outgoing longwave efficiently.
Regarding the resulting net shortwave and longwave radiative fluxes (the sum of short and longwave fluxes), in the T0C0 simulation, the TOA net fluxes increase by 29.6 Wm^{-2} mainly due to the decrease of outgoing shortwave radiation. On the other side, the fluxes into the surface increase by 26.3 Wm^{-2}, which is almost equal to the increase of TOA fluxes. Regarding the overall longwave and shortwave fluxes, the net energy balance of the model increases by 3.3 Wm^{-2} from -132.3 Wm^{-2} to -129.0 Wm^{-2}. In contrast, the total net radiative fluxes decrease by 3.5 Wm^{-2} in simulation $T0C0_{high}$. The main reason for this decrease can be found in missing high clouds for radiation which normally trap outgoing longwave radiation. In simulation $T0C0_{low}$ the total radiative fluxes increase by 7.3 Wm^{-2}. The main reason for this increase is an increase in outgoing longwave radiation from the surface caused by intensified shortwave radiation absorption of the surface.
The previous sections only considered short and longwave radiative fluxes. For the total energy budget of the model domain, sensible and latent heat fluxes must be considered as well. Table 1 shows sensible and latent fluxes from the surface into the atmosphere as well as the total energy budget of all radiative fluxes and the difference to the control simulation. Including sensible and latent heat fluxes into the energy balance, the overall energy budget of simulation T1C1 has a surplus of 15.7 Wm^{-2}. A surplus of the energy budget in the tropical Atlantic is consistent with the literature and transported by meridional large-scale circulations into higher latitudes (Trenberth and Stepaniak, 2004). When the ACRE is switched off, the surplus in the total energy budget is slightly reduced by 0.6 Wm^{-2}. The conclusion to be drawn from this is, that clouds have a slightly positive forcing in the performed simulation over the Atlantic Ocean. High clouds and low clouds have contrary effects regarding the energy budget. While high clouds increase the total energy budget by 3.8 Wm^{-2}, low clouds slightly contract this increase and reduce the energy budget by

-0.9 Wm^{-2}. The sum of radiative heating of high clouds and radiative cooling of low clouds is 2.9 Wm^{-2} and this is not consistent with the overall radiative heating effect of clouds of 0.6 Wm^{-2}. One reason can be found that mid-level clouds are not individually considered. It is likely that mid-level clouds cannot close this gap of 2.3 Wm^{-2}. However, there must be a feedback mechanism between high and low clouds, which leads to an increase in the energy budget.

In conclusion, clouds have an overall radiative heating effect in tropical Atlantic regions. However, high and low clouds have contrary effects on the radiation budget. While low clouds have a positive radiative cooling, high clouds account for radiative heating.

3.2 ACRE in the Control Simulation (T1C1)

This chapter aims to describe the ACRE of the control simulation (T1C1). Figure 4 shows the shortwave, longwave, and net ACRE averaged over the Atlantic ocean of the second simulation day (21st December 2013). The horizontal spatial standard deviation of the ACRE is presented as filled area around the ACRE in figure 4. The strongest influence of ACRE appears in the lower troposphere below 2 km altitude, where level clouds are present. The standard deviation of longwave ACRE is also largest in the lower troposphere, which is an indicator for large regional differences of ACRE and the dependence on cloud cover and cloud type. Within the whole troposphere, longwave ACRE has significantly higher values than shortwave ACRE.

Starting from the surface, where the shortwave ACRE is negative because low clouds block shortwave radiation. The longwave ACRE is positive because low clouds trap the longwave radiation emitted by the surface between the surface and the cloud layer. Moving towards the cloud top, longwave ACRE becomes negative and shortwave ACRE positive, but shortwave ACRE is about a factor of ten weaker than longwave ACRE. Thus, it counteracts the longwave ACRE only very weakly. At higher altitudes, shortwave and longwave ACRE becomes weaker, whereby longwave ACRE still dominates shortwave ACRE.

Summarizing the ACRE in the control simulation, the longwave ACRE dominates the

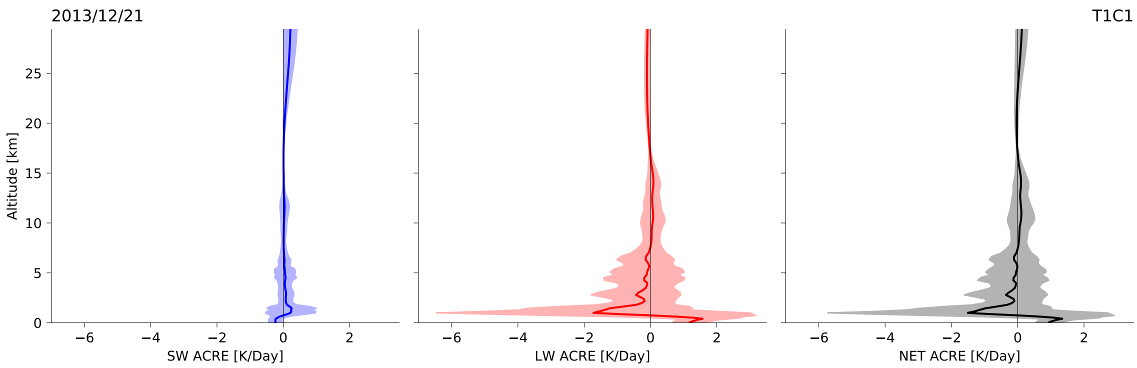

Figure 4: *Shortwave, longwave, and net ACRE over the Atlantic Ocean with standard deviation over cells (filled areas).*

shortwave ACRE. ACRE has the largest impact in the lower troposphere, where longwave ACRE heats the cloud bottom and cools the cloud top. Therefore, further analysis will focus mainly on the longwave ACRE in the lower troposphere and how ACRE affects the low-level cloud cover.

3.3 Domain Mean ACRE Profiles

This section provides an overview of the time and domain mean ACRE profile of each simulation and describes the characteristic features. Figure 5 shows the longwave, shortwave and net ACRE profile for all simulations.
The ACRE profile of the simulation T1C1 has already been discussed in Section 3.2. The T1C0 simulation uses smoothed ACRE profiles introduced in Section 2.3.3 instead of the ACRE profiles calculated by the ICON model. Therefore is the time and domain mean ACRE profile of simulation T1C0 similar to the time and domain mean ACRE profile of the control simulation. However, the contrast in the ACRE profile between clear-sky and cloudy areas disappears in the indirect simulation and probably results in a decrease in turbulent kinetic as well as a weaker circulation within the cloud layer.
During the simulation of the T0C1 case, smoothed ACRE profiles of simulation T1C1 are subtracted from the all-sky radiative heating rates as explained in Section 2.3.4. The direct ACRE should increase the instability, the turbulent kinetic energy and enhance the circulation within the cloud layer. Ideally, the domain and time mean ACRE profile of this simulation should be zero. However, there is a clear negative deflection in the lower troposphere of up to -1.6 K/Day. To address why the ACRE does not fulfill the expectation, a further analysis is necessary and a division into different evaluation areas is indispensable. This analysis will be presented in section 3.5. The ACRE of simulation T0C0 is trivial since this simulation runs only with clear-sky heating rates and the difference between clear-sky and all-sky radiative heating rates is zero.
In simulation $T0C0_{high}$ high clouds are removed for the radiation routine inside the ICON model. However, the ACRE in the lower troposphere is very similar to the ACRE of simulation T1C1. The ACRE in the upper troposphere does not trigger a feedback in the ACRE profile of layers below. In simulation $T0C0_{low}$ the high and mid-level ACRE profile follows the ACRE profile of simulation T1C1. Only in the lower troposphere, where clouds are removed for radiation, the net ACRE is positive and heats with up to 0.4 K/Day due to mid-level clouds, which slightly trap outgoing longwave radiation in the lower troposphere.

3.4 ACRE Influenced Cloud Cover Changes

This section compares the cloud cover of every simulation. The absolute cloud cover increases by 2.2 % if the ACRE is turned off, mainly due to changes in low-level clouds. Low-level clouds increase by 4.7 %. Mid- and high-level clouds decrease slightly by 0.2 % and 0.1 % respectively. When switching the ACRE off for high clouds, the amount of low- and mid-level clouds remain almost the same as in the control simulation, and only the absolute high cloud amount decreases by 1.3 %. As shown in the energy budget analysis in Section 3.1, high clouds have a positive effect on the energy budget, because they block outgoing longwave radiation. However, there are no signs of any feedback mechanisms between high and low clouds regarding the cloud cover.

The absolute amount of low-level clouds increases by 2.2 % if the ACRE is turned off for low clouds, while mid-level cloud cover decreases and high-level cloud cover slightly increases.

In summary, ACRE at high altitudes increases the high-level cloud cover, and ACRE at low-level altitudes decreases the low-level cloud cover.

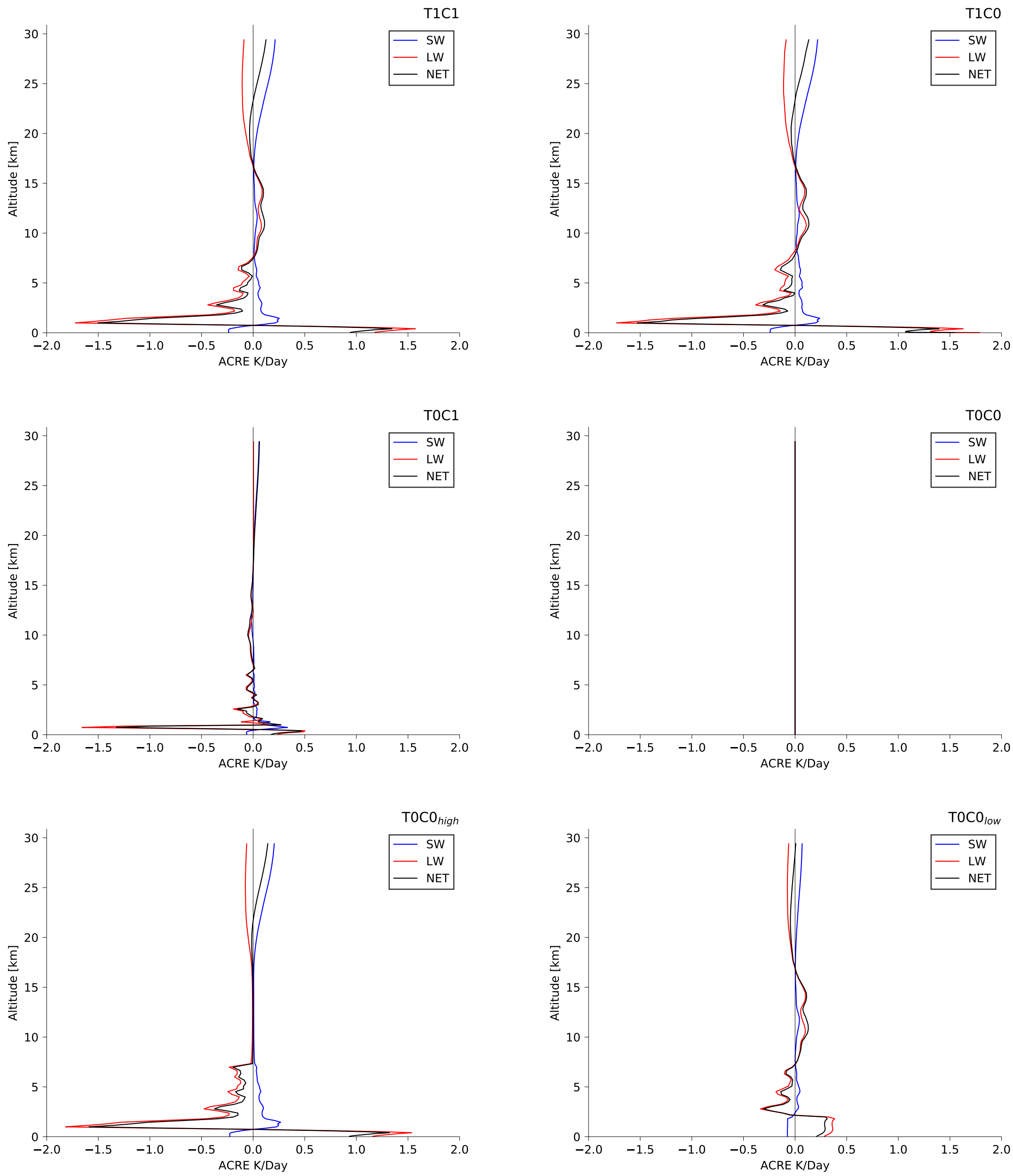

Figure 5: *ACRE profiles of all simulations over Atlantic Ocean, averaged over second simulation day*

Table 2: *Mean cloud cover over Atlantic Ocean of low, mid and high clouds and mean total cloud cover as well as absolute cloud clover changes (numbers in parenthesis). Cloud cover is given in %.*

	T1C1	T1C0	T0C1	T0C0	$T0C0_{high}$	$T0C0_{low}$
High	21.2 (-)	22.8 (1.6)	18.9 (-2.3)	21.1 (-0.1)	19.9 (-1.3)	22.1 (0.9)
Mid	15.3 (-)	15.8 (0.5)	16.2 (0.9)	15.1 (-0.2)	15.1 (-0.2)	14.3 (-1.0)
Low	38.9 (-)	38.0 (-0.9)	46.2 (7.3)	43.6 (4.7)	39.0 (0.1)	41.1 (2.2)
Total	58.0 (-)	58.0 (0.0)	62.3 (4.3)	60.2 (2.2)	57.0 (-1.0)	59.4 (1.4)

For determining the effect of direct and indirect ACRE, this study will use the method of Harrop and Hartmann (2016b). It should be noted that isolating the direct and indirect ACRE in the experiments does not conserve the precipitation as well as that the ACRE is crucial for other feedbacks, such as the self-aggregation of convection (Muller and Bony, 2015). As a result, the large-scale circulation adjusts in each experiment. This can lead to different results in the two possible ways to calculate the cloud cover changes.
Starting with the impact of indirect ACRE on the cloud cover, Table 3 shows the two possible calculations to isolate the indirect ACRE. The indirect ACRE increases the absolute high cloud cover by 2.3 % or 1.7 % and decreases the absolute low-level cloud cover by -7.9 % or -5.6 %. This is the opposite of the results found in the simulations from Harrop and Hartmann (2016b). However, their model domain was smaller, thereby large scale circulations are less well represented. On the other hand, they allowed their experiment to run longer (100 and 120 days) and used the last 50 days for the statistical evaluation. Therefore, it is difficult to compare the results of Harrop and Hartmann (2016b) and the results of this study. The overall cloud cover decreases by -4.3 % or -2.2 %, depending on the formula used to calculate the indirect ACRE.
On the other side, the direct ACRE has the opposite effect. The high-level cloud cover decreases due to the destabilizing effect of ACRE by -1.6 % or -2.3 %. The calculated effect of ACRE on mid-level clouds is ambiguous: When calculating the direct ACRE as T1C1 subtracted by T1C0 the mid-level cloud amount decreases by -0.5 %, while calculating the effect of direct ACRE as T0C1 subtracted by T0C0 the mid-level cloud amount increases

Table 3: *Absolute cloud cover changes due to indirect, direct and total ACRE in % over the Atlantic Ocean*

	Indirect ACRE		Direct ACRE		Total ACRE
	T1C1 - T0C1	T1C0 - T0C0	T1C1 - T1C0	T0C1 - T0C0	T1C1 - T0C0
High	+2.3	+1.6	-1.6	-2.3	0.0
Mid	-0.9	+0.7	-0.5	+1.1	+0.2
Low	-7.3	-5.6	+0.9	+2.6	-4.8
Total	-4.3	-2.3	0.0	+2.0	-2.2

by 1.1 %. Due to the direct ACRE, the absolute amount of low-level clouds increases by 0.9 % or 2.6 %. For both types of calculations, the direct ACRE decreases the high-level cloud amount and increases the low-level cloud amount. However, the overall effect on the total cloud cover is unclear from this method, as the total calculated cloud cover remains or increases by 2.2 %, depending on the formula used to calculate changes in the cloud cover.

3.5 ACRE in Different Low-Level Cloud Regimes

As already mentioned in section 3.2 low-level ACRE has regional differences and depends on the cloud type. For this reason, the model domain is divided into four smaller evaluation areas according to low-level cloud regimes shown in Figure 3.

3.5.1 Influence of ACRE on Shallow Cumulus Cloud Regime in Area a

This section aims to study cloud changes due to indirect and direct ACRE in the evaluation area a. This area is located in the trades, northeast of Barbados, and is characterized by a shallow cumulus cloud regime. Figure 6 shows a snapshot of the low-level clouds of simulation T1C1, T1C0, T0C1, and T0C0 at 12:00 UTC of the 21st December 2013. If clouds interact normal with radiation (T1C1) shallow cumulus clouds have an open cloud structure, clear-sky regions surround the shallow cumulus clouds, and the visible connection between clouds is weak. If the ACRE is switched off (T0C0), larger clouds form, the visible connection between clouds strengthens and fewer single clouds form. Thus, the direct and indirect ACRE apparently increases the amount of clear sky areas in shallow clouds and confines them horizontally.

The total cloud cover decreases for both, indirect and direct ACRE (Table 4), wherein the indirect ACRE dominates the reduction of cloud cover in the lower troposphere and the direct ACRE in the upper troposphere. In the shallow cumulus regime, indirect and direct ACRE reduce the low-level cloud cover, whereby the indirect ACRE dominates the reduction of low-level cloud cover with up to -4.1 %. Figure 7 shows the profiles of ACRE, the cloud cover, the temperature, and relative humidity averaged over the second simulation day (21st December 2013). For this shallow cumulus cloud regime, the ACRE profile is reasonable, the T1C0 simulation has an almost identical profile as T1C1, but the horizontal variance (not shown) in the T1C0 profile is smaller since the ACRE profile of the T1C0 is the smoothed ACRE profile of simulation T1C1. The ACRE profile of simulation T0C1 and T0C0 have comparable structures, but again, the horizontal variance differs. The horizontal variance of ACRE in simulation T0C1 is comparable to T1C1, as there is a contrast between clear-sky and cloudy areas. Simulation T0C0 has zero variance in the ACRE profile since

Table 4: *Absolute cloud cover changes due to indirect, direct and total ACRE in % of area a.*

	Indirect ACRE		Direct ACRE		Total ACRE
	T1C1 - T0C1	T1C0 - T0C0	T1C1 - T1C0	T0C1 - T0C0	T1C1 - T0C0
High	1.8	-0.4	-0.4	-2.6	-0.8
Mid	-0.2	0.1	-1.6	-1.4	-1.6
Low	-4.1	-3.2	-1.3	-0.4	-4.4
Total	-2.2	-2.7	-2.3	-2.8	-5.0

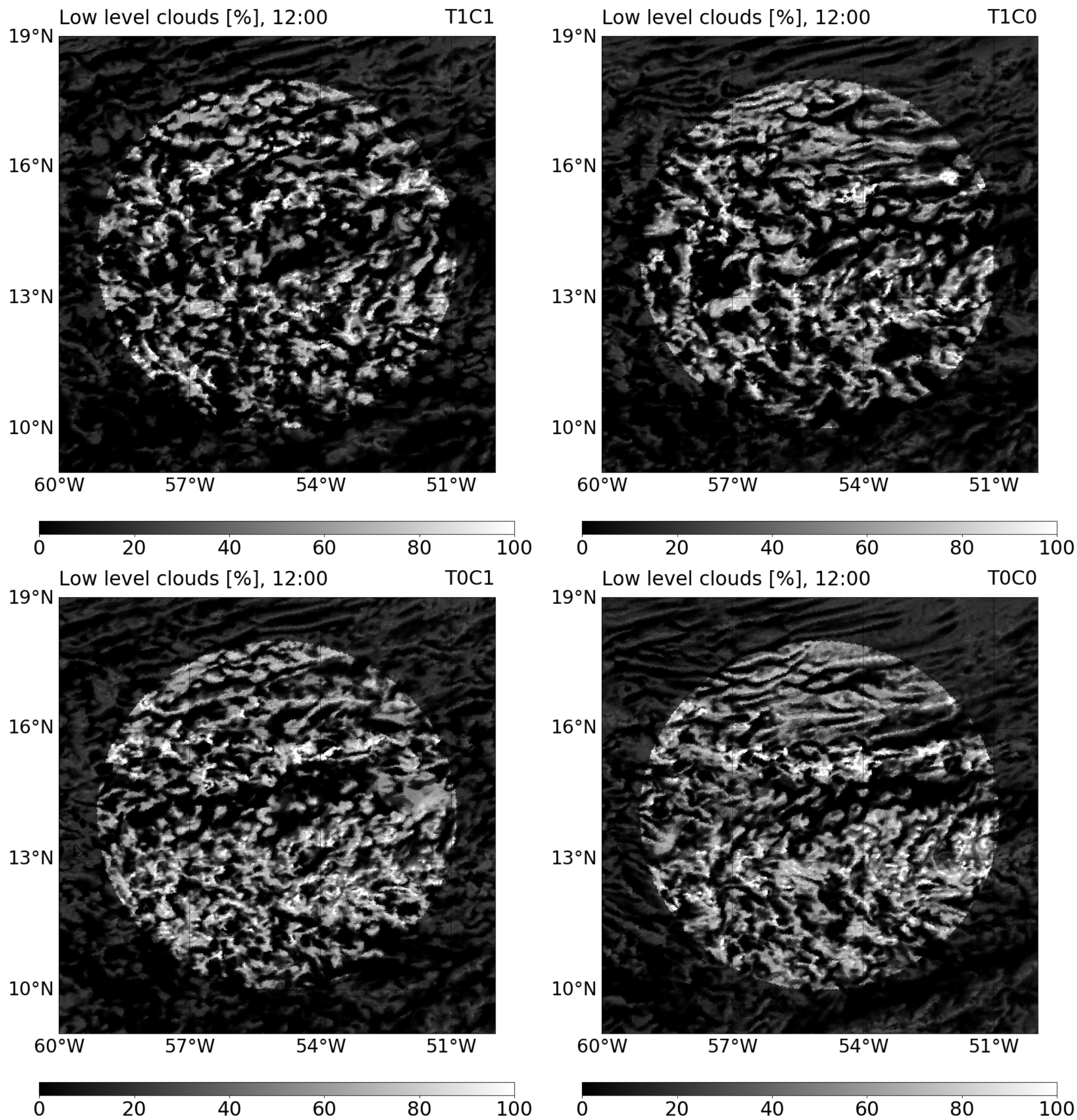

Figure 6: *Snapshot of low-level cloud cover of second simulation day (21st December 2013) at 12:00 UTC for area a.*

this simulation uses clear-sky radiative heating rates only.

In the cloud cover profile, it is notable that in simulations without indirect ACRE (T0) low clouds are slightly shifted towards the surface and the amount of clouds increases. This is also reflected in the temperature profile, which hardly differs between all simulations. However, relative humidity increases in simulations without indirect ACRE (T0) up to a height of about 1 km. The indirect ACRE controls the cloud bottom and top height via the following mechanism: the radiative heating of the cloud bottom and radiative cooling of the cloud top elevates the cloud layer. The elevation of clouds spreads the water vapor from layers near the ground over a larger vertical area. Fewer clouds occur because saturation is reached at fewer points. In contrast, the direct ACRE enhances the entertainment of dry air at the cloud top and thereby reducing cloud top height.

In summary, the ACRE on shallow cumulus clouds, both direct and indirect effects reduce the clouds in the lower troposphere. While the indirect ACRE elevates the cloud top height and spreads the water vapor from layers near the ground over a larger vertical area, the direct ACRE enhances the entertainment of drier air at the cloud top.

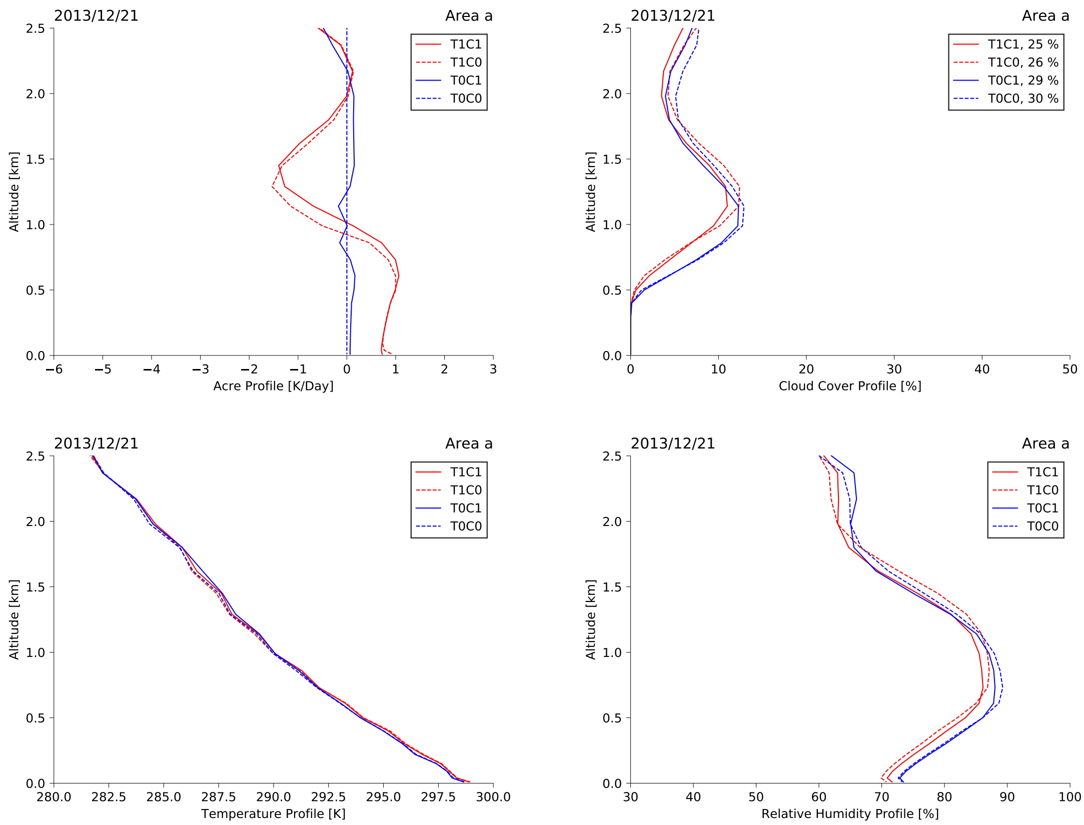

Figure 7: *Profiles of ACRE, cloud cover, temperature and relative humidity in the lower troposphere. Average of 21st December 2013.*

3.5.2 Influence of ACRE on Cloud Regime within the ITCZ in Area b

This area is located within the ITCZ, where convection is mainly driven by the large-scale circulation. Cloud roads form towards the center of the ITCZ. Due to ascending air within the ITCZ low-level cloud cover often represents the the lower part of deeper clouds and therefore low-level clouds are not necessarily separated from higher-level clouds by a cloud-free layer in between. Figure 8 shows a snapshot from all four ACRE simulations. The center of the convecting cluster is cloudy and at the borders cloud-free areas occur when clouds interact normally with radiation. However, the cloud-free areas are reduced in all other simulations, analogous to the results in area a. If the ACRE is switched off (T0C0), cloud streets towards the center of the ITCZ strengthen and only few cloud-free areas are observed.

Table 5 shows the changes in cloud cover for high-, mid- and low-level clouds due to indirect and direct ACRE in area b. Due to ACRE high-level clouds increase by 0.8 % but an assignment to direct and indirect ACRE is difficult, because it is not clear in either case whether clouds increase or decrease, since the result depend strongly on the formula used to calculate the influence of ACRE. Mid-level clouds decrease in total by 3.4 %, this decrease is mainly driven by direct ACRE, the indirect ACRE only plays a minor role for mid-level clouds.

The most significant cloud cover change occurs in the lower troposphere for low-level clouds. The total ACRE decreases low-level clouds by 11.2 %. Both direct and indirect ACRE reduce the low-level cloud cover, but the indirect ACRE is dominant and leads to a reduction in low-level cloud cover of 6.6 % and 8.5 %, respectively. In addition, the direct effect reduces the low-level cloud cover by 2.2 % and 2.6 %, respectively.

Figure 9 shows mean profiles of ACRE, cloud cover, temperature and relative humidity for area b up to a height of 5 km. The difference between cloud bottom radiative heating and

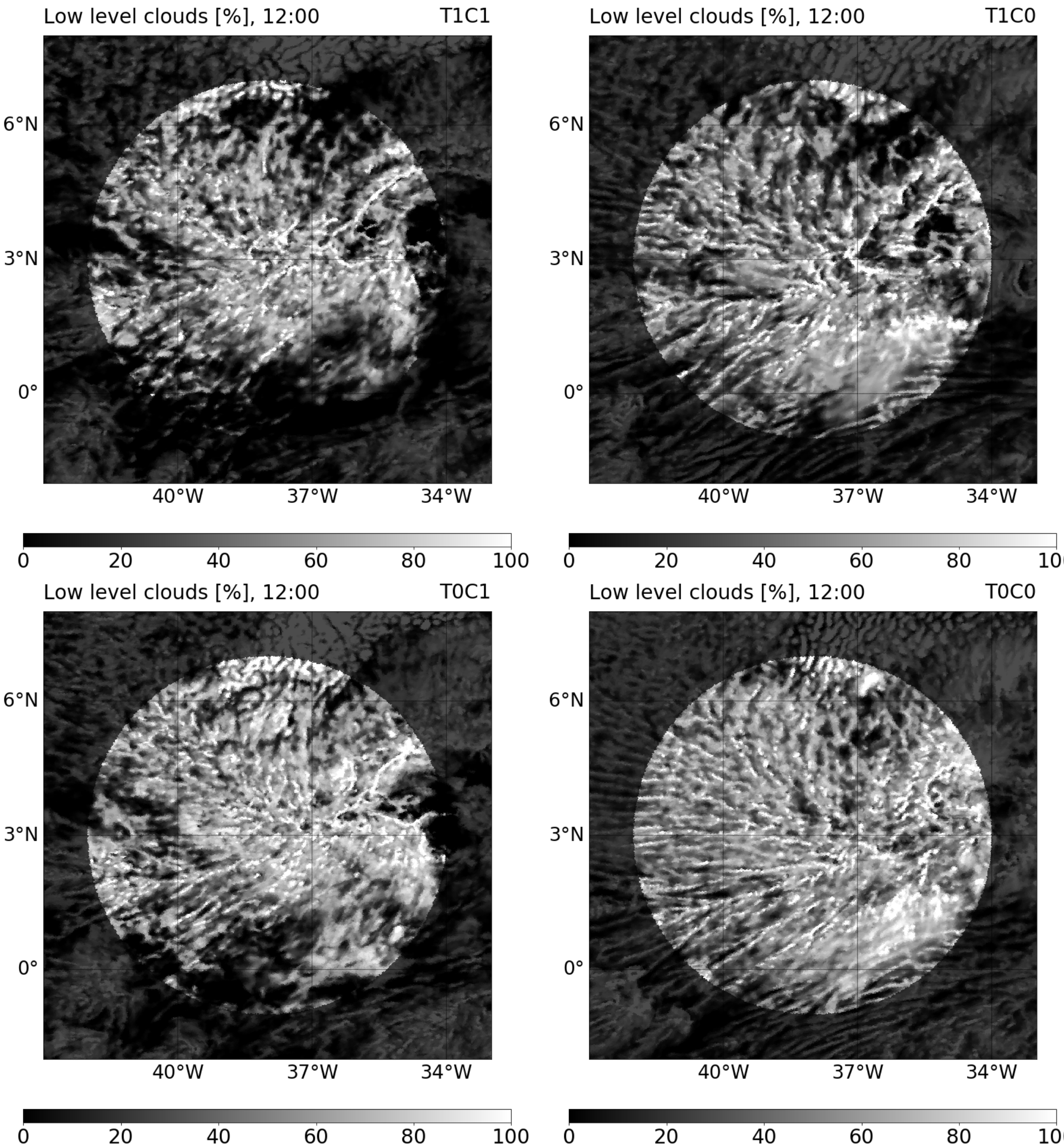

Figure 8: *Snapshot of low-level cloud cover of second simulation day (21st December 2013) at 12:00 UTC for area b.*

Table 5: *Absolute cloud cover changes due to indirect, direct and total ACRE in % of area b.*

	Indirect ACRE		Direct ACRE		Total ACRE
	T1C1 - T0C1	T1C0 - T0C0	T1C1 - T1C0	T0C1 - T0C0	T1C1 - T0C0
High	-0.6	0.9	-0.1	1.4	0.8
Mid	-0.6	-0.8	-2.7	-2.9	-3.4
Low	-6.6	-8.5	-2.8	-4.7	-11.2
Total	-3.9	-4.3	-2.2	-2.6	-6.5

cloud top radiative cooling of the indirect ACRE (T1) is weaker than in area a. Due to the location of area b within the ITCZ, low clouds are part of deep convective circulation, the cloud-free layer between low-level and mid-level clouds disappears and the vertical distribution of the radiative cooling increases. Therefore, no clear cloud top edges form, and an abrupt longwave radiative cooling at the cloud top does not occur. This is reflected in the temperature profile which hardly differs between all simulations. Only from the surface up to a height of 600 m the temperature of simulations with indirect ACRE (T1) slightly increases compared to simulations without indirect ACRE (T0), since the ACRE heats the air below low-level clouds. If the ACRE is switched off, the lower troposphere relative

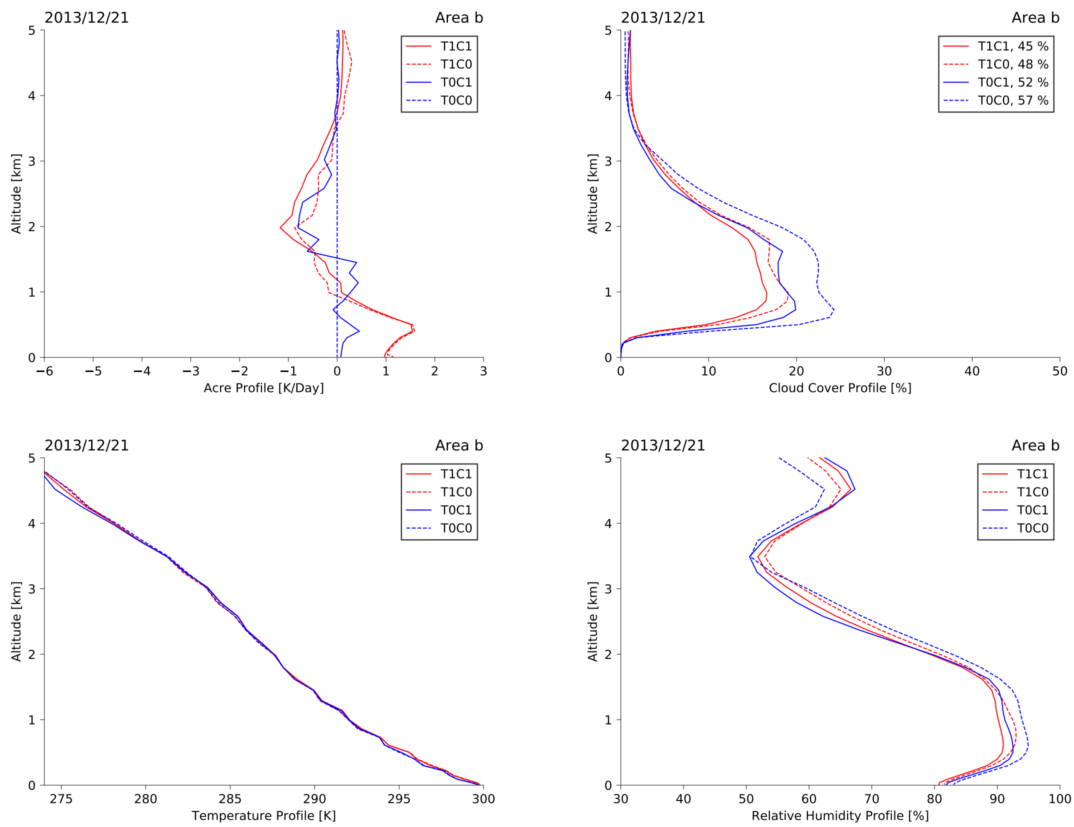

Figure 9: *Profiles of ACRE, cloud cover, temperature and relative humidity in the lower troposphere. Averaged over 21st December 2013.*

humidity increases, and as a result, the cloud cover increases. Harrop and Hartmann (2016a) showed in aquaplanet experiments with fixed sea surface temperature that the ACRE leads to an equatorward contraction of the ITCZ and enhances the meridional circulation (Hadley cell). The contraction of the ITCZ matches the cloud cover snapshot, where the cloud cover contracts towards the ITCZ if the ACRE is switched on. This could explain the increase in low-level clouds if clouds do not interact with radiation. However, a detailed study of this phenomenon is beyond the scope of this work.
Summarizing the ACRE on low-level clouds within the ITCZ, both indirect and direct ACRE reduces clouds up to a height of 5 km. However, the indirect ACRE dominates the reduction of low-level clouds by a factor of two compared to the direct ACRE.

3.5.3 Influence of ACRE on Stratocumulus Deck in Area c

A closed stratocumulus cloud deck characterizes area c. This cloud deck has only very few cloud-free zones, which mainly occur north of 17 ° N. Figure 10 shows the cloud cover of the four ACRE simulations. All four simulations capture the stratocumulus cloud deck with only minor deviations. The clearest difference is that simulation T0C1 shows a brighter cloud deck, which indicates a higher degree of cloud coverage.
The absolute cloud cover changes due to ACRE are listed in Table 6. The total absolute increase of high-level cloud cover due to ACRE is with 1.3 % small, compared to the increase in low-level cloud cover. Mid-level cloud cover decreases due to ACRE. However, once again opposing signals are obtained due to the influence of indirect ACRE on low-level cloud cover. Depending on the calculation method, low-level cloud cover can decrease by -5.8 % or increase by 3.2 %. The direct ACRE increases the cloud cover by 3.4 % or 12.4 %. Because of the substantial differences and partly contradictory results in the cloud cover changes, the question arises, why do the formulas to calculate the changes due to direct and indirect ACRE deliver such different results? In order to answer this question, it is necessary to evaluate vertical profiles of ACRE, temperature, cloud cover and relative humidity. The following paragraphs include this evaluation.
Previous studies showed, that radiative cooling rates at the cloud top of stratocumulus clouds exceed the cloud top radiative cooling of shallow cumulus clouds or deep convective regimes (e.g. Stevens, 2005). The radiative cooling rates at the cloud top of the stratocumulus cloud deck in the control simulation (T1C1), the indirect (T1C0) and direct (T0C1) simulation also exceed cloud top radiative cooling rates of shallow cumulus clouds and deep convective regimes. The ACRE signal of the simulation T1C1 is substantial and ranges from +2.5 K/Day at the cloud bottom to -13 K/Day at the cloud top. The ACRE of simulation T1C0 is comparable to the ACRE of simulation T1C1, but with slightly less radiative heating at cloud bottom and radiative cooling at the cloud top. However, the ACRE profile of simulation T0C1 even exceeds the cloud bottom radiative heating and cloud top radiative cooling of simulation T1C1. Besides that, positive radiative heating occurs above 1 km height. The difference between cloud bottom radiative heating and cloud top radiative cooling is

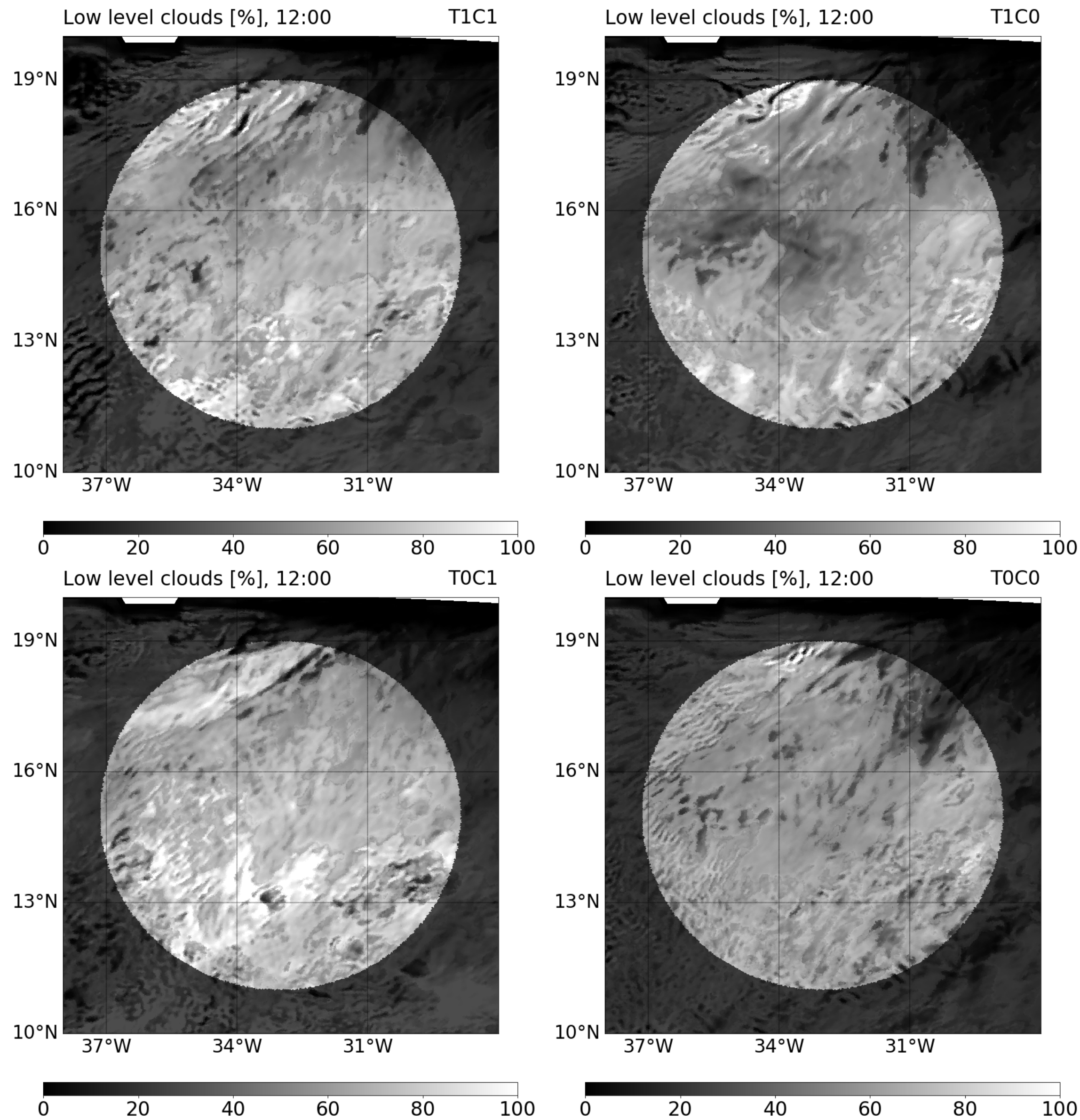

Figure 10: *Snapshot of low-level cloud cover of second simulation day (21st December 2013) at 12:00 UTC for area c.*

Table 6: *Absolute cloud cover changes due to indirect, direct, and total ACRE in % of area c.*

	Indirect ACRE		Direct ACRE		Total
	T1C1 - T0C1	T1C0 - T0C0	T1C1 - T1C0	T0C1 - T0C0	T1C1 - T0C0
High	1.9	0.3	1.2	-0.3	1.3
Mid	-3.0	-1.6	-1.7	-0.4	-3.3
Low	-5.8	3.2	3.4	12.4	6.6
Total	-5.4	2.9	2.3	10.5	5.2

18 K/Day and therefore more effective than in all other simulations. It is also worth noting that the ACRE profile is vertically shifted towards the surface.

As for total cloud cover, simulation T0C1 shows with 67 % low-level cloud cover the highest value, followed by simulation T1C1 with 61 %. Simulation T1C0 has 58 % low-level cloud cover and the lowest value with 55 % occurs in simulation T0C0. However, in simulations without indirect ACRE (T0) low-level clouds subside.
The temperature profile shows an inversion above the stratocumulus cloud deck. This inversion blocks air from rising higher due to stable stratification. The inversion subsides in simulations without indirect ACRE. The relative humidity drops from about 90 % at the inversion bottom to 25 % at the inversion top.
If the direct ACRE is switched off (C0), the inversion shifts towards the surface, which subsides low-level clouds along with the temperature inversion. It can therefore be concluded that the radiative cooling effect of the indirect ACRE at the cloud top elevates the inversion above the cloud layer, and the vertical extension of the MBL increases. Due to the lower inversion when the ACRE is switched off, the vertical profile of relative humidity changes as well. The relative humidity increases within the MBL but due to the lower inversion, humidity can not be transported as high as in experiments with indirect ACRE (T1). The relative humidity drop starts at lower altitudes since the lower inversion prevents moist air from ascending into higher altitudes.
In simulation T0C1 one would expect that the ACRE profile would not differ much from the ACRE profile of the T0C0 experiment since the smoothed ACRE is subtracted at

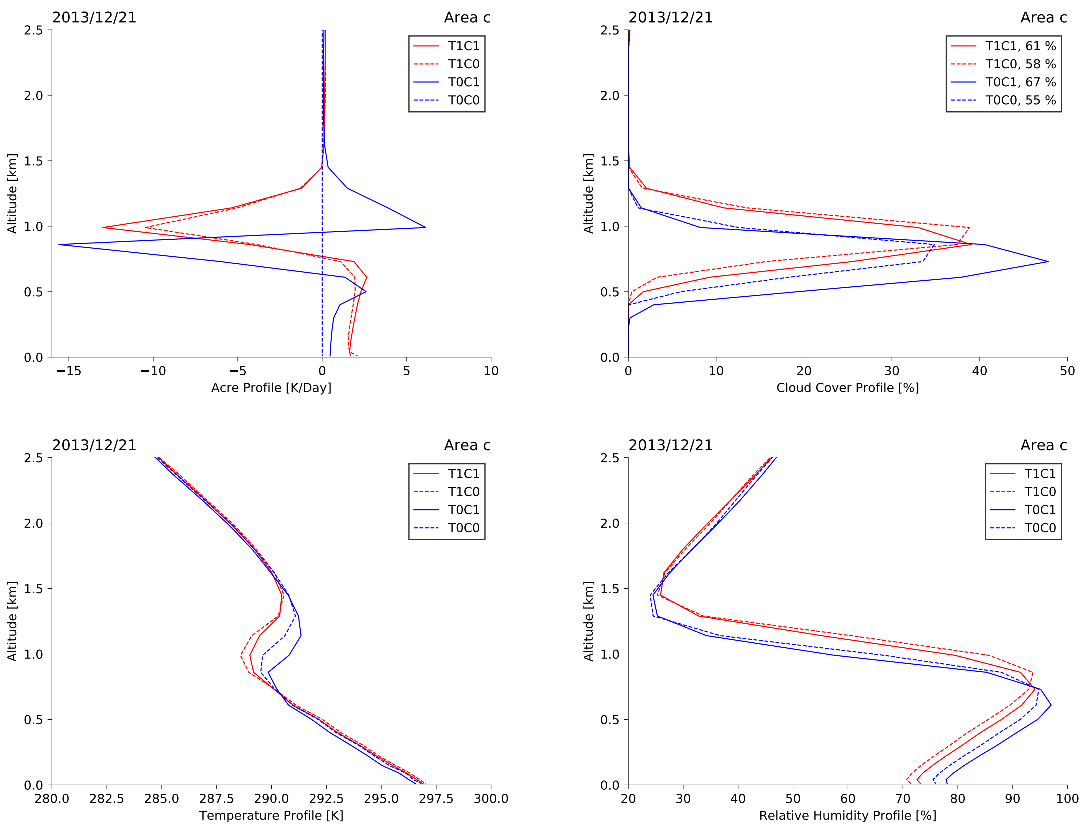

Figure 11: *Profiles of ACRE, cloud cover, temperature and relative humidity in lower troposphere. Averaged over 21st December 2013 and for cloud regime c.*

every radiation time step from the all-sky radiative heating rates. However, the ACRE of simulation T0C1 presents a different picture. The ACRE still heats the MBL under the cloud bottom, with a maximum of 2.5 K/Day at 600 m. Above 600 m the ACRE starts to decrease until it reaches its minimum of about -16 K/Day at the height of 850 m. The minimum of ACRE is shifted towards the surface compared to the ACRE in simulation with the indirect effect. After the minimum, ACRE increases again until it reaches 6 K/Day at the height of 1000 m. Above 1000 m ACRE decreases again until it vanishes at the height of 1500 m. Thus, ACRE generates a sharp contrast between altitudes where it heats the lower troposphere and altitudes where it has a radiative cooling effect. How does this sharp vertical contrast arise between radiative heating and radiative cooling if the smoothed ACRE is subtracted already? This is related to the setup of the T0C1 simulation. As the inversion is shifted towards the surface (as in simulation T0C0), the humidity in the MBL increases at a constant temperature, saturation is reached more quickly and low-level clouds subside. In this constellation, the ACRE of T0C1 is not identical with the subtracted smoothed ACRE, because of the vertical mismatch of ACRE in the T0C1 simulation. Instead of minimizing the vertical difference in the ACRE profile, the ACRE is amplified and causes a positive radiative heating above 1000 m. Other studies showed that for maintaining stratocumulus cloud decks, a strong vertical gradient in the ACRE profile is necessary. The stronger the radiative cooling at the cloud top, the stronger and higher the stratocumulus cloud deck becomes (Schneider et al., 2019).

In summary, horizontal differences between the simulations are small compared to the vertical differences. The indirect ACRE increases the height of the inversion above low-level clouds and thus also lifts low-level clouds. This results in less clouds, since the water vapor spread in the vertical extended marine boundary layer and saturation is reached at fewer points.

3.5.4 Influence of ACRE on a Closed Convective Stratocumulus Regime in Area d

Area d has also characteristic stratocumulus clouds, but in this case there are closed convective cells. Low-level clouds form in ascending areas surrounded by small descending cloud-free areas. This constellation creates a typical honeycomb-like cloud cover, with clouds in the center and cloud-free boundaries (Wood and Hartmann, 2006). Figure 12 shows a snapshot of each ACRE simulation from the 21st of December 2013 at 12:00 UTC. In simulation T1C0, the horizontal size of cloud-free borders between stratocumulus clouds increases slightly, but the cloud-free area in the northeast decreases. Simulation T0C1 has a high cloud cover, the horizontal extent of the cloud-free borders between stratocumulus clouds decrease, and cloud-free areas almost disappear. The T0C0 simulation shows a weakly structured stratocumulus cloud deck with little honeycomb structures and few cloud-free areas. In comparison to area c, the differences between the simulations are stronger in this case.

Table 7 shows the cloud cover changes due to ACRE. Starting with the high cloud amount, both direct and indirect ACRE increase the absolute high-level cloud amount very slightly

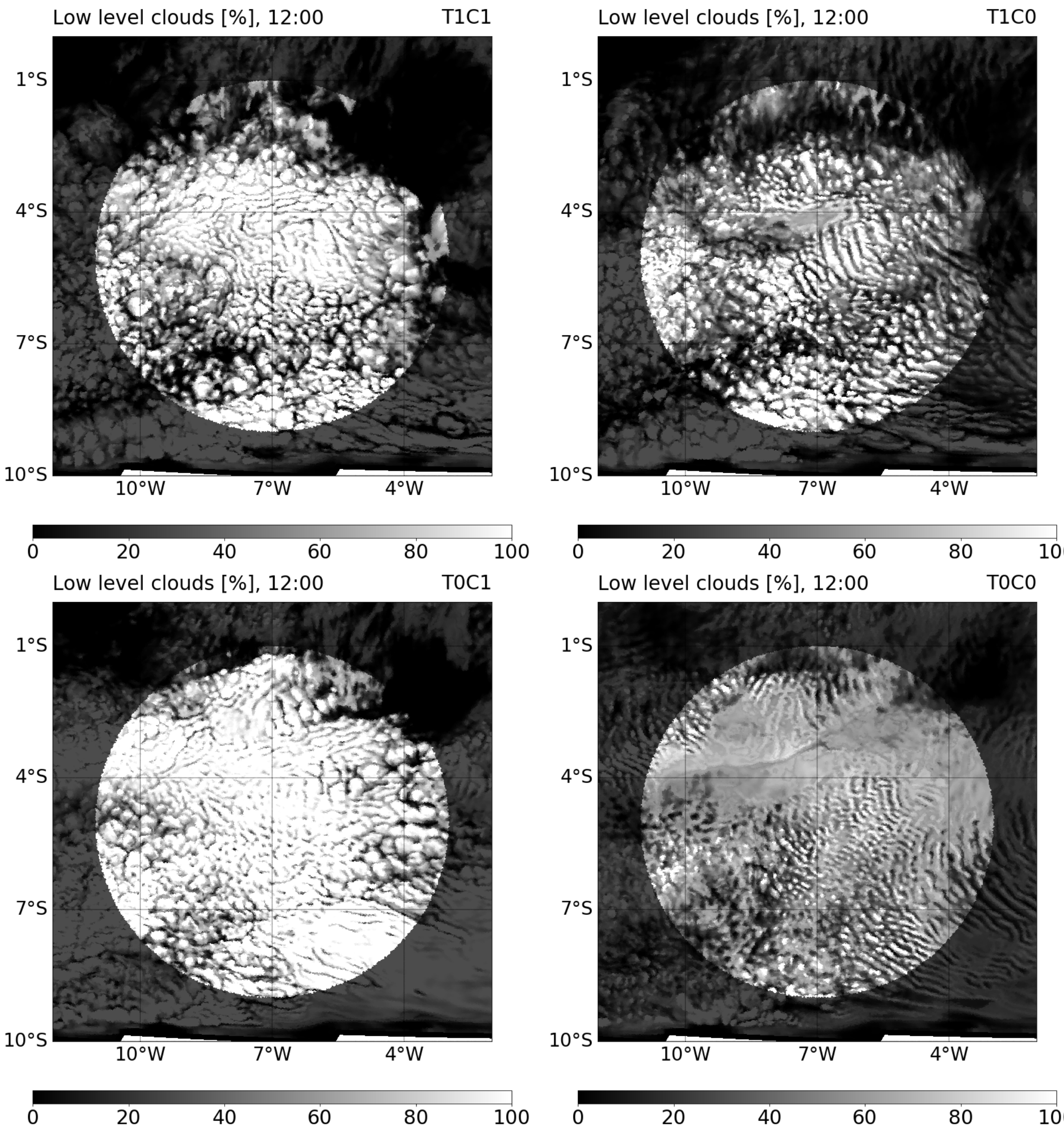

Figure 12: *Snapshot of low-level cloud cover of second simulation day (21st December 2013) at 12:00 UTC for area d.*

between 0.4 % and 0.7 % for indirect and 0.1 % and 0.4 % for direct ACRE. The total high cloud amount increases by 0.8 % due to ACRE. The cloud increase of mid-level clouds is negligible with 0.1 %. Again, the influence of ACRE on low-level clouds is largest. The total low-level cloud amount increases by 5.1 % due to ACRE. However, the indirect ACRE decreases the low-level cloud amount by -18.1 % and -5.1 % respectively. The indirect ACRE, on the other side, increases the low-level cloud amount by 9.4 % and 22.4 %, respectively. As in area c, the values for cloud cover changes vary considerably, depending on the method to calculate the influence of indirect and direct ACRE. The difference for indirect ACRE is 13 % and for direct ACRE is 18,1 %. Nevertheless, the sign of the signal is clear, as the indirect ACRE decreases the low cloud cover, and the direct ACRE increases the low-level cloud cover.

Table 7: *Absolute cloud cover changes due to indirect, direct and total ACRE in % of area d.*

	Indirect ACRE		Direct ACRE		Total
	T1C1 - T0C1	T1C0 - T0C0	T1C1 - T1C0	T0C1 - T0C0	T1C1 - T0C0
High	0.4	0.7	0.1	0.4	0.8
Mid	0.1	0.0	0.1	0.1	0.1
Low	-18.1	-5.1	9.4	22.4	4.3
Total	-16.3	-4.0	9.1	21.4	5.1

In the control simulation (T1C1) ACRE heats the cloud bottom and cools the cloud top as expected (see Figure 13). The smoothed ACRE of simulation T1C1 is almost similar to the original ACRE of simulation T1C1. However, the radiative cooling at the cloud top at about 1.2 km height is weaker in simulation T1C0. Comparing these profiles with the mean ACRE profiles over the Atlantic Ocean it is noticeable that the maximum radiative cooling of ACRE at low-level cloud top exceeds the averaged maximum radiative cooling over the Atlantic Ocean by about -4.5. K/Day. In simulation T0C1, one would expect that the ACRE is near zero, but there is a strong signal of radiative heating at the cloud bottom and radiative cooling at the cloud top despite the fact, that the smoothed ACRE

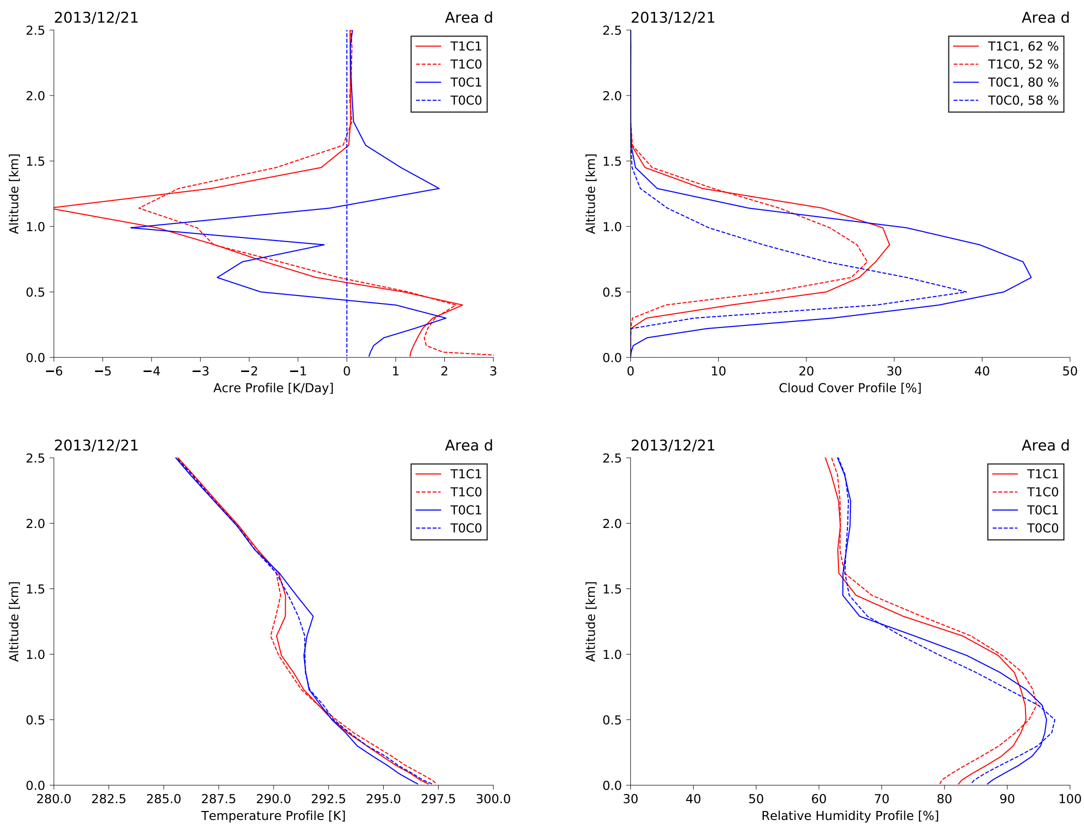

Figure 13: *Profiles of ACRE, cloud cover, temperature and relative humidity in lower troposphere. Averaged over 21st December 2013.*

of the T1C1 simulation is subtracted from the all-sky heating rates. In all simulations, an inversion above low-level clouds determines the height of the cloud top. Due to the missing radiative cooling at the cloud top in simulations without indirect ACRE (T0), the inversion shifts towards the surface. Since the inversion determines the cloud top height, the cloud top of low-level clouds subsides, the vertical extension of clouds is reduced, and the cloud layer contracts vertically. However, the direct ACRE enhances the mesocale cellular convection (MCC) which increases the inflow of moist air into the layer of low-level clouds. As a result, low-level cloud cover increases. This leads to an increased radiative cooling at the cloud top which in turn enhances the MCC. However, the direct simulation consists of a vertical missmatch between the simulated ACRE profiles and the subtracted smoothed ACRE profiles (comparable to the case explained in section 3.5.3). This mismatch can amplify the vertical gradient in the ACRE profiles of the direct ACRE simulation (T0C1) and it is possible that the setup overestimates the direct ACRE effect on clouds.

In order to summarize the complexity of the indirect and direct in a closed convective stratocumulus regime, a conceptual model is presented (see Figure 14). The radiative cooling of the indirect ACRE (colored areas in the background) shifts the inversion to higher altitudes. The direct ACRE enhances the mesocale cellular convection and thereby the moist

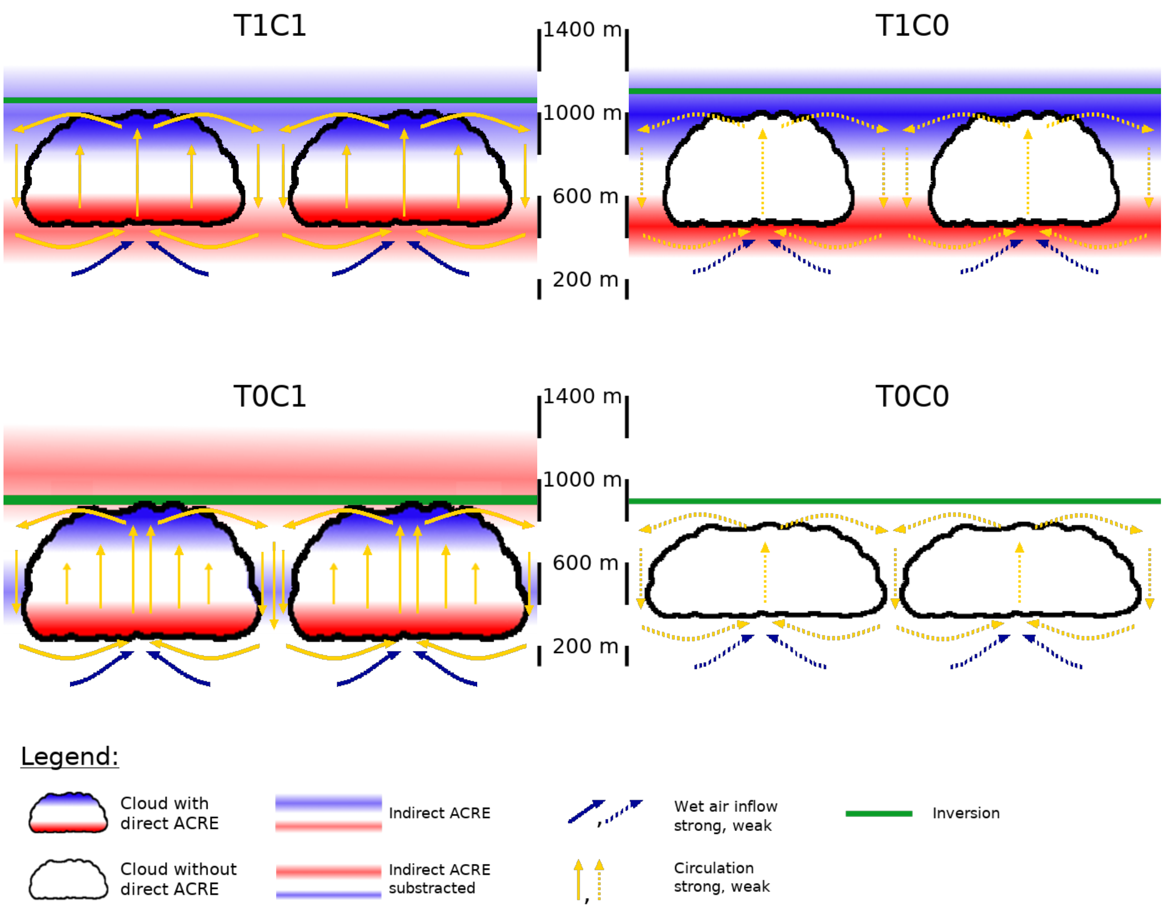

Figure 14: *Conceptual model of the four ACRE simulations in area d. Blue colors indicate radiative cooling and red colors radiative heating.*

supply at the cloud bottom strengthened. However, in the direct ACRE simulation, the subtracted smoothed ACRE does not fit vertically to the actually simulated ACRE, which most probably overestimates the effect of the direct ACRE on cloud cover.

4 Summary and Conclusion

This study has studied the ACRE in realistic high-resolution model simulations over the tropical Atlantic. The main focus was on the energy budget and how clouds in different heights respond to it as well as the influence of the direct and indirect ACRE on low-level clouds in different cloud regimes. The model simulations were performed with the ICON model and the NWP physics where used. The simulations were carried out for the period from the 20^{th} of December 2013 at 00:00 UTC until the 22^{nd} of December 2013 at 00:00 UTC. Due to model spin-up time, the study uses the model results of the second simulated day (21^{st} of December 2013) only.

This study showed that the energy budget has a surplus of 15.7 Wm^{-2} in the tropical Atlantic. If the ACRE is switched off, the radiation routine produces a deficit of 0.6 Wm^{-2} in the energy balance compared to the control simulation. However, low and high clouds have contrary effects. If high clouds do not interact with radiation the energy budget decreases by -3.8 Wm^{-2}. If low clouds do not interact with radiation the energy budget increases by 0.9 Wm^{-2}. However, high clouds block outgoing longwave radiation very efficiently than low clouds reflect incoming shortwave radiation, which is the reason why the radiative heating of high clouds exceeds the radiative cooling of low clouds.

Since in all simulations low-level cloud cover outweigh mid- and high-level cloud cover, ACRE is most influential in the lower troposphere. The longwave ACRE dominates the shortwave ACRE by about a factor of ten. A strong radiative heating of low-level cloud bottom and radiative cooling of low-level cloud top is observed, and the average difference between radiative heating at cloud bottom and radiative cooling the cloud top is 3.5 K/Day. However, ACRE has substantial regional differences and highly depends on the degree of cloud coverage and cloud type.

The domain mean ACRE profiles of the indirect ACRE simulation (T1C0) draws a similar picture as the domain mean ACRE profile of the control simulation (T1C1). However, the domain mean ACRE profile of the direct ACRE simulations (T0C1) has a significant high radiative cooling signal at low-level cloud tops, although one would expect that the mean ACRE profile of the direct ACRE simulation is equal to the ACRE profile of the simulation where all clouds are removed for the radiation routine (T0C0).
ACRE reduces the absolute cloud cover by 2.2 %, whereby the indirect ACRE increases the high cloud amount and reduces the low-level cloud amount. The direct ACRE has the opposite effect. It decreases the high-level cloud amount and increases low-level clouds.
The changes in low-level clouds due to indirect and direct ACRE depends on the cloud type and degree of cloud coverage. In the shallow cumulus cloud regimes, both indirect ACRE and direct ACRE decreases the cloud cover. However, the indirect ACRE dominates the reduction of cloud cover.
In cloud regimes within the ITCZ ACRE reduces low-level clouds and relative humidity. Due to large-scale convergent circulation deeper clouds form and the clear radiative cooling signal

of ACRE at the cloud top weakens and extends across a larger vertical area.
In addition, the response of clouds to indirect and direct ACRE was studied in two inversion topped stratocumulus cloud regimes, one stratocumulus deck, and one closed convective stratocumulus case. In both cloud regimes, the total ACRE increases the low-level cloud cover, whereby the direct ACRE plays the dominant role. The indirect ACRE elevates stratocumulus clouds, due to radiative cooling at the cloud top. This increases the height of the inversion and so the MBL. This mechanism spread the water vapor within the MBL over a larger vertical area and saturation is reached at fewer points. As a result, the indirect ACRE reduces the cloud cover. However, the direct ACRE amplifies mesoscale cell convection and the relative humidity in the MBL. As a result the direct ACRE increase the low-level cloud cover. However, it is possible that the techniques used to isolate the direct ACRE overestimates the effect of the direct ACRE on cloud cover. Due to lower low-level clouds, a vertical mismatch arises between the subtracted smoothed ACRE and the ACRE of direct simulation. This can lead to a situation, where the subtracted smoothed ACRE amplifies the direct ACRE instead of counteracting it.

Outlook

This thesis tested the radiative response of clouds in different heights to the energy budget. However, simulations for this study run for two days, whereby only the second day is used to analyze the model results. Due to the short simulation time, the statements in this study are only valid for the specific weather situation during the second simulation day. With such high-resolution and large model domain, the limit of the simulation time of the ICON model is reached. However, with the steady increase in computing power of supercomputers and further development of the ICON model, it will soon be possible to simulate longer periods with such high resolution. More extended simulation periods would increase the statistical significance of the results.
This study showed that with some model code extensions, the ICON model is capable of reading variable fields during the run time of the model without extending the run time impractically. These model code changes and extension were necessary to use the smoothed ACRE fields in the direct and the indirect stimulation. However, some of the results of the direct ACRE simulation overestimates the direct effect. In order to archive more realistic results in the direct ACRE simulation, the smoothed ACRE of the direct simulation should be subtracted from the radiative heating rates instead of the smoothed ACRE of the control simulation. To realize this, I would suggest transferring the current "offline" smoothing process into the ICON model. This has the advantage that the smoothed ACRE matches the radiative heating rates of the particular simulation. However, the implementation of this routine would be quite complex, since the smoothing process has to be done within the unstructured ICON grid. Furthermore, it is uncertain how this process would extend the run time of the model.

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