Master Thesis

The Hadley Circulation in transient CMIP5 Climate Simulations

by

Nicole Albern

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First reviewer: Prof. Dr. Stefan Bühler
Second Reviewer: Dr. Verena Grützun

Studiengang Meteorologie
MIN-Fakultät
Universität Hamburg
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Abstract

The Hadley circulation plays an important role in the context of climate change, because it is the major meridional circulation system that dominates the tropical to subtropical climate. Thus, it has been investigated extensively during the last decades, but fundamental questions remain. In this thesis, two data sets of idealised climate simulations are analysed. These include simulations of the Coupled Model Intercomparison Project Phase 5 (CMIP5) and the Clouds On-Off Klima Intercomparison Experiment (COOKIE). This thesis focuses on the investigation of the representation of the Hadley circulation in the different simulations, the similarities and differences between the models of one ensemble and the response of the Hadley circulation to idealised forcings.

A good agreement between the models is found in the mean representation of the circulation. However, some models exhibit a generally wider and stronger circulation than other models. A robust widening and weakening of the Hadley cells and the descending branches of the circulation are found for an idealised 1% yearly increase of the atmospheric carbon dioxide concentration and for a uniform increase of the sea surface temperature on an aqua-planet. This is consistent with the results of prior studies. At the same time, changes in the ascending branch’s strength and width are found to be more uncertain in these simulations. The investigation of the effect of cloud-radiation interactions on the Hadley circulation reveals large differences in the magnitude of the models’ responses. However, most of the models show stronger Hadley cells, wider and stronger ascending branches and wider descending branches as soon as cloud-radiation interactions are included in the simulations.
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Chapter 1

Introduction

In times of growing public uncertainty about climate change and its influences on daily life, it is becoming ever more important to understand the main factors that control the Earth’s climate. Large scale circulations and the respective changes need to be well understood, if the assessment and prediction of climate change are to be accurate. The Hadley circulation plays an important role in this context, because it is the major meridional circulation system that dominates the tropical to subtropical climate. It affects, for example, winds, humidity, clouds and precipitation as well as energy and mass transports in the tropics.

The Hadley circulation is driven by the differential heating of the Earth’s surface by the sun. As seen in Figure 1.1, it is characterised by ascending warm and moist air near the equator, a poleward flow in the upper troposphere in both hemispheres, a broad region of descending cold and dry air in the subtropics at around 30° latitude and an equatorward flow near the Earth’s surface. The ascending and descending branches of the circulation are associated with convergence and divergence of air masses and thus with high and low pressure systems. High pressure is found in regions of divergent air, namely near the equator at the Earth’s surface and at about 30° latitude at tropopause level. Analogously, low pressure is found in regions of convergent air. These regions are found near the equator at tropopause level and at about 30° latitude at the Earth’s surface.

The position of the ascending branch of the circulation determines the position of the Intertropical Convergence Zone (ITCZ), which is associated with strong convection and heavy rainfall. At the same time, the Earth’s dry zones are found at the latitudes of the descending branches in both hemispheres. These zones are associated with low precipitation rates and high evaporation rates. Thus, the subtropical deserts are found at the latitude of the descending branches of the Hadley circulation. Changes in the Hadley circulation’s position and width directly influence the positions of the dry zones and the ITCZ. In addition, a strengthening or weakening of the circulation might cause stronger or weaker precipitation and drought events. These effects do not only have an impact on the Earth’s climate, but also on socio-economic issues. Shifts of the humid and arid regions and changes in the strength of precipitation and droughts are of great
importance for people who live in these regions. There are also several indirect effects. The Hadley circulation transports heat and momentum flux from the tropics to the subtropics. These two quantities are important for the development of the subtropical jet streams, which are located at the poleward edges of the two Hadley cells at around 200 hPa height (Figure 1.1). These subtropical jet streams influence the eddies and waves at middle and high latitudes. This influences, for example, the mid-latitude storm tracks (e.g. Yin, 2005). Thus, changes in the Hadley circulation indirectly influence the climate at middle and high latitudes.

Due to its importance, the Hadley circulation has been studied extensively during the last decades. Many different methods were developed for its characterisation and a large amount of idealised climate simulations, reanalyses and observations have been investigated in order to gain a better understanding of the Hadley circulation and its changes. Most of these studies find a widening and weakening of the Hadley circulation, especially if General Circulation Models (GCMs) are investigated. Reanalyses, however, tend to predict a strengthening of the Hadley circulation. Mitas and Clement (2005) found a strengthening of the northern hemisphere winter Hadley cell during the last decades. However, they question the robustness of their result, because the trends vary much between the three investigated reanalyses. In a subsequent analysis Mitas and Clement (2006) compared the strengthening trends for the northern hemisphere winter cell of reanalyses to the weakening trends of climate models. In contrast to this, Clement (2006), Lu et al. (2007), Gastineau et al. (2008), Lu et al. (2008), Gastineau et al. (2009), He and Soden (2015) and others find a weakening of the Hadley cells in simple or comprehensive GCMs. He and Soden (2015) explain some of the factors that might cause a weakening of the circulation. They found that the mean weakening of the tropical circulation is dominated by sea surface temperature (SST) forcings which
control the tropical mean hydrological cycle and stratospheric stratification. At the same time, the radiative warming of the atmosphere by direct CO$_2$ forcings was found to play a minor role. This discrepancy between GCMs on the one hand and reanalyses and observations on the other hand has also been stated in the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013).

Many studies suggest possible reasons for the trends of the Hadley circulation’s strength and width. The argumentation in many of these studies is based on the scaling theory by Salmon et al. (2001). This theory assumes that the horizontal extent of the cells is limited by the presence of baroclinic eddies. These eddies occur polewards of the edges of the cells in the subtropics. Based on the theory by Salmon et al. (2001), Frierson et al. (2007) argue, that the static stability of the subtropics increases in a warmer climate due to a moister atmosphere and higher surface temperatures. For this reason, the latitude at which the baroclinic instability, and thus the eddies, are found, is shifted polewards. This results in a widening of the Hadley circulation. A similar argumentation is also found in Yin (2005). The author found that the increase of the dry static stability and changing meridional SST gradients determine the changes in the baroclinicity in the coupled GCMs. Gastineau et al. (2008) base their argumentation on the southern hemisphere winter Hadley cell. They explain the weakening of this cell with an increase of the dry static stability. At the same time, they associate the poleward expansion of the southern hemisphere winter cell with changes in the transient eddies. Another study that uses the argument of an increasing baroclinic stability in the extratropics to explain the widening and weakening of the Hadley cells was published by Lu et al. (2007). They argue that this increase of baroclinic stability is caused by an increased greenhouse gas concentration. An increase of the dry static stability and a weakening of the whole tropical circulation might also be caused by a uniform SST warming (Gastineau et al., 2009). At the same time, Lu et al. (2009) argue that the widening is completely caused by direct radiative forcings, especially due to greenhouse gases and stratospheric ozone depletion. They found no significant influence of SST forcings. This is supported by Polvani and Kushner (2002) who found that the ozone depletion provokes a poleward shift of the subtropical jet streams due to stratospheric cooling. Min and Son (2013) argue that the ozone depletion in the southern hemisphere summer, which causes a widening of the southern Hadley cell, is anthropogenic.

Johanson and Fu (2009) found that the natural variability of the climate system cannot explain the observed widening of the Hadley circulation. They consider several mechanisms that might cause this widening. These include stratospheric cooling, global warming, Pacific and Indian Ocean warming and changes in the phase speed of the baroclinic eddies. Seo et al. (2014) attribute the changes in the strength of the Hadley circulation to three main factors. These are the meridional potential temperature gradient, the gross static stability and the tropopause height. They argue that the last two factors mainly influence the width of the Hadley cells, whereas the first factor influences the strength of the circulation during December, January and February as well as during June, July and August.
In addition to the influence of the increase of the static stability of the subtropical and mid-latitude troposphere, Lu et al. (2008) detected an influence of a strengthening of the mid-latitude wind at the upper troposphere or lower stratosphere, which is due to an increase in the meridional temperature gradient in the upper troposphere caused by tropospheric warming. According to Lu et al. (2008) this might result in a more poleward located eddy-driven circulation. In addition, they find that the edges of the Hadley cells are located more poleward if the tropopause height increases. The latter was also found by Seidel and Randel (2007).

This recapitulation of the results of prior studies indicates that different approaches detect different changes of the Hadley circulation and offer various explanations. Depending on the data sets, even the sign of the strength’s changes is unsure. In addition, the magnitudes of the trends are strongly dependent on the applied methods and investigated data sets. This suggests that the reasons for the determined changes are not fully understood, yet. Thus, more comprehensive investigations are needed to better understand the complex Hadley circulation and to explain its changes in a warming climate.

This thesis aims at a better understanding of the representation of the Hadley circulation in idealised climate simulations and at the quantification of the circulation’s response to a 1% yearly increase of the atmospheric carbon dioxide concentration. The investigated simulations are part of the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012). The two Hadley cells and the branches of the circulation are analysed individually. The changes of the width and strength of the cells and branches are investigated particularly with regard to a widening and weakening of the Hadley cells and the descending branches as well as a narrowing and strengthening of the ascending branch. Another focus of this thesis lays on the identification of the effect of a temperature increase and of cloud-radiation interactions on the Hadley circulation. This investigation is based on idealised aqua-planet simulations of the Clouds On-Off Klimate Intercomparison Experiment (COOKIE) (Stevens et al., 2012).

Different methods that facilitate the quantification of the Hadley circulation are introduced in chapter 2. In chapter 3 the experiment design of the idealised CMIP5 simulations is described and the participating models are introduced. The investigation of the simulations is divided into two main parts. First, the representation of the Hadley circulation in climate models is analysed. This analysis is based on the MPI-ESM-MR model, which is part of the CMIP5 ensemble. Second, similarities and discrepancies between the models of the ensemble are investigated and the responses to the idealised forcing are quantified. Chapter 4 comprises three main parts. First, the different simulations of COOKIE are explained and the participating models are introduced. The methods, which are presented in chapter 2 have to be adjusted for the investigation of the Hadley circulation on an aqua-planet. These adjustments are depicted in the second part of chapter 4. The results of the investigation are presented in the third part of this chapter and discussed in the last part. Finally, concluding remarks and an outlook on possible next steps of the investigation of the Hadley circulation are given in chapter 5.
Chapter 2

Methods to quantify the Hadley circulation

During the last decades, the Hadley circulation has been studied extensively. Many methods were developed for its characterisation. Some of the most commonly used methods and some methods that are especially developed for this thesis will be described in this chapter. A couple of these methods are applied as part of this thesis, others are described to give a more detailed overview. Reasons for applying and discarding certain methods will be given in the following chapter. The development of the methods is based on the CMIP5 ensemble (section 3.1), especially on the MPI-ESM-MR model.

2.1 Meridional mass stream function $\psi$

The meridional mass stream function $\psi$ is a common measure to calculate several indices that are used to describe and quantify the Hadley circulation. These comprise the horizontal extent, width and strength of the northern and southern Hadley cells. Several studies analysed at least one of these indices. As stated by Davis and Rosenlof (2012), the investigation of the Hadley circulation is based on physically meaningful occurrences of the mass stream function. These include the maximum, minimum and zero isolines of $\psi$.

The monthly zonal-mean meridional mass stream function $\psi$ is defined as the downward integrated monthly-mean zonal-mean meridional velocity $v$:

$$\psi(p, \varphi) = \frac{2\pi a \cos(\varphi)}{g} \int_p^{p_s} v \, dp,$$

(2.1)

with the latitude $\varphi$, the pressure $p$, the surface pressure $p_s$, the average radius of the Earth $a$, and the gravitational acceleration $g$. It is computed from the monthly zonal-mean horizontal velocity $v$ using CDO commands (for documentation see Max-Planck-Institute for Meteorology, 2016). The mass stream function is a function of time, pressure and latitude. It is an indicator of the mean meridional circulation of the atmosphere in kg s$^{-1}$. Thus, it can be used to describe the Hadley circulation in a
Methods to quantify the Hadley circulation

latitude-height plane. This has been widely used (e.g. Hu and Fu, 2007; Lu et al., 2007; Gastineau et al., 2008; Johanson and Fu, 2009; Son et al., 2009; Min and Son, 2013). Positive values of the mass stream function denote a clockwise rotation of air parcels, whereas negative values indicate an anticlockwise movement. The former is associated with the northern Hadley cell, the latter with the southern Hadley cell. The tighter the streamlines of the mass stream function are, the stronger the vertical and meridional horizontal velocities.

In this thesis, the outer edges of the Hadley cells are defined as the latitude poleward of the ascending branch where the mass stream function at 500 hPa, $\psi_{500}$, equals $0 \text{ kg s}^{-1}$, using linear interpolation to account for the grid. This popular measure was successfully used by Frierson et al. (2007), Lu et al. (2007), Lu et al. (2008), Gastineau et al. (2008), and Min and Son (2013) to study the horizontal extent and width of the Hadley cells, for example. Stachnik and Schumacher (2011) used the average value of $\psi$ within the pressure range of 400-700 hPa. Johanson and Fu (2009) and Nguyen et al. (2013) searched for the zero crossing of the mass stream function between 400-600 hPa. All three pressure ranges were investigated in this thesis. The positions of the outer edges of the Hadley cells are very similar for all of them. It was decided to use $\psi_{500}$, because this pressure level is used most frequently in previous studies. The results of this thesis are therefore easier to compare to the results of similar studies that, for example, used other data sets.

Figure 2.1 shows the latitude-height cross section of the mass stream function as a mean over all 140 simulated years of the MPI-ESM-MR model (upper panel). The values of the mass stream function at 500 hPa, $\psi_{500}$, are depicted in the lower panel. This corresponds to the green line in the upper panel of Figure 2.1. The mass stream function at 500 hPa crosses $0 \text{ kg s}^{-1}$ at three latitudes between 50°S and 50°N (red vertical lines in Figure 2.1), if both Hadley cells are well developed. The outer zero crossings correspond to the extratropical edges of the two Hadley cells and the middle zero crossing marks the intersection between the northern and southern Hadley cells. The former are associated with the descending branches of the cells, whereas the latter is associated with the ascending branch of the cells.

In order to determine the latitudes of the two zero crossings poleward of the ascending branch, the latitude of the ascending branch needs to be determined first. This corresponds to the zero crossing that is the closest to the equator. If this isoline is identified, the two zero crossings northwards and southwards of the isoline are set as the outer edges of the cells.

The algorithm that detects the positions of the zero crossings of the mass stream function at 500 hPa does not work properly if at least one of the two cells is not well developed. This is predominantly the case for the northern Hadley cell. It is weakly developed during some months, especially in boreal summer. During these months, the northernmost zero crossing is located in the mid-latitudes and cannot be attributed to the Hadley circulation. Figure 2.2 shows the June of the 90th simulated year of the MPI-ESM-MR model. This month exhibits almost no northern Hadley cell. The dashed lines...
2.1 Meridional mass stream function $\psi$

Figure 2.1: Latitude-height cross section of the mass stream function $\psi$ in $10^9$ kg s$^{-1}$ as a mean over all 140 simulated years of the MPI-ESM-MR model (upper panel). The lower panel shows the mass stream function at 500 hPa, $\psi_{500}$, which corresponds to the green line in the upper panel. The vertical red lines mark the latitudes of 50°N and 50°S. The red horizontal line in the lower panel marks the $\psi_{500}$ zero isoline.

in the upper panel correspond to the southern Hadley cell. The mass stream function at 500 hPa shows no zero crossing in the northern tropical to subtropical latitudes (lower panel). Thus, the algorithm would detect the next zero crossing that is already located in the mid-latitudes at about 55°N. Therefore, it is necessary to set a threshold for the maximum distance between two zero crossings. The distance must not exceed 60°. This is approximately the theoretical width of the total Hadley cell and thus a very conservative threshold for the maximum width of one cell. In addition, some thresholds for the positions of the three zero crossings need to be defined. The values that should not be exceeded are identified by analysing the time series of the positions of the three zero crossings for all models. Figure 2.3 shows the time series of the positions of the three zero crossings of the mass stream function at 500 hPa for all 28 models that are part of the CMIP5 ensemble. It appears that some models exhibit more northward or southward located zero crossings than others, though the positions of the three zero crossings are clearly separable from each other. Thus, it is easily possible to define thresholds for the positions of the three zero crossings. These thresholds are summarised in Table 2.1 and correspond to the axis limits of the vertical axes in Figure 2.3.

The widths of the northern and southern Hadley cells are defined as the distance between the prior calculated zero crossings of $\psi_{500}$. The distance between the southernmost zero crossing and the middle zero crossing is set as the width of the southern Hadley cell. The width of the northern Hadley cell is defined analogously as the distance between the middle and northernmost zero crossings. The distance between the two
Figure 2.2: Same as Figure 2.1, but for the June of the 90th simulated year of the MPI-ESM-MR model.

Figure 2.3: Time series of the position of the zero crossings of $\psi_{500}$ for all 28 models of the CMIP5 ensemble. The limits of the y-axis correspond to the thresholds given in Table 2.1.

Table 2.1: Thresholds for the positions of the $\psi_{500}$ zero crossings.

<table>
<thead>
<tr>
<th>Zero isoline</th>
<th>Minimum latitude [°]</th>
<th>Maximum latitude [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southernmost zero is</td>
<td>-45</td>
<td>-20</td>
</tr>
<tr>
<td>Middle zero isolone</td>
<td>-25</td>
<td>35</td>
</tr>
<tr>
<td>Northernmost zero isol</td>
<td>10</td>
<td>50</td>
</tr>
</tbody>
</table>
outer zero crossings is regarded as the width of the total Hadley cell.

According to Oort and Yienger (1996) the strength of the northern Hadley cell can be specified as the maximum value of the mass stream function between the equator and 30°N. The strength of the southern Hadley cell can analogously be defined by the minimum value of the mass stream function between 30°S and the equator. This established measure was successfully used in many publications to study trends in the strength of the Hadley circulation (e.g. Quan et al., 2004; Mitas and Clement, 2005; Caballero, 2007). Nguyen et al. (2013) want to avoid possible disturbances at the surface and at the top of the atmosphere. Thus, they look at the vertically averaged maximum value of the mass stream function for the height interval between 900-200 hPa. Stachnik and Schumacher (2011) considered only the maximum value of the stream function for heights above 800 hPa, because they want to avoid low-level features near the edges of the cells.

Following these adjustments, the strength of the northern Hadley cell is defined as the maximum value of the mass stream function between the equator and 30°N within the pressure levels of 850-200 hPa, in this thesis. The southern cell is defined analogously as the minimum value of the mass stream function between 30°S and the equator within the same pressure levels. The vertical limits were defined by analysing the pressure levels at which the maximum and minimum values of the mass stream function occur. It was found that these extrema are located between 850 hPa and 250 hPa. As the maximum and the minimum values of the mass stream function do not occur at the upper and lower edges of the cells, the strengths of the cells are not affected by the vertical thresholds of 850 hPa and 200 hPa. The height of the maximum and minimum values of $\psi$ might be shifted with time. Thus it is not advantageous to define a distinct vertical level for which the maximum and minimum values are determined. In this way, it would be possible that the maximum and minimum values are shifted in this distinct pressure level or are shifted out of it. This would lead to a bias in the strength of the Hadley cells and the calculated trend.

In this thesis, the two Hadley cells are considered both separately and together. It is necessary to not only look at the total Hadley cell, because the two hemispheres behave very differently. This is partly due to the land-sea distribution. Additionally, the strong seasonal cycle and interannual variability of the Hadley circulation play important roles. This is for example argued by Nguyen et al. (2013) who use reanalysis data sets. In addition, information about the ascending branch gets lost if only the total Hadley cell is considered.

### 2.2 Horizontal $u$-velocity

Another variable that can be used to characterise the Hadley circulation is the zonal-mean zonal velocity $u$. Positive values of this horizontal velocity indicate westerly winds, negative values indicate easterly winds. The positive maximum values of this quantity are located in the subtropics at around 200 hPa and mark the position of the subtropical
jet streams. The horizontal $u$-velocity delivers information about the strength and the position of the jet streams. It is possible to investigate whether the jets are shifted northwards or southwards and whether they intensify or become weaker during climate change. These changes can be correlated to the change of the Hadley circulation. In addition, the subtropical jets are located at the poleward edges of the Hadley cells. Thus, the distance between the northern hemisphere subtropical jet and the southern hemisphere subtropical jet is a proxy of the horizontal extent of the Hadley circulation. This has been done by Fu et al. (2006), for example. They identified that a reshaping of the upper tropospheric pressure surfaces results in a poleward shift of the jet streams and thus in a widening of the tropical circulation. This is consistent with the results of Hu and Fu (2007), who also analysed the position of the subtropical jet streams.

Figure 2.4 shows the latitude-height cross section of the zonal-mean $u$-velocity com-

![Figure 2.4](image-url)

Figure 2.4: Latitude-height cross section of the zonal-mean $u$-velocity (colors) compared to the zonal-mean mass stream function $\psi$ (contours) for the solstice seasons (upper and middle panel) and for the mean over all time steps (lower panel) of the MPI-ESM-MR model. Positive values indicate westerlies, negative values easterlies.
pared to the zonal-mean mass stream function $\psi$ for the solstice seasons (upper and middle panel) and for the mean over all simulated time steps of the MPI-ESM-MR (lower panel). The jet streams are represented by the darkest blue shapes. It is obvious that the jets in the winter hemisphere are more pronounced than the jets in the summer hemisphere (Figure 2.4, upper two panels). The average over all time steps indicates that the southern hemisphere subtropical jet is developed slightly stronger than the northern hemisphere jet stream (Figure 2.4, lower panel). In both hemispheres and during all seasons, the maximum values of the two jet streams are located close to the zero crossings of the mass stream function, which mark the poleward edges of the Hadley cells. This shows that the $u$-velocity does not deliver additional information about the horizontal extent of the Hadley circulation compared to the mass stream function. Thus, it will not be further used in this thesis.

## 2.3 Divergence $D$

The rising and sinking motion that is part of the Hadley circulation is strongly linked to convergence and divergence of air masses (Figure 1.1). The divergence field $D$ is defined as the spatial derivative of the horizontal wind field:

$$D = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}, \quad (2.2)$$

with the zonal velocity $u$ and the meridional velocity $v$. The divergence field is computed from monthly horizontal $u$- and $v$-velocities using CDO commands (for documentation see Max-Planck-Institute for Meteorology, 2016). It is available for each time step and each grid point.

The stream lines of the mass stream function suggest that the convergent and divergent areas are located near the ground and at about 200 hPa (Figure 2.1). Nonetheless, the divergence field was analysed for each height level that is resolved by the MPI-ESM-MR model. The analysis reveals that the idealised picture of zonally symmetric divergent and convergent areas does not correspond to the model simulations. For example, the influence of the orography is noticeable near the ground at 950 hPa (Figure 2.5, lower panel). The continents, especially the mountains, are clearly visible in this height level. This shows that the ground effect is too large to be able to use the divergence field at 950 hPa to analyse the Hadley circulation. The wavelike structures in Figure 2.5 are possibly an artefact of the calculations and should not occur. They are probably due to the fact that the model simulations are performed in the spectral space. Afterwards the results are transformed into grid space. However, the distribution of the divergent and convergent areas are plausible.

The divergence field at 200 hPa exhibits distinct convergent and divergent areas (Figure 2.5, upper panel). They correspond approximately to the expectations. As they are not zonally symmetric, it is not possible to deduce information about the horizontal extent of the Hadley circulation from them. The analysis of the divergence field at
2.4 Velocity potential $\chi$

For each irrotational flow, a scalar potential can be defined, such that the horizontal velocity of the flow equals the negative gradient of the potential. Using the horizontal wind field $V_h$, the potential is called the velocity potential $\chi$. As the divergence field $D$ (section 2.3) is defined as the horizontal gradient of the horizontal wind field, the velocity potential is also associated with the divergence field:

$$D = \nabla_h \cdot V_h = -\nabla^2 \chi.$$  (2.3)
Using the definition with the minus sign, the divergent wind flows from the maximum to the minimum of the velocity potential field (Tanaka et al., 2004). Many studies investigate the velocity potential at 200 hPa, $\chi_{200}$, with regard to the strength of the Hadley circulation and reveal similar results for different data sets (e.g. Krishnamurti, 1971; Tanaka et al., 2004; Gastineau et al., 2009; Shin et al., 2012; Viswambharan and Mohanakumar, 2014). Negative values of $\chi_{200}$ indicate large-scale upper-tropospheric convergence, positive values indicate large-scale upper-tropospheric divergence. The first is associated with the descending branch of the Hadley circulation whereas the latter is associated with the ascending branch near the equator.

One of the first who used the velocity potential to investigate tropical circulations was Krishnamurti (1971). The author detected that the time mean of the velocity potential represents vertical circulations well and that it can be used to analyse east-west circulations like the Walker circulation. Tanaka et al. (2004) developed new methods to separate the Hadley, Walker and monsoon circulations and to investigate the interannual variability of these tropical circulations quantitatively. In their analysis, they consider the Hadley circulation as the zonal mean of the velocity potential. The Walker and monsoon circulations are represented by the deviations from the zonal mean. Tanaka et al. (2004) study the intensities of these circulations by analysing peaks in the velocity potential field at 200 hPa. As they use reanalysis data sets for their study, Tanaka et al. (2004) point out that the peak value in the northern hemisphere might be more representative for the analysis due to poor data quality in the southern hemisphere. They define a Hadley circulation index HI$_{\chi}$ for the strength of the Hadley circulation. During January the Hadley circulation index corresponds to the negative peak value of $\chi_{200}$ in the northern hemisphere. In July the index is associated with the positive peak value of $\chi_{200}$ in the northern hemisphere. Figure 2.6 shows the values of the zonal-mean velocity potential at 200 hPa, $\chi_{200}$, as a mean over all Januays (upper panel) and all Julys (lower panel) of the MPI-ESM-MR model. The peaks in the northern hemisphere that are indicated by the red arrows, are clearly observable.

The method by Tanaka et al. (2004) was applied in several other studies. For example, Shin et al. (2012) investigate the area of arid regions and the strength of the Hadley circulation during the second half of the twentieth century. Others analyse the seasonal impact of the Southern Annular Mode on the Hadley and Walker circulations (Viswambharan and Mohanakumar, 2014). Gastineau et al. (2009) analyse the connection between the sea surface temperature change and the distribution of precipitation which is associated with the large-scale circulation. They use the definition by Tanaka et al. (2004) to investigate the location of changes in the large-scale atmospheric circulation. They argue that the analysis of the Hadley circulation index based on the velocity potential allows to validate the changes in the Hadley circulation that are found using the meridional stream function. They find out that the results of the two indices are qualitatively consistent. However, the Hadley circulation index based on the velocity potential delivers stronger changes than the index based on the meridional stream function (Gastineau et al., 2009).
Methods to quantify the Hadley circulation

In this thesis, idealised climate simulations are investigated instead of reanalysis data sets. For this reason, the same data quality is available for both hemispheres. Thus, the Hadley cell index based on the velocity potential is calculated from the peak value of the velocity potential at 200 hPa for both the northern and the southern hemisphere for all Januarys and all Julys. For the northern hemisphere the minimum (maximum) value of $\chi_{200}$ was derived for all Januarys (Julys) between 0° and 40°N (0° and 30°N). In the southern hemisphere the maximum (minimum) value of $\chi_{200}$ was calculated for all Januarys (Julys) between 30°S and 0° (40°S and 0°) (Figure 2.6).

Figure 2.7 shows the time series for all 140 Januarys (upper panel) and Julys (lower panel) of the Hadley cell index that is based on the velocity potential $HI_{\chi}$ and the Hadley cell index that is based on the mass stream function $HI_{\psi}$. The latter corresponds to the strength of the northern and southern Hadley cells. The calculation of the strength of the two Hadley cells based on $\psi$ is described in section 2.1. The absolute value of $HI_{\psi}$ is significantly different for the two hemispheres both in January and in July. The absolute value of $HI_{\chi}$ is similar for the two hemispheres. However, the Hadley cell in the winter hemisphere is stronger than the cell in the summer hemisphere for both indices. The time series of the winter hemispheres show larger interannual variability than the time series of the summer hemispheres for $HI_{\psi}$. For $HI_{\chi}$ the interannual variability is similar for both hemispheres and months.

The method by Tanaka et al. (2004) does not take into account that the Hadley cell is expected to expand through climate change. This does not only include a horizontal
expansion, but also an increase in the height of the tropopause and thus a vertical expansion of the Hadley cell (e.g. Santer et al., 2003). This change is attended by a vertical shift of the convergence and divergence regions, such that these regions are no longer located in the 200 hPa level. This results in a bias in the Hadley cell index that is based on the velocity potential. Apart from that, the velocity potential at 200 hPa only delivers information about the strength of the Hadley circulation. It cannot be used to determine the extent of the Hadley circulation or the width and strength of the ascending and descending branches of the circulation. Tanaka et al. (2004) pointed out that the peak in the velocity potential at 200 hPa must not coincide with the core of the upward or downward motion. On this account and to be consistent within the analysis of the Hadley circulation change, it was decided to use the Hadley cell index based on the mass stream function instead of $HI_\chi$ for the further steps of the investigation.

### 2.5 Tropopause height

The width of the tropical belt cannot only be determined by applying the methods described above. There are other variables that can be used. For example, Seidel and Randel (2007) define the edges of the tropical belt using the tropopause height. They count the days per year for which the tropopause height exceeds 15 km at each latitude. The latitudes at which the amount of days per year is greater than 300, 200 or 100 days, are set as the edge of the tropical belt. Seidel and Randel (2007) argue that the determination of the edges of the tropical belt using the tropopause height...
is possible, because the probability density function of the tropopause height shows a bimodal distribution in the subtropics. They associate the first mode, which shows tropopause heights greater than 15 km, with tropical conditions and the second mode with tropopause heights lower than 13 km with subtropical conditions.

Depending on the number of days per year for which the tropical tropopause height must be exceeded, Seidel and Randel (2007) get different widths of the tropical belt. These range from 43° latitude (300 days per year), over 57° latitude (200 days per year) to 66° latitude (100 days per year). In their study, they focus on the frequency threshold of 300 days per year. Compared to the results of the mass stream function which reveals widths of 50°-70° latitude the width of the tropical belt is too small (see section 2.1 and section 3.2.2, for example). The relatively large range is due to the large annual cycle of the Hadley circulation.

Lu et al. (2009) use the same method as Seidel and Randel (2007) to analyse the width of the tropical belt with the help of reanalysis data sets and general circulation models. They use a tropopause height threshold of 120 hPa which corresponds to heights larger than 15 km. As a frequency threshold Lu et al. (2009) use 200 days per year. Using these thresholds they get similar results as Seidel and Randel (2007) for the reanalysis data sets they use.

Birner (2010) criticises the approaches made by Seidel and Randel (2007) and Lu et al. (2009), because two more or less arbitrary thresholds have to be defined. One threshold is needed for the tropopause height and another one for the number of days per year for which this height is exceeded (frequency of occurrence). Birner (2010) analysed the sensitivity of the widening trend that was reported by Seidel and Randel (2007) with regard to the chosen thresholds and the data sets. The author detected that the reanalysis data set that was used by Seidel and Randel (2007) shows strong sensitivities of the widening trend. Moreover, he identified that the tropopause height threshold of 15 km that was chosen by Seidel and Randel (2007) and Lu et al. (2009) is very sensitive to changes. Even small changes of the threshold cause large changes in the width of the tropical belt.

Birner (2010) developed objective criteria to calculate the width of the tropical belt. These criteria are based on hemispheric statistics of the tropopause height. Applying these new methods, the tropopause height threshold can be a function of time, hemisphere and data set. In the prior studies by Seidel and Randel (2007) and Lu et al. (2009) the tropopause height threshold was only a function of longitude, which is less adaptable to different data sets.

Although the tropopause height is a function of time and thus able to adjust for seasonal, interannual and long-term changes, Birner (2010) states that the different reanalysis data sets reveal very different long-term trends for the width of the tropical belt. Some of them are positive, some are insignificant and some are even negative. Nevertheless, the seasonal and interannual variations of the edges of the tropical belt seem to be robust among the different reanalysis data sets.

As this thesis focuses on long-term trends, it was decided not to use the tropopause
2.6 Vertical pressure velocity $\omega$

The meridional mass stream function delivers indirect information about the width and strength of the ascending and descending branches of the Hadley cells by looking at the values and the tightness of the stream lines, though this method is not very accurate. Other variables need to be analysed to quantify these characteristics of the Hadley circulation in detail. The vertical pressure velocity $\omega$ is one of the variables that can be used. It describes the Lagrangian tendency of air pressure in Pa s$^{-1}$ or hPa day$^{-1}$. Thus, it is the derivative of air pressure $p$ with respect to time $t$:

$$\omega = \frac{dp}{dt}. \quad (2.4)$$

In the $p$-system, where height is described by air pressure, $\omega$ represents the vertical component of air velocity. Downward motion corresponds to a positive tendency of air pressure, whereas upward motion is associated with a negative tendency. In the analysed data set, the vertical pressure velocity is defined for each time step and each grid point. For the analysis of the width and strength of the Hadley cells’ branches, the vertical pressure velocity needs to be averaged zonally. Thus, it becomes a function of time, latitude and height.

The detection of the edges of the ascending and descending branches of the two Hadley cells is similar to the detection of the edges of the Hadley cells using the meridional mass stream function. Instead of $\psi_{500}$ the vertical pressure velocity at 500 hPa, $\omega_{500}$, is used. The edges of the branches are defined as the latitudes at which $\omega_{500}$ equals 0 hPa day$^{-1}$, using linear interpolation to account for the grid. Figure 2.8 shows the latitude-height cross section of the mass stream function in contours and the zonally averaged vertical pressure velocity in colours (upper panel). Especially in the tropics it is obvious that the strongest upward and downward motions are located at the edges of the Hadley cells. This corresponds to the narrowest stream lines of the mass stream function. Similar to Figure 2.1, the value domain of the vertical pressure velocity at 500 hPa, $\omega_{500}$, is illustrated in the lower panel of Figure 2.8. The values correspond to the values that are reached at the green line in the upper panel. The edges of the ascending and descending branches of the Hadley circulation are denoted from South to North as “A”, “B”, “C” and “D”. For example, the southern edge of the ascending branch is by definition the northern edge of the southern descending branch (denoted as
Figure 2.8: Latitude-height cross section of the mass stream function $\psi$ in $10^9 \text{kg s}^{-1}$ (contours) and the vertical pressure velocity $\omega$ (colours) as a mean over all 140 simulated years of the MPI-ESM-MR model (upper panel). The lower panel shows the vertical pressure velocity at 500 hPa, $\omega_{500}$, which corresponds to the green line in the upper panel. The vertical red lines mark the latitudes of 50°N and 50°S. Blue colours correspond to a downward motion, red colours to an upward motion. The edges of the branches are marked from South to North as “A”, “B”, “C” and “D”.

“B” in Figure 2.8). For the meanings of “A”, “B”, “C” and “D” see Table 2.2.

The first step in the analysis of the edges of the branches is the detection of the ascending branch. For this, the latitude of the minimum value of $\omega_{500}$ is searched for in a latitude area of 50°S to 50°N (red vertical lines in Figure 2.8). The limitation of the latitude area is necessary to avoid the detection of possible strong updrafts at higher latitudes. The latitudes of the two zero crossings that are the closest ones to the latitude of the minimum value of $\omega_{500}$ are set as the edges of the ascending branch of the Hadley circulation, denoted as “B” and “C”. The northern edge of the ascending branch is by definition also the southern edge of the northern descending branch (denoted as “C” in Figure 2.8). Thus, only the northern edge of this descending branch is missing as soon as the edges of the ascending branch are detected. The latitude of the zero crossing northwards of “C” is set as the northern edge of the northern descending branch (denoted as “D”). If the northern Hadley cell is developed weakly, no zero crossing can be found northwards of “C” that still lies in the considered latitude area. Then “D” is set to a missing value. This happens predominantly during boreal summer. The southern edge of the southern descending branch, denoted as “A”, is treated analogously. It is set as the latitude of the zero crossing southwards of “B”. Thresholds for the positions of the four zero crossings of $\omega_{500}$ must be defined. Similar to the thresholds for the $\psi_{500}$ zero crossings, the thresholds are assessed by looking at the time series for the latitude
Table 2.2: Thresholds for the positions of the $\omega_{500}$ zero crossings.

<table>
<thead>
<tr>
<th></th>
<th>Minimum latitude [°]</th>
<th>Maximum latitude [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Southern edge of SH descending</td>
<td>-60</td>
</tr>
<tr>
<td>B</td>
<td>Southern edge of ascending / Northern edge of SH descending</td>
<td>-35</td>
</tr>
<tr>
<td>C</td>
<td>Southern edge of NH descending / Northern edge of ascending</td>
<td>-10</td>
</tr>
<tr>
<td>D</td>
<td>Northern edge of NH descending</td>
<td>10</td>
</tr>
</tbody>
</table>

of the four zero crossings for all models. Table 2.2 summarises the applied thresholds.

The width of each of the three branches is defined as the distance between the zero crossings, similar to the width of the Hadley cells. However, the algorithm is not applicable to every single month of the 28 models, especially if the branches are not shaped as expected. For example, areas of weakly descending air might occur in the ascending branch or areas of weakly ascending air in a descending branch of the circulation. This happens during the December of the 69th simulated year of the MPI-ESM-MR model, amongst others (Figure 2.9). Slightly north of the equator, a weak updraft and a weak downdraft are visible, especially in the lower panel, which shows the values of $\omega_{500}$. To eliminate most of these weak updrafts and downdrafts, a running mean over seven latitude grid points is calculated. Only the strongest of the weak up- and downdrafts remain by using the running mean. The new $\omega_{500}$ time series is applied to the above described calculation of the zero crossings of the vertical pressure velocity and used for the further steps of the study.

By analysing the results of the running mean over one to 16 latitude grid points, it was determined over how many grid points the running mean should be calculated to remove most of the weak up- and downdrafts and, at the same time, to influence the width of the branches as little as possible. The number of grid points is hereafter referred to as “windowsize”. As a first step, a linear regression was calculated for the time series of the width of each branch. Afterwards, the standard deviation between the time series and the linear regression was determined. This method returned varying windowsizes for which the standard deviation was least. As this result was not satisfying, it was decided to try another approach. For this approach the amount of detected zero crossings between 50°S and 50°N, 55°S and 55°N, and 60°S and 60°N, was analysed depending on the windowsize that was used for the running mean. The aim was to find the windowsize for which the amount of zero crossings in the considered latitude area was the closest to four, because the three branches of the Hadley circulation ideally exhibit four zero crossings. The frequency distribution of the zero crossings showed the best result for a windowsize of 7 for all three latitude areas. Thus, it was decided to use the running mean over 7 latitude grid points for further analysis.

The analysis of the time series of the branches’ widths for all models reveals that the northern descending branch is much too small for some months and models. Several methods were tried to find an appropriate threshold for the minimum width of the
northern descending branch of the Hadley circulation. Finally, the mean minus two times the standard deviation was calculated for each month. In order to get a statistically significant result, the size of the sample was maximised by calculating the value for all 28 models and 140 time steps that are available for each month. In this way, a mean annual cycle is obtained (Fig. 2.10). The largest values are reached during boreal winter, when the northern descending branch is strongly developed. The mean width and standard deviation decrease during boreal spring, reach their minimum during mid of boreal summer, and start to increase again during boreal fall. As the data is nearly normally distributed, approximately 2.28% of the time steps for each month show a width that is smaller than the calculated value.

All small peaks in the time series of the width of the northern descending branch occur in July and August when the branch is weakly developed. For this reason, it was decided to use the minimum value of 7.25°, which occurs during July, as threshold for the minimum width of this descending branch. The two northernmost zero crossings of $\omega_{500}$ are set to missing values for all months, for which the distance between the two northernmost zero crossings of $\omega_{500}$ is smaller than this threshold. This results in a not defined width of the northern descending branch and the ascending branch for these months. The width of the ascending branch is also set to missing value, because a too small descending branch might indicate a too large ascending branch.

The ascending branch and the southern descending branch also exhibit peaks in the time series of the width of the branches for some time steps and models. The influence of these peaks on the trends that are calculated from the time series was examined as part of the thesis. The trends were calculated for the time series that contain the
peaks for all models. Afterwards the peaks were removed and the trends were computed again. The comparison of the two trends revealed that the removal of the peaks hardly influences the trends. This is probably due to the fact that these peaks are very rare compared to the peaks in the northern descending branch. They had influenced the trends and were thus removed for the further analysis of the time series. The peaks in the ascending branch and the southern descending branch were not removed, because they do not influence the results significantly.

Finally, the strength of the updrafts and downdrafts needs to be determined. It is defined analogously to the strength of the two Hadley cells. The strength of the updraft is set as the minimum value of the vertical pressure velocity between the prior calculated zero crossings of the upwelling air near the equator, considering the pressure levels of 850-200 hPa. The strength of each of the two downdrafts is set as the maximum value of the vertical pressure velocity within the zero crossings of the downward motion areas for the same pressure levels. Similar to the analysis of the strength of the two Hadley cells (section 2.1), the vertical positions of the extrema of \( \omega \) were analysed. It turned out that the extrema occur at heights between 925 hPa and 250 hPa. However, the low heights are very rare. Thus, the detection of the strengths of the branches is not influenced by the thresholds.

To sum up, six methods were introduced in this chapter. Two of the six methods are further used in this thesis to investigate the Hadley circulation. These two methods are referred to as \( \psi \)-approach and as \( \omega \)-approach. The \( \psi \)-approach uses the mass stream function to investigate the position of the zero crossings of \( \psi_{500} \) as well as the width and strength of the two Hadley cells. The \( \omega \)-approach uses analogous characteristics of the vertical pressure velocity to analyse the position, width and strength of the branches of the Hadley circulation. Thus, six different quantities are investigated in total. In this thesis, these quantities are named “indices” of the Hadley circulation or “Hadley-indices”. Note that the positions of the zero crossings of \( \psi_{500} \) and \( \omega_{500} \) are also referred to as “edges” of the cells and branches, respectively. The other four methods are not further used in this thesis, because they were found to be not suitable to describe the Hadley
circulation properly (divergence) or because they deliver similar information about the characteristics of the Hadley circulation as the mass stream function and the vertical pressure velocity (horizontal $u$-velocity, velocity potential, tropopause height).
Chapter 3

Coupled Model Intercomparison Project Phase 5 (CMIP5)

In this chapter, the representation of the Hadley circulation in transient climate simulations is investigated. For this, idealised simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5) are analysed. In the first part of the chapter, section 3.1, the experiment design of the idealised experiment and the participating models are introduced. The second part, section 3.2, aims at the understanding of the representation of the Hadley circulation in climate models. For this reason, the Hadley circulation of the MPI-ESM-MR model is analysed in detail. Similarities and differences in the representation of the Hadley circulation in the CMIP5 ensemble and the responses to an idealised forcing are analysed in section 3.3. This section aims, amongst others, at the identification of robust responses of the Hadley circulations of the model ensemble to the idealised forcing.

3.1 Data

The Coupled Model Intercomparison Project (CMIP) was initiated to analyse and compare the model output from coupled ocean-atmosphere-cryosphere-land General Circulation Models (GCMs) to widen the knowledge of climate variability and climate change (Meehl et al., 2000; Taylor et al., 2012). This is facilitated by establishing an understanding of the processes that determine the climate system (Meehl et al., 2005). These processes can be understood by analysing the response of the climate system to idealised forcings. Building upon earlier phases of CMIP, the first model output of the Coupled Model Intercomparison Project Phase 5, CMIP5, was available in 2011. This phase contributed mainly to the IPCC AR5, which was published in 2013 (IPCC, 2013).

Taylor et al. (2009) and Taylor et al. (2012) summarise the experiment design of CMIP5. Taylor et al. (2012) outline three main aims of this CMIP phase. These include the estimation of mechanisms that cause differences in the model output, especially due to feedbacks and processes that are not well understood yet. Additionally, the accuracy of climate predictions is examined. For this, special attention is given to
decadal predictions of forecast systems. The third main aim is to determine reasons for
the different behaviour of similarly forced climate models. These objectives are reached
by performing a broader set of experiments with models with a higher spatial resolution.

More than 20 modelling groups are taking part in CMIP5, using more than 50
models (Taylor et al., 2012). Most of the simulations are performed with atmosphere-
ocean global climate models (AOGCMs), as in the earlier CMIP phases. It is possible to
customise the models such that they are coupled to biogeochemical components, which
can then be associated with a carbon cycle model. These newly added models are called
Earth System Models (ESMs).

CMIP5 is the first CMIP phase which contains two different types of climate change
experiments. These include long-term simulations and newly added near-term climate
predictions. The latter are also referred to as decadal prediction experiments (Taylor
et al., 2012). The long-term and near-term simulations are further divided into a “core”
set of experiments and “tier” experiments. Due to the large number of simulations, the
modelling groups are expected to perform the “core” simulations, whereas the “tier”
experiments are optional. The “core” of the long-term experiments includes runs of the
Atmosphere Model Intercomparison Project (AMIP) (Gates, 1992), a control run and
a historical twentieth-century simulation. Additionally, there are projection simulations
with prescribed emissions and diagnostic experiments with idealised forcings (Taylor
et al., 2009). The two “tiers” include more specialised experiments that aim at under-
standing specific aspects of the climate system and climate change (Taylor et al., 2012).
Detailed descriptions of the different climate simulations, that are part of CMIP5, can
be found in Taylor et al. (2009) and Taylor et al. (2012). Additional information can be
obtained from the CMIP web page (http://cmip-pcmdi.llnl.gov/).

In this thesis, the model output from 28 models that are taking part in CMIP5 are
investigated. One main aim of the study is to analyse the intermodel spread of these
CMIP5 models with respect to changes in the Hadley circulation and to find robust
responses of the ensemble members. For this reason, the response of the climate system
of the different models to an idealised 1% yearly increase of the atmospheric carbon
dioxide \((\text{CO}_2)\) concentration is investigated. The objective of this transient climate
simulation, which is called the 1pctCO2 experiment, is to investigate the differing model
responses to the same prescribed forcing, while all other forcings are omitted (Taylor
et al., 2009).

The models that are examined in this thesis are summarised in Table 3.1 and Ta-
ble 3.2. The tables contain the vertical and horizontal resolutions of the grids of each of
the models and the modelled time period. For some models the resolution or the mod-
elled time period varies between the horizontal and vertical wind components, which
are examined in this thesis. For these models, the spatial and temporal resolutions for
both wind components are depicted separately in the tables. The provided model out-
put from most of the models exhibits 17 vertical grid points (pressure levels, “plev”) that
range from 1000 hPa to 10 hPa. Seven models include more pressure levels. These
models exhibit pressure levels up to 5 hPa (CSIRO-MK3-6-0), 1 hPa (CanESM2 and
GFDL-CM3), 0.4 hPa (MRI-CGCM3), 0.1 hPa (MPI-ESM-LR and MPI-ESM-MR), and 0.03 hPa (MIROC-ESM). Whereas the pressure levels are similar for the different models, the horizontal resolution varies significantly. The focus of this thesis lies on the zonal mean of the analysed variables (see sections 2.1 and 2.6). Thus, only the resolution and range of the latitude values (“lat”) are summarised in Table 3.1 and Table 3.2. The Chinese model FGOALS-g2 exhibits the coarsest resolution with 60 latitude grid points. With 240 grid points, the finest grid is used by the Italian model CMCC-CM. Note that the same variable dimension of “lat” of two different models does not imply that they are using the same grid. For example, the CSIRO-Mk3-6-0 and the IPSL-CM5A-LR both exhibit 96 latitude grid points. However, the minimum and maximum latitude values between these two models do not match. This indicates that the grids are not the same.

In the 1pctCO2 model experiment the preindustrial atmospheric CO$_2$ concentration doubles at around year 70 and quadruples at around year 140. The provided model output from several of the investigated models exhibits longer time periods than the 140 years that are mandatory for the experiment (e.g. CCSM4, GISS-E2-H, MPI-ESM-MR). Most of the modelling groups associate the modelled time period with the years 1850–1989. This is due to the fact that the initial CO$_2$ concentration is set to preindustrial conditions. Nevertheless, the model set-up is very idealised and the timestamp is more or less arbitrary. For this reason, the time series that are shown in this thesis do not contain year dates, but the label “months/years since begin of model run”.

Table 3.1: Overview of the CMIP5 models used in this thesis. The variables “lat” and “plev” indicate the latitude and the pressure levels, respectively. Models that contain different time periods or spatial resolutions for the two variables, are listed separately.

<table>
<thead>
<tr>
<th>Model</th>
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<th>Variable Dimension</th>
<th>Variable min</th>
<th>Variable max</th>
</tr>
</thead>
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<td></td>
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<td>100000</td>
<td>1000</td>
</tr>
<tr>
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<td>87.864</td>
</tr>
<tr>
<td></td>
<td></td>
<td>plev [Pa] 17</td>
<td>100000</td>
<td>1000</td>
</tr>
<tr>
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<td>89.142</td>
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<tr>
<td></td>
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<td>1000</td>
</tr>
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</tr>
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<td></td>
<td></td>
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<td>1000</td>
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<tr>
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3.2 Results for the MPI-ESM-MR model

In this section, the Hadley circulation of the MPI-ESM-MR model is investigated in detail. For this, the six Hadley-indices of the $\psi$-approach (section 2.1) and the $\omega$-approach (section 2.6) are analysed. In order to get an overview of the representation of the Hadley circulation in the model simulations, the mean structure and characteristics of the Hadley circulation are analysed in the first part of this section (section 3.2.1). In the second part, each of the six Hadley-indices is analysed with respect to its annual cycle (section 3.2.2). In the third part of this section, the Hadley-indices are compared to each other to determine the interdependences of different indices (section 3.2.3).

3.2.1 Characteristics of the Hadley circulation

In order to get a first overview of the structure of the Hadley circulation within one year, Figure 3.1 shows the latitude-height cross sections of the mass stream function and the vertical pressure velocity for the four seasons as means over all 140 simulated years. The abbreviations DJF, MAM, JJA, and SON stand for boreal winter (December, January, February), boreal spring (March, April, May), boreal summer (June, July, August), and boreal fall (September, October, November), respectively. During the equinox seasons, the two Hadley cells and the two descending branches are well developed and the updraft exhibits its weakest strengths (Figure 3.1, right column). During the solstice seasons the cell and descending branch in the winter hemisphere are much wider and stronger than the cell and descending branch in the summer hemisphere, which are developed weakly (Figure 3.1, left column). The ascending branch exhibits its largest strengths during these seasons.

The southern hemisphere winter (summer) cell is stronger than the northern hemisphere winter (summer) cell. This is probably caused by the land-sea distribution. Cook (2003) identified that the presence or absence of continents strongly influences the Hadley circulation. The author identified that the winter hemisphere Hadley cell strengthens in the presence of continents, because the surface friction increases the angular momentum flux into the atmosphere. In addition, the summer cell is weaker in the presence of continents, due to the development of a strong monsoon in the northern hemisphere summer, which transports mass out of the subtropics (Cook, 2003).

While the smaller summer Hadley cell is completely located in one hemisphere, the winter cell exhibits a cross-equatorial position. Thus, the ascending motion of the winter Hadley cell takes place in the summer hemisphere. This means that the Hadley cell transports energy and mass from the summer hemisphere into the winter hemisphere. Note that the stronger southern hemisphere winter cell advances further into the northern hemisphere than the weaker northern hemisphere winter cell into the southern hemisphere.

During all four seasons, the ascending branch of the Hadley circulation is stronger and narrower than the two descending branches, which are much wider and weaker. This is most clear for the solstice seasons (Figure 3.1, left column). If the Hadley...
circulation is considered as a closed system, the descending motion should compensate the ascending motion. This assumption is only partly fullfilled, because the Hadley circulation exchanges energy with the extratropics and is thus no closed system. As a first approximation, the Hadley circulation will be considered as a closed system in this thesis.

### 3.2.2 Annual cycle of the Hadley circulation

The Hadley circulation is characterised by a strong annual cycle, which is mainly caused by a varying incoming solar radiation at a point of the Earth’s surface during the year. In this section, the results are presented on the basis of the MPI-ESM-MR model. However, the results are similar for the 1pctCO2 climate simulations of all 28 models of the CMIP5 ensemble.

The annual cycle of the Hadley circulation is apparent in all six Hadley-indices that are analysed in this thesis. In order to become aware of the strong annual cycle of the Hadley-indices, the time series of the width of the Hadley cells based on the \( \psi \)-approach are shown in Figure 3.2 together with linear regression lines. The slopes and intercepts of the regression lines are given in the label of Figure 3.2. Hereafter, the slopes of the regression lines are referred to as "trend" of the Hadley-indices.

The trends for the width of the northern, southern and total Hadley cells are very small. A widening during the 140 simulated years is found for all three cells. The northern Hadley cell exhibits the smallest widening trend of about \( 7.7 \cdot 10^{-5} \) degree per month, followed by the southern Hadley cell (about \( 1.2 \cdot 10^{-3} \) degree per month). The largest widening of about \( 1.3 \cdot 10^{-3} \) degree per month is found for the total Hadley cell. The last value corresponds to the sum of the trends for the width of the northern and...
Figure 3.2: Time series of the width of the northern (upper panel), southern (middle panel) and total (lower panel) Hadley cells based on the $\psi$ approach for the MPI-ESM-MR. Red lines correspond to linear regressions of the time series. The regression coefficients of the three time series are given in the legend of the respective panel.

The fact that the trend for the width of the northern Hadley cell is much smaller than the trend for the width of the southern Hadley cell is probably caused by the land-sea distribution as explained above.

Each of the three time series in Figure 3.2 comprises 1680 values. Due to this length of the time series, a detailed analysis of the annual cycle of the index is difficult. The same accounts for the other five Hadley-indices. For this reason, a mean annual cycle is calculated for each of the six Hadley-indices, by taking the mean over all 140 January values, all 140 February values, and so forth. The mean annual cycles of the Hadley-indices are shown in Figure 3.3 for the $\psi$-approach and Figure 3.4 for the $\omega$-approach. They are investigated in detail in the next step of the analysis.

Investigation of the mean annual cycles of the Hadley-indices based on the $\psi$-approach

The upper panel of Figure 3.3 shows the mean annual cycle of the positions of the zero crossings of $\psi_{500}$. The position of the southernmost zero crossing exhibits the smallest annual cycle of about $8^\circ$ latitude. With a magnitude of about $13^\circ$ the northern descending edge has a larger annual cycle than the southern descending edge. The largest annual cycle is present in the position of the ascending edge, which moves about $33^\circ$ latitude during a year.

The analysis of the mean annual cycles of the two descending edges of the Hadley circulation reveals that the two edges are nearly located in the same latitude area, just on the opposite hemisphere. The two edges reach their northernmost and southernmost
Figure 3.3: Mean annual cycles of the Hadley-indices based on the $\psi$-approach: positions of the $\psi_{500}$ zero crossings (a), width of the northern, southern and total Hadley cells (b) and strength of the northern and southern Hadley cells (c) for the MPI-ESM-MR model.
positions in later months of the year the more northward the edge is located. For both edges the time difference between the reaching of the southernmost and northernmost positions is four months. This indicates that the width of the total Hadley cell decreases between February and May and increases between June and September. This behaviour is also visible in the middle panel of Figure 3.3, which shows the mean annual cycles of the widths of the northern, southern and total Hadley cells. As the positions of the two descending edges exhibit a small annual cycle, the width of the total Hadley cell also shows a small annual cycle of about 12° latitude. As the width of the total Hadley cell is defined as the distance between the positions of the two descending edges, the width of the total Hadley cell is always the sum of the width of the northern and the width of the southern Hadley cells (Figure 3.3, b)).

The annual cycle of the position of the ascending edge looks more like a sine wave than the annual cycles of the positions of the two other edges. Thus, the time difference between the achievement of the southernmost and northernmost positions of the ascending edge is six months and not four months as for the descending edges. As the annual cycle of the position of the middle zero crossing is much larger than the annual cycles of the positions of the two outer zero crossings, the position of the middle zero crossing mainly determines the width of the northern and southern Hadley cells. This explains why the annual cycles of 31° latitude for the northern Hadley cell and 27° latitude for the southern Hadley cell are similar. The magnitude of the annual cycle of the width of the northern cell is slightly larger than the one of the southern cell, because the northern and middle zero crossings move towards each other during some months and apart from each other during other months, while the position of the southern zero crossing is more constant during the year. If the middle edge is located more southward, which is the case during the northern hemisphere winter months, the southern cell is small and the northern cell is much wider. The opposite behaviour is found during the northern hemisphere summer months. During this period, the northern Hadley cell is much smaller than the southern Hadley cell.

A similar behaviour is found for the strength of the northern and southern Hadley cells (Figure 3.3, c)). Note that the strength of the northern Hadley cell is depicted as positive values of the mass stream function while the strength of the southern Hadley cell is depicted as negative values. Thus, a larger absolute value of the strength corresponds to a stronger Hadley cell. A value close to 0 kg s⁻¹, however, is linked to a weak Hadley cell. In consideration of this definition of the Hadley cells’ strengths, a strong and wide Hadley cell exists at the same time, whereas a weaker cell is found during the same months as a smaller Hadley cell. For this reason, the shape of the mean annual cycles of the width and the strength of the northern cell agree very well. The same accounts for the shape of the mean annual cycles of the two indices for the southern Hadley cell. This agrees also very well with the results of the analysis of Figure 3.1.

The annual cycle of the northern Hadley cell’s strength exhibits a magnitude of about 203 · 10⁹ kg s⁻¹. Thus, it is smaller than the annual cycle of the southern Hadley cell’s strength, which shows a magnitude of about 288 · 10⁹ kg s⁻¹. This does not imply
that the southern Hadley cell exhibits the smallest and largest absolute values of the mass stream function. Instead, the northern Hadley cell reaches the least strengths and the southern Hadley cell exhibits the largest strengths. These extreme values are reached during DJF and JJA. The strength of the northern Hadley cell is weakest during June. During this month it reaches mean values of about $32 \cdot 10^9 \text{ kg s}^{-1}$. The southern cell exhibits its minimum strength of about $-52 \cdot 10^9 \text{ kg s}^{-1}$ during January. Compared to the magnitude of the annual cycle of the mean strength of the two cells, the difference between the absolute values of the northern cell minimum strength and the southern cell minimum strength is small (about $20 \cdot 10^9 \text{ kg s}^{-1}$). At the same time, the difference between the absolute values of the northern cell maximum strength ($235 \cdot 10^9 \text{ kg s}^{-1}$) and the southern cell maximum strength ($-340 \cdot 10^9 \text{ kg s}^{-1}$) is larger than $100 \cdot 10^9 \text{ kg s}^{-1}$, which is about half the magnitude of the strength of the northern cell and five times the difference between the absolute values of the minimum strengths of the two cells.

Investigation of the mean annual cycles of the Hadley-indices based on the $\omega$-approach

Similar to the positions of the zero crossings of $\psi_{500}$, the positions of the zero crossings of $\omega_{500}$ are clearly separable from each other (Figure 3.4, a)). With a movement of about $8^\circ$ the southernmost edge shows the smallest annual cycle of the four edges of the Hadley circulation’s branches. The northernmost edge exhibits the second smallest annual cycle of about $14^\circ$. The positions of these two outer zero crossings are almost mirrored at the equator. At the same time, the annual cycles of the positions of these two zero crossings are phase-delayed by one to two months.

The positions of the two middle edges of the branches have the largest annual cycles. Thus, the order of the magnitudes of the annual cycles of the branches’ edges correspond very well with the order of the magnitudes of the annual cycles of the positions of the $\psi_{500}$ zero crossings. For both approaches, the smallest annual cycle is found for the position of the southernmost zero crossing, followed by the position of the northernmost zero crossing, and the largest annual cycle is found for the position of the middle zero crossing(s). The positions of both middle edges of the branches move about $24^\circ$ per year. As it was already found for the positions of the two outer edges, the positions of the two ascending edges are nearly mirrored at the equator. During the year the two edges move nearly in phase. This explains why the magnitude of the annual cycle of the width of the ascending branch is only about half as large as the magnitude of the annual cycles of the two descending branches. The magnitude of the first is about $10^\circ$, whereas the magnitudes of the latter are about $18^\circ$ for the northern descending branch and $19^\circ$ for the southern descending branch (Figure 3.4, b)).

The widths of the two descending branches show a negative correlated behaviour during large parts of the year. This means that the width of the northern descending branch decreases while the width of the southern descending branch increases and vice versa. This behaviour is also apparent in the strength of the two descending branches
3.2 Results for the MPI-ESM-MR model

Figure 3.4: Mean annual cycles of the Hadley-indices based on the $\omega$-approach: positions of the $\omega_{500}$ zero crossings (a), width (b) and strength (c) of the ascending and descending branches for the MPI-ESM-MR model.
This means that the strength and width of the northern descending branch change almost in phase. The same accounts for the strength and width of the southern descending branch. The comparison of the mean annual cycles of the width and strength of the two descending branches reveals that the descending branch of the stronger winter Hadley cell is wider and stronger than the descending branch of the weaker summer Hadley cell.

The mean annual cycles of the strength of the two descending branches have a similar magnitude of about 18 hPa day$^{-1}$ for the northern descending branch and 15 hPa day$^{-1}$ for the southern descending branch. This result contrasts the findings for the strength of the Hadley cells based on the mass stream function, which differ significantly. The smallest values for the branches’ strengths are found for the northern descending branch, whereas the largest values are found for the southern descending branch. The same order was found for the cells’ strengths. The northern descending branch reaches its minimum strength during August and its maximum strength during January. The maximum and minimum values for the southern descending branch are found during similar months, but with a phase shift of about six months. Thus, the maximum strength of the southern descending branch is found during July, whereas the minimum strength is reached during December.

The ascending branch exhibits a width between approximately 24° and 33° latitude. It is smaller than the winter hemisphere descending branch and wider than the summer hemisphere descending branch. The annual cycle’s magnitude of the ascending branch’s strength, which is about 30 hPa day$^{-1}$, is between one-third and twice as large as the annual cycles of the descending branches’ strengths. At the same time, the ascending branch is much stronger than the two descending branches. The minimum absolute value that is reached by the ascending branch (-33 hPa day$^{-1}$) is larger than the maximum strengths that are found for the two descending branches (30 hPa day$^{-1}$ for the northern and 32 hPa day$^{-1}$ for the southern descending branch). The maximum strength of the ascending branch of about -63 hPa day$^{-1}$ is approximately twice as large as the maximum strengths of the two descending branches. Whereas the annual cycles of the widths and strengths of the two descending branches follow approximately a sine curve, the annual cycles of the ascending branch look different. The annual cycles of the ascending branch fluctuate much more and do not exhibit a clear maximum and minimum.

**Investigation of the anomaly time series**

The strong annual cycles of the Hadley-indices dominate the time series which show each time step of the 140 simulated years. This was shown exemplarily for the width of the northern, southern and total Hadley cells based on the mass stream function in Figure 3.2. The strong annual cycle superimposes the natural variability of the climate system that can be deduced from the different Hadley-indices. Thus, the analysis of the low frequent variability of the indices and the climate system is not possible. For this reason, the anomaly time series of the Hadley-indices are investigated in addition to the
mean time series of the six indices. The anomaly time series are calculated by subtracting the mean annual cycles of the indices, that are shown in Figure 3.3 and Figure 3.4, from each simulated year. In other words, the mean January value of the index is subtracted from each 140 January values of the index. This procedure is repeated for the remaining eleven months. In this way, the natural variability of the indices is identifiable.

Figure 3.5 shows the anomaly time series for the width of the northern, southern and total Hadley cells together with linear regression lines for each cell. As for the time series that contain the annual cycle of the index (Figure 3.2), the regression coefficients of the time series are given in the legend of each panel of Figure 3.5. In order to derive the anomaly time series, the mean annual cycle of the index was subtracted from the time series that contains the annual cycle. Thus, it was expected that the trends of the time series with and without an annual cycle are similar. The comparison of the trends of the two time series satisfies this expectation. The monthly trends that are shown in Figure 3.2 and Figure 3.5 only change in the fourth position after decimal point.

Each of the anomaly time series exhibits a lot of noise and some larger positive or negative peaks (Figure 3.5). These peaks can be associated with periodic or quasi-periodic variabilities of the climate system that affect the Hadley circulation. Examples for these variabilities are the El Niño Southern Oscillation (ENSO) with a time scale of four to six years (Krishnamurti et al., 2013) or the Pacific Decadal Oscillation (PDO) with a time scale of 15 to 25 years and 50 to 70 years (Mantua and Hare, 2002). The anomaly time series of the different indices are very long. Thus, a qualitative

![Figure 3.5: Anomaly time series of the width of the northern (upper panel), southern (middle panel) and total (lower panel) Hadley cells based on the $\psi$-approach for the MPI-ESM-MR. Red lines correspond to linear regression lines of the time series. The regression coefficients of the three time series are given in the legend of the respective panel.](image-url)
analysis of the time series cannot facilitate a detection and quantification of the periodic properties of the indices. A Fourier analysis, however, reveals the frequency of periodic characteristics of the indices and thus of the variability of the climate system itself.

The Fourier transformations (FFTs) of the anomaly time series of the widths of the northern and southern Hadley cells are shown in Figure 3.6 for different periods. The upper panels for the northern and southern cells depict periods of up to 600 months or 50 years. The middle and lower panels show a zoom into the Fourier transformation. The middle panels show periods up to 100 months, whereas the lowermost panels show periods up to 24 months or two years. The Fourier transformations of the anomaly time series of the width of the two Hadley cells do not show a sharp spectrum. Instead, they

![FFT for Width of NH Hadley Cell](image)

![FFT for Width of SH Hadley Cell](image)

Figure 3.6: Fourier transformations of the anomaly time series of the width of northern (upper three panels) and southern (lower three panels) Hadley cells for the MPI-ESM-MR model.
exhibit a lot of white noise. This is caused by the fact that the “periodic” variabilities of the climate system and thus the Hadley-indices are not perfectly periodic.

The Fourier transformations of both the northern and southern Hadley cells exhibit the two largest peaks at a period of about twelve months. These peaks can be associated with the annual cycle of the Hadley circulation. This indicates that the anomaly time series still contain influences of the annual cycle. The applied method to calculate the anomaly time series does not take into account that the Hadley circulation exhibits a widening trend during the 140 simulated years. Thus, the trend induced components of the annual cycle of the Hadley circulation remain even though the mean annual cycle was subtracted from the time series.

The Fourier transformation of the width of the northern Hadley cell exhibits a peak at about 160 months, though the resolution of the Fourier transformation is not high at these periods. This peak could be associated with the Pacific Decadal Oscillation. Such a peak is not observable in the Fourier transformation of the width of the southern Hadley cell, which shows a minimum at this period. The Fourier transformations of both cells do not exhibit a peak that can be associated with ENSO. Thus, it can be concluded that there are no dominating peaks in the Fourier transformations of the anomaly time series of the width of both Hadley cells that would correspond to the ENSO or PDO time scales. The same accounts for the Fourier transformations of the other five Hadley-indices (not shown).

3.2.3 Correlations of the Hadley-indices

In this section, the interdependence of the different Hadley-indices of the MPI-ESM-MR model is investigated. In addition, possible reasons for the strong correlation of some indices are given.

Correlations between Hadley-indices of the ψ-approach

First, the correlation between the strength and width of the Hadley cells are analysed. For this, the time series of the two Hadley-indices that contain the annual cycle are compared to each other (Figure 3.7). The left cloud of points exhibits only negative values for the strength of the Hadley cell. Thus, it corresponds to the southern Hadley cell. Accordingly, the right cloud of points, which shows only positive strengths, represents the northern Hadley cell. The four different colours of the scatter points represent the four seasons, the single months of a season have different markers. Thus, all twelve months are distinguishable.

As already indicated in section 3.2.2, the two Hadley-indices are strongly correlated. The correlation of the two indices reveals correlation coefficients of 0.95 for the northern Hadley cell and -0.89 for the southern Hadley cell. Note that the negative correlation coefficient of the southern Hadley cell is caused by the definition of the strength of this cell. Large negative values of the strength of the southern Hadley cell correspond to a strong cell and not to a weak cell. Thus, the negative correlation coefficient also
indicates a correlation of the two indices and not an anti-correlation.

The northern and southern Hadley cells show an anti-correlated behaviour. A weak and narrow Hadley cell is found during the summer months of each hemisphere, whereas a strong and wide Hadley cell develops during winter. Intermediate conditions are found during spring and fall. For this reason, the four seasons are clearly distinguishable from each other for both Hadley cells.

Each Hadley cell exhibits a similar strength and width during the three summer months. The same accounts for the winter months. Thus, the three months of the respective season and cell are hardly distinguishable. The opposite behaviour is found for the equinox seasons, for which the spread between the three months of the respective season is much larger. The largest spread is found during spring of each hemisphere. The strengths and widths of the three months are very variable and thus three clouds of points are found. During fall the spread is a bit smaller than during spring. Two clearly distinguishable clouds of points are found for this season, because the first two months after summer show a similar width and strength for the respective cell, whereas the last month of fall exhibits significantly different widths and strengths of the cell.

As the four seasons, and for the equinox seasons even the single months, exhibit very different strengths and widths of the two Hadley cells, the hypothesis arises that the strong correlation of these Hadley-indices is caused by the strong annual cycle of the indices and not by the dynamics of the system. To check this hypothesis, the correlation between the anomaly time series of the two indices is investigated (Figure 3.8). The clouds of points for the northern and southern Hadley cells indicate that the two anomaly time series of the strength and width of the Hadley cells are hardly correlated. This is
3.2 Results for the MPI-ESM-MR model

Figure 3.8: Correlation between the strength and width of the Hadley cells for the anomaly time series that contain each time step of the MPI-ESM-MR model.

supported by the correlation coefficients, which show values of about 0.1 for the northern and -0.1 for the southern Hadley cell. These results corroborate the hypothesis that the strong correlation of the two Hadley-indices is caused by the annual cycle of the indices. This indicates that different mechanisms control the variability of the annual cycle and the internal variability of the system.

The analysis of the correlation of the anomaly time series of the strength and width of the northern Hadley cell shows that most of the outliers in the strength of the cell occur during winter and spring. This applies for the positive as well as for the negative anomalies (Figure 3.8, upper panel). The same result is found for the southern Hadley cell (Figure 3.8, lower panel). A possible explanation for this behaviour is the fact that the largest absolute values of the mass stream function occur during these seasons, whereas the smallest values occur during summer. Thus, the difference between an anomalous strong or weak Hadley cell and the mean value for the respective month is larger during winter than during summer, because the absolute value of the strength is larger. For the width of the Hadley cells, the most outliers occur during November.

Correlations between Hadley-indices of the ω-approach

The strength and width of the three branches of the Hadley circulation are weaker correlated than the strength and width of the two Hadley cells (Figure 3.9). The correlation of the two indices reveals correlation coefficients of 0.65 for the northern hemisphere descending branch, 0.4 for the ascending branch and 0.7 for the southern hemisphere descending branch. Note that the positive value for the correlation coefficient of the ascending branch corresponds to an anti-correlation, because the strength of this branch is defined by negative values of the vertical pressure velocity.

The correlation between the strength and width of the two descending branches
indicates that a narrow and weak or wide and strong branch is found at the same time. The first applies for the summer months, the latter for the winter months for both branches. Thus, the northern and southern hemisphere descending branches exhibit an anti-correlated behaviour (Figure 3.9). This is in good agreement with the results for the correlations of the strength and width of the two Hadley cells (Figure 3.7). For the ascending branch, a narrow branch occurs in conjunction with a strong branch, a wide branch in conjunction with a weak branch. This explains the anti-correlation that is found for this branch.

In contrast to the results for the correlations based on the $\psi$-indices, the correlations of the strength and width of the three branches do not exhibit a clearly distinguishable intermediate condition for spring and fall. Instead, the scatter points are located more on top of each other and do not build a line as for the Hadley cells. This behaviour is most pronounced for the ascending branch. The fact, that the scatter points are closer to each other and form a broader cloud of points explains the smaller correlation coefficients of the $\omega$-indices compared to the $\psi$-indices.

The correlation of the strength and width of the branches decreases, if the anomaly time series of the strength and width are used to calculate the correlation coefficients. The correlation coefficient amount to -0.35 for the northern hemisphere descending branch, 0.25 for the ascending branch and -0.4 for the southern hemisphere descending branch. Thus, the coefficients change their sign for the two descending branches and decrease by 0.15 (ascending branch) to 1.1 (SH descending branch). This further supports the hypothesis that the correlation between the Hadley-indices are dominated by the annual cycle of the indices.
Correlations between Hadley-indices of the $\psi$-approach and the $\omega$-approach

So far, the correlations between the strength and width of the cells and the strength and width of the branches have been analysed. The next step in the comparison of the Hadley-indices is the investigation of the correlation between the widths of the cells and the widths of the branches as well as the correlation between the strengths of the cells and the strengths of the branches. The correlations between the widths of the cells and the widths of the branches are shown in Figure 3.10. The black solid lines mark the “1:1”-lines which correspond to a correlation coefficient of 1.0.

The widths of the northern Hadley cell and the northern hemisphere descending branch (a) as well as the widths of the southern Hadley cell and the southern hemisphere descending branch (f) are strongly correlated. The first exhibit a correlation coefficient of 0.85 and the latter of 0.95. The scatter points of both correlations are located close to the “1:1”-line. The development of the southern Hadley cell and the southern hemisphere descending branch is hardly disturbed by continents. Thus, the linear shape in (f) is pronounced stronger than in (a). The correlation between the northern Hadley cell and the northern hemisphere descending branch (a) reveals that the JJA Hadley cell is smaller than the JJA branch during most months, whereas the DJF Hadley cell is wider than the DJF branch. The branch’s width is much more variable during DJF than the cell’s width. This results in a more or less horizontal distribution of the blue markers in (a). The widths of the cell and branch exhibit similar values during the two equinox seasons.

A similar, but horizontally mirrored, distribution as for (a) is found for the correlation between the width of the northern hemisphere descending branch and the width of the

![Figure 3.10: Correlation between the widths of the Hadley circulation’s branches and the widths of the Hadley cells for each time step of the MPI-ESM-MR model.](image-url)
southern Hadley cell (d). These two Hadley-indices are anti-correlated with a correlation coefficient of -0.7. This means that a wider (narrower) branch is found during the same months as a narrower (wider) cell. This behaviour was already indicated in section 3.2.1 and section 3.2.2. As for (a), the width of the branch is much more variable during DJF than the width of the cell, which results in a more or less horizontal distribution of the blue markers in (d). The markers of the remaining months are nearly linearly distributed.

A similar, but horizontally mirrored, behaviour as for (f) is found for the correlation between the width of the southern hemisphere descending branch and the width of the northern Hadley cell (c). These two indices have a correlation coefficient of -0.85, which indicates an anti-correlation of the two Hadley-indices. The markers of SON, DJF, and MAM are nearly located on a diagonal line. During most of the JJA months, the cell and branch are narrower than indicated by the line that is formed by the other seasons.

With correlation coefficients of 0.4 (b) and -0.4 (e), the correlations of the width of the two cells and the width of the ascending branch reveal weaker correlation coefficients than the other four comparisons. The clouds of points rather represent vertical lines than diagonal lines. This behaviour can be explained by the fact that the annual cycle of the cells' widths is much larger than the annual cycle of the width of the ascending branch.

Finally, the correlations between the strengths of the cells and the strengths of the branches are investigated (Figure 3.11). Note that the strength of the southern Hadley cell and the strength of the ascending branch are defined by negative values of the two quantities. Thus, a positive correlation coefficient for (b), (d) and (f) corresponds to an anti-correlation of the two indices. The same accounts for negative correlation coefficients for (a), (c) and (e).

As for the correlations of the widths of the branches and the widths of the cells, the strongest correlations are found for (a) and (f). They exhibit correlation coefficients of 0.95 for the strength of the northern hemisphere descending branch and the strength of the northern Hadley cell (a) and -0.9 for the strength of the southern hemisphere descending branch and the strength of the southern Hadley cell (f). The clouds of points exhibit a curved shape for the northern hemisphere (a) and a more linear shape for the southern hemisphere (f).

The strongest anti-correlations are found for (c) and (d). These two correlations exhibit correlation coefficients of 0.9 for the strength of the northern descending branch and the strength of the southern Hadley cell (d) and -0.8 for the strength of the southern descending branch and the strength of the northern Hadley cell (c). The clouds of points of both correlations exhibit a curved shape. If a line were placed into the clouds of points, the southern Hadley cell or the northern descending branch would be too strong to match the line during JJA. The opposite behaviour would be found for most of the remaining year. During these months, the cell and branch would be too weak to match the line (d).

The weakest anti-correlation is found for the correlation of the strength of the ascending branch and the strength of the northern Hadley cell (b), which exhibit a correlation coefficient of 0.4. The cloud of points illustrates an arrow for this correlation. The tip
of the arrow marks the weakest updrafts which are found during May. The strength of
the Hadley cell is very similar for these months. The strength of the cell varies much
more for the months for which the strongest updrafts are reached. This happens during
DJF, when the northern cell is strong, during JJA, when the northern cell is weak, and
during November, when the northern cell exhibits a medium strength.

The strength of the ascending branch and the strength of the southern Hadley cell
(e) show a stronger correlation than (b). The correlation coefficient amounts to 0.7 for
this correlation. During large parts of the year, the scatter points form a well developed
line. Towards the end of the year, the strength of the branch becomes more variable,
whereas the cell exhibits a similar strength during this time. This results in a more or
less horizontal line of the November and DJF scatter points.

As shown exemplarily for the correlation between the width and strength of the
Hadley cells, the strong correlation between the widths of the cells and branches and
between the strengths of the cells and branches are mainly caused by the annual cycle
of the indices. For the correlation of the anomaly time series of these indices the
correlation coefficients strongly decrease compared to the ones that are determined for
the correlation of the time series that contain the annual cycle (not shown here).

To sum up, the main results of the investigation of the representation of the Hadley
circulation in the MPI-ESM-MR model are that the cells and branches of the circulation
and thus the Hadley-indices exhibit large annual cycles. These annual cycles cause
strong correlations or anti-correlations between the Hadley-indices. The correlations are
reduced if anomaly time series are investigated. The investigation of the anomaly time
series and their Fourier transformation revealed that no dominant peaks are found that
could be associated with the ENSO and PDO time scales.
3.3 Results for the CMIP5 ensemble

In this section, similarities and discrepancies in the representation of the Hadley circulation in the CMIP5 ensemble are investigated. Section 3.3.1 focuses on the mean structure of the Hadley circulation, whereas the correlations between annual mean time series of the Hadley-indices are analysed in section 3.3.2. In section 3.3.3 the responses of the Hadley circulations to an idealised forcing are analysed. The model spread of the CMIP5 ensemble is quantified and it is investigated if there are robust responses of the Hadley circulations of the ensemble.

3.3.1 Characteristics of the Hadley circulation

This section provides an overview of the mean structure of the Hadley circulation in the 28 CMIP5 models. It is, thus, the basis for the model comparison of the CMIP5 models that aims at quantifying the spread of the ensemble in the modelling and response of the Hadley circulation to an idealised increase of the atmospheric CO$_2$ concentration.

The comparison of the mean structure of the Hadley circulation of the 28 investigated CMIP5 models reveals intermodel differences. In order to get a first overview of these differences, Figure 3.12 depicts the latitude-height cross sections of the Hadley circulation of all 28 CMIP5 models as means over all simulated time steps. All models exhibit two well pronounced Hadley cells. For most of them, the two outer zero crossings of the mass stream function at 500 hPa are located at almost the same latitude. At the same time, the middle zero crossing of $\psi_{500}$ is located in the northern hemisphere. Thus, the mass stream function shows a wider and stronger southern Hadley cell for most of the models. For some models the two cells have almost the same strength (e.g. ACCESS1-3, BCC-CSM1-1, INMCM4, IPSL-CM5B-LR).

The intermodel differences that are found for the vertical pressure velocity are larger than the intermodel differences that are found for the mass stream function. The largest differences occur in the updrafts of the Hadley circulation, which are shown in red colours in Figure 3.12. Some models, like the CSIRO-Mk3-6-0 or MIROC5, exhibit a very strong and narrow updraft. Other models have a relatively wide and weak updraft (e.g. BCC-CSM1-1, CMCC-CM, CNRM-CM5-2). Again other models tend to develop a double Intertropical Convergence Zone (ITCZ) with two stronger updrafts (e.g. GFDL-CM3, GISS-E2-H, MRI-CGCM3). However, these two stronger parts of the updraft are not separated by a downdraft, which would be typical for a double ITCZ.

In addition, an updraft is found in the South of the strong ascending motion at greater heights (700-100 hPa) whereas at lower heights (925-700 hPa) a descending motion is present in the simulations of almost all models. This behaviour is most prominent in the simulations of the CSIRO-Mk3-6-0 model. Exceptions of this behaviour are found in the simulations of the GFDL models and the MIROC-ESM, which also exhibit an updraft at lower heights.

The intermodel spread for the downdrafts is not as large as the spread for the updrafts. The widths and strengths of the southern hemisphere descending branches are
similar for the different models. The same accounts for the widths and strengths of the northern hemisphere descending branches. The strongest descending motions are found equatorwards of, but still close to, the outer zero crossings of the mass stream function for almost all models. The sole exception is the GISS-E2-H model which exhibits a weak updraft within the northern hemisphere downdraft region. This updraft crosses the 500 hPa level. Thus, the presence of the updraft affects the detection of the width of the northern hemisphere descending branch. This also affects the determined strength of the downdraft, if the maximum vertical velocity occurs northwards of the small updraft.

The updrafts and downdrafts do not reach the lowermost pressure level between
1000 hPa and 925 hPa in all 28 simulations. This level exhibits a more or less uniform bright colouring, which corresponds to very weak ascending or descending motions. The GISS-E2-H model does not even show any vertical motion in this pressure level (white colouring in Figure 3.12). This indicates that the models do not properly simulate the vertical pressure velocity at ground level. Thus, the vertical velocities of this pressure level cannot be used to investigate the Hadley circulation. They are excluded in the analysis of the Hadley circulation and its changes.

To sum up, the analysis of the mean structure of the Hadley circulation of the CMIP5 ensemble shows that the overall structure of the Hadley circulation is similar between the models. Differences are found as soon as the cross sections are investigated more in detail. The largest differences occur in the ascending vertical velocity of the Hadley circulation, whereas the intermodel differences in the descending branches of the circulation and the two Hadley cells based on the mass stream function are smaller.

### 3.3.2 Correlations of the Hadley-indices

In this section, the interdependence of the different Hadley-indices is investigated for the CMIP5 ensemble. As detailed descriptions of the annual cycles of the Hadley-indices are given in section 3.2.2 and section 3.2.3 on the basis of the MPI-ESM-MR model, the annual cycles of the indices are not described in this section. Instead, the section focuses on the similarities and discrepancies between the models of the ensemble.

**Correlations between Hadley-indices of the \( \psi \)-approach**

Similar to Figure 3.7, the correlation between the strengths and widths of the Hadley cells can be investigated for the time series that contain all 1680 simulated time steps. A detailed analysis of the 28 correlations would exceed the scope of this thesis. Instead, the mean annual cycles of the indices are compared to each other to demonstrate the mean differences and similarities between the models. Figure 3.13 shows the correlation between the strength and the width of the two Hadley cells for the mean annual cycles of all 28 CMIP5 models and for the model mean (black curve). As already indicated in section 3.2.3, the two indices exhibit a strong correlation for both Hadley cells. Thus, a linear structure is found for the mean correlations of all models. This statement is further supported by the correlation coefficients. They range between about 0.92 and 0.98 for the northern Hadley cell and about -0.91 and -0.99 for the southern Hadley cell. The model mean exhibits correlation coefficients of about 0.97 (northern cell) and -0.96 (southern cell), respectively. Note again, that the negative values of the correlation coefficients for the southern cell are caused by the definition of the strength of this cell. This is described in detail in section 3.2.3.

At first sight, the shapes of the curves of the different models look similar (Figure 3.13). However, the curves are shifted against each other and, for some models, tilted compared to the model mean. The largest spread in the cells’ strengths is found during the winter seasons of both hemispheres when the cells reach their maximum
3.3 Results for the CMIP5 ensemble

Figure 3.13: Correlation between monthly mean time series of the strength and width of the Hadley cells for the CMIP5 ensemble and the model mean. Positive values of the strength correspond to the northern Hadley cell, negative values to the southern Hadley cell.

strength. The southern cell of the INMCM4, for example, exhibits a maximum strength of about $-140 \cdot 10^9$ kg s$^{-1}$. At the same time, the MPI-ESM-MR shows a strength of about $-340 \cdot 10^9$ kg s$^{-1}$. For the model mean, the difference between the minimum and maximum strength of the southern Hadley cell during a year is about $200 \cdot 10^9$ kg s$^{-1}$. Thus, the model spread for the maximum strength of the southern Hadley cell is approximately as large as the magnitude of the annual cycle of the model mean. The model spread for the strength of the northern Hadley cell is smaller than the model spread for the strength of the southern Hadley cell. The difference between the strongest and weakest winter Hadley cells is about $150 \cdot 10^9$ kg s$^{-1}$ for this cell. At the same time, the magnitude of the annual cycle of the model mean is about $200 \cdot 10^9$ kg s$^{-1}$. Thus, the difference between the strongest and weakest winter Hadley cell is approximately 75% of the magnitude of the annual cycle of the model mean. The smallest model spread in the strength of the cells is found during the summer season of each hemisphere, when the cells are developed weakly.

These results indicate that the models differ much more than it was assumed at first sight of Figure 3.13. The discrepancies between the models are mainly caused by the varying representation of the Hadley circulation in the different models. Some models tend to develop generally weaker and smaller cells than others which exhibit stronger and larger cells (section 3.3.1). Similar results were found by Nguyen et al. (2013) who investigated the correlation between the strength and the width of the Hadley cells of eight reanalyses (their Figure 3b). The mean structures of the correlations of the CMIP5 simulations and the reanalyses that are investigated in Nguyen et al. (2013) look similar. However, the values of the strength and width of the Hadley cells vary between the two data sets. The Hadley cells in the idealised climate simulations are smaller and stronger.
than the cells in the reanalyses. Note that Nguyen et al. (2013) use a slightly different method to calculate the width and strength of the Hadley cells.

Figure 3.14 shows the correlation between the strength of the northern Hadley cell and the position of the northern descending edge of the cells as well as the correlation between the strength of the southern Hadley cell and the position of the southern descending edge of the cells for the CMIP5 ensemble as well as for the model mean. Note that the position of the northern edge is given in °N and the position of the southern edge is given in °S.

The shapes of the correlations for the northern and southern Hadley cells in Figure 3.14 differ much more than the shapes that are shown in Figure 3.13. A triangular shape of the curves is found for the northern Hadley cell. This is caused by a fast and strong weakening of the cell and slight equatorward shift of the northern descending edge during late boreal winter and spring, followed by a fast poleward shift at more or less constant strength of the cell during boreal summer. The third wing of the triangular shape represents a slower equatorward shift of the edge and intensification of the cell during boreal fall and early winter. The curves of the southern Hadley cell exhibit a more linear shape, though the curves exhibit a crossover between summer and winter.

The shapes of the correlations between the strength of the northern cell and the position of the northern descending edge and the correlation between the strength of the southern cell and the position of the southern descending edge already indicate that the first two indices are less correlated than the latter two indices. This is further supported by the correlation coefficients that are determined for each model of the ensemble. The

![Figure 3.14: Correlation between the monthly mean time series of the strength and the positions of the descending edges of the Hadley cells for the CMIP5 ensemble and the model mean. Positive values of the strength correspond to the northern Hadley cell, negative values to the southern Hadley cell. The position of the northern edge is given in °N, the position of the southern edge is given in °S.](image-url)
coefficients range between about -0.05 and -0.55 for the northern cell and between about
-0.6 and -0.95 for the southern cell. The model mean exhibits correlation coefficients of
about -0.4 for the northern cell and -0.9 for the southern cell.

Similar characteristics of the correlation between the strength and the position of
the edges of the two Hadley cells are found for the CMIP5 ensemble and the reanalysis
ensemble of Nguyen et al. (2013). As for the correlation between the strength and width
of the cells, the idealised climate models and the reanalyses exhibit different values of
the indices, though the shapes of the curves are analogous for the two ensembles. The
differences in the strength of the cells of the climate models and the reanalyses have
been discussed in the framework of Figure 3.13. Thus, the differences in the positions
of the two edges of the cells need to be investigated. It turns out that the edges
of the cells are located more equatorward for the CMIP5 model mean than for the
reanalysis model mean. This result agrees well with the findings that the cells of the
CMIP5 model mean are smaller and stronger than the cells of the reanalysis model mean.

Correlations between Hadley-indices of the $\omega$-approach

Both the correlations between the strengths and the widths of the cells and between
the strengths and the positions of the descending edges of the cells exhibit no obvious
single outliers for the CMIP5 ensemble (Figures 3.13 and 3.14). In contrast to this
result, the correlations between the strengths and the widths of the three branches of
the Hadley circulation exhibit clear outliers for all three correlations (Figure 3.15). One
striking outlier in the correlation of the northern hemisphere descending branch is the
GISS-E2-H (Figure 3.15, left panel). While all other models exhibit a weakening and
narrowing of the branch during boreal summer, this model shows a strengthening and
widening of the branch for the monthly mean time series.

The southern hemisphere descending branch also exhibits distinct outliers (Fig-
ure 3.15, right panel). The CNRM-CM5 and CNRM-CM5-2 exhibit a strongly distorted
shape of the line compared to most of the other simulations. This is caused by the fact
that these two models develop a stronger and much smaller branch during boreal sum-
mer than the other models of the ensemble. The difference in the widths of the branches
between the two CNRM models and the models which exhibit the greatest width of the
branch (e.g. BCC-CSM1-1-M, CCSM4, CESM1-BGC) is larger than 15°. These mod-
els are also outliers, which exhibit a wider and weaker branch than the majority of the
models and the model mean.

For the ascending branch, no clear structure of the annual cycle of the correlation
is visible (Figure 3.15, middle panel). The curve of the model mean exhibits several
crossovers during the year. The shape of the curves and the correlation coefficients
of about -0.65 to about 0.6 indicate that the two indices are weakly correlated. The
strengths and widths of the ascending branches are very differently represented in the
CMIP5 ensemble. The CSIRO-Mk3-6-0 is one of the outliers in the cloud of curves. For
the mean time series, this model develops a much stronger ascending branch than the
Figure 3.15: Correlation between the monthly mean time series of the strengths and widths of the branches of the Hadley circulation for the CMIP5 ensemble and the model mean.

In order to prove the large differences between the models of the CMIP5 ensemble, Figure 3.16 shows the correlation between the strength and the width of the ascending branch for four selected models for the time series that contain every time step of the simulation. The CMCC-CM exhibits the most linear shape of the ensemble for the correlation between the two indices (upper left panel). The CSIRO-Mk3-6-0, which was found to be a strong outlier in the correlation of the mean time series, exhibits a rather triangular shape with large spreads in the strength and width of the branch (upper right panel). The FGOALS-g2 shows a round shape (lower left panel). If the two outliers during a June and July are neglected, the model exhibits a very small spread for the width and strength of the branch during the year. A similar shape is found for the HadGEM2-ES (lower right panel). However, this models exhibits a larger spread in the width and strength of the branch.

3.3.3 Trends of the Hadley-indices

In section 3.3.1 and section 3.3.2 the similarities and discrepancies in the representation of the Hadley circulation in the CMIP5 ensemble were investigated. It was found that the mean structure of the circulation is similar for the ensemble, though differences in the representation of the circulation were found as soon as the Hadley-indices were investigated in detail. In this section, the trends of the Hadley-indices in a changing climate are analysed. The aim of the analysis is to quantify the model spread and to investigate whether there are robust trends among the models, even though the representation of the Hadley circulation varies among the models.

The intermodel spread of the CMIP5 ensemble is caused partially by different re-
Figures 3.16, 3.17, 3.18 and 3.19 show the decadal trends for the Hadley-indices based on the $\psi$-approach, whereas Figures 3.20, 3.21 and 3.22 show the decadal trends for the Hadley-indices based on the $\omega$-approach. The same colours are used for the same models in all six Figures. In addition, the bars of models that are part of the same modelling centre or institution exhibit the same colouring. Significant trends are marked
with a black diamond in all Figures. The intermodel spread for each index is quantified by the model mean (vertical red line) plus and minus the standard deviation of the ensemble (grey area).

**Investigation of the Hadley-indices based on the $\psi$-approach**

First, the decadal trends for the widths of the northern, southern and total Hadley cells are investigated (Figure 3.17). Positive trends correspond to a widening, negative trends to a narrowing of the cell. All models exhibit a significant widening of the southern and total Hadley cells (Figure 3.17, middle and right panels). Note that the trend for the total Hadley cell equals the sum of the trends for the northern and the southern Hadley cells. This is caused by the fact that the width of the total Hadley cell is defined as the sum of the width of the northern and the width of the southern Hadley cells.

The trends for the width of the northern Hadley cell are much smaller than the trends that are found for the width of the southern and total Hadley cells (Figure 3.17, left panel). In addition, the sign of the trend of the northern cell’s width is more uncertain than for the southern and total Hadley cells’ widths. Twelve models exhibit a significant widening of the northern Hadley cell, whereas three models show a significant narrowing of this cell. The trends of the remaining 13 models are too small to reject the null-hypothesis which is tested for the calculation of the p-value. Thus, they are classified as “not significant”. Three factors indicate that the northern Hadley cell also widens if the atmospheric CO$_2$ concentration is increased. These are, firstly, the fact that more models show a significant widening than a significant narrowing of the cell. Secondly, the model mean exhibits a widening of the cell of about 0.03° dec$^{-1}$ (degree per decade). Thirdly, the grey bar lies in large parts in the “positive” area that indicates a widening of the cell and only in a small part in the “negative” area that indicates a narrowing.

Though the sign of the trend for the northern cell is much more uncertain than the sign of the trend for the southern cell, the model spreads are similar. The grey bars cover areas of about 0.1° dec$^{-1}$ for both cells. The model spread for the total cell is slightly larger. It amounts to about 0.14° dec$^{-1}$.

If the trends for the widths of the northern and southern Hadley cells are ranked from the largest to the smallest values, the order of the models is not the same for the two cells. This means that two different models exhibit the largest widening trends for the northern and southern Hadley cells. The northern and southern Hadley cells of one model react differently to an increase of the atmospheric CO$_2$ concentration. Thus, a ranking of the models based on the magnitude of the trends is difficult, because it is strongly dependent on the reference. This applies for the trends of all six Hadley-indices. For this reason, the ranking of the models based on the trends of the Hadley-indices will not be further analysed in this thesis.

Different models of the same modelling centre or institution can show various trends for the width of the northern, southern and total Hadley cells. The two BCC-CSM1 models exhibit very similar trends for the southern and total Hadley cells (Figure 3.17,
3.3 Results for the CMIP5 ensemble

Figure 3.17: Trends for the widths of the northern (left panel), southern (middle panel) and total (right panel) Hadley cells for the CMIP5 ensemble. Significant trends are marked with black diamonds at the horizontal bars. The read vertical lines show the trends for the model means, the grey bars indicate the model spreads.

For the northern Hadley cell, however, the BCC-CSM1-1 model shows a significant widening of the cell whereas the BCC-CSM1-1-M shows a not significant slight narrowing (Figure 3.17, left panel). A different behaviour is found for the IPSL models. The trends for the width of the northern Hadley cell are similar for these models. Two out of three models show similar trends for the southern and total cells (IPSL-CM5A-LR, IPSL-CM5A-MR). The trends for the IPSL-CM5B-LR for these cells are only about half as large as for the other two models. This behaviour is probably caused by the fact that the IPSL-CM5B-LR model uses other physical parameterisations than the two IPSL-CM5A models. The FGOALS and NorESM models are examples for model simulations for which the responses of the widths of the Hadley circulations to a warming climate are similar among the different models of the same institution. Similar results are found for the other five Hadley-indices. They will not be discussed for every index, because the focus of the study lies on the model spread of the ensemble.

Previous studies used different data sets and, partly, other methods to quantify the changes of the width of the Hadley circulation in a changing climate. However, many of them also find a widening of the Hadley circulation in simple and comprehensive climate models as well as in reanalyses, though the magnitude of the trend is uncertain. Here, only some trends that are given in degree per decade are presented, because they are comparable to the widening that is found for the CMIP5 ensemble. Other studies quantify the widening in degree per Kelvin warming (e.g. Lu et al., 2007).

Based on the tropopause height that is determined from radiosonde data and reanal-
yses, Seidel and Randel (2007) identified a widening of the tropical belt of about 5-8° during 1979-2005, which corresponds to a trend of about 1.9-3° dec⁻¹. At the same time, Hu and Fu (2007) detect a widening of 2-4.5° since 1979 (about 0.7-1.7° dec⁻¹ for a 27 year period) in reanalyses and outgoing longwave radiation data sets. Similar widening trends were found by Hudson et al. (2006) using ozone data (about 1.1° dec⁻¹) and by Fu et al. (2006) who analysed the position of the jet streams which was derived from satellite data (about 0.8° dec⁻¹).

Most of these trends are about ten times the mean widening trend that was found for the total Hadley cell in the idealised CMIP5 experiment in this thesis (about 0.18° dec⁻¹). This indicates that the climate models underestimate the trends that are determined from reanalyses and observations, which is also stated in the IPCC AR5 (IPCC, 2013). However, one main aim of this thesis is to investigate if there are robust changes of the Hadley circulation. The widening of the circulation is one of the robust changes. Further investigations are needed to better estimate the magnitude of the widening in a future climate.

The analysis of the widening trends of the Hadley cells does not provide any information about the direction and strength of the shift of the individual edges of the cells and thus the cells themselves. This information can be deduced from the trends for the positions of the zero crossings of $\psi_{500}$ (Figure 3.18). Positive trends correspond to a northward shift of the respective edge, negative trends to a southward shift. A shift of both edges, of only one edge, or no shift of the edges of the cells is possible. Some of the possible shifts of the two edges of a cell and the resulting trend for the width of the cell are subsequently explained on the basis of the northern Hadley cell of the ACCESS1-3 model, the CMCC-CM model and the IPSL-CM5A-MR model.

The ACCESS1-3 model shows a significant narrowing of the northern Hadley cell (Figure 3.17, left panel). Both edges of this Hadley cell, the northern descending edge and the ascending edge, exhibit a northward shift (Figure 3.18, left and middle panels). The narrowing trend is caused by the fact that the northward shift of the southerly edge (the ascending edge) is stronger than the northward shift of the northerly edge (the northern descending edge) of this cell. Thus, the ascending edge approaches the northern descending edge, which results in a narrowing of the cell.

The CMCC-CM model exhibits a very small widening of the northern Hadley cell (Figure 3.17, left panel). As for the ACCESS1-3 model both edges of this Hadley cell exhibit a northward shift (Figure 3.18, left and middle panels). In contrast to the shifts of the two edges of the ACCESS1-3 model, the two edges of the CMCC-CM model exhibit similar trends for the shifts. The trend for the northern edge is slightly larger than the trend for the southern edge. This results in a small widening of the Hadley cell.

The IPSL-CM5A-MR model shows a significant widening of the northern Hadley cell (Figure 3.17, left panel). The northern descending edge exhibits a northward shift and the ascending edge exhibits a southward shift (Figure 3.18, left and middle panels). This results in a widening of the northern Hadley cell.
Figure 3.18: Trends for the positions of the northern descending edge (left panel), the ascending edge (middle panel) and the southern descending edge (right panel) of the CMIP5 ensemble. Significant trends are marked with black diamonds at the horizontal bars. The read vertical lines show the trends for the model means, the grey bars indicate the model spreads.

The comparison of all 28 models reveals that the two descending edges of the Hadley cells both exhibit a poleward shift for all models, which corresponds to a widening of the total Hadley cell (Figure 3.18, left and right panels). This is consistent with the results that are found for the widening trends of the total Hadley cell (Figure 3.17, right panel). The trends for the southern descending edge are larger than the trends for the northern descending edge for each individual model and for the model mean. This explains why all trends for the southern descending edge are significant, whereas for the northern descending edge 22 trends are significant. The model spreads for the trends for the positions of the two descending edges are similar. They amount to about 0.08° deg⁻¹ (NH descending edge) and about 0.1° deg⁻¹ (SH descending edge). As no trends indicate an equatorward shift of the two edges, the grey bars are entirely located in the areas which indicate a poleward shift of the edges. Thus, the sign of the shift of the two descending edges is robust among the models of the ensemble.

The trends for the position of the ascending edge are even smaller than the trends for the position of the northern descending edge for most of the models. Northward and southward shifts of this edge are found among the models. The trends that indicate a southward shift of the ascending edge are smaller than the trends that indicate a northward shift. This explains the mean trend and the magnitude of the model spread (about 0.06° deg⁻¹). None of the southward shifts are significant, whereas 14 models show a significant northward shift. Thus, the latter is more likely than the first. This is
further supported by the bar which represents the model spread, though the shift of the ascending edge is not as robust as the shifts of the two descending edges of the cells.

The next step of the model comparison is the analysis of a possible strengthening or weakening of the Hadley cells (Figure 3.19). Note that positive trends for the strength of the northern and southern cells describe opposing behaviours of the two cells. The strength of the northern Hadley cell is defined by maximum values of the mass stream function. Thus, a positive trend for the strength corresponds to a strengthening of this cell. However, the strength of the southern Hadley cell is defined by minimum values of $\psi$. For this reason, a positive trend for the strength of this cell correlates with a weakening of the cell, because the strength of the cell becomes less negative.

A significant weakening of the northern Hadley cell is indicated by 25 models, whereas one model exhibits a significant strengthening of this cell (Figure 3.19, left panel). Most of the weakening trends are larger than the two strengthening trends. At the same time, the weakening trends are very variable among the models. This explains the large model spread of about $0.84 \cdot 10^9 \text{kg s}^{-1} \text{dec}^{-1}$. Though, the model mean and the model spread indicate that a weakening of the northern Hadley cell is much more certain than a strengthening of the cell.

A significant weakening of the southern Hadley cell is shown by 16 models whereas five models show a significant strengthening (Figure 3.19, right panel). Most of the weakening trends are larger than the strengthening trends. The sole exception is the strengthening trend of the MPI-ESM-MR model (about $1.0 \cdot 10^9 \text{kg s}^{-1} \text{dec}^{-1}$). The

![Figure 3.19](image-url)
seven non-significant trends are very small and indicate almost no change of the Hadley cell’s strength. The fact that strengthening, weakening and almost no trends are found for changes in the strength of the southern Hadley cell, indicates that the changes of the strength of this cell are much more uncertain than the changes of the strength of the northern Hadley cell. This is further supported by the model spread of about $1.0 \cdot 10^9 \text{kg s}^{-1} \text{dec}^{-1}$, which allows, in conjunction with the model mean, a weakening or strengthening of the cell. This contrasts the results for the widening of the Hadley cells that is more robust for the southern than for the northern Hadley cell.

As already indicated in chapter 1, several studies investigated the changes in the width and strength of the Hadley circulation as well as the position of the edges of the Hadley cells. Depending on the data set and applied method, some of them also find a widening and weakening of the Hadley cells (e.g. Frierson et al., 2007; Lu et al., 2007; Gastineau et al., 2008; Lu et al., 2008; Gastineau et al., 2009; He and Soden, 2015), whereas others find a widening and strengthening of the Hadley circulation (e.g. Mitas and Clement, 2005). The first applies predominantly for the investigation of climate simulations whereas the latter applies for the investigation of reanalyses and observational data sets. Thus, the results of other studies that investigated climate simulations are in good agreement with the results of the investigation of the CMIP5 1pctCO2 experiment.

Investigation of the Hadley-indices based on the $\omega$-approach

The last step of the model comparison of the CMIP5 ensemble is the investigation of the decadal trends of the Hadley-indices that are based on the $\omega$-approach. Figure 3.20 shows the trends for the widths of the northern hemisphere (NH) descending branch, the ascending branch and the southern hemisphere (SH) descending branch of the Hadley circulation (from left to right). As for the trends for the width of the Hadley cells a positive trend corresponds to a widening, a negative trend to a narrowing of the branches.

All models show a significant widening of the southern descending branch of about $0.22^\circ \text{dec}^{-1} \pm 0.07^\circ \text{dec}^{-1}$. 22 models show a significant widening of the northern descending branch. The model spread of about $0.12^\circ \text{dec}^{-1}$ is slightly smaller than the spread for the width of the southern descending branch. One model shows a very small and thus not significant narrowing trend (NorESM1-M). Thus, the models agree well on a widening of the two descending branches, which indicates that the signal is robust. The widening trends for the southern descending branch are larger than the trends for the northern descending branch, which is also seen in the mean trends of about $0.09^\circ \text{dec}^{-1}$ (northern descending branch) and $0.22^\circ \text{dec}^{-1}$ (southern descending branch), respectively. This result matches well with the findings for the trends of the width of the Hadley cells based on the mass stream function. For them, the trends are also larger for the width of the southern cell.

The trends for the width of the ascending branch are not in such a good agreement as the trends for the width of the two descending branches (Figure 3.20, middle panel). A significant narrowing of the ascending branch is found for 14 models, four models
show a significant widening of this branch. A group of four models exhibits very small trends. Thus, half of the models show a significant narrowing of the ascending branch, whereas the other half show widening, narrowing or almost no trends. This indicates that a narrowing of the ascending branch is more likely among the models than a widening or no change of the width. This is further supported by the mean trend which indicates a narrowing of about 0.03 ° dec$^{-1}$.

The investigation of the trends for the positions of the zero crossings of $\omega_{500}$ reveals possible shifts of the branches (Figure 3.21). A positive trend for the position of an edge corresponds to a northward shift of the edge, a negative trend to a southward shift. All models show a significant poleward shift of the southern hemisphere descending edge. A similar result is found for the northern hemisphere descending edge, for which 20 models show a significant poleward shift. Only the NorESM1-M model exhibits a not-significant equatorward (southward) shift of the northern hemisphere descending edge. This model is also the only model which exhibits a narrowing trend for the width of the northern hemisphere descending branch (Figure 3.20, left panel). This narrowing is caused by a southward shift of both edges of this branch, whereas the southerly edge (NH ascending edge) shows a smaller trend than the northerly edge (NH descending edge).

The analysis of the trends of the two outer edges of the branches shows that the direction of the shifts of the two outer zero crossings is robust among the models (Figure 3.21, left and right panels). This robustness of the change is also found in
Figure 3.21: Trends for the positions of the northern descending edge (left panel), the northern ascending edge (second from the left panel), the southern ascending edge (second from the right panel) and the southern descending edge (left panel) for the CMIP5 ensemble. Significant trends are marked with black diamonds at the horizontal bars. The read vertical lines show the trends for the model means, the grey bars indicate the model spreads.

The mean trends of the models and the model spread for both edges. Most of the models show a poleward shift of the two outer edges and thus a widening of the total width of the branches of the Hadley circulation. This was also found for the direction of the shifts of the outer zero crossings of $\psi_{500}$ and the width of the total Hadley cell. The trends for the position of the southern hemisphere descending edge are larger than the trends for the position of the northern hemisphere descending edge for most of the models. This applies also for the mean trends. The sole exceptions are the FGOALS-g2 and the IPSL-CM5B-LR models which show the opposite behaviour. This is also in good agreement with the results for the shifts of the edges of the Hadley cells.

As for the trends for the position of the middle zero crossing of $\psi_{500}$, the directions of the shifts of the two ascending edges of the branches are not as robust and clear among the models as the results for the two outer edges of the branches (Figure 3.21). 13 models show a significant southward shift of the northern hemisphere ascending edge, five models show a significant northward shift of this ascending edge. A similar result is found for the southern hemisphere ascending edge, though northward shifts dominate this edge. Twelve models show a significant northward shift, five models a significant southward shift of the southern hemisphere ascending edge. The trends for the model means of the two ascending edges also indicate an equatorward shift of the two edges.
However, the model spreads indicate that both signs for the shifts are possible for both edges.

Finally, changes in the strengths of the two descending branches and the ascending branch are investigated (Figure 3.22). Note that positive trends for the strength of the ascending and descending branches indicate opposing behaviours of the branches. The strengths of the two descending branches are defined by the maximum values of the vertical pressure velocity. Thus, a positive trend for the strength of a descending branch corresponds to a strengthening of this branch. The strength of the ascending branch is defined by minimum values of the vertical pressure velocity. Positive trends for the strength of this branch, therefore, indicate a weakening of the branch, because the strength gets less negative.

Almost all models show a significant weakening of the two descending branches (Figure 3.22, left and right panels). The sole exception is the GISS-E2-H model which exhibits a significant strengthening of the southern hemisphere descending branch. The model spreads are small for both branches. Thus, the weakening of the descending branches is robust for the ensemble. The trends for the strength of the northern hemisphere and southern hemisphere descending branches are similar for each individual model and for the model mean. This contrasts the results for the trends of the widths of the two descending branches, which are larger for the southern hemisphere descending branch than for the northern hemisphere descending branch for most of the models (Figure 3.20). The weakening of the descending branches can be explained by an increase in the static stability of the atmosphere. A detailed analysis of this quantity and its influence on the strength of the descending branches is performed in section 4.3.1 on the basis of idealised aqua-planet simulations.

Again, the trends for the ascending branch are more uncertain than the trends for the two descending branches. This is apparent in the model spread, which is more than three times larger than the spread for the two descending branches. Half of the models show a significant weakening of the ascending branch, eight models exhibit a significant strengthening. This results indicate that a weakening of the ascending branch is more likely than a strengthening of this branch. This is also seen in the model mean. These results contradict the expectations that a narrowing of the ascending branch is linked to a strengthening of the branch. This behaviour is found for some models (CCSM4, CESM1-BGC, GFDL-ESM2M, GISS-E2-H, MRI-CGCM3, NorESM1-M, NorESM1-ME), but the majority of the models shows a narrowing and weakening or even a widening and weakening of the ascending branch.

The changes of the width and strength of the branches of the Hadley circulation in a changing climate have not been studied as extensively as the changes of the width and strength of the Hadley cells. Bony et al. (2013) analysed the effect of the atmospheric \( \text{CO}_2 \) concentration on the tropical circulation and regional precipitation. They found that about half of the circulation changes in the tropics are independent of an increase in global surface temperature. These changes are rather caused by a weaker net radiative cooling of the atmosphere owing to an increase of the atmospheric \( \text{CO}_2 \) concentration.
Figure 3.22: Trends for the strengths of the northern descending branch (left panel), the ascending branch (middle panel) and the southern descending branch (right panel) of the Hadley circulation for the CMIP5 ensemble. Significant trends are marked with black diamonds at the horizontal bars. The read vertical lines show the trends for the model means, the grey bars indicate the model spreads.

This affects the strength of vertical motions in the atmosphere. Bony et al. (2013) analyse the large-scale vertical motion of the atmosphere to explain the changes in precipitation patterns. In this thesis, the method by Bony et al. (2013) is applied to the 1pctCO2 CMIP5 simulations to check if the trends of the Hadley-indices are reproducible with another method.

Bony et al. (2013) calculate the monthly mean ascending ($\omega^\uparrow$) and descending ($\omega^\downarrow$) motions. The first step of the analysis is the calculation of the vertical mean of $\omega$ for each grid point equatorwards of 30° latitude. Afterwards, the mean vertical velocities are calculated for all positive (descending) values and all negative (ascending) values of the vertical pressure velocity. The strength of the tropical overturning circulation $I_c$ is then defined as the difference between the mean downward and upward vertical velocities:

$$I_c = \omega^\downarrow - \omega^\uparrow.$$  \hspace{1cm} (3.1)

Note that this definition of the strength of the tropical overturning circulation also contains influences of the Walker circulation. Using this method, the strengths of the Hadley and Walker circulations cannot be separated. The three indices $I_c$, $\omega^\downarrow$ and $\omega^\uparrow$ are referred to as “Bony-indices”.

The three Bony-indices are calculated for each time step. Afterwards a linear regression is performed for the time series of each index to receive the trends of the indices.
Finally, as for the six Hadley-indices, the decadal trends of the Bony-indices are determined. These trends are shown in Figure 3.23. As for the trends of the strength of the branches of the Hadley cells based on the $\omega$-approach, positive trends for the ascending and descending areas indicate opposing behaviours. Positive trends for the descending areas correspond to a strengthening of the circulation, positive trends for the ascending areas to a weakening of the circulation.

All models exhibit a significant weakening of the descending areas (Figure 3.23, left panel). This is consistent with the prior results for the trends of the strength of the descending branches (Figure 3.22, left and right panels). Exhibiting a small model spread, the weakening of the areas of descending motion is again a robust signal for the ensemble. The trends for the areas of ascending motion are again much more uncertain (Figure 3.23, middle panel). 16 models show a significant weakening of the areas of ascending motion, five models show a significant strengthening of the areas of ascending motion. Most of the weakening trends are larger than the strengthening trends. This explains why the model mean indicates a weakening of the areas of ascending motion. However, the model spread also allows strengthening trends. This is also in good agreement with the prior results, though the signs of the trends of the Bony-indices and the Hadley-indices do not agree for all models. Some of them show a weakening of the asc-

Figure 3.23: Trends for the strengths of the descending (left panel) and ascending (middle panel) areas as well as for the strength of the tropical overturning circulation (right panel) based on the method by Bony et al. (2013) for the CMIP5 ensemble. Significant trends are marked with black diamonds at the horizontal bars. The read vertical lines show the trends for the model means, the grey bars indicate the model spreads.
3.3 Results for the CMIP5 ensemble

cending areas based on the Bony-approach and, at the same time, a strengthening of the ascending branch based on the $\omega$-approach (e.g. GFDL-ESM2M, the IPSL models). The opposite behaviour, a strengthening of the ascending areas based on the Bony-approach and a weakening of the ascending branch based on the $\omega$-approach is also present for some models (e.g. BCC-CSM1-1-M, the MPI models).

The model spread for the change of the strength of the tropical overturning circulation is larger than many of the trends (Figure 3.23, right panel). This indicates that the magnitude of the trends for the strength of the circulation is much more uncertain than the magnitudes of the trends for the areas of ascending or descending motions. However, the model mean and most of the models show a weakening of the tropical overturning circulation, 25 of them with a significant trend. The sole model which exhibits a not-significant strengthening is the GISS-E2-H. The trends for the strength of the tropical overturning circulation can be compared to the trends for the strength of the Hadley cells based on the $\psi$-approach (Figure 3.19). The majority of the models show a significant weakening of the northern and southern Hadley cells. Thus, the results of the two methods agree well, even though some models exhibit a significant strengthening of the northern and southern Hadley cells based on the $\psi$-approach.

To sum up, the Hadley-indices and the Bony-indices deliver similar results. This indicates that the results of the analysis are reliable. The models agree well on the changes of the Hadley cells and the branches of the Hadley circulation that is caused by an external forcing, namely an increase in the atmospheric CO$_2$ concentration.
Chapter 4

Clouds On-Off Klima Intercomparison Experiment (COOKIE)

During the last decades, many studies investigated the impact of cloud radiative effects on the tropical circulation. They identified that these effects are important for the development and change of the circulation (e.g. Sherwood et al., 1994; Fermepin and Bony, 2014; Li et al., 2015). Su et al. (2014) emphasise the role of cloud feedbacks as a major source of uncertainties in model predictions. As cloud radiative effects are of great importance, they are analysed in this chapter to quantify their impact on changes in the Hadley circulation. In order to find robust influences of the cloud-radiation interactions, their effects are compared to the effect of a temperature increase. For this, idealised aqua-planet simulations from the Clouds On-Off Klima Intercomparison Experiment (COOKIE) (Stevens et al., 2012) are analysed with respect to changes in the Hadley cells’ widths and strengths as well as changes in the branches’ widths and strengths. Changes that are caused by an increase in the sea surface temperature will be separated from changes that are caused by cloud-radiation interactions.

In section 4.1 the model set-up is explained more in detail. The circulation in the aqua-planet configuration is more zonally symmetric than the circulation in the configuration with orography that was used for the analysis of the CMIP5 ensemble. For this reason, the methods that were developed for the CMIP5 ensemble had to be adjusted. The adjustments are summarised in section 4.2. Finally, the results of the analysis are shown in section 4.3 and discussed in section 4.4.

4.1 Data

In this chapter, idealised aqua-planet simulations are analysed with respect to changes in the Hadley circulation. The simulations are part of the Clouds On-Off Klima Intercomparison Experiment (COOKIE) that was initiated to determine robust effects of
cloud-radiation interactions and to facilitate physical understanding of the relevant processes (Stevens et al., 2012). The atmosphere-only simulations use zonally uniformly distributed sea surface temperatures (SSTs), following the “Qobs” profile. The SSTs of the “Qobs” profile exhibit a maximum of 27°C at the equator. They decline throughout the tropical and subtropical latitudes and are set to a constant value of 0°C poleward of 60° latitude. According to Neale and Hoskins (2001) this profile is the closest one to the observed Earth’s zonal-mean surface temperatures compared to other idealised aqua-planet sea surface temperature profiles.

To study the impact of clouds on climate and climate change, the COOKIE simulations contain two different specifications of clouds. In the first set-up, the “clouds-on” simulations, cloud-radiation interactions are not modified. In the second set-up, the “clouds-off” experiment, cloud-radiation interactions are disabled. Stevens et al. (2012) suggest two ways to perform the second set-up. Firstly, it is possible to make the clouds transparent in the call to radiation. This treatment is the safest and easiest way. The second option is to use clear-sky irradiances instead of all-sky irradiances for the calculation of surface and atmospheric heating. Though this method is more error-prone than the first one, Stevens et al. (2012) favour this second option. Note that clouds and precipitation can develop in the “clouds-off” experiment even if the clouds are made transparent to radiation.

In addition to the two specifications of clouds, two different warming states of the COOKIE simulations are analysed. The first warming state, which is hereafter referred to as the “Control” run, uses fixed “Qobs” sea surface temperatures. In the second warming state, which is called the “4K” run, the SSTs of the “Qobs” profile are uniformly raised by 4 K to simulate global warming (Taylor et al., 2009, 2012).

Both the different cloud specifications and the different warming states of COOKIE use fixed SSTs without a mixed-layer ocean. The atmospheric CO₂ concentration is set to 348 ppmv, which corresponds to the mean concentration of the AMIP (Atmospheric Model Intercomparison Project) (Gates, 1992) period. The models are run in perpetual equinoctial conditions without a seasonal cycle but with a diurnal cycle. Aerosols are either set to zero or are specified to not contribute to radiative transfer. In addition, sea ice is prohibited at high latitudes. Additional information about the experiment set-up is available from the technical reports of CMIP5 (Taylor et al., 2009, 2012) and COOKIE (Stevens et al., 2012).

Six modelling centres contributed their simulations of the two cloud configurations and two warming states of the aqua-planet configuration to COOKIE. The models are summarised in Table 4.1. Except for the MPI model, all modelling centres used the same model version as for CMIP5. The Max Planck Institute for Meteorology used a slightly newer version, which contains bug fixes, but the mean climate is not significantly altered compared to the older version used in CMIP5 (Fläschner, 2016).

Fläschner (2016) analysed the sea surface temperature profiles that are used in the COOKIE simulations. The author identified that some of the models do not use the “Qobs” profile, even though this is prescribed by the COOKIE protocol. Fläschner
(2016) describes that the MRI-CGCM3 model peaks at higher SSTs at the equator while the IPSL-CM5A-LR model exhibits lower equatorial SSTs than the “Qobs” profile. This complicates the comparison to the other models. The MIROC5 model uses different SST profiles in the clouds-on and clouds-off simulations. While the clouds-off simulations use the prescribed “Qobs” profile, the two clouds-on simulations show a SST profile with steeper gradients near the equator. This constrains the interpretation of the results of the MIROC5 model, since they might arise from the differing SST profiles (Fläschner, 2016).

The structure of the model output is the same as for the CMIP5 data set that is described in section 3.1. The data is available on gaussian grids with a monthly resolution (monthly means). The different spatial resolutions and the modelled time periods are summarised in Table 4.1. The horizontal and vertical resolutions of the six models are similar to the values of the corresponding models in Table 3.1 and Table 3.2. However, some models exhibit other vertical grid points than the CMIP5 models. Additionally, not all models that contribute to COOKIE were analysed as part of the CMIP5 1pctCO2 study. For these reasons, all six COOKIE models are summarised in Table 4.1, though some information doubles.

Most of the models exhibit five years of data (CNRM-CM5, MIROC5, MPI-CM5-LR, MRI-CGCM3, HadGEM2-A clouds-off Control and clouds-off 4K). The IPSL-CM5A-LR (clouds-on Control, clouds-off Control, clouds-off 4K) simulates seven years, HadGEM2-A (clouds-on Control and clouds-on 4K) 9.9 years, and IPSL-CM5A-LR (clouds-on 4K) 14 years. For the analysis of the Hadley circulation in the different simulations, the zonally averaged variables are averaged over all available time steps of the respective

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</tbody>
</table>

Table 4.1: Overview of the COOKIE models used in this thesis. The variables “lat” and “plev” indicate the latitude and the pressure levels, respectively. If the numbers vary between the four simulations of each model, all four numbers are listed in the table and separated by “/”. The order of the list meets the following: clouds-on Control, clouds-on 4K, clouds-off Control, clouds-off 4K. If only one number is given, it applies for all four simulations of the respective model.
As discussed in section 3.1, the different models have different horizontal and vertical resolutions. The two warming states and cloud configurations of each model exhibit, however, the same spatial resolutions, both in the horizontal and vertical direction. Except for the MRI-CGCM3 model, all models have 17 vertical grid points (pressure levels, "plev") which range from 1000 hPa to 10 hPa. The MRI-CGCM3 model has six more levels that reach pressure values of 0.4 hPa. The IPSL-CM5A-LR and the MPI-CM5-LR have the coarsest horizontal resolutions with 96 latitude grid points ("lat"). The MRI-CGCM3 exhibits the finest horizontal resolution by using 160 latitude grid points.

4.2 Adjustment of methods

Two main characteristics of the COOKIE simulations necessitate the adjustment of the methods that are presented in chapter 2. First, the circulation strongly responds to the absence of the orography. As the circulation on an aqua-planet is not disturbed by any effects that could be caused by the orography, the circulation is much more symmetric around the equator than the circulation on a planet with orography. Figure 4.1 shows the latitude-height cross sections of the mass stream function and vertical pressure velocity as means over all time steps of the MIROC5 model for the clouds-on Control and clouds-off Control simulations. The cross sections illustrate well that the Hadley circulation is arranged symmetric around the equator. As the COOKIE aqua-planet simulations do

![Figure 4.1: Latitude-height cross sections of the mass stream function $\psi$ in $10^9$ kg s$^{-1}$ (contours) and the vertical pressure velocity $\omega$ (colours) as a mean over all time steps of the MIROC5 model for the clouds-on Control (a) and clouds-off Control (b) simulations.](image)
not exhibit a seasonal cycle (section 4.1), the circulation is similarly developed during all simulated time steps. For this reason, it is easily possible to calculate time averages without the loss of any information about the shape and strength of the two Hadley cells and the three branches.

The second characteristic concerns the ascending branch of the circulation. Some of the COOKIE models, including MIROC5, develop a double Intertropical Convergence Zone (ITCZ) in the absence of cloud-radiation interactions. Figure 4.1 shows this behaviour. For the clouds-on configuration, the strongest ascending motion and the intersection of the two Hadley cells are located close to the equator. For the clouds-off configuration, the strongest ascending motion is separated by a region of weaker ascending air. This behaviour was extensively investigated by Harrop and Hartmann (2016), who analysed the connection between the tropical circulation and cloud radiative effects. They found that the equatorward contraction of the ITCZ in the clouds-on experiment compared to the clouds-off experiments is caused by the cloud radiative heating in the upper troposphere. This heating results in an increased temperature, a weakened CAPE and thus in a contraction of the convective regions. Table 4.2 summarises the characteristics of the ITCZ in the different cloud configurations and warming states of the six models of the COOKIE ensemble. The adjustments for the $\psi$-approach and the $\omega$-approach are depicted in section 4.2.1 and section 4.2.2, respectively.

Table 4.2: Overview of the characteristics of the ITCZ in the COOKIE simulations.

<table>
<thead>
<tr>
<th>Model</th>
<th>Clouds-off Control</th>
<th>Clouds-off 4K</th>
<th>Clouds-on Control</th>
<th>Clouds-on 4K</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNRM-CM5</td>
<td>double ITCZ</td>
<td>double ITCZ</td>
<td>double ITCZ</td>
<td>double ITCZ</td>
</tr>
<tr>
<td>HadGEM2-A</td>
<td>single ITCZ</td>
<td>single ITCZ</td>
<td>single ITCZ</td>
<td>single ITCZ</td>
</tr>
<tr>
<td>IPSL-CM5A-LR</td>
<td>double ITCZ</td>
<td>double ITCZ</td>
<td>double ITCZ</td>
<td>double ITCZ</td>
</tr>
<tr>
<td>MIROC5</td>
<td>double ITCZ</td>
<td>double ITCZ</td>
<td>double ITCZ</td>
<td>double ITCZ</td>
</tr>
<tr>
<td>MPI-CM5-LR</td>
<td>double ITCZ</td>
<td>double ITCZ</td>
<td>single ITCZ</td>
<td>single ITCZ</td>
</tr>
<tr>
<td>MRI-CGCM3</td>
<td>single ITCZ</td>
<td>single ITCZ</td>
<td>single ITCZ</td>
<td>single ITCZ</td>
</tr>
</tbody>
</table>

4.2.1 Meridional mass stream function $\psi$

As for the CMIP5 data (section 2.1), the meridional mass stream function $\psi$ is calculated for each time step from the monthly-mean zonal-mean meridional velocity $v$, using CDO commands (for documentation see Max-Planck-Institute for Meteorology, 2016). For all simulations of the different models, it is then averaged over all simulated time steps. Thus, a mean mass stream function latitude-height cross section is obtained for all four simulations of each model.

Contrary to the investigation of the CMIP5 simulations, it must be considered that some models exhibit a single ITCZ and some models a double ITCZ for the different cloud configurations (Table 4.2). This affects the detection of the positions of the edges of the Hadley cells. To account for that, the method that was used for the CMIP5 model output has to be adjusted. In the first step of the new analysis procedure, the
maximum horizontal extent of the Hadley cells in 500 hPa has to be determined. This extent is received by visual inspection of the latitude-height cross sections of the mass stream function for all models. The inspection reveals that the two Hadley cells are located poleward of 40° latitude in all simulations. In the next step, the positions of the zero crossings of the mass stream function at 500 hPa, $\psi_{500}$, are searched for between 40°S and 40°N. The different treatments for models which exhibit a single or double ITCZ are explained on the basis of the MPI-CM5-LR model.

Figure 4.2 shows the latitude-height cross sections of the mass stream function in contours and the vertical pressure velocity in colours as a mean over all time steps of the MPI-CM5-LR 4K simulations (upper panels of a) and b)). The values of $\psi_{500}$ are depicted in the middle panels. These values correspond to the values that are reached at the green lines in the respective upper panels. If the model exhibits a single ITCZ, which is the case for the clouds-on 4K simulation of the MPI-CM5-LR, three zero crossings are found in the latitude range between 40°S and 40°N (Figure 4.2, a)). In that case, the positions of all three zero crossings are used to define the edges of the two Hadley cells. In contrast to this, five zero crossings are found, if the model exhibits a double ITCZ. The double ITCZ characteristic of the MPI-CM5-LR clouds-off 4K experiment becomes especially apparent from the vertical pressure velocity at 500 hPa (lower panels of Figure 4.2 a) and b)). For this simulation five zero crossings of $\psi_{500}$ are found between 40°S and 40°N. The first and fifth zero crossings of $\psi_{500}$ correspond to the outer edges of the Hadley cells. The third zero crossing corresponds to the intersection of the two Hadley cells. The second and fourth zero crossings occur due to the development of a double ITCZ. These two zero crossings are caused by a weak local maximum and local minimum of $\psi_{500}$ close to the equator. Thus, the second and fourth zero crossings are neglected in the further analysis and the positions of the first, third and fifth zero crossings are set as the edges of the Hadley cells. The exact position of the zero crossings is again calculated using linear interpolation to account for the grid.

The width and strength of the two Hadley cells are defined as in section 2.1. The width of the southern Hadley cell is set as the distance between the southernmost and middle zero crossings of $\psi_{500}$, whereas the width of the northern Hadley cell is defined as the distance between the middle and northernmost zero crossings. The strength of the northern Hadley cell is specified as the maximum value of the mass stream function between the equator and 30°N within the pressure levels of 850-200 hPa. The strength of the southern Hadley cell is analogously defined as the minimum value of $\psi$ between 30°S and the equator within the same pressure levels.

4.2.2 Vertical pressure velocity $\omega$

For the detection of the position of the up- and downdrafts of the Hadley circulation, the methods that are described in section 2.6 had to be adjusted to ensure the analysis of the COOKIE aqua-planet simulations. Like the position of the Hadley cell’s edges, the position of the edges of the drafts are affected by the fact that the circulation is
Figure 4.2: Mean over all time steps of the MPI-CM5-LR model for the clouds-on 4K (a) and clouds-off 4K (b) simulations. The upper panels depict the latitude-height cross sections of the mass stream function $\psi$ in $10^9 \text{kg s}^{-1}$ (contours) and the vertical pressure velocity $\omega$ (colours). The middle panels of a) and b) show $\psi_{500}$ and the lower panels show $\omega_{500}$. 
more symmetric than in the CMIP5 simulations and by the development of a double ITCZ in some simulations. For the analysis of the Hadley circulation’s branches, the vertical pressure velocity $\omega$ is averaged zonally. Afterwards time averages are calculated to obtain a mean circulation pattern for each of the four simulations of the different models.

The fact that some models exhibit a single ITCZ whereas others exhibit a double ITCZ affects the detection of the positions of the zero crossings of the vertical pressure velocity at 500 hPa, $\omega_{500}$. As mentioned above, Figure 4.2 shows the latitude-height cross section of the mass stream function in contours and the vertical pressure velocity in colours as a mean over all time steps of the MPI-CM5-LR model for the clouds-on 4K and the clouds-off 4K configurations (upper panels of a) and b)). The values of $\omega_{500}$ are illustrated in the lower panels of a) and b). The values correspond to the values that are reached at the green line in the upper panels. The MPI-CM5-LR model exhibits a strongly developed double ITCZ for the clouds-off 4K configuration, whereas the clouds-on 4K configuration shows a single ITCZ with a strong ascending motion close to the equator.

The MPI-CM5-LR (clouds-off 4K) model is the only model that shows a weak downdraft within the updraft at 500 hPa, if the mean over all time steps is considered. Several of the other analysed simulations also exhibit a double ITCZ (Table 4.2). For them, the weak downdrafts, which occur occasionally within the updraft regions, are located at higher pressure levels around 200 hPa. Thus, the downdrafts within the updraft regions do not affect the detection of the zero crossings of $\omega_{500}$ for all simulations except for the MPI-CM5-LR clouds-off 4K run. As the behaviour of the MPI-CM5-LR clouds-off 4K simulation is unique within the analysed model ensemble, it was decided to add the horizontal extent of the weak downdraft to the updraft region, to be consistent within the analysis. Thus, the two middle zero crossings of $\omega_{500}$ are ignored for the detection of the edges of the up- and downdrafts.

An adjusted method was applied to detect the edges of the up- and downdrafts of the Hadley circulation. The first step of the analysis is to find the zero crossings of $\omega_{500}$ for all latitudes. Afterwards, the position of the minimum value of $\omega_{500}$ is determined for each hemisphere between the equator and 30° latitude. The minimum values are determined separately for both hemispheres to account for possible weak downdrafts near the equator, if the simulation exhibits a double ITCZ. The area of the weak downdraft would thus be added to the region of the updraft. As explained above, this is only important for the MPI-CM5-LR clouds-off 4K simulation. The two zero crossings that are located northwards of the northern minimum (“C” and “D” in Figure 4.2) and southwards of the southern minimum (“A” and “B” in Figure 4.2) are set as the four edges of the up- and downdrafts. If the model exhibits a single ITCZ with one strong updraft around the equator, the two minimum values lie around the equator and belong to the same peak in $\omega_{500}$ (Figure 4.2, a)). The exact position of the zero crossings is then again calculated by using linear interpolation to account for the grid.

The width and strength of the ascending and descending branches of the Hadley
4.3 Results for the COOKIE ensemble

In this section, the response of the Hadley circulation to two different forcings is investigated. The investigation is based on the idealised aqua-planet simulations of the Clouds On-Off Kclimate Intercomparison Experiment. The two forcings are, first, a uniform increase of the sea surface temperature by 4 K and, second, the inclusion or neglecting of cloud-radiation interactions. The first is referred to as "temperature effect" (section 4.3.1), the latter as "cloud-effect" (section 4.3.2).

The investigation of the trends of the Hadley-indices of the CMIP5 ensemble revealed that some of the trends are much more certain and robust than others. One main aim of the "temperature effect" analysis is to investigate if the robust responses of the Hadley circulation to an increasing atmospheric CO₂ concentration are also found for a uniform temperature increase. This is also an aim of the "cloud effect" analysis. Another major aim of this investigation is the detection of uncertainties which are caused by a lack of understanding of cloud-radiation interactions.

4.3.1 Temperature effect

The Hadley circulation in the COOKIE ensemble is investigated under two main aspects. In this section, the "temperature effect" is analysed. For this, the response of the Hadley circulation to a uniform increase of the sea surface temperature by 4 K is investigated for both cloud configurations by comparing the Hadley-indices that are determined from the Control and from the 4K simulations. The changes of the Hadley-indices between the two simulations that are compared to each other are considered as "trends" of the indices.

Investigation of the Hadley-indices based on the ψ-approach

First, the responses of the Hadley-indices based on the ψ-approach are analysed. Figure 4.3 shows the widths (upper panel) and strengths (lower panel) of the Hadley cells as well as the positions of the ψ₅₀₀ zero crossings (middle panel) for all four simulations of each of the six models that take part in the experiment. The markers of the Control and 4K simulations are connected for both cloud configurations of the individual models. This simplifies the analysis of the "temperature effect" at first sight of the Figure.

The uniform temperature increase causes a widening of the northern, southern and total Hadley cells for both cloud configurations for most of the models (Figure 4.3, upper panel). Only the MPI-CM5-LR model exhibits a narrowing of the southern Hadley cell.
Figure 4.3: Effect of a temperature increase on the Hadley-indices based on the $\psi$-approach: width of the Hadley cells (upper panel), position of the edges of the cells (middle panel), and strength of the Hadley cells (lower panel).
for the clouds-off simulation. The model spread of the clouds-on experiments is much smaller than the model spread of the clouds-off simulations for all three cells. In addition, the trends that are found for the clouds-on experiments are similar for all six models and all three cells.

A different behaviour is found for the response of the width of the Hadley cells in the clouds-off simulations. These simulations exhibit a larger model spread and differing trends for the width of the Hadley cells in a warmer climate. The MPI-CM5-LR model exhibits a considerably larger widening trend for the northern Hadley cell than the other five models. This large trend is caused by a substantial southward shift of the ascending edge of this model by more than 2° latitude (middle panel of Figure 4.3). The remaining five models exhibit smaller trends which are at most half as large as the trend for the MPI-CM5-LR.

Four models show a northward shift of the ascending edge in the clouds-off experiment (HadGEM2-A, IPSL-CM5A-LR, MIROC5, MRI-CGCM3), two models show a southward shift (CNRM-CM5, MPI-CM5-LR). The clouds-on simulations reveal a similar uncertainty for the direction of the shift of the ascending edge. Again, four models exhibit a northward shift and two models a southward shift, though the direction of the shift is reversed for some models compared to the clouds-off simulations. For the clouds-on experiment the CNRM-CM5 model shows a northward shift and the MRI-CGCM3 model a southward shift. The directions of the shifts of the remaining models are equal to the direction that is found for the clouds-off simulations.

The directions of the shifts of the two descending edges are much more certain among the models than the directions of the shifts of the ascending edges (Figure 4.3, middle panel). All models exhibit a poleward shift of the two descending edges for the clouds-on as well as for the clouds-off simulations. Except for the MPI-CM5-LR clouds-off simulation, the trends for the position of the northern hemisphere descending edge and the trends for the width of the northern Hadley cell are similar for both cloud configurations. This is caused by the slight shifts of the ascending edges for most of the models. The same accounts for the trends for the width of the southern Hadley cell and the trends for the position of the southern hemisphere descending edge for most of the simulations. Exceptions for this behaviour are found in the clouds-off experiments of the MPI-CM5-LR and the MIROC5 models.

As for the trends for the width of the cells, the model spreads for the trends for the positions of both descending edges are smaller for the clouds-on than for the clouds-off experiments. However, most of the models exhibit similar trends for the positions of the descending edges in a warmer climate for both cloud configurations. Only the CNRM-CM5 clouds-off simulation shows much smaller trends than the other models.

The strengths of the Hadley cells in the clouds-off and clouds-on experiments are very different (Figure 4.3, lower panel). However, all simulations except for the MPI-CM5-LR clouds-on simulation indicate a weakening of the northern and southern Hadley cells for both cloud configurations. The MPI-CM5-LR clouds-on simulation exhibits a strengthening of both Hadley cells. The investigation of the Hadley cells’ strengths
reveals that the six COOKIE models form two clusters for the clouds-on simulations and three clusters for the clouds-off simulations. These clusters arise, because some of the models exhibit a single ITCZ and others a double ITCZ for the different configurations. The two Hadley cells are stronger if a model has a single ITCZ and weaker if the model has a double ITCZ. As already indicated in Table 4.2, the HadGEM2-A, MIROC5, MPI-CM5-LR and MRI-CGCM3 exhibit a single ITCZ for the clouds-on simulations, whereas the CNRM-CM5 and IPSL-CM5A-LR exhibit a double ITCZ. The MIROC5 and MPI-CM5-LR change over to a double ITCZ in the clouds-off experiment. Thus, the Hadley cells are remarkably weaker in the clouds-off than in the clouds-on simulations for these two models.

Compared to the other five models, the CNRM-CM5 exhibits very weak Hadley cells in the clouds-off simulations. The strengths of the northern and southern Hadley cells do hardly change in a warmer climate for this cloud configuration. The large weakening of the circulation in the clouds-off experiment compared to the clouds-on experiment owes to the fact that the double ITCZ of this model strongly intensifies in the clouds-off simulations compared to the clouds-on simulations. This behaviour is observable in Figure 4.4, which shows the characteristics of the Hadley circulation for the clouds-on Control (left) and clouds-off Control (right) simulations. In the clouds-off Control experiment the updrafts are weaker and the peaks of ω500 are located further away from each other compared to the clouds-on Control experiment. This results in wider and
weaker Hadley cells, a weaker and wider updraft and weaker and narrower downdrafts in the clouds-off compared to the clouds-on experiment.

So far, the responses of the Hadley-indices that are based on the $\psi$-approach have been analysed. The analysis revealed that the changes of the width and strength of the cells as well as of the positions of the descending edges are robust for both cloud configurations. The sole exception is the shift of the ascending edge which varies greatly between the different models. Most of the models show a widening and weakening of the Hadley cells for both cloud configurations. This widening is mainly caused by a poleward shift of the two outer edges of the cells. However, the model spreads for the width of the cells and the positions of the $\psi_{500}$ zero crossings are much smaller for the clouds-on than for the clouds-off simulations.

Investigation of the Hadley-indices based on the $\omega$-approach

The next step of the analysis of the “temperature effect” is the investigation of the responses of the Hadley-indices that are based on the $\omega$-approach. Most of the three indices exhibit similar model spreads and thus uncertainties for the clouds-on and clouds-off simulations (Figure 4.5). The responses of the three Hadley-indices to an increase of the surface temperature are analysed in detail for both cloud configurations.

The northern and southern hemisphere descending branches of the Hadley circulation exhibit a widening for both cloud configurations for most of the models (Figure 4.5, upper panel). Only the CNRM-CM5 exhibits a narrowing of the northern hemisphere descending branch for the clouds-off simulation. In contrast to the results for the width of the two Hadley cells (Figure 4.3, upper panel), the model spread for the width of the two descending branches are similar for the clouds-on and clouds-off simulations. The spread for both cloud configurations is larger than for the clouds-on simulation for the width of the Hadley cells. This indicates that the characteristics of the mass stream function are much more similar among the models than the vertical velocities.

The model spread for the ascending branch’s width is larger than the spread for the widths of the two descending branches. At the same time, it is very similar for the clouds-on and clouds-off experiments. However, the trends for the width of the ascending branch are smaller and more uncertain than the trends for the width of the two descending branches. For the clouds-off simulations, three models exhibit a widening of the ascending branch (IPSL-CM5A-LR, MIROC5, MPI-CM5-LR), two models exhibit a narrowing (HadGEM2-A, MRI-CGCM3) and one model exhibits almost no trend for the width of this branch (CNRM-CM5). At the same time, four models show a widening of the ascending branch in the clouds-on experiment (CNRM-CM5, IPSL-CM5A-LR, HadGEM2-A, MIROC5), one model shows a narrowing (MPI-CM5-LR) and one models exhibits almost no trend (MRI-CGCM3). Thus, the MIROC5 and IPSL-CM5A-LR models are the only models which indicate a clear widening of the ascending branch in a warmer climate for both cloud configurations. The fact that more models exhibit a widening and not a narrowing of the ascending branch, indicates that this behaviour of
Figure 4.5: Effect of a temperature increase on the Hadley-indices based on the $\omega$-approach: width of the branches (upper panel), position of the edges of the branches (middle panel), and strength of the branches (lower panel).
the width of the ascending branch is more likely in a warmer climate.

The two outer edges of the branches based on $\omega_{500}$ (Figure 4.5, middle panel) show a similar behaviour as the two outer edges of the cells based on $\psi_{500}$ (Figure 4.3, middle panel). Most of the models exhibit a poleward shift of the two outer edges of the branches for both cloud configurations. The sole exception is the northern hemisphere descending edge of the CNRM-CM5 model, which exhibits an equatorward shift in the clouds-off simulation. This model and simulation shows also the smallest trend for the shift of the southern hemisphere descending edge. All other models show very similar trends for the shifts of the two outer edges for both cloud configurations. However, the model spread for the clouds-off simulations is larger than the model spread that is found for the clouds-on simulations. This is also in good agreement with the results for the shifts of the outer edges of the Hadley cells (Figure 4.3, middle panel).

The positions of the two ascending edges exhibit smaller trends than the positions of the descending edges for both cloud configurations. As for the ascending edge of the Hadley cells, the directions of the shifts of the two ascending edges of the branches are much more uncertain than the directions of the shifts of the descending edges. Four models exhibit a poleward shift of the northern hemisphere ascending edge (CNRM-CM5, IPSL-CM5A-LR, HadGEM2-A, MIROC5) and two models exhibit an equatorward shift of this edge (MPI-CM5-LR, MRI-CGCM3) for the clouds-on experiment. A similar behaviour is found for the southern hemisphere ascending edge of this experiment. Five models show a poleward shift and only the MPI-CM5-LR model shows an equatorward shift of this edge.

The model ensemble exhibits an even larger uncertainty for the shifts of the two ascending edges for the clouds-off experiment. Both ascending edges move poleward in the simulations of the IPSL-CM5A-LR, MIROC5, and MPI-CM5-LR. This results in a widening of the ascending branch for these models. The two ascending edges are shifted equatorwards in a warmer climate for two models (HadGEM2-A, MRI-CGCM3), which results in a narrowing of the ascending branch for these two models. The CNRM-CM5 model exhibits very weak poleward shifts of the two ascending edges. Thus the width of the ascending branch hardly changes for this model.

To sum up, the models exhibit similar trends for the positions of the different edges, but the actual positions of the edges vary a lot among the models. The latter applies especially for the positions of the ascending edges. A similar result is found for the strength of the ascending and descending branches of the Hadley circulation (Figure 4.5, lower panel). Especially for the two descending branches most of the models exhibit similar weakening trends, whereas the absolute strength of the branches is very variable among the models.

In contrast to the strength of the two Hadley cells, the strength of the three branches do not deliver information about the characteristics of the ITCZ of the single models for most of the simulations. Although the model spread is relatively large for both cloud configurations, the models are not clustered as in the lower panel of Figure 4.3. Instead, the strengths of the models are evenly distributed for most simulations and branches.
The sole exception of this behaviour is found in the strength of the ascending branch of the clouds-on simulation, for which a clustering of the four models that exhibit a single ITCZ and the two models that exhibit a double ITCZ is found.

Corresponding to the widening of the two descending branches that was determined for most models, the two descending branches exhibit a weakening for most models for both cloud configurations. The sole exception is again the CNRM-CM5 model, which exhibits a slight strengthening of the two branches for the clouds-off experiment. The changes in the strength of the ascending branches are again much more uncertain than the changes in the strength of the two descending branches. Four models exhibit a weakening (CNRM-CM5, IPSL-CM5A-LR, MIROC5, HadGEM2-A) and two models a strengthening (MPI-CM5-LR, MRI-CGCM3) of the ascending branch for the clouds-on experiment. For the clouds-off experiment the CNRM-CM5 model also shows a strengthening of the ascending branch. Thus, three models indicate a strengthening and three models a weakening of the ascending branch in this experiment. The comparison of the changes of the strength and the width of the ascending branch reveals a contradictory behaviour for some simulations. The MPI-CM5-LR, for example, shows a widening and strengthening of the ascending branch, whereas others exhibit a narrowing and weakening (HadGEM2-A clouds-off). This result suggests again that the trends in the width and strength of the ascending branch are not as robust and certain as the trends in the width and strength of the descending branches of the Hadley circulation.

To sum up, the analysis of the responses of the Hadley-indices based on the $\omega$-approach revealed that the changes of most indices are robust for both cloud configurations. A widening and weakening of the descending branches is predicted by almost all models for both cloud configurations. The widening of the descending branches is mainly caused by a poleward shift of the two outer edges of the branches, whereas the shifts of the two ascending edges are much more uncertain. In addition, the changes in the width and the strength of the ascending branch are uncertain for both cloud configurations. The magnitude of the trends are largely independent of the cloud configurations. However, the values for the width, strength and position of the edges of the branches vary a lot between the different models.

The weakening of the descending branches of the Hadley circulation, quantified by changes in the vertical pressure velocity $\omega$, can be explained through changes in the static stability $\sigma$ and changes in the cooling rate $Q$. Zelinka and Hartmann (2010), for example, use the following definition of the vertical pressure velocity to explain changes in the strength of the vertical velocity in tropical regions:

$$\omega = \frac{Q}{\sigma}.$$  \hfill (4.1)

This definition is valid for stable stratified atmospheres and assumes no tendency or horizontal transport. In addition, it only applies for convection free regions, for which the surface sensible heat flux and the latent heat flux are negligible (Zelinka and Hartmann, 2010). Thus, it is not applicable for the updraft regions of the Hadley circulation.
The static stability can be described through equivalent terms. It is, for example, inversely proportional to changes of the potential temperature $\theta$ with height:

$$\sigma = -\frac{T}{\theta} \frac{\partial \theta}{\partial p} = \frac{\kappa T}{p} - \frac{\partial T}{\partial p} = \frac{\Gamma_d - \Gamma}{\rho g} = \frac{\kappa T}{p} \left(1 - \frac{\Gamma}{\Gamma_d}\right).$$

(4.2)

In these equations, $\kappa = R_d/c_p$ is the ratio of the gas constant of dry air and the specific heat of air at constant pressure, $\Gamma_d$ the dry adiabatic lapse rate, and $\Gamma$ the actual lapse rate. The variables $T$, $p$ and $g$ describe the temperature, the pressure, and the gravitational acceleration, respectively. In this thesis, the term after the second equality sign is used to calculate static stability profiles for every latitude that is resolved by the models. For this, temperature profiles from the COOKIE simulations are used.

The changes of the vertical pressure velocity, the static stability and the cooling rate in the descending branches of the Hadley circulation are similar for all models of the COOKIE ensemble. For convenience, they are described on the basis of the HadGEM2-A model in the following analysis. The first step of the investigation is the analysis of the latitude-height cross sections of the three variables for the four simulations (Figure 4.6). The knowledge of the structure of the variables facilitates the understanding of the relative changes of the three quantities, which is the second step of the analysis (Figure 4.7). The relative changes of the quantities are calculated as follows:

$$x_{rel} = \frac{x_{4K} - x_{Control}}{x_{Control}}.$$  

(4.3)

The variable $x$ is a place holder for $\omega$, $\sigma$ and $Q$, respectively. The subscripts $4K$ and Control refer to the 4K simulations and the Control simulations. The relative change of the quantity, $x_{rel}$, is calculated for both cloud configurations.

As described above, the HadGEM2-A exhibits a single ITCZ for both cloud configurations and thus a strongly pronounced updraft (Figure 4.6, upper panel). This updraft weakens in a warmer climate for both cloud configurations, though it exhibits a narrowing for the clouds-off experiment and a widening for the clouds-on experiment. The descending branches exhibit a widening and weakening in a warmer climate for both cloud configurations (see also Figure 4.5).

The exact latitude and height of the weakening and strengthening of the branches can be deduced from the upper panel of Figure 4.7, which shows the relative changes of the vertical pressure velocity for both cloud configurations. Blue colours indicate negative relative changes of $\omega$ and thus a weakening of the circulation. Red colours indicate positive relative changes of $\omega$ and thus a strengthening of the circulation. The magenta and cyan contours represent the zero isolines of $\omega$ for the Control and 4K simulations, respectively. A weakening is found throughout most parts of the descending branches. Only the regions around the zero isolines of $\omega$ exhibit large positive values which are caused by a changing sign of the vertical velocity between the Control and 4K simulations in these regions.
Figure 4.6: Latitude-height cross sections of the vertical pressure velocity $\omega$ (upper panel), the static stability $\sigma$ (middle panel), and the cooling rate $Q$ (lower panel) for the four simulations of the HadGEM2-A.

Compared to the vertical pressure velocity, the static stability $\sigma$ exhibits a homogeneous and simple structure throughout most parts of the troposphere (Figure 4.6, middle panel). The values range between around 0.0 K hPa$^{-1}$ and around 0.1 K hPa$^{-1}$ for most parts of the latitude-height cross section. The stability increases rapidly in heights above around 200 hPa, where the tropopause is found and the stratosphere begins. The middle panel of Figure 4.7 shows the relative changes of the static stability in a warmer climate as it is simulated for both cloud configurations. The static stability increases in a warmer climate for heights below around 200 hPa. Above around 200 hPa the static stability exhibits a strong decrease. This is approximately the height of the tropopause and thus the maximum height of the Hadley cells.

The model output does not provide any information about the cooling rate $Q$. Thus, the cooling rate has to be calculated. There are two main possibilities to do this. First, radiation models can be used. This can be complicated, because the presence of clouds in the areas of descending air might strongly influence the calculated cooling rates (see references in Zelinka and Hartmann (2010)). A much easier approach is the application of equation 4.1. The application of this equation is also error-prone, because it assumes that no other factors than the cooling rate and the static stability influence the vertical pressure velocity. This assumption has not been verified in this thesis. However, the second approach was applied in this thesis, because the exact values of the cooling rate were not of interest. Instead, the relative changes of the cooling rate are important to explain which factor, the static stability or the cooling rate, dominates the changes in the vertical pressure velocity.

The latitude-height cross sections of the calculated cooling rates are shown in the lower panel of Figure 4.6 to get an overview of their mean structure. Due to the homogeneous structure of the static stability, the structure of the cooling rate correlates
well with the structure of the vertical pressure velocity. The descending branches of the Hadley circulation exhibit a cooling throughout the whole latitude area and for all heights below around 200 hPa. This cooling is approximately constant with height. Consistent with the results of Zelinka and Hartmann (2010), who calculated the cooling rates with a radiation model, the values of the cooling rate decrease in the upper troposphere above around 200 hPa and reach negative values, corresponding to a radiative warming, above around 100 hPa height. Though, a heating of the regions of ascending motions is plausible, these regions must not be examined in detail, because equation 4.1 applies only for non-convective regions. This heating is caused predominantly by latent heat release through condensation of water vapour.

The latitude-height cross sections which show the relative change of the cooling rate in a warmer climate, indicate almost no change of the cooling rate in the centre of the descending branches at around $10^\circ$ to $30^\circ$ latitude in both hemispheres and for both cloud configurations (Figure 4.7, lower panel). The greater the distance to the core of the branches, the larger the relative changes of $Q$ are. These changes imply larger cooling rates in a warmer climate at the outer edges and at the top of the branches.

The comparison of the relative changes of $\sigma$ and $Q$ reveals that the changes in the static stability are much larger than the changes in the cooling rate throughout large regions of the descending branches (Figure 4.7). This indicates that the changes in the static stability dominate the changes in the vertical pressure velocity. According to equation 4.1, a larger relative change in $\sigma$ than in $Q$ indicates a negative relative change of $\omega$. This behaviour is confirmed by the determined relative changes of $\omega$ (Figure 4.7, upper panel).
Investigation of spatial changes of $\psi$ and $\omega$

So far, the Hadley circulation and its changes in a warmer climate have been quantified by analysing the values and trends of the six Hadley-indices. These indices represent single points of the $\psi$ latitude-height cross section and the $\omega$ latitude-height cross section. Thus, the analysis of the Hadley-indices does not deliver any information about changes in the structure of the cells or branches. For this reason, the changes in the latitude-height cross sections of the mass stream function and the vertical pressure velocity are shown in Figure 4.8 and Figure 4.9 for both cloud configurations. The contours correspond to the values of the Control simulation. They are used as reference for the changes in $\psi$ and $\omega$. The colours show the difference between the 4K and the Control simulation. Thus, positive values for the change of the mass stream function, $\Delta \psi$, indicate that the $\psi$-value of the 4K simulation is larger than the value of the Control simulation. Negative values indicate inverse behaviour. The same applies for changes in the vertical pressure velocity, $\Delta \omega$. The latitude-height cross sections are shown exemplarily for the simulations of the IPSL-CM5A-LR, the MPI-CM5-LR and the MRI-CGCM3. Thus, the analysis includes a model which exhibits a double ITCZ for all simulations (IPSL-CM5-LR), a model which exhibits a single ITCZ for the clouds-on and a double ITCZ for the clouds-off simulations (MPI-CM5-LR), and a model which exhibits a single ITCZ for all simulations (MRI-CGCM3).

At first sight, the most obvious changes in the latitude-height cross sections of $\psi$ in the clouds-off simulations are the positive changes in the southern Hadley cell and the negative changes in the northern Hadley cell (Figure 4.8, left panel). These changes indicate a weakening of the two Hadley cells for all three models. Compared to the Control simulation, the weakening is found throughout the whole cells for the IPSL-CM5A-LR and the MRI-CGCM3. The strongest weakening is found at around 300 hPa height for these two models. Negative changes are found at the cells' poleward edges. These negative changes indicate a widening of the Hadley cells.

The changes in the MPI-CM5-LR model are distributed differently than the changes in the other models. The strongest weakening is found equatorwards of the cells' centres, whereas a strengthening of the northern and southern cells is found polewards of the cells' centres. This applies especially for the southern Hadley cell. These changes of $\psi$ indicate a southward shift of the southern Hadley cell for the MPI-CM5-LR model. These results for the three models show that the changes of the latitude-height cross sections of $\psi$ agree well with the results for Hadley-indices (Figure 4.3).

Similar results as for the clouds-off simulations are found for the clouds-on simulations of the IPSL-CM5A-LR and the MRI-CGCM3 models (Figure 4.8, right panel). Both models exhibit a widening and weakening of the two Hadley cells. The same applies for the two models that are not shown here. The sole exception is the MPI-CM5-LR model which shows a strengthening of the circulation equatorwards of the cells' centres and a weakening polewards of the cells' centres. This is again in good agreement with the results that are found for the Hadley-indices. Based on the Hadley-indices, the MPI-
CM5-LR model is the only model that exhibits a strengthening of the two Hadley cells in the clouds-on experiment (Figure 4.3).

The fact that the MPI-CM5-LR model shows the same signs for the changes of the Hadley circulation in the clouds-off experiment, but different signs for the changes in the clouds-on experiment, indicates that the cloud-radiation interactions are represented differently in this model compared to the other five models that take part in COOKIE. This would explain, why the MPI-CM5-LR model is the sole model which exhibits a strengthening of the Hadley circulation in a warmer climate for the clouds-on experiment. For the clouds-off experiment, for which the cloud-radiation interactions are neglected, the trends for the strength of the circulation have the same sign as for the other five models. This would also explain, why the MPI-ESM-MR and for some indices also the MPI-ESM-LR are clear outliers in the CMIP5 ensemble (section 3.3).

One aspect under which the Hadley circulation has not been investigated so far in this thesis is the vertical dimension of the Hadley cells. The analysis of the latitude-height cross sections of the mass stream function facilitates this investigation. Whereas a weakening of the Hadley cells is found for pressure levels between about 925 and 250 hPa, a strengthening of the circulation is found for pressure levels above about 250 hPa for all models and both cloud configurations. This indicates a vertical expansion of the Hadley cells in a warmer climate. This result is independent of cloud-radiation interactions and is also found for the branches of the Hadley cells (Figure 4.9). As for the Hadley cells, the vertical expansion of the branches takes place at pressure levels above about 250 hPa. Below this pressure level the models behave differently, especially in the regions
of ascending air.

In both cloud configurations, all shown models exhibit a weakening throughout the whole region of descending air (Figure 4.9). A positive change of the vertical pressure velocity is found at the poleward edges of the descending branches for all models. This positive change indicates a widening of the two descending branches. This is in good agreement with the results of the Hadley-indices based on the $\omega$-approach (Figure 4.5).

The areas of ascending motion exhibit different structures of $\Delta \omega$, depending on the analysed model and cloud configuration. In the clouds-off experiment, for example, the two models which have a double ITCZ, namely the IPSL-CM5A-LR and the MPI-CM5-LR, show a positive change of $\omega$ at the centre of the updraft region and a negative change at the edges (Figure 4.9, left panel). The negative changes extend further into the area around the edge of the ascending branch for the MPI-CM5-LR than for the IPSL-CM5A-LR. This indicates a weakening of the whole updraft region for the IPSL-CM5A-LR. A weakening is found at the centre of the area of ascending motion for the MPI-CM5-LR, whereas a strengthening is found for the outer areas of this branch. This is caused by an intensification of the double ITCZ in a warmer climate for this model. This intensification comes along with a strengthening of the two maxima of rising air and a weakening of the updraft in between the two maxima. The MRI-CGCM3 exhibits different characteristics for this cloud configuration. This model shows a strengthening of the centre of rising air and a weakening at the outer edges of the updraft. This weakening is caused by a poleward shift of the zero isolines of $\omega$ and thus by a narrowing of the ascending branch in a warmer climate.
The region of ascending air is much smaller in the clouds-on than in the clouds-off simulations of the MRI-CGCM3 model for both warming states (see contours in Figure 4.9 for Control simulation, 4K simulation not shown). The changes in $\omega$ are located in a smaller area in the clouds-on than in the clouds-off experiment, though the structures of $\Delta \omega$ are similar for both cloud configurations, because the updrafts and downdrafts exhibit a comparable behaviour in the two cloud configurations. Similar results are found for the IPSL-CM5A-LR, for which the structures in $\Delta \omega$ are even more similar for the two cloud configurations.

The changes in the updraft region of the clouds-on simulation of the MPI-CM5-LR model differ considerably from the changes in the clouds-off simulation. Whereas a weakening of the centre of the updraft was found for the clouds-off experiment, the clouds-on experiment reveals a very strong intensification of the centre of the updraft region. A contrary behaviour is also found for the areas around the edges of the updraft. A strengthening of the ascending air was found for this region for the clouds-off experiment. In the clouds-on experiment, however, a weakening of this region is detected. These characteristics are caused by the fact that the MPI-CM5-LR model exhibits a double ITCZ in the clouds-off experiment and a single ITCZ in the clouds-on experiment. As in the clouds-off experiment, the strongest updraft intensifies in the clouds-on simulation. The main difference that causes the strongly varying structures of $\Delta \omega$, is the location of the area of the maximum updraft. For the clouds-on simulation, this area is located around the equator, whereas two maxima are found at around 10° latitude in both hemispheres in the clouds-off simulation.

4.3.2 Cloud effect

The analysis of the responses of the Hadley-indices to an increase of the sea surface temperature by 4K revealed a smaller model spread for the clouds-on than for the clouds-off experiment for many Hadley-indices (section 4.3.1). This applies especially for the indices that are based on the $\psi$-approach (Figure 4.3). However, similar trends were found for the different models for most of the indices for both cloud configurations. This indicates that the Hadley circulations respond similarly to an increase of the sea surface temperature for both cloud configurations. The analysis, however, does not provide any information about the effect of cloud-radiation interactions on the Hadley circulation, because the two cloud configurations have been treated separately for the investigation of the “temperature effect”.

The differing results for the clouds-on and clouds-off simulations indicate that the effect of cloud-radiation interactions is not well understood yet. This section focuses, for this reason, on the effect of cloud-radiation interactions on the Hadley circulation. The response of the Hadley circulation to cloud-radiation interactions is investigated by comparing the Hadley-indices that are determined from the clouds-off experiment to those that are determined from the clouds-on experiment. Thus, the analysis focuses on the isolation of the most fundamental influences of cloud-radiation interactions on
the Hadley circulation. It is performed for both warming states, to further investigate the role of cloud-radiation interactions and the response of the Hadley circulation in different climates.

**Investigation of the Hadley-indices based on the \( \psi \)-approach**

As a first step to quantify the effect of cloud-radiation interactions on the Hadley circulation, the responses of the Hadley-indices based on the \( \psi \)-approach are analysed. Similar to Figure 4.3, Figure 4.10 exhibits the widths (upper panel) and strengths (lower panel) of the Hadley cells as well as the positions of the \( \psi_{500} \) zero crossings (middle panel) for both cloud configurations and both warming states for each model of the COOKIE ensemble. The markers of the two Control simulations as well as the markers of the two 4K simulations are connected for the individual models. This simplifies the analysis of the “cloud-effect” at first sight of the Figure.

Whereas most models showed similar responses of the Hadley-indices based on the \( \psi \)-approach to a temperature increase (Figure 4.3), the models exhibit very different responses of the indices to cloud-radiation interactions (Figure 4.10). For the Control simulation two models exhibit a similar widening of the northern, southern and total Hadley cells (HadGEM2-A, MRI-CGCM3). These two models are the only models which have a single ITCZ in both cloud configurations and both warming states. The other four models show very variable narrowing trends for the Hadley cells if cloud-radiation effects are included. The CNRM-CM5 and the MIROC5 exhibit very strong narrowing trends for all three cells and both warming states. This is caused by the development of a single ITCZ for the MIROC5 and a weaker pronounced double ITCZ for the CNRM-CM5 if cloud-radiation interactions are included.

The MPI-CM5-LR exhibits a comparable large trend for the northern Hadley cell in the 4K simulations, but not in the Control experiment. The IPSL-CM5A-LR shows similar trends as the HadGEM2-A and MRI-CGCM3, but with the opposite sign. This indicates that the trends for the width of the cells have similar magnitudes for models which exhibit a single or double ITCZ in both cloud configurations, though the signs of the changes do not agree.

The investigation of the positions of the cells’ edges reveals that the large discrepancies in the changes of the width of the Hadley cells are caused by the differing changes of the positions of the cells’ edges (Figure 4.10, middle panel). The narrowing of the Hadley cells of the CNRM-CM5, IPSL-CM5A-LR, MIROC5 and MPI-CM5-LR models are caused by an equatorward shift of the two descending edges for both warming states. However, the positions of the \( \psi_{500} \) zero crossings and the shifts of the positions are very different for the four models.

The HadGEM2-A and MRI-CGCM3 models show a widening of the Hadley cells. This widening is caused by a poleward shift of the two outer edges of the Hadley cells of these models. The ascending edges exhibit slight northward shifts in the Control simulations and slight northward (HadGEM2-A) or southward (MRI-CGCM3) shifts in the 4K
Figure 4.10: Effect of cloud-radiation interactions on the Hadley-indices based on the $\psi$-approach: width of the Hadley cells (upper panel), position of the edges of the cells (middle panel), and strength of the Hadley cells (lower panel).
simulations. Most of the other four models also exhibit slight northward or southward shifts of the ascending edges in the Control and 4K simulations. The sole exception is the MPI-CM5-LR model which shows a northward shift of about 1.5° latitude for the ascending edge in the 4K simulation. These results emphasise the uncertainty in the position and shift of the ascending edge. This uncertainty has also been identified for the response of the Hadley circulation to an increase of the surface temperature (section 4.3.1). However, the shifts of the ascending edges are much smaller than the shifts of the descending edges. The latter are much more certain among the models, which is consistent with the results that were found for an increase of the surface temperature. Thus, the uncertainty in the shifts of the ascending edges has little consequence for the change of the width of the northern and southern Hadley cells. It has no consequence for the change of the width of the total Hadley cells.

For the strength of the northern and southern Hadley cells a similar clustering of the models is found as the one that was detected for the “temperature effect” (Figure 4.3). One cluster contains the weaker Hadley cells that are found for the models which exhibit a double ITCZ in both warming states (CNRM-CM5, IPSL-CM5A-LR). The other cluster contains stronger Hadley cells. These cells are found for the models which exhibit a single ITCZ in both configurations or switch from a double to a single ITCZ as soon as cloud-radiation interactions are included. Except for the IPSL-CM5A-LR model the cells are generally stronger if cloud-radiation interactions are included in the simulations. The IPSL-CM5A-LR model shows stronger Hadley cells in the clouds-off simulations for both warming states. The individual models exhibit similar trends for the changes in the strengths of the cells for both warming states. This indicates that the changes in the strengths of the Hadley cells between the two cloud configurations are much larger than the changes between the two warming states (compare Figure 4.10 and Figure 4.3). Thus, the uncertainty in the effects of the cloud-radiation interactions is larger than the strengthening or weakening of the circulation that is induced by a warmer climate system.

Investigation of the Hadley-indices based on the \( \omega \)-approach

The changes in the branches’ widths that are caused by the “cloud effect” are much more certain among the COOKIE models than the changes in the width of the Hadley cells (Figure 4.11, upper panel). All models exhibit a widening of the descending branches and a narrowing of the ascending branch for both warming states as soon as cloud-radiation interactions are included in the simulations. This agreement in the changes of the ascending branch’s width contradicts the prior results. For an increase of the surface temperature the changes of this branch’s width were uncertain and large model spreads were found. Most of the models show similar trends for the width of the ascending branch for both warming states. Thus, the trends are almost independent of the sea surface temperature. The CNRM-CM5 exhibits the smallest widths for the descending branches and the largest widths for the ascending branches for all simulations. This is caused by the fact that this model exhibits a stronger pronounced double ITCZ than the
4.3 Results for the COOKIE ensemble

other models. However, this model also exhibits the smallest trends for the widths of the branches.

The narrowing of the ascending branches is caused by a symmetric equatorward shift of both the northern hemisphere ascending edge and the southern hemisphere ascending edge for all models (Figure 4.11, middle panel). Again, similar trends are found for both warming states for the individual models. The magnitudes of the trends correspond well with the results for the “temperature effect”, for which also only small changes in the position of the $\omega_{500}$ zero crossings were found (Figure 4.5, middle panel).

The effect of the cloud-radiation interactions on the position of the two descending edges of the branches is much more uncertain than the effect on the position of the two ascending edges, which contradicts the results of the prior investigations. Half of the models exhibit a distinct equatorward shift of the descending edges (CNRM-CM5, MIROC5, MPI-CM5-LR), two models exhibit a distinct poleward shift of the descending edges (HadGEM2-A, MRI-CGCM3), and the IPSL-CM5A-LR exhibits almost no trend for most of the comparisons. For this model a distinct poleward shift is only found for the northern hemisphere descending edge in the 4K simulation.

The two models which show a distinct poleward shift of the two descending edges of the branches are again the only models which exhibit a single ITCZ in both cloud configurations. For these two models the distance between the two northern hemisphere edges and the two southern hemisphere edges increases if cloud-radiation interactions are included. This explains the widening of the descending branches and the narrowing of the ascending branches. At the same time, the widening of the descending branches and the narrowing of the ascending branches of the CNRM-CM5, MIROC5, and MPI-CM5-LR are caused by the fact that the ascending edges exhibit a stronger equatorward shift than the descending edges.

In theory, a widening of a branch is accompanied by a weakening and a narrowing is accompanied by a strengthening of the branch. The latter is found for the ascending branch of all models for both warming states (Figure 4.11, lower panel). Some models show weaker strengthening trends of this branch (CNRM-CM5, IPSL-CM5A-LR), others exhibit a strong strengthening (MRI-CGCM3, MPI-CM5-LR 4K experiment), and again others exhibit a medium strengthening (HadGEM2-A, MIROC5, MPI-CM5-LR Control experiment).

The largest strengthening trends are not found for the models which exhibit the largest narrowing trends. This indicates that other factors than solely the width of the branch determine the strength of the vertical motions. One of these factors is the characteristic of the ITCZ. The MRI-CGCM3 model, for example, exhibits a single ITCZ for both cloud configurations. Thus, only a smaller narrowing trend is found for the ascending branch of this model compared to the other models of the ensemble. However, the ITCZ strongly intensifies for the clouds-on compared to the clouds-off experiment for both warming states. Another example is the IPSL-CM5A-LR model which has a double ITCZ for both cloud configurations. This model also shows a medium narrowing of the ascending branch. However, the branch exhibits a similar strength in all four
Figure 4.11: Effect of cloud-radiation interactions on the Hadley-indices based on the $\omega$-approach: width of the branches (upper panel), position of the edges of the branches (middle panel), and strength of the branches (lower panel).
The effect of cloud-radiation interactions on the strength of the two descending branches is much more uncertain than the effect on the strength of the ascending branch. Half of the models exhibit a strengthening of the descending branches if cloud-radiation interactions are included in the calculations (CNRM-CM5, HadGEM2-A, MPI-CM5-LR). At the same time, the other half of the models shows a weakening of the descending branches (IPSL-CM5A-LR, MIROC5, MRI-CGCM3).

The changes in the structures of the $\psi$ and $\omega$ cross sections that are found for the "cloud effect" are similar to the changes that are found for the "temperature effect" of the MPI-CM5-LR clouds-on experiment (not shown). For all models and both warming states a weakening of the Hadley cells is found equatorward of the cells’ centres. A strengthening of the cells is found poleward of the cells’ centres. Both the weakening and strengthening trends range over the whole height of the cells. The strengthening of the ascending branches also ranges over the whole height of the circulation. For the comparison of the clouds-off and clouds-on experiments, no vertical expansion of the circulation is found. Thus, this expansion is probably caused by the increase of the surface temperature and cloud-radiation interactions do hardly influence the height of the Hadley circulation.

4.4 Discussion

The response of the Hadley circulation, quantified by the Hadley-indices, to a temperature increase and to the effect of cloud-radiation interactions has been investigated in section 4.3. For the "temperature effect" the analysis of the Hadley-indices based on the $\psi$-approach revealed that the changes of the different indices are robust for most of the indices for both cloud configurations. This applies especially for the changes in the width of the cells, the positions of the descending edges and the strength of the cells. Nevertheless, the values of the indices vary greatly between the individual models. This indicates an uncertainty in the proper modelling of the Hadley circulation. However, the results agree well with the results that were found for an idealised increase of the atmospheric CO$_2$ concentration, which also involves a temperature increase (section 3.3). For the CMIP5 ensemble, robust changes were found for the same Hadley-indices of the $\psi$-approach.

A similar result is found for the Hadley-indices based on the $\omega$-approach. A robust widening and weakening of the descending branches and robust poleward shifts of the descending edges of the branches were found. As for the cells, the shifts of the positions of the ascending edges and the changes of the width and strength of the ascending branch are much more uncertain. This has also been found for the CMIP5 ensemble.

The large agreement between the two experiments (CMIP5 1pctCO2 and COOKIE "temperature effect") and the two different forcings indicates that a widening and weakening of the Hadley cells as well as a widening and weakening of the descending branches are very robust in a warming climate. The changes of the width and strength of the
ascending branch are much more uncertain. Thus, further investigations are needed to be able to better predict the changes of the ascending branch.

The results of the investigation of the “cloud-effect” support the initial statement that cloud-radiation interactions are not well understood yet. The analysis revealed large discrepancies between the six participating models, especially for the Hadley-indices based on the $\psi$-approach. This contrasts the results of the CMIP5 1pctCO2 and the “temperature effect” investigations, for which the trends of the $\psi$-indices were more robust than the trends of the $\omega$-indices. However, the Hadley cells are stronger as soon as cloud-radiation interactions are included. The ascending branch of the circulation is found to be wider and weaker. In consideration of the fact that the changes of the ascending branch were the most unsure changes in the CMIP5 1pctCO2 and the “temperature effect” investigations, it is surprising that the ascending branches of all six models respond similarly to the inclusion of cloud-radiation interactions. The descending branches of the circulation widen in the presence of cloud-radiation interactions. The change of the strength of these branches is unsure.
Chapter 5

Conclusions and outlook

In this thesis, the Hadley circulation and its response to idealised forcings is investigated. First, an overview of the most commonly applied methods and some new methods is given. This overview also includes the two variables which are analysed in this thesis, namely the mass stream function $\psi$ and the vertical pressure velocity $\omega$. Based on these two variables, six different Hadley-indices are investigated to quantify the Hadley circulation and its changes. The first three indices are defined to analyse the width and strength of the Hadley cells as well as the positions of the cells’ edges. These three indices are based on the mass stream function. Thus, they are referred to as $\psi$-approach. Three similar Hadley-indices facilitate the investigation of the width and strength of the branches of the Hadley circulation as well as of the positions of the branches’ edges. These three indices are based on the vertical pressure velocity and, hence, referred to as $\omega$-approach.

As a first step, the Hadley circulation of the idealised CMIP5 (Coupled Model Intercomparison Project Phase 5) 1pctCO2 experiment is investigated. One main aim of the analysis is the detailed investigation of the representation of the Hadley circulation in transient climate simulations. This analysis is performed on the basis of the MPI-ESM-MR. In addition, similarities and discrepancies between the models of the ensemble are quantified and the responses of the Hadley circulation to an idealised 1% yearly increase of the atmospheric CO$_2$ concentration are investigated in order to find robust changes of the circulation.

The analysis of the characteristic behaviour of the Hadley circulation of the MPI-ESM-MR within one year reveals that the winter cell is much wider and stronger than the summer cell. The first exhibits a cross-equatorial position. During the equinox seasons both cells exhibit similar widths and strengths. Similar results are found for the descending branches, which are wider and stronger during winter than during summer and exhibit similar widths and strengths during the equinox seasons.

The second step of the analysis of the MPI-ESM-MR is the detailed investigation of the annual cycles of the six Hadley-indices. The annual cycles of the widths of the two Hadley cells and the two descending branches are dominated by the large annual cycles of the ascending edges, whereas the outer edges of the cells and branches exhibit
small annual cycles. The strong annual cycle of the Hadley circulation superimposes the natural variability of the climate system. Thus, the Fourier transformations of the anomaly time series of the Hadley-indices are investigated. However, the Fourier transformations do not exhibit a sharp spectrum and thus no dominating peaks that could be associated with ENSO or the PDO.

The correlations of the different Hadley-indices reveal large interdependencies of the different indices, especially for the $\psi$-approach. It is shown that the large correlations or anti-correlations are mainly caused by the annual cycles of the Hadley-indices and not by the dynamics of the climate system. This indicates that different mechanisms control the variability of the annual cycle and the internal variability of the climate system.

In the next part of the thesis, the CMIP5 ensemble is investigated. In order to quantify similarities and discrepancies between the models, the mean structures of $\psi$ and $\omega$ are investigated as well as the correlations of the annual mean time series of selected indices. It is found that the discrepancies between the models are caused by different representations of the Hadley circulation in the different models. Some models tend to develop generally weaker and narrower cells and branches whereas others develop a wider and stronger circulation.

The analysis of the correlations of the annual mean time series of the indices reveal a good agreement with results of Nguyen et al. (2013), who investigated reanalyses. However, the cells of the idealised CMIP5 simulations are narrower and stronger than the cells in the reanalysis ensemble. The detailed investigation of the model spread of the CMIP5 ensemble reveals that the discrepancies between the models are larger than assumed at first sight. Especially the correlation between the $\omega$-indices exhibits more outliers than the correlation between the $\psi$-indices. This indicates that the representation of the mass stream function is more robust in the ensemble than the representation of the vertical pressure velocity.

The similarities and discrepancies of the CMIP5 ensemble are also investigated on the basis of decadal trends of the indices. This analysis facilitates the quantification of the model spread and of robust responses of the different indices to an increase of the atmospheric CO$_2$ concentration. The initial hypothesis of a widening and weakening of the cells and descending branches is corroborated. The trends are found to be robust among the models. The widening trends are mainly caused by robust poleward shifts of the outer edges of the cells and branches. The widening and weakening of the cells matches well with the results of other studies that investigated the change of the Hadley circulation in climate simulations (e.g. Lu et al., 2007; Gastineau et al., 2008). However, the magnitude of the trends strongly depends on the data set and the applied methods.

The changes of the position of the ascending edges of the cells and branches are more uncertain among the models. The uncertain trend for the positions of the ascending edges of the branches results in an uncertain trend for the width of the ascending branch. However, a narrowing is more likely than a widening. At the same time, a weakening of the ascending branch is more likely than a strengthening. This contradicts the initial hypothesis that the ascending branch strengthens and narrows in a warmer climate. The
results for the changes of the strengths of the branches and cells are reproducible with another method. This further corroborates the robustness of the results.

In the last chapter of this thesis, the influences of a temperature increase and the effect of cloud-radiation interactions are investigated separately. For this, the model output of idealised aqua-planet simulations of the Clouds On-Off Klimate Intercomparison Experiment (COOKIE) is analysed. The “temperature effect” and “cloud effect” are analysed separately, because the investigation aims at the quantification of the influences of both effects on the Hadley circulation. In addition, the robustness of the responses of the Hadley-indices to the two effects are compared to the responses of the indices to an idealised increase of the atmospheric CO$_2$ concentration.

Similar to the results for the CMIP5 ensemble, a uniform increase of the SST results in a robust widening and weakening of the Hadley cells and the descending branches. This result is found for both cloud configurations. The widening is again caused by poleward shifts of the descending edges, whereas the shifts of the ascending edges are more uncertain. It is shown that the widening of the descending branches is dominated by changes in the static stability. Changes in the cooling rate are found to play a minor role. These results indicate that the increase of the atmospheric CO$_2$ concentration and the surface temperature work in the same direction. However, the magnitudes of the trends are not comparable, because the configurations of the simulations differ greatly (e.g. no orography and seasonal cycle in COOKIE).

The shifts of the ascending edges of the cells and branches and thus the changes of the width of the ascending branch, are again more uncertain. In contrast to the CMIP5 ensemble a widening and weakening of the ascending branch is more likely than the narrowing and weakening that was found for the CMIP5 ensemble. This contradicts the expectation of a narrowing and strengthening of the ascending branch even more.

The investigation of the latitude-height cross sections of changes of $\psi$ and $\omega$ shows that the changes in the strength and width of the cells and branches extend over the whole vertical extent of the circulation. In addition, a vertical expansion of the cells and branches in a warmer climate is found for both cloud configurations. This vertical expansion is not found for the “cloud effect”.

The comparison of the clouds-off and clouds-on simulations facilitates the isolation of the most fundamental influences of cloud-radiation interactions on the Hadley circulation. It is found that the responses of most of the Hadley-indices are much more uncertain than the responses to a temperature increase and an increase of the atmospheric CO$_2$ concentration. The responses are strongly dependent on the development of a single or double ITCZ in the different simulations. The only changes which are found to be robust are a strengthening of the Hadley cells as soon as cloud-radiation interactions are included as well as a widening of the descending branches and a narrowing and weakening of the ascending branch. The changes in the width of the cells and descending branches are very robust in the 1pctCO2 experiment and for the COOKIE “temperature effect” investigation. The fact that the changes are not robust for the “cloud effect” indicates that the effect of cloud-radiation interactions are not well understood, yet.
In order to better understand the characteristics of the Hadley circulation, future investigations should also consider the seasonal behaviour of the Hadley circulation. This will facilitate the assessment of different influences of the seasons on the Hadley circulation and enable better predictions of the circulation’s changes. For this, the determination of seasonal trends of the Hadley-indices would be of avail. The analysis of these trends allows to determine if the four seasons exhibit similar or different influences on the decadal widening and weakening of the Hadley cells and the descending branches of the circulation. If the trends of the four seasons differ, explanations for the discrepancies must be found. In addition, the changes in the width and strength of the ascending branch need to be investigated more in detail, because these changes are found to be inconsistently represented in different climate models. Another interesting aspect that has been neglected in this thesis is the regional change of the Hadley circulation, for example in the Atlantic or Pacific Oceans and over the continents (e.g. Schwendike et al., 2015).

More comprehensive investigations of the Hadley circulation are needed in the future to better understand and predict changes in the Hadley circulation in a changing climate. For example, the role of different parameters which might influence the Hadley circulation are not well enough understood to reliably determine their influence on the circulation. These include, amongst others, the effect of changing SSTs and greenhouse gas concentrations. This understanding is easier established if idealised and simple models are used instead of comprehensive GCMs. As soon as the parameters are better understood in the idealised models, further improvements of the comprehensive climate models are possible. As stated by Knutti and Sedlacek (2013) these improvements of the models are necessary, because the models of the current CMIP ensembles contain several limitations. For example, several processes and feedbacks are not well enough represented in the current models. Mitas and Clement (2005) argue that the cloud parameterisations and convective schemes might affect the representation of the Hadley circulation in climate models and reanalyses.

Finally, the results of the climate models have to be compared to observations to evaluate the trends that are found in the climate models. This is necessary, because even if all models show the same trends, it is possible that they are not representative for the changes of the real Earth’s climate. Thus, it is important to compare the results to measurements (e.g. satellites). However, the limited time period of the measurements might alter the detected trends, because the measurements might be influenced by events like El Niño and thus overestimate or underestimate the trends that would be received from longer measurements. This results in differing magnitudes for the trends that are determined from the measurements and the models. In order to reliably predict the tendency of climate change, the signs of the trends of the models and measurements must agree.
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Nicole Albern