Convective momentum transport in fine-scale weather forecasts over Cabauw

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Challenge the future

Convective momentum transport in fine-scale weather forecasts over Cabauw

by

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Preface

Weather is always present in daily life. It already fascinated me at a very young age. The weather regained my interest when I was going on a trip to the mountains where it is important to judge if the weather is safe enough to continue the journey. In that respect, clouds play an important role in assessing the evolution of the weather during the day. Moreover, clouds have triggered me to start studying Geoscience and Remote Sensing (GRS); during the Master Event at the TU Delft, the 3D modelling of the cloud evolution caught my eye and woke up my interest even further. Although I have tried to keep my master broad by looking at many different fields next to atmospheric track of GRS, I was sure to look for a master project in atmospheric science. I am delighted to have had the opportunity to work in the group of Dr. Louise Nuijens and experience the start of the CloudBrake research group.

The GRS community, within which the CloudBrake group is situated, is thanked for the motivating and 'gezellige' atmosphere. The involvement of the group with each other is very stimulative and supportive. Furthermore, I would like to thank Prof. dr. Harm Jonker, Dr. ir. Remco Verzuijlberg and ir. Pim van Dorp from Whiffle for providing the data from their model's forecast over Cabauw for a complete year, the discussions over the results and for updating the model for us to look at individual feedbacks and conditioned fluxes. It has been very nice working with you. Prof. dr. Harm Jonker and Dr. ir. Remco Verzuijlberg are especially thanked for taking part in my committee.

In particular I would like to thank Dr. Louise Nuijens, my committee chair and daily supervisor. I am very thankful that I was encouraged to grow in conducting good research and improve on my skills ranging from criticising my own work, to presenting results in the best format and academic writing. Louise was always available for questions and doubts and to focus my enthusiasm and my wandering thoughts to keep me on track.

A.M. Koning
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Abstract

In this study we are specifically interested in the role of convective momentum transport in a commercial fine-scale LES model that is used for wind predictions in the wind-energy sector. With this model, forced with the ECMWF IFS, a year-long of daily forecasts are run over Cabauw, the Netherlands, at a resolution of 40m in the horizontal and a resolution in the vertical of 8m that decreases with height to 80m. At this location atmospheric conditions range from stable to convective boundary layers, from clear sky to overcast days. The number of days with cumulus convection are surprisingly large: 144 out of 365 days.

Focusing on daytime hours, we separate days with and without cumulus convection, and with small and large cloudiness. For these different categories we show how the normalised momentum flux, and what this implies for drag in the lowest kilometre of the atmosphere. Here we are mindful of differences in background winds between the categories. A similar exercise is performed by separating cumulus days on surface buoyancy flux and cloud depth; four groups of increasing convection have been obtained.

It is found that in the presence of cumulus convection, the momentum transport is less linear than on overcast days. Clear-sky days show more drag in the lower half of the mixed layer compared to the cumulus case. Near cloud base, the drag is similar to that of cumulus days.

Separating cumulus days on convection we found that with decreasing buoyancy flux, the normalised momentum transport behaves less linear: in general cumulus days with the largest convection showed linear behaviour in the sub-cloud layer, cumulus days with the lowest convection showed a profile that tends to increase the wind speed near the surface and shows drag near cloud base.

Finally, using sensitivity experiments in which we remove the latent heating effect on buoyancy, we that the presence of moist convection specifically, change momentum mixing near and above cloud base, but not in the sub-cloud layer underneath.

Contents

1

Introduction

Wind energy as a renewable energy source is becoming more important for society, and the prediction of low-level wind speed at high temporal and spatial resolution is of high interest for the wind-energy sector. Because of its fluctuating behaviour, wind predictions and wind energy forecasts are performed in many different ways: approaches range from pure statistical analysis (e.g. Sánchez [2006]), Kalman filters (e.g. Cassola and Burlando [2012]) and neural networks in machine learning algorithms (e.g. Grassi and Vecchio [2010]) to numerical weather prediction. To predict winds at specific locations using numerical weather predictions, fine-scale models such as Large Eddy Simulations (LES) have an advantage over regional models, as they have a better representation of small-scale processes such as turbulence and convection, which are believed to be critical for low-level wind speed.

In this study we analyse convective momentum transport over Cabauw, using the commercial fine-scale LES model of Whiffle. We seek to answer the following questions, to address the importance of convective momentum transport for the prediction of low-level winds:

- How do low-level winds change depending on the character of momentum transport?
- How does the momentum transport change in the presence of cumulus convection?
- How does the behaviour of the momentum flux change with different depths and strength of convection?
- How does the presence of clouds, and thus moist convection, influence the behaviour of the momentum transport?

Our analysis entails year-long daily forecasts by Whiffle's fine-scale LES model over Cabauw, the Netherlands. In this year-long data set, days with and without cumulus convection and days with large and small cloudiness are observed. The weather conditions vary from stable to convective boundary layers and from clear sky to overcast. In our data set only nine out of 366 days have found to be cloudless. Because of its frequent occurance, shallow cumulus convection is very important in this study: especially over land in the tropics and Northern mid-latitudes it has an average daytime occurrence of about 30% in the period between June and August [van Stratum et al., 2014]. Despite its frequent occurrence, shallow cumulus convection is not a well researched topic, especially its relation to momentum transport. We want to partially fill this gap of knowledge by looking at the vertical structure of the wind, cloud depth and momentum transport contribution by shallow cumulus convection to the total momentum transport.

The lack of research in the coupling between wind, momentum transport and (shallow) cumulus convection can be explained by the difficulty in obtaining useful observation profiles. Obtaining direct measurements are often limited to aircraft measurements, tethered balloon systems or multiple-radiosonde ascents, which lack continuity in measurements. However a couple of field campaigns have been carried out over the years. A study that is important for this research is the study of LeMone and Pennell [1976]. They used the NCAR DeHavilland Buffalo aircraft to take measurements on three days with increasing convective conditions over sea near Puerto Rico. The character of the momentum transport for cases that differ from suppressed with very little shallow cloudiness to slightly enhanced with active cumulus that reach up to 2000m is exposed: the momentum transport is found to decrease linearly from the surface to cloud base, except for the enhanced case. This indicates a different behaviour of the momentum flux below cloud base for different convective cases. They also showed that the momentum fluxes normalised with their surface values have very little correlation with the mean wind profile in the mixed layer. We will investigate whether similar characteristics are found over land at mid-latitudes and make use of these findings by separating the days on different amount of cloudiness and comparing the associated normalised momentum fluxes.

Because measurements of momentum transport are difficult to obtain, LES models offer an opportunity to study the processes in more detail than observational possible and provide the possibility of testing sensitivity to individual parameters. From the LES study of Schlemmer et al. [2017], the contribution of shallow cumulus convection to momentum transport is known to be significant in the Rain in Cumulus over the Ocean (RICO) case and the Cold-air Outbeak (CONSTRAIN) case, which are both over water. Brown et al. [2002], have studied shallow cumulus convection over land that will typically show a stronger and more fluctuating forcing than the relative steady cumulus convection over sea. With their study over the Southern Great Plains site of the Atmospheric Radiation Measurement Program and is based on an idealisation of observations made. They found that many characteristics of the cumulus layer that were previously found in studies of quasi-steady convection over sea are reproduced in the more strongly forced and unsteady situation over land. These results are proven consistent between eight independent models with a range of numerical resolution show similar results. This gives confidence in finding similar momentum transport characteristics in our study as found in LeMone and Pennell [1976].

Because of the many detailed diagnostics that can be obtained from LES and the possibility to test sensitivity to an individual feedback, the choice for LES data is made. However, opposed to Brown et al. [2002], we will not use idealised cases of LES, but as posed before, year-long daily weather predictions over the year 2016. Hereby, we aim to enlarge the understanding of changes in momentum transport induced by different degrees of convection, the presence of clouds and for different background winds and point out important processes to improve the model further. Even though the LES offers a great way of experimenting with different sensitivities and analysing (individual) processes, it should be kept in mind that observational data of realistic events still remain important as LES is often idealised and needs continuous verification.

In the coming chapters the reader will be provided with the processes and mechanisms involved in answering our main research questions. Thereafter, the methodology of the study that includes a description of the LES data that were provided by Whiffle will be given. Convection in the presence of different cloudiness and clear-sky convection will be addressed, although our focus will be remain mostly on cumulus convection. The results and analysis of the different amounts and strengths of convection together with a review on the quality of the made categories will be provided in Chapter 4. The conclusions are summarised in Chapter 5.

2

Theoretical background

To answer the research questions posed in Chapter 1 the relevant mechanisms for convection and momentum transport must be identified. The aim of this chapter is to understand the process of convection and momentum transport and the way they are related to each other. Then the relation between momentum transport and the vertical wind profile is explained. The role of cloudiness in these processes will, too, be discussed.

2.1. Convection

Convection is the movement within the air column due to density differences in the air that are caused by differences in temperature. Convection in the atmosphere is driven by the heating of the Earth's surface by solar radiation that in turn heats the air directly above the surface. This is visualised in Figure 2.1. Convection is usually organised in thermal plumes that rise as the heated air becomes positively buoyant. Between small regions of strong updraught thermals, where a vertical velocity is commonly around 1-2 m/s and can be as high as 5 m/s, larger regions of weak cool downdrafts exist. The two-way circulation that is associated with the rising plumes and the cooler downdrafts is responsible for the mixing of the atmospheric boundary layer and subsequently of the mixing of temperature, humidity and winds from different heights [Stull, 1988, Chapter 11][Wallace and Hobbs, 2006].

2.1.1. Selecting on convection depth

The data set will be separated based on convection depth to answer how the behaviour of momentum transport changes with the depth of convection. This paragraph discusses a few parameters that are considered a measure for the convection depth.

Cumulus clouds when compared to clear sky days or general cloudy days are expected to have more convection. At the top of strong thermals that contain enough moisture to form clouds, cumulus clouds arise. Cumulus have a typical root structure at the surface, as is shown in Figure 2.1. On clear sky days no latent heat release is available due to a lack of moisture and subsequently the convection stops at the inversion. Partially cloudy days and overcast days are thought to have less direct interaction with the sub-cloud layer than cumulus clouds.

Surface buoyancy flux is a measure of the strength of a rising thermal. The larger the surface buoyancy flux the larger the difference in virtual potential temperature and thus the stronger the convection. With stronger convection the thermal is expected to reach higher and mix more vigorously.

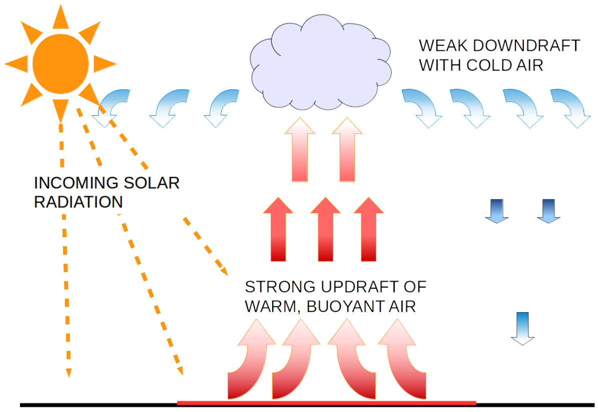

Figure 2.1: Incoming solar radiation heats the Earth's surface, causing the warmed air above the surface to become buoyant and rise upward. The strong updraughts of warm, buoyant air are called thermals. Between thermals, usually a larger area of subsiding cold air exists. If the thermal is moist enough at the top of the mixed layer, a cloud can form. The thermal is sometimes referred to as the 'cloud root'.

Cloud depth is used as indicator of convection depth. When a thermal from the mixed layer overshoots its inversion, it is already negatively buoyant. When the parcel rises, it condenses and subsequently leases latent heat, becoming more buoyant. When there is enough energy to become positively buoyant again, it rises even further until it becomes colder than the environment yet another time, though it may overshoot the limit of convection because of its inertia. With the rising air parcel, the moisture, temperature and wind are mixed.

Vertical velocity represents the strength of the updraught thermal in the sub-cloud layer (updraught conditioned) or in the cloud core (cloud core sampled) and therefore can characterise the convection strength. Stronger updraught are expected to have stronger mixing and reach higher. When looking at the vertical velocity sampled on the cloud core, this is similar to looking at the mass flux contribution. The larger the mass flux at cloud base, the more convection is expected.

Selection on weather conditions such as background wind and similar drag profiles in the momentum flux can also be used. Then we can see what type of convection is related to the specific conditions we are looking at.

2.2. Momentum transport

As wind from different heights are mixed the vertical wind profile will change in time. The mixing of momentum because of convection is called convective momentum transport. Although organised plumes can cause a lot of convective momentum transport, the total flux consists also of momentum transport by turbulent eddies and other processes such as shear. This section will introduce the causes of momentum transport, show how the convective part of momentum transport is extracted and explain momentum transport influences the wind tendency.

2.2.1. Processes causing momentum transport

Momentum transport denotes the change of the wind at a defined location in time. Processes at any scale contribute to the local time rate of change of the wind velocity: large scale tendencies such as pressure differences, geostrophic wind and advection can alter the wind. However, the large scale tendencies are prescribed for our model and only small scale turbulent processes are regarded in this study. The change of small scale turbulence takes place on much smaller time scales. The change of the local wind in time scales with the turbulent momentum transport. Mathematically this is expressed as:

$$\frac{\partial U}{\partial t} \sim -\frac{\overline{\partial \tau}}{\partial z} \tag{2.1}$$

In this equation, $U = \sqrt{u^2 + v^2}$ and represents the total wind speed, where u and v are the zonal and meridional wind velocities. The momentum transport for the total wind is defined as $\tau = \sqrt{(\overline{w'u'})^2 + (\overline{w'v'})^2}$, consisting of the momentum transport in both the u- and v-wind.

Shear, drag and turbulent eddies contribute to the small scale turbulent momentum transport and these need to be separated from the convective contribution in which we are interested.

2.2.2. Convective momentum transport

Our interest is only the convective part of the momentum transport. The contribution of convection to the total momentum transport, which includes shear and small scale eddies, should be extracted and compared to the total momentum transport. Knowing that the thermals organise in regions of large updraughts, the data can be sampled on updraught parcels. Although these parcels will contain both small scale eddy updraughts and convective updraughts, it will provide a rough estimation of the contribution to the total momentum transport. In the cloud layer, it is known that most transport is carried by the cloud-core in which large updraughts are found. These updraughts are caused by air parcels that regain buoyancy through latent heat release at cloud base. Cloud-core sampling is therefore used to review the convective momentum transport in the cloud layer.

In large domain LES studies, when the cloud contribution to the total transport of a variable ϕ is of interest, the flux is usually estimated using the mass flux approximation:

$$w'\phi' \approx M \times (\phi_{core} - \overline{\phi}) \tag{2.2}$$

as described by Siebesma et al. [2003], where $w'\phi'$ denotes the flux, M represents the mass flux ($a_{core} \times w_{core}$), the averaged variable of all core samples is denoted byϕ_{core} and $\overline{\phi}$ is the variable average over the entire domain that is considered to represent the environment outside the cloud. The variable ϕ usually represents the humidity or temperature. If looking at the momentum flux, ϕ can represent either u or v. The momentum flux for the total wind U will be calculated as: $\tau \sim \sqrt{(M \times (u_{core} - \overline{u}))^2 + (M \times (v_{core} - \overline{v}))^2}$.

The mass flux approximation works well for heat and humidity fluxes, however, for momentum transport it is not a good approximation, as for instance is seen in Schlemmer et al. [2017] and Brown et al. [2002].

2.2.3. Wind tendency

The tendency of the wind is described by Equation 2.1. The change in the wind depends on the friction (drag) in the momentum transport profile, which is simply the derivative of the profile of the momentum transport. The turbulent flux represents transports of fluctuations in the wind velocity (U') by fluctuations in the updraught velocity (w'). Depending on the difference between the velocities at different levels and the vertical updraft velocity, the amount of momentum transport is determined. Note that with wind velocities the flux can be negative, however, when a negative wind velocity is considered, this might increase the wind speed.

Instead of explicitly describing the effect of convective transport on the change in the variable, the effect of convective transport is mostly described as down-gradient and up-gradient mixing in literature. Hereby is meant that in down-gradient mixing there is more vertical mixing and the gradient in the

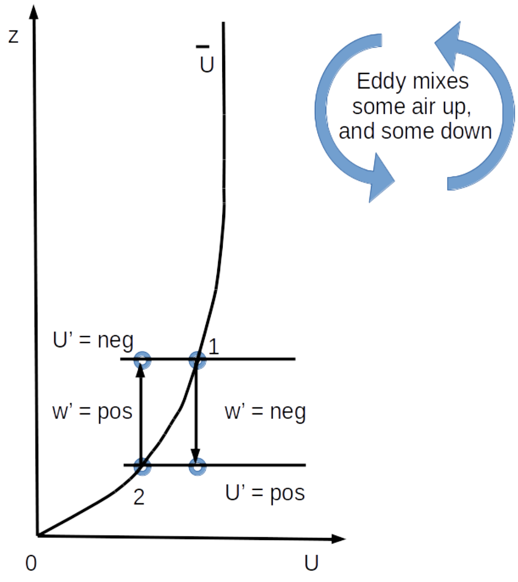

Figure 2.2: Example of a negative down-gradient mixing. The wind speed with higher velocity is mixed downward where a lower mean velocity is present. Low velocity is mixed to an environment with higher mean velocity.

profile will disappear. Up-gradient mixing will enhance the gradient and in case of momentum transport it will increase large velocity winds and decrease low velocity winds.

In our LES output, the total momentum transport of the resolved flux and sub-grid flux together is given, making it possible to directly analyse the amount of momentum transport over the domain (horizontally averaged). We will be use conditionally sampled fluxes for our analysis, but on-the-fly we will test how well the mass-flux parametrisation is compared to the conditionally sampled momentum flux (results are provided in the appendix).

3
Methodology

In this chapter, the used data is described followed by a description of the method that is used to answer the questions that have been posed in Chapter 1. The motivation for this approach is given and the selection criteria that are used are defined.

3.1. LES Data

The commercial LES model of Whiffle is forced with the Integrated Forecast System (IFS) of the European Centre for Medium-Range Weather Forecasts, ECMWF. The year-long daily forecasts are run over Cabauw, the Netherlands, at a resolution of 40m in the horizontal and a resolution of 8m in the vertical that dynamically decreases with height to a resolution of 80m. The LES runs for a period of 21:00 - 23:59 UTC the next day. Only the time interval of 00:00 - 23:59 will be considered to avoid possible spin-up influences. It should be noted that for incoming radiations, the radiation scheme of ECMWF is used and thus the formed clouds in the LES do not affect the radiation.

From LES the vertical profiles of individual parameters and the total (i.e. resolved and sub-grid) fluxes are used. In addition, we can also make use of conditionally sampled vertical profiles for certain conditions and time-series such as surface buoyancy flux, radiation flux and cloud cover.

3.2. Strategy

3.2.1. The convective part of momentum flux

This section provides the strategy used to answer how the convective contribution to the momentum transport changes in the presence of cumulus convection. Because of the interest in the contribution of convection to the total momentum transport, the retrieval of the convective part of the total momentum transport is shown. At last, to compare the different days and different times on a day, the handling of the diurnal cycle is explained.

Selecting convective days

Different days bring different convection. During clear sky days, buoyancy caused by incoming solar radiation plays an important role, whereas during overcast days, mixing is less pronounced, as shown by He et al. [2013]. Other processes become more responsible for the transports. When cumulus are present, they indicate or even contribute to enhanced convection.

To view the difference in convective contribution to the total momentum transport for cumulus days, in which we are most interested, cloudless days and general cloudy days, the year-long daily forecasts are separated in four groups: clear-sky days, days with low cloudiness, overcast days and cumulus days. The latter overlaps fully with the other two cloudy days.

Clear-sky days are selected based on cloud cover. If the cloud cover exceeds 0.003% (e.g. 5 of the 128x128 grid boxes in the horizontal plane) at any time between 11-18h UTC, the day is rejected as clear sky day. Clear-sky days are important to review the effect of moist feedback that is present in other categories.

Partially cloudy days are thought more likely to contain clouds with roots on the surface. Therefore this category is separated from the high cloud amounts: more convection is expected when these clouds are present with respect to the presence of for example stratocumulus clouds. Partially cloudy days are selected based on cloud cover: the cloud cover should exceed 0.003% and not be larger than 50% at any time between 11-18h UTC.

Overcast days contain days that do not belong to the clear-sky category nor to the partially cloudy category. With this category can be tested if there is more convection when also deeper clouds or stratocumulus are present. It can also be that cumulus clouds exist below stratocumulus clouds and therefore this category should not be disregarded. overcast days are selected based on cloud cover: the cloud cover at any time between 11-18h UTC should exceed 0.003% and the average cloud cover should exceed than 50%.

Cumulus days are selected based on the properties of cumulus clouds. Naturally, the cloud cover should exceed the clear sky threshold of 0.003%. Positive mass flux in the cloud core, represented by $a_{cc} \times w_{cc}$, is expected near the lifting condensation level (LCL), which is generally between 990m and 1020m. On average, the mass flux between 11-18h UTC and between 990-1020m should be positive. Cumulus can co-exist with stratocumulus higher up, but when fog is present the day is disregarded as cumulus day. This restricts the average cloud fraction between 11-18h UTC to be less than 0.003% below 500m. The cloud fraction averaged between 11-18h UTC between 500 and 5000m should exceed the clear sky condition, but as cumulus do not have a large cloud fraction (usually 5-20%), the average should not exceed 50%.

As could have been noticed, the criteria of all categories are reviewed between 11-18 UTC, which corresponds to 9-16h or 8-15h local time; summer- and wintertime respectively. It should be noted that during wintertime, sunrise is always before 9h local time and sunset at earliest around 16:30h, so there is maximally one hour that does not contain day-time data. During 11-18h local time it is always daytime in summer.

Conditional sampling of convective fluxes

Among others, vertical profiles of moisture, potential temperature, liquid water potential temperature, u-wind, v-wind and their fluxes are given for five different conditions. Conditionally sampled fields can be used to obtain the convective part of the momentum transport in LES. For the vertical profiles, conditionally sampled variables are available for the following cases:

1. No condition: all
   Averages over the complete horizontal domain for every height. This variable is used as the environment variable in the mass flux approximation, because the effect of the cloud core contributions, which have very low fraction of the domain, become negligible.
2. In cloud: $q_l > 0$
   If only the processes in the cloud are reviewed, all parcels containing liquid water are sampled.
3. Updraught: $w > 0$
   Below cloud base, the thermals have a positive vertical velocity. As convection causes positive vertical movement, these updraught values can reveal both the processes below cloud base and

the positive updraught in the cloud layer. updraught is not necessarily caused by convection. Small scale turbulence can also contribute to the conditioned fluxes.

4. In cloud and updraught: $q_l > 0$ and $w > 0$
   the parcels that contain liquid water and are going up are of interest. Some parcels may have positive buoyancy with respect to their environment and therefore move upward, but also overshooting thermals will be taken into account. The mass flux will always be positive for this condition.

5. In cloud-core: $q_l > 0$ and $\theta_v > \theta_{v,avg}$
   Transport due to moist convection is carried by the cloud core, where the updraught velocity is highest and most vigorous. The cloud core contains liquid water and should be positive buoyant with respect to its environment. Latent heat release is responsible for the positive buoyancy.

Using the conditionally sampled fields, the convective part of momentum transport can be estimated. In many studies the mass flux approximation that is discussed in Chapter 2 is used for estimating the convective transport of moist and heat. However, using the conditioned flux, it is possible to look directly at the contributions of the cloud core (which is thought to represent the moist convection contribution)

Dealing with the diurnal cycle

To compare the different categories or sub-groups with each other in a fair way, it should be kept in mind that the top of the mixed-layer is not at a constant height; its height differs during the day due to the diurnal cycle. The mixed-layer height is growing from sunset, finding its maximum after midday and decreases again. In addition, the mixed-layer height also differs from day to day. Therefore, the variables and fluxes will be normalised in height with the inversion height. Given that there is some degree of ambiguity in the definition of the inversion height, we have chosen to use the height at which the buoyancy flux is most negative as the inversion height. This is assumed to be near cloud base. In some cases to better view the tendencies or character of a flux, the flux variable will be normalised by a suitable value. In some cases this will be the surface value of the flux, in other cases this is the surface value of the total flux.

3.2.2. Change in convective momentum flux with changing convection

To answer the research question regarding the change in momentum flux with changing convection, the cumulus category is subdivided in four subgroups, selected on a specific variable that represents the amount of convection. The groups are assumed to have similar climatology, therefore the feedback of convection on the contribution to the total momentum transport can be reviewed objectively.

Selecting convection strength on surface buoyancy flux

The motivation for selecting the groups on different convection depth using surface buoyancy flux stems from the idea that a large surface buoyancy flux causes larger and stronger thermals that mix the atmosphere more vigorously. If thermals come higher, latent heat release will provide new energy to become more buoyant and rise even further, also mixing higher levels.

Selecting convection strength on cloud depth

Cloud depth on the other hand, is assumed a measure for convection as deeper clouds usually accompany deeper convection. By sorting the cumulus days into convection strength categories, we expect to find characteristics of these sub-categories that can indicate the amount of momentum transport based on the findings of LeMone and Pennell [1976].

3.2.3. Sensitivity study on moist convection

Opposed to observational data, contributions of individual processes can be reviewed in LES. Using sensitivity studies individual feedback processes that take place in the atmosphere can be reviewed. Because the climatologies of the different sub-groups of the cumulus category are not exactly alike, sensitivity experiments in which the latent heating effect on the buoyancy is removed are used to test if the same changes are observed. Because the same days are simulated, only without the moist convection, the contribution of moist convection can be objectively. The change momentum mixing near cloud base and in presence of moist convection specifically, is shown. Clouds are allowed to form in the simulation, however, the moist convection they are associate with is not present. As all other circumstances have not changed, this is a good indicator for the contribution of moist convection to the total transport.

4

Results & Discussion

In this chapter, the results are presented. The strategy, as presented in Chapter 3 has been applied to the data and this chapter discusses outcomes. The structure of this chapter follows the same structure as the approach: firstly, the convective part of the cumulus category will be compared to the clear-sky and cloudy categories. Thereafter, the convective part of the total momentum transport with increasing convection within the cumulus category will be shown. At last, the sensitivity study are presented, in which ten days with moist convection are compared to the same ten days without moist feedback.

4.1. The convective part of momentum flux

Selecting convective days

The categories have been selected as described in Chapter 3. All 366 days have been assigned to a category. The distribution of the days among the categories is as follows:

- clear sky: 9 days
- partially cloudy: 215 days
- overcast : 142 days
- cumulus: 149 days

It should be noted that 129/149 days in the cumulus category are overlapping with the partially cloudy category. This was expected as the cloud fraction of the cumulus category cannot exceed 50%, although the cloud cover can. As there can be clouds at different heights, or clouds during hours with positive surface buoyancy that are not in the time-frame between 11-18 UTC, some of the cumulus days do overlap with the overcast days.

A drawback of the used selection criteria is the discrepancy between the time-frame of the selection and the time-frame of the analysis. The latter contains all hours that have positive surface buoyancy, the former only includes the hours between 11-18h UTC are considered. The clear sky days are very under represented, which could be the result of a too strict selection criterion. As only a threshold selection criterion is used, finding the right level of the threshold can be challenging. The strict selection criterion was used to keep the presence of clouds in the clear-sky category to a minimum.

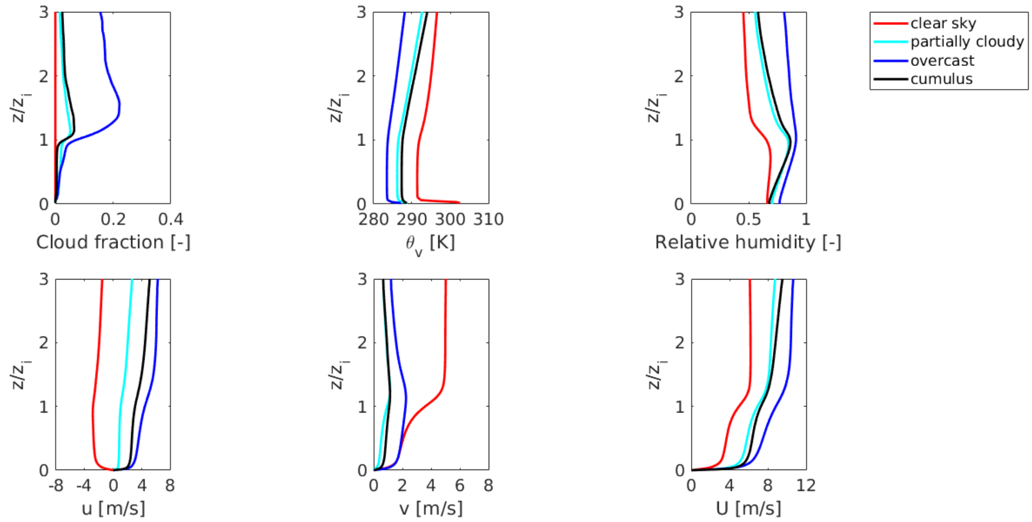

Figure 4.1: The vertical profile of the cloud fraction, virtual potential temperature, relative humidity, zonal wind speed, meridional wind speed and total wind speed are shown for the clear sky (red), partially cloudy (cyan), overcast (blue) and cumulus (black) days. The profiles are first normalised in height by z_i and then averaged over all hours with positive surface buoyancy of every day in the category. The shown profile is the mean of the daily averages. As expected the cloud fraction increases with the selection criteria that are mostly based on cloud cover. The total wind increases with cloud cover as found over the Atlantic ocean by Brueck et al. [2014]. The relative humidity is clearly larger for the case with the most clouds.

The maximum cloud fraction and the cloud depth, as shown in 4.1, increase from clear sky days to partially cloudy, cumulus and overcast days. The cloud fraction of the overcast days is lower than expected. However, the average cloud cover between 11-18 UTC can still remain below 50% when the overlap between clouds was low, when there was both a cloud near $z/z_i = 1$ and at different heights at different times, or when the selection window contained a large cloud cover but the hours with positively buoyant surface fluxes have less cloud cover.

On the clear sky days, of which the statistics are poor due to the low amount of days, the u-wind is directed oppositely from the other categories: easterly winds. As the easterly winds come from land instead of sea, it is expected that this brings less humidity. The overcast days have largest total wind, lowest virtual potential temperature and the largest relative humidity. Notice that with the increase in (low-level) cloud cover, the total wind speed increases as well. This is in agreement with the findings of Brueck et al. [2014] over the North Atlantic trade wind region and surprisingly this is similar over land. The difference in relative humidity between partially and overcast days is not very high; only aloft cloud base, the difference increases. In all four categories, θ_v is nearly constant with height indicating the sub-cloud layer is well-mixed. The relative humidity increases with height in the cloudy cases, obviously the largest increase for the overcast category. Above $z/zi = 1$, the conditions become weakly stable, only the clear sky a transition layer after $z/zi = 1$ is visible, as seen in the relative humidity and θ_v. Another remarkable profile is the v-wind of the clear sky days: the profile shows much more shear than its u-wind or the v-winds of the other categories. The difference in wind speed with respect to the wind above $z = z_i$ is much higher than in every other category.

Apart from the clear sky days, the categories do not have systematically different weather conditions. Therefore the categories can be compared in a reasonably fair way. The clear sky category is treated with extra care. It is important to be able to view the effect of the amount of cloudiness on momentum transport that are captured in the different categories under similar circumstances. Only then the effect of cloud cover on the momentum transport can be assessed individually.

The virtual heat flux, mass flux and total momentum flux are shown in Figure 4.2. Each profile has been normalised in height and are averaged over all positive buoyant hours on all days in the category and the mean of the daily-averages is taken. Cumulus and partially cloudy start with the largest surface buoyancy flux, followed by clear sky days and overcast days experience least surface flux (see Table

4.1). Comparing the values of the surface buoyancy fluxes to the case of LeMone and Pennell [1976], the surface fluxes we have obtained are considerably larger. This is most likely due to the stronger forcing that is present on land with respect to the case over sea. The shape of the profiles, however, is similar to the case of LeMone and Pennell [1976] and they all follow a straight path up to $z/z_i = 1$.

Noteworthy is the mass fluxes of the overcast days; especially above $z/z_i = 1.5$, the mass flux of the overcast days becomes larger than the flux on cumulus days. Whereas it is expected that cumulus days have a large mass flux because the category is selected on positive buoyancy flux between 900-1200m, which had been assumed to be near cloud base, the large clouds are assumed to block a fair amount of incoming solar radiation, preventing the Earth's surface to heat and subsequently provide less energy to rising thermals that are assumed responsible for large updraughts. However, due to its large cloud fraction, the cloud core fraction of the overcast category is approximately three times larger than the cumulus cloud-core fraction just above the mixed layer height, and aloft nearly eight times larger (not shown). Cumulus days thus have a much larger updraught velocity than the overcast days. The partially cloudy days do not have such a large average mass flux, and the difference between them and the cumulus category is rather high. The typical cloud core fraction in shallow cumulus fields is approximately 2-8% [Vilà-Guerau de Arellano et al., 2015] and the updraught velocity about 1-2 m/s [Stull, 1988], therefore the average mass flux of the partially cloudy days seems to be low. As the cloud fraction of the partially cloudy days is comparable to the cloud core fraction of the cumulus days ($\sim 2\%$) , the vertical velocity during partially cloudy days is about half as large as on cumulus days.

The momentum fluxes increase with the amount of cloudiness, especially near the surface. The difference between the cloudy cases is much less than the difference between cloudy and clear-sky cases. Qualitatively, the magnitude of momentum transport corresponds with the magnitude of the total wind: on clear sky days, the wind speed is lowest and also the momentum transport is least strong. On the overcast days, the wind speed is highest and the magnitude of momentum transport is too.

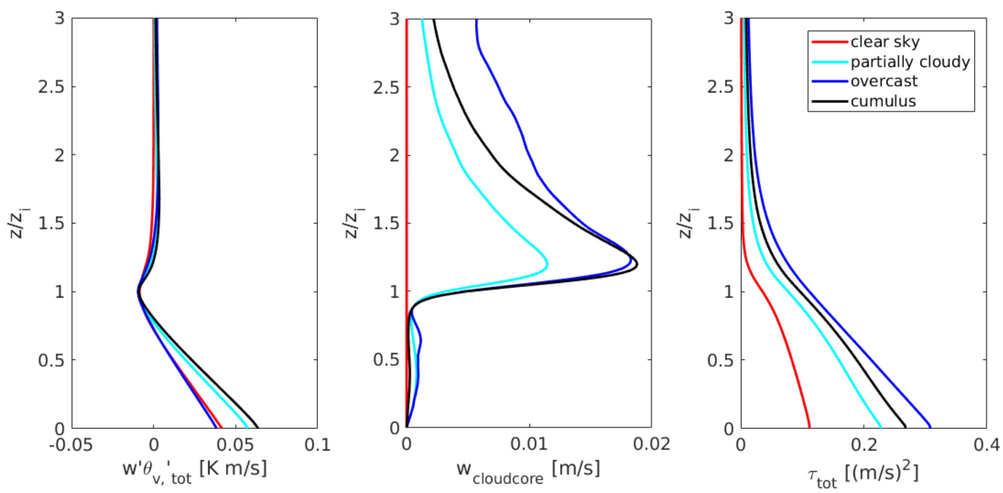

Figure 4.2: Figure: The vertical profile for the four categories of the virtual heat flux, mass flux ($a_{cloudcore} * w_{cloudcore}$) and total wind speed flux, normalised in height by z_i and then averaged over all hours with positive surface buoyancy of every day in the category. Subsequently the daily means are averaged per category.

Table 4.1: Surface buoyancy flux values and maximum normalised surface buoyancy values for the 4 different categories and the results from the field campaign from LeMone and Pennell [1976].

	$(w'\theta_v')_0$ [Km/s]	$(w'\theta_v')_{cloudbase}/(w'\theta_v')_0]$
LeMone & Pennell (1976)	0.020	-0.1
Clear sky	0.045	-0.3
Partially cloudy	0.063	-0.28
overcast	0.046	-0.43
Cumulus	0.067	-0.23

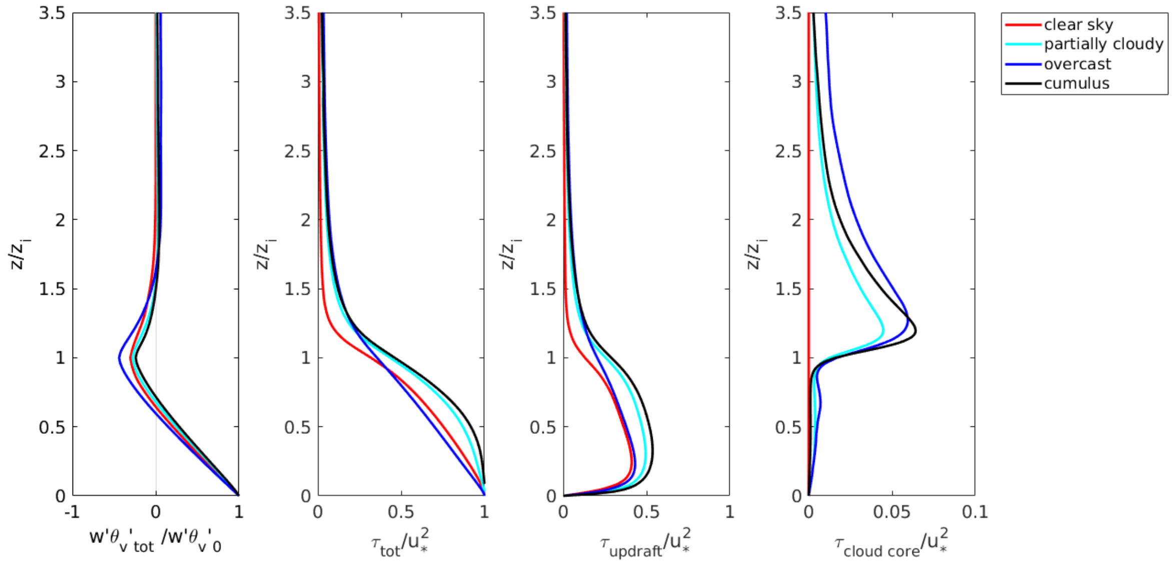

Figure 4.3: The vertical profile of the four categories of the total momentum flux, updraught contribution to the total flux and the cloud-core contribution to the total flux. The profiles are normalised in height by z_i and the surface value of the total momentum flux, averaged over all hours with positive surface buoyancy. The mean of all normalised averages of each day are visualised for the clear sky category (red), partially cloudy days (cyan), overcast days (blue) and cumulus days (black).

4.1.1. Conditional sampling of convective fluxes

By comparing the normalised profiles of the momentum flux from the different categories, the tendency of the wind can be determined for every category. In addition, the contribution of the updraught and cloud core to the total transport can be reviewed per category. Figure 4.3 shows the normalised virtual heat flux and the total momentum transport, the updraught contribution to the total momentum transport and the cloud core contribution for every category. In the first panel, the normalised buoyancy flux is shown. The behaviour of the virtual heat flux is similar, independent of the amount of cloudiness. Comparing the normalised virtual heat flux value obtained in the cumulus category to Nicholls and LeMone [1980], the values agree. Nicholls and LeMone [1980] state that a value of -0.2 is a generally accepted value for a convection-driven, cloud-free boundary layer and thus concluded that the sub-cloud layer is unaffected by the presence of cumulus clouds. Yet, our clear sky case has a more negative value than our cumulus category which is in contradiction with the argument above.

Remarkable is the different character of the total momentum flux for the overcast category: it shows less drag near cloud base and continues linearly from the surface up to $z/z_i = 1.4$. All other categories show a change in slope near $z/z_i = 1$, increasing the drag. Lowest drag is found in the lower part of the mixed layer, where the cumulus and clear-sky days have a nearly vertical momentum flux profile. The overcast days are most strongly mixed, as can be seen in the virtual temperature profile in Figure 4.1. However, overcast days have the lowest surface buoyancy flux. The mixing could be due to shear-generated mechanical turbulence, as the U-profile shows most shear in the sub-cloud layer and the wind speed are highest. This is often found near fronts or low pressure centres that often accompany overcast cloudiness [Stull, 1988, Chapter13]. Because the sub-cloud layer is very well-mixed, the profiles of the momentum flux are quite linear and because there is no prominent inversion jump, there is very little drag near cloud base. For the other cases that are less well-mixed, there is more drag. The clear sky days, having a similar surface buoyancy flux as the overcast category, also show an almost linear momentum flux profile from the surface to a fraction below cloud base. Just below cloud base a considerable drag is visible. This can be explained by the pronounced jump in the U-profile near cloud base. The drag is similar to the drag in the cumulus and partially cloudy days.

The contribution of cloudiness to the total momentum transport is not much: at most approximately 5% of the surface flux is transported in the cloud. The overcast days show a very small contribution of cloud core transport below cloud base. This is even less in the partially cloudy days and none for the cumulus and clear sky days. The three cloudy cases have similar momentum transport in the cloud layer, indicating that the vertical velocity w' or U' are similar. From the U-wind in Figure 4.1, the shear in U is similar for the partially and overcast days, only the cumulus days have somewhat more shear towards $z/z_i = 3$. In every category, dry convection below cloud base explains approximately half of the total momentum flux.

4.2. Change in convective momentum flux with change in convection

In the 146 cumulus days, different convection depth is present. Assuming similar climatology in these 146 days, the days have been divided in four quartiles with increasing convection. When assuming a similar climatology, we assume the days differ only in the parameter on which the convection strength is selected. The division is made based on surface buoyancy flux and cloud depth during day-time hours. In the coming two sections, the results of these two separations will be shown.

4.2.1. Momentum flux change with increasing convection selected on surface buoyancy flux

From the former paragraph we expect that in better mixed layers that also mix with the cloud layer the momentum profile will behave in a more linear way. As there are many days with different convection strengths within the cumulus category, the category is divided in four subgroups with increasing convection (increasingly well mixed layers) as selected on surface buoyancy flux is shown in this paragraph. Hereby we hope to get more insight in the effect of surface buoyancy on the momentum flux profile.

The minimum buoyancy flux, shown in the first panel of Figure 4.4, becomes most negative at cloud base for the days having lowest surface buoyancy and least negative for the days with the highest surface buoyancy flux. All profiles show a linear behaviour, as expected from the former results for the categories. Remarkable is that the normalised flux does not become more positive in the cloud layer, which would have been expected if the parcel gains energy from the latent heat release and consequently can become positively buoyant again. In the second panel, all profiles show that the momentum flux at the top of the mixed layer is still quite high: at least 40% of the surface value. The different quartiles reveal different characters in the total momentum flux. The larger the surface buoyancy flux, the more linear the profile becomes, which indicates a similar tendency throughout the mixed layer. The momentum flux profile that is seen from the lowest buoyant quartile, tending to increase the winds at low levels and decrease them at higher levels, is striking. Although the U profile of this quartile has most shear and largest inversion jump (not shown), the nature of this profile is not yet fully understood.

From the fourth panel, it can be seen that the magnitude of the surface buoyancy flux does not necessarily accompany deeper cumulus clouds. The momentum flux in the cloud core is only between 5-10% of the surface value. The cloud core contribution is around 25-30% of the total flux at $z/z_i = 1.5$. The fluxes of the second and third quartile contribute more than those of the first and fourth quartile. The updraught contribution increases with increasing buoyancy flux and is responsible for 50-65% of the total flux between $z/z_i = 0.2$ to $z/z_i = 1$, which is usual.

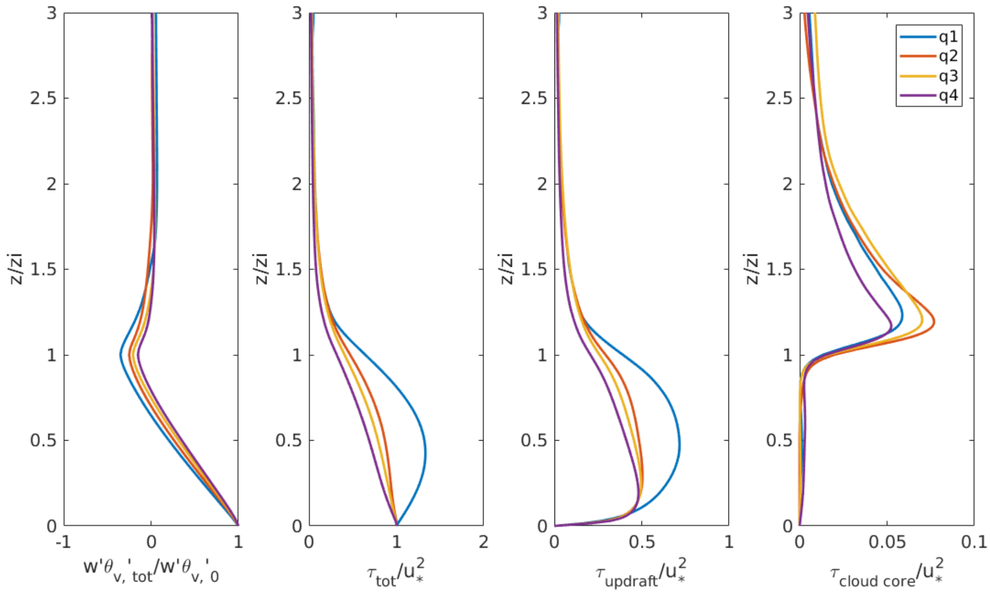

Figure 4.4: The vertical profile of the four quartiles with increasing surface buoyancy of the total buoyancy flux, total momentum flux and the conditioned updraught and cloud core momentum fluxes. The profiles are normalised in height by z_i and the surface value of the total flux and then averaged over all hours with positive surface buoyancy. The mean of the day-means are shown.

4.2.2. Momentum flux change with increasing convection selected on cloud depth

Increasing cloud depth can indicate deeper convection, as is also seen in the difference in fluxes in between the overcast, partially cloudy and cumulus days. Therefore, also the cloud depth has been used to separate on different amount of convection. In this section, the results of the selection of cloud depth will be presented and compared to the results of the selection based on surface buoyancy flux.

As noted in the previous section, stronger buoyancy does not necessarily give deeper clouds. This is also seen in the first panel of Figure 4.5, where the normalised buoyancy fluxes are shown for quartile 1 to 4 have increasing cloud depth. The fourth quartile (purple) is slightly more negatively buoyant at cloud base, however, it becomes most buoyant aloft. The first quartile that indicates the shallowest cloud depth is least negative, becomes zero aloft and exhibits similar behaviour to the clear sky category.

The second panel, in which the total normalised momentum transport is visualised, shows that with higher cloud depth, the tendency in the momentum transport is more similar throughout the mixed layer. The second quartile shows a very different characteristic from the other quartiles: the momentum transport first increases up to half the mixes layer, and gradually turns to a strong negative slope. The second quartile in the cloud depth selected case resembles the total and updraught momentum transports of the first quartile in the surface buoyancy flux selected case. The U profile of the second quartile is equal to the profile of the second quartile, except near cloud base, where an inversion jump is visible. The tendency to strongly increase the wind in the lowest part of the mixed layer is not well understood.

As had been expected, the cloud core contribution increases with cloud depth. Although it is maximally 10% of the total momentum flux at the surface, its contribution with respect to the total flux in the cloud layer becomes increasingly larger with cloud depth: from 2%, 22%, 45% to 55%. Below cloud base, the updraught contribution is between 50-60%, above it is largely dependent on the cloud core contribution, which also updraught, there contributions range from 50-78%. Although it was expected that most of the cloud contribution is carried by the cloud core, convection within other parts of the cloud may account for the discrepancy between updraught and cloud core contribution above the cloud

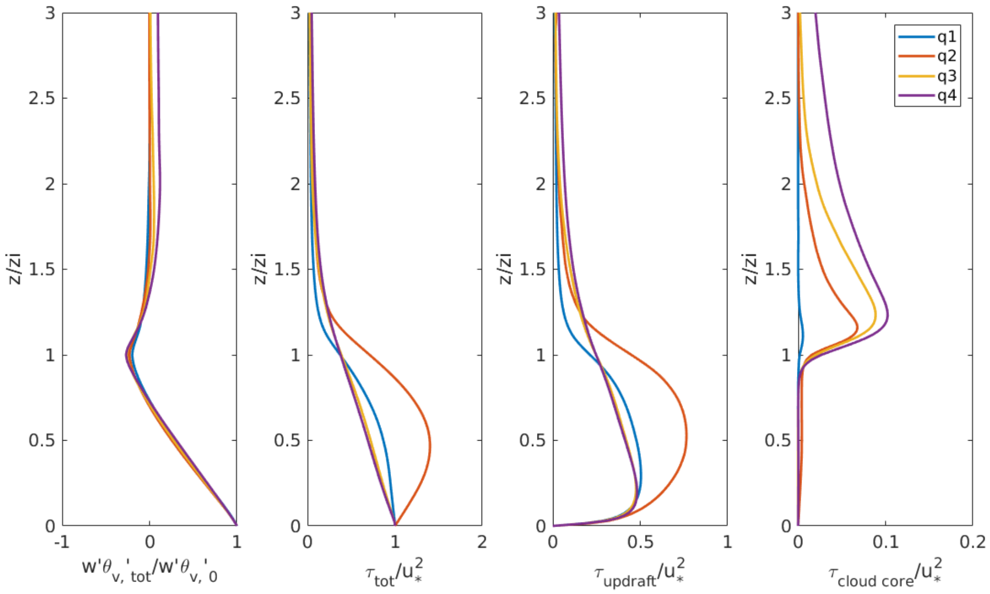

Figure 4.5: The vertical profile of the four quartiles with increasing cloud depth of the total buoyancy flux, total momentum flux and the conditioned updraught and cloud core momentum fluxes. The profiles are normalised in height by z_i and the surface value of the total flux and then averaged over all hours with positive surface buoyancy. The mean of the day-means are shown.

base. This can be tested with the conditionally sampled momentum flux on cloudy parcels. Although no fog was allowed during the selection of cumulus days, the second quartile does have a cloud core updraught in the mixed layer.

Because the selection on cloud depth and surface buoyancy flux result in very different profiles, we can conclude that the cloud depth is not dependent on surface buoyancy, although initially we thought that with a stronger surface buoyancy larger clouds could form. We can also state that with increasing surface buoyancy and increasing cloud depth (except for the second quartile selected on cloud depth), the momentum profile becomes more linear below cloud base and that with decreasing convection the drag near cloud base increases.

4.3. Sensitivity study on moist convection

In the former section, the climatology of the cumulus category has been assumed similar for all quartiles. However, differences in the climatology affect the fluxes and thus change the wind tendency. To avoid this problem, the same day has been simulated with and without moist feedback. This means the feedback of latent heat release during cloud formation is removed, however, the simulation still allows clouds to form. The resulting momentum fluxes and the updraught and cloud core contributions are visualised in Figure 4.6.

In the lowest half of the mixed layer, the fluxes are nearly identical. Only the cloud core contribution is much higher for the case without moist feedback. This is mostly because often smaller clouds form in the case without moist feedback. In other cases, a lower statocumulus cloud is found. The statocumulus is here found below the definition of z_i, because the minimum in the buoyancy flux can be in the middle of the stratocumulus cloud. The moist case has a cumulus profile, as expected, the case without moist feedback on the other hand shows a more stratocumulus profile. From the first two panels, we can observe that the moist convection above the mixed layer does not influence the flux underneath.

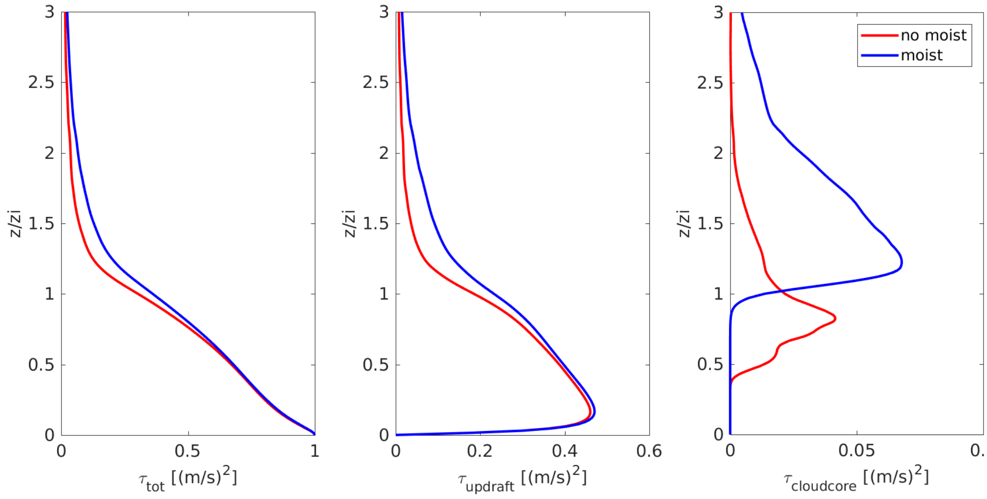

Figure 4.6: The vertical profile of the four quartiles of the total buoyancy flux, total momentum flux and the conditioned updraught and cloud core momentum fluxes. The profiles are normalised in height by z_i and the surface value of the total flux and then averaged over all hours with positive surface buoyancy. The mean of the day-means are shown.

5

Summary & conclusions

By separating year-long daily forecasts made by the fine-scale LES model of Whiffle on cloudiness and subsequently on convection strength, we analysed the change in the momentum transport in the lower atmosphere when cumulus convection is present compared to other cloudiness. Thereafter the change in the momentum transport profile is explored with increasing convection within the cumulus category. This strategy is used to answer the following research questions:

- How does the momentum transport change in the presence of cumulus convection?
- How does the behaviour of the momentum flux change with different depths and strength of convection?
- How does the presence of clouds, and thus moist convection, influence the behaviour of the momentum transport?

In this section, the research questions are answered and the most striking results are summarised. There will be clarified what is not yet understood and suggestions for further research are given.

The momentum transport in the presence of cumulus convection differs from days with clear-sky convection and convection on overcast days. In the latter two cases, there is less surface buoyancy flux however, the momentum flux profile is mostly linear in the mixed layer. For the cloudless days, this should be zero above the inversion and thus a drag found below cloud base. The overcast day is very well mixed even the inversion jump is smoothed in this case, so almost no drag is present.

The momentum flux shows more drag near cloud base with decreasing convection and gains an increasingly more continuous profile in the sub-cloud layer with increasing convection. This is shown by selection of convection both on surface buoyancy flux and cloud depth. This hypothesis is not confirmed by the results of the categories, as the overcast days have least surface buoyancy and most linear momentum flux profile and by the second quartile that is selected based on cloud depth. The explanation for the well-mixed layer that causes the linearity in the momentum flux of the overcast category is turbulence generated by wind shear. For the second quartile in the cloud depth selection it is possible that the first quartile is mostly clear sky and that the effect that is also seen in the low surface buoyancy quartile is captured in the second quartile of the cloud depth selection. The behaviour of these two quartiles that show similar profiles of the total momentum flux is partly understood. The drag near the cloud base finds its origin in the inversion jump. However, the wind-increasing tendency in the lower part of the sub-cloud layer is not yet understood.

From the sensitivity study on moist convection, it is shown that the presence of clouds, does not change the sub-cloud momentum fluxes. Only the upper part of the mixed layer is influenced, however this is mostly caused by stratocumulus formation. As expected, the moist flux is higher above cloud base than the profile of the case without moist feedback. Stratocumulus forms in some cases, in other cases the cloud that forms is smaller than in the case with moist convection, explaining the present yet smaller cloud core flux above the cloud base. We can conclude that the cloud does not affect the dry convection beneath cloud base. However, the cloud could be responsible for the inversion jumps that cause the shear as mentioned in the former paragraph.

Other results that have been found during our study are listed below:

- Selecting convection on surface buoyancy flux, the updraught contribution to the total momentum flux is about 50% and in the cloud layer, the cloud core contribution is around 25-33%.
- Selecting convection on cloud depth, the updraught fluxes explain more than in the buoyancy selection: 50-78%. The cloud core contribution, increases with cloud depth and explains 2-60% of the total flux, depending on the cloud depth.
- For both selections of convection, the cloud core momentum flux is maximally 10% of the total surface flux.
- Most drag in the momentum flux is found near cloud base.
- It was expected that the cloud depth depends on the surface buoyancy flux, however, this is invalidated by our data: the amount of surface buoyancy does not influence the cloud depth.

From the findings, different types of selections can be thought of: a selection on background wind within the cumulus category would be interesting to better compare the effect of background wind on the momentum transport and within a range of background wind to compare different convection without the influences of the background wind. Selection on the drag in the momentum flux could give an indication of the typical circumstances for such a behaviour in momentum transport. This could help identify whether a large inversion jump is typical for a strong drag or if this occurs when the wind comes from a certain direction.

Separating the individual u- and v-winds would be interesting. Especially differences when selecting on background wind, the individual winds should be considered because they often accompany certain weather types.

Furthermore, the outstanding cases in the selection on convection depth that had very different tendency in momentum flux at low cloud depths and lowest surface buoyancy flux should be further looked into.

From the limitations of this method, I would recommend to try a selection based on conditions during the hours that are analysed: hours with positive surface buoyancy. Furthermore, to prove that the LES results are trustworthy and according to reality, the observation tower in Cabauw can be used to observe similar patterns in wind at different surface buoyancy strengths and with different cloud depths.

Regarding the model, it would be interesting to see if the momentum transport changes much when interactive radiation is realised. After this realisation, the comparison with regional models such as the ECMWF model to review the differences in wind prediction and subsequently the wind prediction skill and the origin of these differences are a very interesting topic.

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A

Appendix

The mass flux approximation is a well-known tool for estimating the total flux. For the total humidity for instance, it is shown many times that the mass flux approximation works well. The momentum flux however, cannot be well assessed by the mass flux approximation. This is similar to what we have found, as can be seen in Figure A.1 and Figure A.2.

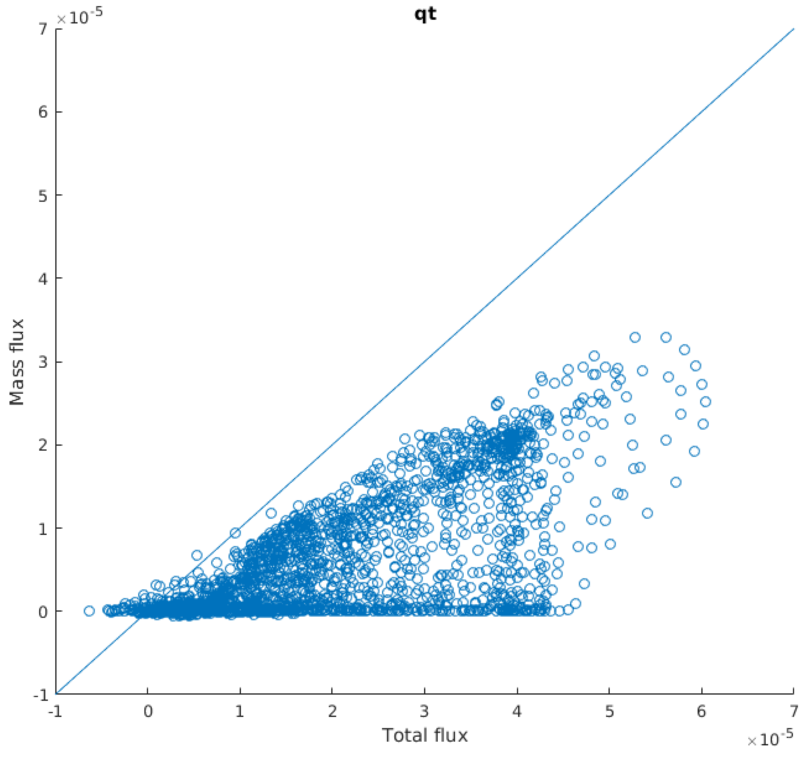

Figure A.1: Mass flux approximation versus total flux of the total humidity. A large number of points is approximately 80% of the total flux.

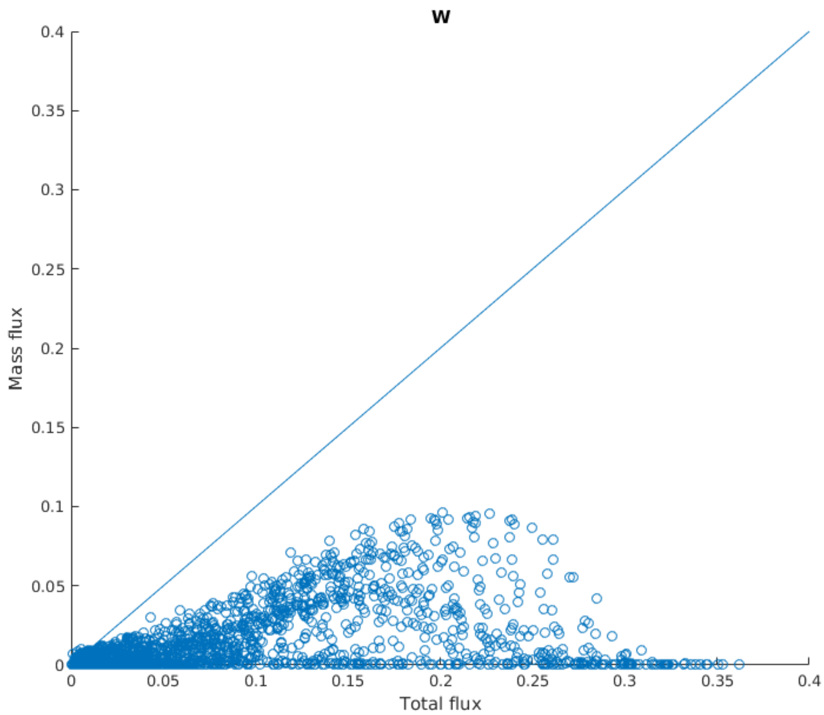

Figure A.2: Mass flux approximation versus total flux of total wind. Approximately 40% or less of the total flux is estimated by the mass flux approximation.