Impact of a large-scale offshore wind farm on meteorology:
Numerical simulations with a mesoscale circulation model

Master Thesis

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Abstract

In this thesis the meteorological effects of a large-scale (9000 km²) offshore wind farm in the North Sea were simulated using the MM5 mesoscale model. The wind farm was simulated by introducing a higher roughness length (0.5 m) in the area of the wind farm. The meteorological effects were examined by comparing model runs with and without wind farm. Turbulent kinetic energy, cloud formation, precipitation and wind speed reduction were studied. Two case studies with westerly flows were performed. The first case study begins at 00 UTC July 1st 2001 and ends at 18 UTC July 3rd 2001. The second is from 00 UTC October 2nd 1999 to 18 UTC October 4th 1999.

The model was evaluated by comparing observational measurements with the model output. This was done at two places near the Dutch coast, de Kooij and Schiphol. Observational values of wind speed, wind direction and temperature were compared using two boundary layer schemes (ETA and MRF). Then these standard runs were compared with two other runs that included the wind farm.

We compared the wind reduction results of the mesoscale model with a conceptual model. The conceptual model is based on a model by Emeis and Frandsen (1993), where the reduction of horizontal wind speed is computed from a balance between a loss of horizontal momentum and replenishment from above by turbulent fluxes. As regards wind reduction calculations the MM5 model yields comparable results as obtained by the Emeis and Frandsen model.

In case 1, where no clouds were present, the model simulated enhanced cloud formation above the wind farm. The second case, which was partly cloudy, showed no significantly cloudiness increase. The rainfall however did show dramatic changes. The Dutch coast received less but large parts of the North Sea more precipitation.

Preface

Writing this thesis has been a joyful experience. But of course this thesis would not be what it is without the help of a lot of people. First I would like to thank Jordi Vilà for his daily assistance, teaching me to use the MM5 model, refreshing my boundary layer knowledge and having lunch with me every day. Then I would like to thank Han van Dop, my advisor from the Utrecht University, for supplying me with the subject of this thesis and arranging the contact with Wageningen. Also Aarnout van Delden should be thanked for making the observational data available. Erik Holtslag helped me with the data from the HYDRA project and Mariska Harte from the Coast en Sea department supplied me with some practical information about real-life wind farms.

I would especially like to thank all the people at the department in Wageningen for making me feel at home from day one. Sara, Sandra and Nina thanks for being able to talk about something else then wind farms and boundary layers. Jeroen and Jeroen from Utrecht should both be thanked for their moral support they gave me through MSN in times of research-trouble. I wish them both good-luck writing their master thesis.

Pim, January 2004
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1. Introduction

Wind energy is one of the most promising forms of renewable energy. According to the Danish power companies it is the only renewable energy source that can do without subsidies to be compatible with fossil fuel energy (http://www.windpower.org/, 2003). It is not surprising that a lot of countries invest large amounts of money in wind turbines, wind farms and offshore wind farms. Especially this last category has seen an upward trend in the last decade (http://www.ewea.org/, 2003). This is mainly because countries are running out of appropriate on-land places to build large-scale wind farms (Barthelmie, 1996).

This trend is also due to the better wind regime at sea than at land, with higher wind speeds and less turbulence giving the turbines a longer expected lifetime (Folkerts, 2001). The more turbulent the air encountering a wind turbine is, the higher the load on a wind turbine will be and the sooner it will be malfunctioning. The low turbulence, i.e. low values of turbulent kinetic energy, at sea is due to the fact that daytime convection, an important source of thermally induced turbulence, is small over a water surface. A second factor is the fact that roughness elements are generally smaller over a water surface, even in moderate to strong winds, than over an urbanized land surface.

Sunlight will penetrate several meters below the sea surface, whereas on land the radiation from the sun only heats the uppermost layer of the soil, which thus becomes much warmer. Consequently the daytime temperature difference between the surface and the air will be smaller above sea than above land (http://www.windpower.org/, 2003). Also due to the higher roughness length above land there is more vertical shear, making the boundary layer less stable than above sea. The boundary layer is the lowest 1-2 km of the atmosphere, the region most directly influenced by the exchange of momentum, heat, and water vapour at the earth’s surface (Kaimal, 1994).

Finally the trend towards more offshore wind farms is due to the improvement of the efficiency of the wind turbine itself. Because of the increasing power output the state-of-the-art wind turbines provide, the costs of establishing a wind farm at sea and the costs of transporting the produced energy back to land are earned back sooner. All this makes investing in offshore wind farms more interesting.

In June 2003 the European Union had an installed capacity of 24.626 MW in wind energy (http://www.ewea.org/, 2003). Planned projects at sea will add several thousand megawatts to this (Barthelmie, 2002). The current European turbines provide about 216.000 GWh/year; an average Dutch household uses about 3400 kWh/year (http://www.nuon.nl, 2003). The latest EWEA (European Wind Energy Association) target is to have 86 million Europeans getting its energy from the wind by 2010. The Dutch government goals are to have 6000 MW of offshore wind energy ready by the year 2020. A pilot project is right now being performed near Egmond where Shell and NUON are building an approximately 100 MW wind farm in a 40-km² area.
If all the plans for large-scale wind farms are conducted in 2020 and perhaps even more in 2050, wind turbines will cover considerable parts of the Dutch coastal North Sea area. For these planned wind farms to be successful, research has been performed on how to extract as much power out of the turbines in the farm as possible. Placing several wind turbines behind each other causes the last wind turbine to catch less wind, and consequently less energy, then the first in line, the so called wake effect. The wake effect of a wind turbine is the wind velocity decrease and turbulence increase downstream of the turbine rotor (Folkerts, 2001). In a wind farm a wake effect across a large area is produced. In other words there is a wind speed reduction and turbulence increase over a large area. This might have consequences for the meteorological conditions in the area of the wind farm and even further away from the farm.

Wake-effect research has been done under the flag of the EU project ENDOW (EfficieNt Development of Offshore Wind farms). The ENDOW project mainly focuses on evaluating, enhancing and interfacing wake and boundary layer models for utilization offshore (Barthelmie, 2002). The ENDOW project resulted in a significant advance in the state of the art in both wake and marine boundary layer models leading to improved prediction of wind speed and turbulence profiles within large offshore wind farms (Barthelmie, 2002).

Because of the importance for energy companies to have accurate predictions on the power output of a wind farm, a lot of the research done in ENDOW focuses on improving prediction of wind speed and turbulence profiles inside the wind farm. Few of the research focus on the effects of a wind farm on the meteorological conditions in the area around the wind farm. It is widely presumed that small wind farms will have a negligible effect on these conditions, but until now few studies have been done on large-scale wind farms.

Bearing in mind the above considerations, it is not surprising that the ministry came with questions about the effects of large-scale wind farms on the local climate. (See the appendix for the Dutch research proposal.) The research presented in this Master thesis attempts to give answers to the next two questions.

1. What are the effects of a large-scale wind farm in the North Sea on the meteorological variables wind speed, wind direction, turbulence and cloud and rain formation near the wind farm and in the Dutch coastal area?

2. What is the reduction of the wind speed inside a large-scale wind farm, and what are the effects on power output?

For this study we have used a mesoscale atmospheric circulation model, MM5 to perform two case studies. For these studies the version 3.5 of the mesoscale model MM5 is used. MM5 is a non-hydrostatic Mesoscale Model developed at the Pennsylvania State University (PSU) and the National Center of Atmospheric Research (NCAR).
The MM5 model is designed to simulate or predict mesoscale and regional-scale atmospheric circulation. (http://box.mmm.ucar.edu/mm5/, 2003) With this model, simulations of several thermodynamic variables, with and without a wind farm, were performed and compared.

The wind farm was modelled by modifying the models terrain database. The terrain was modified in two separate ways: by presenting an idealized 100-meter high hill in the North Sea and second by changing the roughness length of the area where the wind turbines could be placed. The area that was modified is shown in figure 1. This location of the wind farm was chosen for two reasons. First the wind farm should be 30 km out of the Dutch coast and second it should be situated on the Dutch continental shelf. Taken only these things into account, a rectangular area of about 9000 km\(^2\) is available for wind farming.

Variables like wind speed, wind direction and temperature have been compared with observational values at station de Kooij (06235 synoptic code) and Schiphol Airport (06240 synoptic code). Cloud and rain formation and turbulence enhancement were also examined using vertical as well as horizontal cross-section plots. A second aim of the research was to study in more detail the wind reduction in and around the wind farm and the consequences on the energy output.

The outline of this thesis is as follows. In chapter 2 the synoptic situation of the case studies will be discussed. Next there will be a discussion about the results that MM5 produced on turbulence, clouds and rain. In chapter 4 the conceptual model by Emeis and Frandsen (1993) that prescribes the wind reduction inside a large-scale wind farm will be explained. Then there will be a chapter on the loss of power output due to the wind reduction inside the wind farm. Finally some conclusions will be made in section 6.
2. Synoptic situation

In order to analyse the most appropriate situation a westerly flow over the North Sea and the wind farm was selected. Statistically, a westerly flow is the most common flow for this area. The undisturbed flow is west of the wind farm and the effects on the farm itself and on the Dutch coast can be examined. Two situations were found suitable:

The first case study begins at 00 UTC July 1st 2001 and ends at 18 UTC July 3rd 2001. During these 66 hours a high-pressure system is moving from the south of Great Britain towards Denmark. This system gives for the first 39 hours of the model run, moderate westerly winds in the area of the wind farm and along the Dutch coast. After that the wind changes to north before turning to east. In the vicinity of the wind farm it is partly cloudy and temperatures are between 15 °C at night and 23 °C during daytime. Figure 2 shows a time series of the evolution of this high-pressure area and its winds. As can be seen in figure 2b, the core of the high-pressure area is directly above the wind farm.

The second case study is in the period from 00 UTC October 2nd 1999 to 18 UTC October 4th 1999. During the whole period the wind has a westerly component in the area of the wind farm due to a low-pressure area that moves from the north of Scotland along the coastline of Norway to the north. Here higher wind speeds, more cloudiness and precipitation is observed than in case 1.
3. Experimental set-up

A non-hydrostatic mesoscale circulation model, the MM5 model, was used to carry out the numerical simulations. The model uses a nested grid system. For this case study a two-way nested system has been used. This means there is a two-way information exchange between the different domains. In this research we used three domains, with one large ‘mother domain’ and two smaller embedded domains. In this case domain 3 again is embedded in domain 2. Domain 1 has a resolution of 45 by 45 km and includes the north of France, most of Great Britain and Denmark. Domain two has a resolution of 15 by 15 km and includes northern Belgium, eastern England and the Netherlands as far east as Lake IJssel. The resolution of the third domain is 5 by 5 km and is mostly over the North Sea. In the last domain we modified surface properties in order to simulate the presence of the wind farm. (See figure 1)

A key methodological question of this research was: How to model a large-scale offshore wind farm in MM5? In the state of the art models, used for wind farm modelling, every single wind turbine and its wake, is modelled separately. These models then examine the interaction with and superposition on neighbouring turbines (Crespo, 1999). These models however have a much smaller resolution (in the order of 10 by 10 m) than the MM5 model that was used for this research. It may be clear that MM5 is unsuitable for modelling a single wind turbine and its wake, so we had to come up with another solution. We choose to represent the farm by the introduction of a 100m high hill or by increasing the roughness of the area. In both cases all the other surface boundary conditions were kept the same. The roughness length value of 0.5 m was proposed based on a study by Lettau (1969) and Betz law as explained below.

3.1 Description of Betz Law

One of the most important laws in wind energy is Betz Law. (http://www.windpower.org, 2003) In a very simplified way it explains how much energy an ideal wind turbine would take out of the wind. In chapter 5 we will look in more detail what happens with a flow encountering a wind turbine. For this paragraph we will follow the classical derivation of Betz law.

The wind turbine rotor must obviously slow down the wind as it captures its kinetic energy and converts it into rotational energy. This means that the wind will be moving more slowly to the left of the rotor than to the right of the rotor. Since the amount of air entering through the swept rotor area from the right (every second) must be the same as the amount of air leaving the rotor area to the left, the air will have to occupy a larger cross section (diameter) behind the rotor plane. (http://www.windpower.org, 2003)

The more kinetic energy a wind turbine extracts from the wind, the more the wind will be slowed down as it leaves the other side of the turbine. Hypothetically if we extract all the energy from the wind, the air would move away with speed zero. In that case we would not extract any energy at all, since all
of the air would be prevented from entering the rotor of the turbine. In the other extreme case, the wind could pass through the turbine without being hindered at all. In this case we would not have extracted any energy from the wind.

So there must be some way of breaking the wind, which is in between these two extremes, with an optimum efficiency in converting the energy in the wind to useful mechanical energy. It turns out that an ideal wind turbine would slow down the wind by 2/3 of its original speed (http://www.windpower.org, 2003). The physical derivation is given below:

First we make the assumption that the average wind speed through the rotor area is the average of the undisturbed wind speed before reacting with the wind turbine, \( v_1 \), and the wind speed after the passage through the rotor plane, \( v_2 \), i.e. \( (v_1 + v_2)/2 \). The mass of the air streaming through the rotor during one second is:

\[
m = \rho F (v_1 + v_2)/2
\]  
(3.1)

where \( m \) is the mass, passing through the turbine, per second, \( \rho \) is the density of air, \( F \) is the swept rotor area and \( [(v_1 + v_2)/2] \) is the average wind speed through the rotor area. The power extracted from the wind by the rotor is equal to the mass times the drop in the wind speed squared (according to Newton’s second law):

\[
P = (1/2) m (v_1^2 - v_2^2)
\]  
(3.2)

Substituting the expression for \( m \) (3.1) into (3.2) we get the following expression for the power extracted from the wind:

\[
P = (\rho/4) (v_1^2 - v_2^2) (v_1 + v_2) F
\]  
(3.3)

Now compare our result with the total power in the undisturbed wind, \( P_0 \), streaming through exactly the same area \( F \), with no rotor blocking the wind.

\[
P_0 = (\rho/2) v_1^3 F
\]  
(3.4)

The ratio between the power extracted from the wind and the power in the undisturbed wind is then:

\[
(P/P_0) = (1/2) (1 - (v_2/v_1)^2) (1 + (v_2/v_1))
\]  
(3.5)

We now plot (http://www.windpower.org, 2003) \( P/P_0 \) as a function of \( v_2/v_1 \) (see figure 3). We can see that the function reaches a maximum for \( v_2/v_1 = 1/3 \), and that the maximum value for the power extracted from the wind is 0.59 or 16/27 of the total power in the wind. In the rest of this paper we will make the assumption that all the wind turbines work at Betz maximum.
3.2 Lettau’s roughness length

Lettau (1969) suggested a method for estimating the aerodynamic roughness length based on the average vertical extent of the roughness elements ($h^*$), the average silhouette or vertical cross-section area presented to the wind by one element ($s_i$), and the lot size per element. $S_L = (\text{total ground surface area} / \text{number of elements})$

$$z_0 = 0.5h^* \frac{s_i}{S_L} \quad (3.6)$$

(See Stull p. 379) This relationship is acceptable when the roughness elements are evenly spaced, not too close together, and of similar height and shape. (Stull, 1988) In this case the wind farm satisfies all these prerequisites. Using the following values $h^*=100$ m, $s_i=6648$ m$^2$ and $S_L= 900,000$ m$^2$ it follows that $z_0 = 0.37$ m. We assume, using Betz Law, that one third of the wind passes the turbine unaffected. In this case it is more appropriate to have $s_i = 2/3 * 6648 = 4432$ m$^2$. In this case $z_0 = 0.25$ m. In this example we assumed a wind farm with 10,000 turbines. The maximum amount of wind turbines, which can be installed on this area, can be estimated from the empirical rule that the minimum separation should be 7.5 times the rotor diameter. We then arrive at a number of 19,000 turbines with a corresponding $z_0$ of 0.5 m. This value was used in the model calculations.

3.3 Sensitivity analysis on the physical parameterisation

The first part of the research was comparing the observations at stations de Kooij and Schiphol with the model values using planetary boundary layer (PBL) schemes MRF (Medium-Range Forecast) and ETA (Eta-Mellor-Yamada). These runs were done to test the model performance. The MRF and ETA schemes are commonly applied in numerical weather forecast models. The differences between the two schemes will briefly be explained below.

The dynamics of the PBL in a numerical model, closely depend on the parameterisation of the surface fluxes. In MM5 the surface sensible and latent heat flux are parameterised as (Dudhia, 2000):

$$H_s = \rho_a c_p C_g V_a (\theta_g - \theta_s)$$

$$E_s = \rho_a L_v M C_q V_a [q_{vs} (T_g) - q_v]$$

$c_p$, $L_v$ and $M$ are the specific heat, latent heat of vaporization of water and the moisture ratio and air density at the lowest level. $\theta_g$ and $q_{vs}$ are the potential temperature and the water vapour mixing ratio at surface level where $q_{vs}$ is a function of the surface temperature $T_g$ $C_g$ and $C_q$ are transfer coefficients for heat and water vapour. MRF uses different values for $C_g$ and $C_q$ whereas ETA assumes that $C_g$ and $C_q$ have the same value (Dudhia, 2000).
As well as the surface fluxes, the turbulent transport of heat and moisture throughout the whole convective PBL plays an important role in the maintenance and development of the PBL. The MRF mixing scheme uses a non-local, first order closure scheme (Dudhia, 2000). The ETA scheme needs to calculate the turbulent kinetic energy (TKE) and a master length scale in order to calculate turbulent fluxes. Due to the local character of this scheme the turbulent transport depends in contrast to the MRF scheme on the local mean gradients in the PBL. The MRF scheme does not include TKE, but is more efficient in computer time then the ETA scheme (Dudhia, 2000). Because we were interested in examining TKE enhancement due to the wind farm all the results presented in the next chapter are acquired using the ETA boundary layer scheme.

3.4 Setting up the model

First we performed two evaluation runs using the two different PBL schemes mentioned above. After these ‘standard’ evaluation runs (without terrain modifications) two additional runs were performed; one consisted of modelling a 100-meter high hill, the other of modelling an area of higher roughness length (0.5 m instead of 0.01 m). Both modifications were done in the third domain. (see figure 1) In both cases the adjusted area was 9000 square kilometres in size. These cases were done to check how sensitive the model was to modifications of the terrain files. The terrain files contain information about some variables like the roughness length.

Figure 4 shows the model agrees quite well with the observations, especially the 2-m temperatures and the wind direction. This means that in general the synoptic situation (the passing of the high pressure area) is well modelled. The model also shows similar results as the reanalysis NCEP maps. (http://www.wetterzentrale.de/, 2003) It can be seen that for the 2-m temperatures and the wind direction all of the runs are quite similar.

Figure 4a shows that overall the model slightly underestimates the actual wind speed measured at The Kooij. This is probably due to the fact that the model grid point is not exactly at the same position as The Kooij station. Especially in the area of land-water crossings the change in wind speed can be rather high. The same patterns for wind speed, temperature and wind direction were observed for Schiphol Airport.

It can be seen that especially with strong westerly winds (0 to 22 hours) the higher roughness run gives lower values then the normal run. Differences roughly vary between 0.5 and 1.5 m/s. With lower wind speeds from the west or north (22 – 46 hours) the effect is less pronounced. As the wind turns eastwards (46-66 hours) the two runs show similar results since de Kooij is in an upwind position with respect to the wind farm.

These first results suggest that using a higher roughness length to represent the wind farm is better then using a hill because the hill does not give any wind speed reduction, not even in the vicinity of the wind farm. The wind simply flows over the hill, almost unchanged. Not any cloud or rain enhancement was seen
either. That is the reason to use an area of 0.5 m roughness length to represent the wind farm in the next part of this paper. To obtain a better view of the wind reduction inside and outside the wind farm this parameter will be examined at 12 different positions on the map. (see figure 5 for more details) Results from this analysis will be given in section 4.
4. MM5 results

In this section the results of the MM5 model are discussed. With the use of these results we will give answers to the two research questions from the first section. We will focus on two aspects. First we consider turbulence and cloud formation. This is for example interesting for people living nearby the wind farm. We will also consider the wind speed reduction. This is interesting for energy companies because wind reduction has large impact on the energy output of the wind turbines.

Model results will be presented in either horizontal cross-sections or vertical cross-sections. In the vertical cross-sections the wind farm is denoted by small dots at the bottom of the graph. The vertical cross-sections have all been made perpendicular to the wind farm, from east to west. In the horizontal plots the wind farm is represented by a bold rectangle in the North Sea. Figures from both case 1 and 2 will be presented. Case 1 has weak westerly winds for the first 40 hours. Case 2 has higher westerly wind speeds during the whole run. For more details see chapter 2.

Some of the figures show the difference between the results obtained between two simulations. This means that MM5 calculated the difference between the run with the wind farm and without the wind farm (control run). I.e. if there is a positive value for a parameter in a difference figure, it means this parameter has increased due to the wind farm. Increases are indicated by a continuous line, decreases by a dashed line.

4.1 Effects on turbulence and cloud mixing ratio due to the presence of the wind farm

The presence of the wind farm disturbs the meteorology in and outside the wind farm. In this paragraph the results on turbulence and cloud formation will be discussed. To verify the link between cloud formation and an increase in turbulence due to the wind farm we will first study this last variable. We decided to use turbulent kinetic energy (TKE) in m$^2$/s$^2$ as the variable for the turbulence, because it is suitable for boundary layer use. The TKE is defined as:

$$TKE \equiv \left( u'^2 + v'^2 + w'^2 \right) 2 \quad (m^2/s^2) \quad (4.1)$$

Where $u'$, $v'$ and $w'$ are the fluctuating components of the three wind vectors $u$, $v$ and $w$. As can be seen in figure 7 there is an increase in TKE due to the wind farm. However on the lee-side of the wind farm there is a decrease of TKE. This is due to the lower wind-speed values. In the southern part of the wind farm values increased from 1.3 m$^2$/s$^2$ to 3.1 m$^2$/s$^2$ due to the wind farm for 12 UTC September 3rd (case 2).

Figure 8 shows the time evolution of the TKE for the control run and the run with wind farm. The first figure shows the bulk TKE for a position inside the wind farm. The bulk TKE is defined as the average TKE over the whole boundary layer. The height of the boundary layer was defined as the height at
which the value for TKE became constant. The second figure shows the ground level (\(z=0\)) TKE. As can be seen in the figures, there is not much change in the bulk TKE due to the wind farm. Close to the surface, the TKE however is higher for the run with the presence of a wind farm.

As a result of the flow disturbances and increased TKE, one could expect an increase of cloud formation. This was the case for one of the two cases. Figure 9 shows that the enhanced cloud formation occurred just above the wind farm for case 1. Figure 9 a shows the column-integrated cloud water in mm, this is the column-integrated value of the total cloud-mixing ratio. The total cloud-mixing ratio itself is shown in figure 10 a, b, c for a time series of six hours in a vertical profile. (\(a = 12\) UTC, \(b = 15\) UTC and \(c = 18\) UTC on July 2\(^{nd}\)) The total cloud-mixing ratio is the amount of grams of cloud water or ice per kilogram air. The areas with high TKE values reasonably coincide with the areas of increased cloud formation for the first case (see figure 9 a and b).

In the hours before the times shown in figure 10 a, b, c we did not observe any formation of clouds. The core of the cloud is positioned at the left border of the wind farm. This is as expected because this is the position where the air is lifted due to the encounter with the first rows of wind turbines (i.e. the first area with higher roughness length). This is shown by the upward arrows in figure 10; these denote wind difference arrows between the run with wind farm and the one without. Especially at the 12 and 15 UTC-figures the core of the cloud coincides with the relative updraft. After 18 UTC the cloud enhancement has not been seen anymore. The core of the clouds is at approximately 1 km height. At first the cloud is about 300 m thick but it grows to a thickness of 1000 m at 18 UTC. The second case did not show any cloud enhancement due to the wind farm. This is probably due to the fact that clouds were already present in the area of the wind farm and along the Dutch coast in the second case.

For case 1 the extra cloud formation results in some rainfall. Considering the amount of precipitation calculated by the model in figure 11 a it is seen that on the 2\(^{nd}\) of July a small patch with a maximum amount of 8 mm of rain is predicted in the area of the wind farm. Most of the precipitation values are between 1 and 3 mm however. During the run without the wind farm there was no precipitation. Figure 11 b shows a totally different result for case 2. During the second case there already were clouds with precipitation present. Figure 11 b shows no change in rainfall for the area of the wind farm itself, but large effects on the areas surrounding it. Large parts of the Dutch coast receive less precipitation, but large parts of the North Sea surrounding the wind farm get more. For example the parts of the Dutch coast southeast from the wind farm go down from 26 mm to 11 mm in 24 hours, a reduction of 57%.

During the last 24 hours of the second run the wind shifted from due west to north-northwest. The period with due westerly winds is accountable for the area with rain-enhancement south west of the wind farm. The northerly component is accountable for the area with more precipitation north of the wind farm. All the precipitation that accumulates before the wind farm cannot fall again after it. This is the reason why the Dutch coastal area receives less precipitation in this case.
4.2 Wind speed reduction

To answer the second question we study in more detail the variations of the wind speed. The average reduction of the wind speed for case 1 (during the first 39 hours) is deducted for 12 points in and near the wind farm (see figure 5). The same was done for the complete second case (66 hours). Finally we consider what the effects of the wind reduction are on the average power output of the wind farm. In order to do this analysis, we introduce the Weibull function and the power curve.

Figures 12 a and b show the wind reduction due to the wind farm for case 1 (21 UTC July 1st) and case 2 (00 UTC October 3rd). As expected the wind is especially reduced in the area of the wind farm, but for the first case large parts of the North of the Netherlands are affected too. Both figure a and b show a pushing-up effect (an enhancement of the wind speed) similar to the one observed at for example mountain ranges. However because a wind farm is not a continuous and solid obstacle this is no behaviour one would expect to observe.

At 12 points in and around the wind farm we studied the wind reduction in more detail (see table 1 and figure 5) for case 1. Point A1 is the upper left position and C4 the position down right. It was found that on average the highest wind reduction was found in the middle of the wind farm (B2). For this analysis we used values of the first 39 hours (with westerly winds). All wind speeds below 2.0 m/s were neglected, because the model did not react in an appropriate way to these low values. At the points further away from the wind farm one would expect to see a downward trend in the wind reduction. In this case that is true for A4 and C4 results but not so for B4. The average reduction first goes down to about 17% but then goes up again to 23%. No apparent reason could be found for this behaviour.

Table 1. Wind speed reduction for 12 points in and around the wind farm, for case 1 and 2.

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<th>CASE 1</th>
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<td>B</td>
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<td>-17%</td>
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<td>C</td>
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<td>0,5%</td>
<td>-54%</td>
<td>-3,5%</td>
<td>3,2%</td>
</tr>
<tr>
<td>B</td>
<td>-1,1%</td>
<td>-52%</td>
<td>-7,2%</td>
<td>8,0%</td>
</tr>
<tr>
<td>C</td>
<td>1,7%</td>
<td>-41%</td>
<td>-4,3%</td>
<td>2,3%</td>
</tr>
</tbody>
</table>

For the second case (with higher wind speeds), the reduction inside the wind farm was found to be even higher then in the first case. But the distance in which the wind picks up to the speed before encountering the wind farm is shorter. As can be seen in table 1, there is an average increase of wind speed in the area of the Dutch coast. This is due to the pushing up effect the wind farm in this model
produces. During the 66 hours the area with an increase in wind speed moves along the Dutch coast creating an average wind speed increase in A4, B4 as well as C4.

4.3 Power reduction

The power in the wind is equal to the third power of the wind speed. It may be clear that even a small wind speed reduction can have big consequences for the power output of a wind turbine. For the determination of the power output of the wind farm we first analyse the change in power output of a single wind turbine that has to deal with a certain wind reduction due to the other wind turbines standing in its path (the wake-effect).

For this analysis two things are important. First the distribution of the wind speed with time is needed, the so-called Weibull function. (http://www.windpower.org/, 2003). Second, we need the power curve of the wind turbine. The power curve shows the power that is produced at a certain wind speed. Using these functions we can compute the average power output of a wind turbine on a certain location.

First we studied the wind distribution for a location on the North Sea near the wind farm. We used data, from the last 20 years, from the HYDRA project from measurement post Noordwijk (lat 52.2, long 4.3) (http://www.knmi.nl/samenw/hydra/) to produce this distribution (figure 13 a). This post lies within the North Sea close to where the wind farm is positioned.

For this analysis we used the NEG Micon 92/2750. This turbine is one of the larger types and has a blade diameter of 92 m and a maximum power output of 2750 kW. Figure 13 b shows the power curve for this type of turbine. As can be seen this wind turbine has a cut-in wind speed of 4 m/s and a cut-out wind speed of 25 m/s. If one combines figures 13 a and b one can determine the average power output in kWh/year. Without taking into account the wake-effect this turbine on this location would roughly produce $12 \times 10^6$ kWh/year. This is enough to provide about 3500 Dutch households of electricity.

Combining the figures 13 a and b gives figure 13 c. Averaged over a year the most energy is produced at 11 m/s. All the wind speed values between 9 and 16 m/s give good results for this type of turbine on this location.

Now we will consider the consequence the wake-effect has on the wind farms power output. We presume there is a westerly flow across our wind farm. We further presume the first four rows of turbines are not affected by the wake-effect (5% of the total amount of wind turbines) and that the other wind turbines are confronted with a wind reduction of 30%. In this case the power output for the average wind turbine lowers to $6 \times 10^6$ kWh/year, i.e. a decrease of 50%.
5. The physics of a wind farm

In this chapter a simple conceptual model by Emeis and Frandsen (1993), the E&F-'93-model, of the wind reduction in a large-scale wind farm is presented. The purpose of this is to compare the wind speed reduction the MM5 model provides with a conceptual model. It gives an indication if the prescribed roughness length results in reasonable wind reduction values.

Emeis and Frandsen (1993) wrote a simple conceptual model of the reduction of wind speed inside an infinite cluster of wind turbines. They computed the reduction of horizontal wind speed from a balance between a loss of horizontal momentum and replenishment from above by turbulent fluxes. The reduction parameter is dependent on four variables: $\Delta z$, $e$, $c_t$ and $l$. $\Delta z$ is the height interval between the turbine and the undisturbed flow. $c_t$ is the drag coefficient of the wind turbines (per horizontal area covered by the turbines). $e$ is the drag coefficient of the surface the turbines are standing on. $l$ is a mixing length. In the next section it will be explained how these variables are calculated.

5.1 Wind speed in a wind turbines-canopy layer

Emeis and Frandsen (1993) start with a simple configuration: a horizontal flow $u_0$ approaches an infinite cluster of wind turbines. The turbine masts are so thin that they have no influence on the flow. The presence of the turbines causes a reduction in the wind speed and this results in a vertical velocity gradient: $\Delta u/\Delta z = (u_0 - u_i)/\Delta z$. $u_0$ is the wind speed at hub height after passing the turbine, $u_i$ is the undisturbed wind speed and $\Delta z$ is the height interval between the turbine and the undisturbed flow (See figure 6). The loss of specific horizontal momentum per unit height interval is:

$$m = c_t u_0^2,$$

(5.1)

Where $c_t$ is the drag coefficient of the wind turbines (per horizontal area covered by the turbines). It is calculated in the following way:

$$c_t(z) = \frac{d}{A_i} \sum_i \frac{1}{2} D_i(z) c_i(z),$$

(5.2)

where $D_i(z)$ and $c_i(z)$ are respectively the cross-wind dimension (the area covered by the blades) and drag coefficient of obstacle no. $i$ and $A_i$ is the total area occupied by the obstacles and $d$ is the diameter of the rotor blades. $c_t(z)$ has been taken constant with height at 0.04 m$^{-1}$, which is the drag coefficient for a turbine blade. (http://www.windpower.org, 2003). Calculating $c_t$ for a large-scale wind farm (19,000 turbines at 9000 km$^2$ with a blade diameter of 92 m all working on Betz maximum) gives a $c_t$ of 0.026.

The vertical velocity gradient induces a turbulent downward momentum flux which acts against the reduction of the wind speed $u_i$. This turbulent momentum
flux per unit horizontal area is to a first approximation proportional to the vertical velocity gradient. \( \tau \) is defined positive downwards.

\[
\frac{\tau}{\rho} = K_m \frac{\partial u}{\partial z} \equiv K_m \frac{u_0 - u_h}{\Delta z}
\]

(5.3)

Where \( K_m \) is a turbulent exchange coefficient (defined below) and \( \Delta z \) is the height interval between the turbines and the undisturbed flow \( u_0 \) (see figure 6). The flow is in an equilibrium if the downward turbulent momentum flux exactly balances the momentum loss due to the turbines. By doing so we obtain the following expression:

\[
c_t u_h^2 = K_m \frac{u_0 - u_h}{\Delta z}
\]

(5.4)

From equation 5.4 the reduction factor for the wind speed can be estimated \( R_t = u_t / u_0 \). In order to make this simple approach more realistic, Emeis and Frandsen (1993) assumed that there is a rough surface below the turbines that takes out momentum proportional to a drag coefficient \( c_r \). In other words \( c_r \) is the drag coefficient of the surface the turbines are standing on. So it has high values for rough areas and low values for smooth ones.

\( c_r \) is defined as:

\[
c_r = \frac{u_*^2}{u_{10}^2}
\]

(5.5)

Where \( u_* \) is the friction velocity and \( u_{10} \) the wind speed at 10 meters height. We deducted \( c_r \) for one point in the North Sea where the wind farm would be by taken a time average of \( u_* \) and \( u_{10} \). Case 1 gives values of respectively 0.17 and 5.3 m/s. This gives for \( c_r \) a value of 0.0011. In case 2 the average values for \( u_* \) and \( u_{10} \) are: 0.51 m/s and 12.1 m/s. \( c_r \) then equals 0.0018.

We then introduce the effective drag coefficient:

\[
c_{eff} = c_t + c_r
\]

(5.6)

The ratio of the wind speed inside the wind farm (where \( c_{eff} = c_t + c_r \)) to the undisturbed wind speed (where \( c_{eff} = c_t \)) at hub height \( h \) is then:

\[
R_t = R_u (c_{eff} = c_t + c_r) / R_u (c_{eff} = c_t)
\]

(5.7)

Assuming that the turbulent exchange coefficient \( K_m \) depends on the actual flow one can express \( K_m \) as: \( K_m = l^2 (u_0 - u_h) / \Delta z \) where \( l \) is a mixing length, (5.4) becomes:
By taking the square root of (5.8), the reduction factor \( R_u = u_h/u_0 \) reads:

\[
R_u = \frac{1}{1 + \frac{\Delta z \sqrt{c_{eff}}}{l}} \tag{5.9}
\]

According to (5.7) the ratio of the wind speed inside the infinite cluster to the wind speed at hub height outside the cluster is:

\[
R_c = \frac{1 + \frac{\Delta z \sqrt{c_s}}{l}}{1 + \frac{\Delta z \sqrt{c_{eff}}}{l}} \tag{5.10}
\]

The reduction of wind speed at hub height \( R_c \) depends on the ratio of \( \Delta z \) over \( l \), the turbine drag coefficient \( c_s \) and the surface drag coefficient \( c_t \). This is the general formula that we have been seeking without making severe a priori assumptions on the vertical flow profiles, but only on some basic mechanisms of turbulent vertical momentum exchange.

We now need appropriate expressions for \( l \) and \( \Delta z \). Emeis and Frandsen give an example when \( \Delta z \) is considerably larger than the hub height \( h \). They presume the mean mixing length then should be about \( 0.5 \kappa \Delta z \). The ratio \( \Delta z/l \) then is \( 2/\kappa \), with \( \kappa \) being the von-Karmann constant (0.4). In case 1 we obtain a value of 36%. In case 2, \( R_c \) results in a reduction of about 34%.

### 5.2 Using mixing length representation depending on the stability

Instead of using \( l = 0.5 \kappa \Delta z \), we wanted to use a representation of the mixing length that is more dependant on the meteorological circumstances. We decided to use an expression for the mixing length suggested by André (1978):

\[
l = \left( \frac{\phi_m}{\kappa \Delta z} + \frac{1}{l_0} \right)^{-1} \tag{5.11}
\]

Where \( \phi_m \) is a dimensionless shear and \( l_0 \) is a the mixing length for neutral stability. There are numerous different expressions for \( l_0 \). Meller and Yamada (1974) use an expression depending on the kinetic energy distribution with height. Blackadar (1962) uses an expression depending on the geostrophic wind speed and Coriolis number. Arrit (1987) uses a fixed value of 100 m for \( l_0 \). We decided to use the expression for \( l \) we used before \( (l = 0.5 \kappa \Delta z) \) for \( l_0 \). i.e. now \( l_0 = 0.5 \kappa \Delta z \). This is a reasonable assumption because \( \Delta z \) is in the order of hundred meters. This can be seen when considering the expression for the wind
speed depending on height and roughness (5.12). We can calculate $\Delta z$ for $\nu = 1/3 \, \nu_0$ (Betz Law). Where $\nu_0$ is the undisturbed wind speed at a certain height and $\nu$ is the wind speed at hub height.

$$u = \frac{\nu}{\kappa} \ln\left(\frac{z}{z_0}\right)$$

(5.12)

In this case $\Delta z$ always is in the order of hundred meters. With these assumptions the expression for $\Delta z/l$ becomes:

$$\frac{\Delta z}{l} = \frac{\phi_m + 2}{\kappa}$$

(5.13)

The expression for the dimensionless shear $\phi_m$ is as follows: (Kaimal, 1994)

$$\phi_m = \left(1 + 16\left(\frac{z}{L}\right)^{\frac{1}{4}}\right) \quad \text{for } -2<z/L<0 \quad (\text{unstable}) \quad (5.14 \ a)$$

$$\phi_m = \left(1 + 5\left(\frac{z}{L}\right)^{\frac{1}{4}}\right) \quad \text{for } 0<z/L<1 \quad (\text{stable}) \quad (5.14 \ b)$$

With $z$ being a reference height and $L$ the Monin-Obukhov length. The ratio between the two is determined through:

$$\frac{z}{L} = \frac{g}{\bar{\theta}^2} \left(\frac{w'\theta'}{\kappa \nu}ight)$$

(5.15)

(Kaimal, 1994) $z/L$ is a stability parameter for the surface layer. Negative $z/L$ ratios mean an unstable atmosphere and positive a stable one. In formula 5.15 $\left(\frac{w'\theta'}{\bar{\theta}}\right)$ denotes temperature flux at the surface, $\bar{\theta}$ indicates the average boundary layer potential temperature and $\nu$ is the friction velocity. All these values have been taken from the MM5 output.
Table 2. Model output and stability parameter calculations

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \omega' ) (Km/s)</td>
<td>0.0051</td>
</tr>
<tr>
<td>( u^* ) (m/s)</td>
<td>0.10</td>
</tr>
<tr>
<td>( z ) (m)</td>
<td>100</td>
</tr>
<tr>
<td>( z/L )</td>
<td>-6.34</td>
</tr>
<tr>
<td>( \phi_m )</td>
<td>0.314</td>
</tr>
<tr>
<td>( K_m ) (m²/s)</td>
<td>13.11</td>
</tr>
<tr>
<td>( \omega' ) (Km/s)</td>
<td>-0.0023</td>
</tr>
<tr>
<td>( u^* ) (m/s)</td>
<td>0.16</td>
</tr>
<tr>
<td>( z ) (m)</td>
<td>100</td>
</tr>
<tr>
<td>( z/L )</td>
<td>0.77</td>
</tr>
<tr>
<td>( \phi_m )</td>
<td>4.87</td>
</tr>
<tr>
<td>( K_m ) (m²/s)</td>
<td>1.31</td>
</tr>
</tbody>
</table>

The reduction parameter \( R \) for case 1 now is 39% instead of the 36% calculated at the previous section, an increase of 8%. The reduction parameter for case 2 is 55% instead of 34%, an increase of 62%. In the stable case the reduction increases considerably. That is not surprising because the turbulent fluxes, that should supply faster moving wind from above, are smaller in a stable environment and thus the wind speed reduction is reduced slower.

Wind reduction factors produced by the MM5 model are comparable with the factors the E&F-'93-model produced.

Table 3. The average wind reduction calculated by the MM5 model and the E&F-'93-model.

<table>
<thead>
<tr>
<th>Average wind reduction</th>
<th>MM5 model</th>
<th>E&amp;F-'93 model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>35 %</td>
<td>39 %</td>
</tr>
<tr>
<td>Case 2</td>
<td>50 %</td>
<td>55 %</td>
</tr>
</tbody>
</table>
6. Conclusions and recommendations

In this research the meteorological disturbances created by the construction of a large-scale wind farm were studied using a mesoscale model. The effects of the wind farm were reproduced by modifying the characteristics of a considerable part of the North Sea and prescribing a higher roughness length (0.5 m) in the area of the wind farm. The meteorological effects were examined by comparing model runs with and without the wind farm. Turbulent kinetic energy, cloud formation and wind speed reduction were analysed in detail. Two case studies characterised by a synoptic situation with westerly flows were under study. The first situation study begins at 00 UTC July 1st 2001 and ends at 18 UTC July 3rd 2001. The second case study is in the period from 00 UTC October 2nd 1999 to 18 UTC October 4th 1999. Both case studies show different effects of the wind farm on the meteorological variables, especially for cloud formation.

The model was evaluated by comparing observations to the model output. This was done at two places near the Dutch coast, de Kooij and Schiphol. Only the de Kooij evaluation is presented in this thesis, but Schiphol showed comparable results. Wind speed, wind direction and temperature were compared using two boundary layer schemes (ETA and MRF). The standard runs were compared with two other runs that included the wind farm represented by a 100 m hill or an increased roughness length. Results are shown in figure 4. The 100 m hill gave no satisfactionary results; therefore we decided to use an increased roughness length to represent the wind farm.

The effects on wind speed are partly as expected. The area with higher roughness length clearly slows down the wind inside the wind farm area and in the area surrounding the wind farm. However it also creates a pushing-up effect somewhere on the lee-side of the wind farm. Question remains: is this a model artefact or something that could happen in real life? Because of the non-solid structure of the obstacle we would not expect this behaviour.

Wind reduction factors produced by the MM5 model however are comparable with the factors calculated by means of the E&F-'93-model. Especially when including a stability parameter in the expression for the mixing length.

Table 3. The average, in space and time, wind reduction calculated by the MM5 model and the E&F-'93-model.

<table>
<thead>
<tr>
<th>Average wind reduction</th>
<th>MM5 Output</th>
<th>E&amp;F-'93-model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>35 %</td>
<td>39 %</td>
</tr>
<tr>
<td>Case 2</td>
<td>50 %</td>
<td>55 %</td>
</tr>
</tbody>
</table>

The above percentages are first order estimates and should be handled with care. Due to the wind reduction the power output of the average wind turbine will decrease. Without taking into account the wake-effect a NEG MICON 92/2750 turbine in the North Sea would roughly produce $12.10^6$ kWh/year. This
is enough to provide about 3500 Dutch households of electricity. Now we presume the first four rows of turbines in the wind farm are not affected by the wake-effect (5% of the total amount of wind turbines) and we presume the other wind turbines are affected by a wind reduction of 30%. In this case the power output for the average wind turbine lowers to $6.10^6$ kWh/year, i.e. a decrease of 50%.

With respect to the cloud formation the following conclusions can be made: For case 1, where no clouds are present, the model simulates enhanced cloud formation due to the wind farm. The clouds were only been in the area of the wind farm. The second case, where cloud cover was already present, showed no clear enhanced cloud formation. However, for this case study, spatial patterns of precipitation show dramatic changes. In the Dutch coast there is less precipitation but in large parts of the North Sea more precipitation. I.e. the amount of clouds was not very much affected, but the characteristics of the clouds were.

A huge square of wind turbines not being the most realistic configuration, we studied alternative wind farm designs by placing patches of wind turbines in the same area as well. In this case wind reductions were lower, but cloud formation remained as before, but on smaller scale. Future research should however include more precise information on the size of the wind farm and the configuration of the wind turbines. Other more practical things that should be taken into account for example are: boat travelling routes and the amount of migratory bird routes.

Future research should focus on a more reliable representation of the wind farm. One might argue that an increased roughness length is a very crude way of working, but in first instance it was the most adequate way of representing the wind farm with this mesoscale model. Future work could be addressed to couple a real wind farm model with a mesoscale model, to get more reliable results.

Upcoming studies should bear in mind that stability factors play an important role in the reduction of the wind speed. A reduction model as Emeis and Frandsen use misses vital information. We made up for that by introducing a stability parameter in the mixing length equation. Other points of interest might be the effect the wind farm has on the waves in the North Sea. Changes in waves can have effects on sandbank formation.
Literature


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AFSTUDEEROPDRACHT
LOKALE KLIMAATVERANDERING DOOR GROOTSCHALIGE
WIND-ENERGIEWINNING OP DE NOORDZEE

Binnenkort worden de eerste windparken op de Noordzee aangelegd. Deze zijn nog bescheiden van omvang; de effecten van deze windparken op wind- en zeestromingen en op golven lijken verwaarloosbaar. Op langere termijn wordt gedacht aan veel grootschaliger exploitatie van windenergie op de Noordzee. Vooral het NCP (Nederlands Continentaal Plat) is een gunstige locatie, vanwege het windklimaat, de relatieve ondiepte, de geschiktheid van de bodem voor fundering en vanwege de grote energievraag in de naaste omgeving. De mogelijke omvang van het windpark zou 10.000 km² kunnen bedragen: een strook van 150 km N-Z, westelijk begrensd door het Engelse CP en oostelijk begrensd door een 30 km brede open zone langs de Nederlandse kust. Hier zouden 5-10 duizend molens met een vermogen van 5 Megawatt geplaatst kunnen worden. Het gaat om gevaartes van ruim 100 meter hoog (inclusief wieken), die ongeveer 50% van de beschikbare windenergie wegvangen. (De maximaal beschikbare windenergie is bepaald door de snelheid waarmee impuls van hoger naar lager gelegen luchtlagen wordt overgedragen).

Het is waarschijnlijk dat een dergelijk windpark een significante invloed heeft op het windklimaat op de Noordzee. Ter plaatse van het windpark zal de windsnelheid sterk worden gereduceerd. Maar ook in een grotere omgeving zal de invloed merkbaar zijn. De vraag is tot hoeveel die invloed zich uitstrekt. Maar er is meer. De lokale ruwheidvergroting van het zeeoppervlak door het windpark veroorzaakt ook een windcirkulatie die gepaard gaat met verticale luchtstromingen. Dit betekent dat er een invloed kan zijn op het neerslagpatroon in de omgeving van het windpark. In feite is er sprake van lokale klimaatverandering. Vragen zijn: wat is de aard van de klimaatverandering en over welke afstand strekt deze zich uit?

Figure 1 a
The three domains. Domain 1 has a resolution of 45x45 km, domain 2 of 15x15 km and domain 3 of 5x5 km. The A indicates the position of station de Kooij, B of Schiphol Airport.

Figure 1 b
Enlargement of domain 3 with the 9000 square kilometre wind farm indicated. The numbers on the axis represent the grid points. One grid point equals 5 kilometres.
Figure 2 (a, b, c)
Synoptic situation at 12 UTC on July 1st, 2nd and 3rd 2001 (horizontal wind vectors and sea level pressure contours) in domain 1. Half a bar on a wind barb means 5 knots (about 2.5 m/s) a whole bar is 10 knots.

a

b

c
Figure 3
This graph shows the relation between the amount of wind that is stopped by the wind turbine \( \frac{v_2}{v_1} \) and the power that is taken out the wind compared to the total power in the wind \( \frac{P}{P_0} \). As can be seen the maximum for \( \frac{P}{P_0} \) is reached for \( \frac{v_2}{v_1} \) equals 1/3. Figure taken from http://www.windpower.org (2003)
Figure 4 (a, b, c)
Comparison of the model output for wind speed, temperature and wind direction with the observations at De Kooij. The comparison was made for the standard ETA run, the ETA run with hill and the ETA run with higher roughness and the MRF run. Starting 00 UTC July 1st until 18 UTC July 3rd 2001.
Figure 4c: Wind direction comparison The Kooij
00 UTC July 1st - 18 UTC July 3rd 2001

Wind direction (degrees)

Time (h)
Figure 5
Domain 2 (grid size 15x15 km) with the wind farm shown by the box. The dots represent the 12 positions that were used to determine the wind reduction factor. The top left dot is A1 and the bottom right is C4.
Figure 6
Basic momentum budget for an ensemble of wind turbines in a turbulent flow. The momentum loss due to the turbines is compensated by downward turbulent momentum flux.
Figure 7
Figure 8 a, b
Time series for the bulk TKE and ground level TKE during for case 2 in the middle of the wind farm.
**Figure 9 a, b**

a: The column-integrated value of the cloud mixing ratio (g/kg) in mm, difference plot, 12 UTC July 2nd 2001. Contour interval 0.03 mm. The highest value is 0.21 mm.

b: The turbulent kinetic energy (TKE) in m²/s² for the same time as figure 8a. Difference plot.
Figure 10 (a, b, c)
Time series of total cloud mixing ratio for case 1, difference plot in g/kg, 12 UTC, 15 UTC, 18 UTC July 2nd 2001. Contour interval 0.05 g/kg.
Wind speed difference vectors. Maximum vertical values: a: 3.9 cm/s, b: 8.3 cm/s and c: 3.4 cm/s.
Figure 11 a, b
Difference results in total precipitation for case 1 and 2 in mm. Both for a 24h period. (case 1: 00 UTC July 2nd – 00 UTC July 3rd 2001; case 2: 18 UTC October 3rd – 18 UTC October 4th 1999)
Figure 12 a, b
Wind speed difference (m/s), 21 UTC July 1st 2001. Contour interval 0.5 m/s.
Wind speed difference (m/s), 00 UTC October 3rd 1999. Contour interval 1 m/s.
Figure 13 (a, b, c)
Wind speed frequency table meetpost Noordwijk.
The power curve for the NM92/2750 wind turbine.
The average power production.

Wind speed distribution at meetpost Noordwijk

Power Curve: NM92/2750
Average Power

output * prob (kW)

wind speed (m/s)

c.