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The effect of wind farming on mesoscale flow

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Abstract This paper addresses the modification of the wind profile due to a wind farming, and the impact of wind farm design parameters and meteorological parameters on the wind profile. The wind profiles were obtained with the planetary boundary layer method MFwWF.

Resolved profiles show how most of the wind speed change occurs in the lower part of the boundary layer whereas most of the wind direction change occurs in the upper part, and that the thinner the boundary layer or the larger the surface roughness, the larger the wind direction change. Near a 5 MW wind turbine with a rotor diameter of 100 m operating at full load the velocity deficit is of the order of 5%, the wind direction change is increased with 1 ... 2 deg, and the velocity recovery distance is 20 rotor diameters. For a wind farm with 22 of these turbines these numbers separated at 10 rotor distances are 15%, 2 ... 3 deg, and at least 2 wind farm length scales.

Initial velocity deficits and velocity recovery distances show the impact of nominal power density and geostrophic velocity for a wind farm which consists of 22 wind turbines with a nominal power of 5 MW. The initial velocity deficit relative to the upstream velocity decreases with increasing geostrophic velocity in general, and ranges from 6% (at a turbine separation of 14 rotor diameters) to 32% (at a separation of 5 rotor diameters) if the velocity at hub height is halfway cut-in and nominal. At this hub-height velocity the absolute initial velocity deficit reaches a maximum (of 1.2 m/s in the case of a nominal power density of 5 MW/km^2) and the velocity recovery distance relative to the wind farm length scale is of the order of 20. The relative velocity recovery distance for other geostrophic velocities varies between 0 (at low geostrophic velocities) and a limit value of the order of 40 (at high velocities).

Key words Wind farm wake effect, Wind resource assessment

1. Introduction

Offshore wind farms tend to be placed closer together over the years, as already illustrated by OWEZ and Princess Amalia Wind Farm (separated 15 km) in the Netherlands or Horns Rev I and II (separated 23 km) in Denmark. Since these separation distances are between 5 and 10 times the wind farm's horizontal scale, the velocity deficit due to an upstream wind farm may be considerable [1]. If so, energy production loss and mechanical load increase are expected to be significant. For this reason the dedicated planetary boundary layer method MFwWF has been developed, which method computes the interaction between a wind farm and the prevailing wind.

In this paper we present the modification of the wind profile due to a wind farm as obtained with MFwWF, and the impact of wind farm design parameters and meteorological parameters. We start with brief descriptions of prior work on modelling wind farm wakes (section 2) and the new dedicated planetary boundary layer method MFwWF (section 3). Next, velocity profiles (section 4) and first insights on the impact of wind farm design parameters and meteorological parameters are addressed (section 5). Finally, we summarize the findings, and introduce the future developments (section 6).

2. Prior work

A wind farm wake study requires simulation of mesoscale atmospheric flow together with energy extraction/redistribution due to wind turbines. The studies that have been published so far can be subdivided into two categories: self-similar approaches and mesoscale approaches. In a self-similar approach [2][3] the convective force and the spanwise turbulent flux gradients are assumed to dominate the flow, allowing for standard wake-like solutions. In a mesoscale approach, on the other hand, the flow is assumed to be dominated by the Coriolis force and the vertical turbulent flux gradients, opening the door to either extra surface drag approaches [4] or more generic mesoscale approaches [5][6][7]. As is shown in other publications [8][9], neither the self-similar wake approach nor the extra surface drag approach is valid because over the separation distance between wind farms the convective and the Coriolis forces are of equal order of magnitude so that neither can be neglected. Although this was already implicitly recognized in the more generic approaches, these studies lack realistic formulations for the turbulence and the wind turbines.

3. Flow model

The planetary boundary layer method MFwWF is a CFD method that is based on three principles [8][9]. First, neutral planetary boundary layer flow with wind farming essentially is steady and two-dimensional; where the convective forces, the Coriolis forces, the vertical and spanwise gradients of the turbulent momentum fluxes, and the external forces that represent wind turbines all have the same order of magnitude. Second, a numerical representation of the momentum equations in the form of backward differences allows for an implicit solution of the two horizontal velocity components in vertical direction, iterating on the turbulent viscosity, and a marching solution in the horizontal directions. And third the continuity equation is satisfied by employing the Lagrange multiplier method to the velocity components that satisfy the continuity equation.

Because of its mixed implicit/explicit character the planetary boundary layer method MFwWF is computationally fast and cheap, which is beneficial for applications in wind farm siting studies. In that context MFwWF can be used to estimate the effect of nearby wind farms on the electricity production of a given wind farm.

4. Resolved velocity profiles

4.1. Empty set

In this section the resolved velocity profiles for the empty set, that is a domain without wind farming, are presented. Figure 1 shows four vertical profiles in a 200 x 200 km^2 domain, and valid for a geostrophic height of 500 m and a surface roughness length of 0.1 mm. The figures display the streamwise velocity versus height, the spanwise velocity, the angle between the streamwise and the spanwise velocity, and a hodograph of the two velocity components. The data in the figure is in qualitative agreement with the observed height dependence of undisturbed wind, where most of the velocity change occurs in the lower part and most of the direction change occurs in the upper part of the boundary layer, but it is too early to decide on the quantitative agreement.

The figures 2 and 3 display a much thicker boundary layer (1500 m) with the same surface roughness, and the same boundary layer thickness in combination with a much rougher surface (1 cm). The figures show that the thinner the boundary layer or the larger the surface roughness, the larger the twist in the velocity profile. Again this qualitative agreement with observations is to be collaborated with quantitative data.

4.2. Wind turbine and wind farm

The modification of the wind profile due to an hypothetical wind turbine is studied for a turbine with a nominal power of 5 MW operating at full load, and having a rotor diameter of 100 m and a hub height of 70 m. Figure 4 shows that the initial velocity deficit is of the order of 5% and that the velocity twist is increased with 1 ... 2 deg. The velocity recovery distance is 20 rotor diameters.

The hypothetical wind farm consists of 22 turbines with a rotor diameter of 100 m, a hub height of 70 m and a nominal power of 5 MW. The turbine separation distance is 1 km (10 rotor diameters) so that the nominal power density is 5 MW/km^2. Figure 5 shows that if the wind farm operates at full load the initial velocity deficit is of the order of 15% and that the velocity twist is increased with 2 ... 3 deg. The velocity recovery distance is at least 2 wind farm length scales.

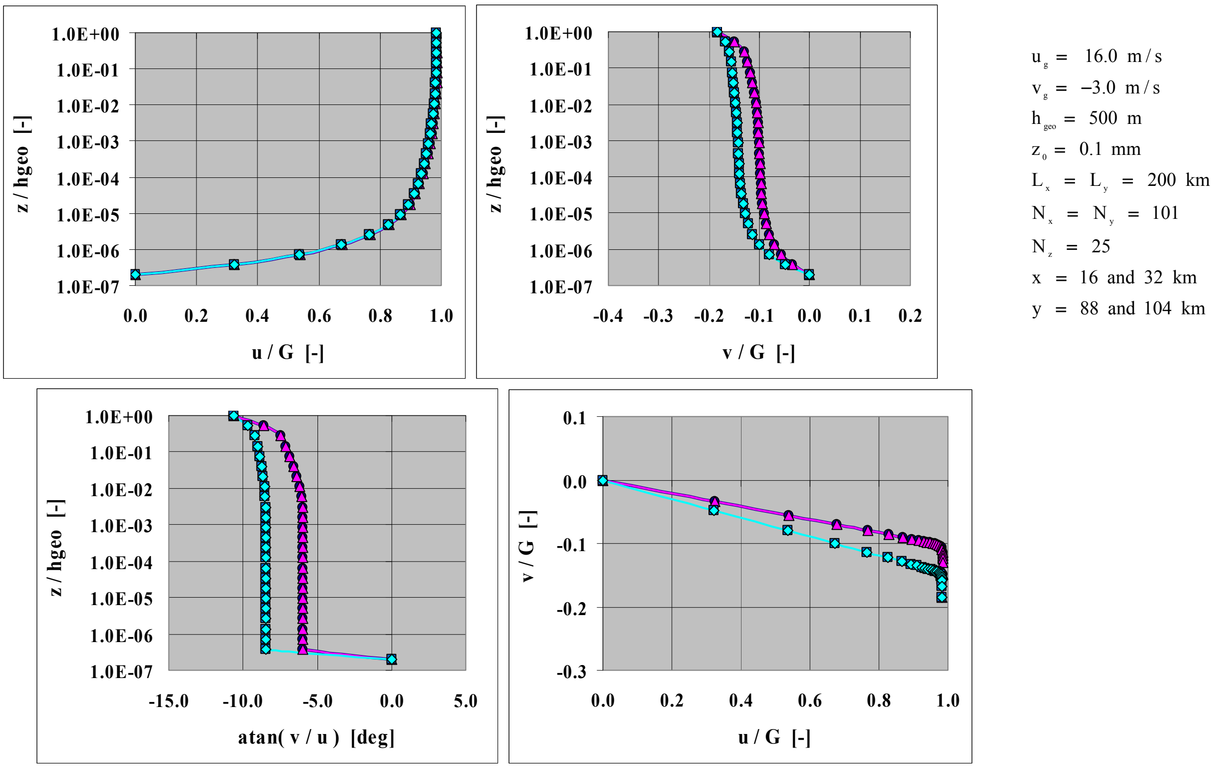


Figure 1: Vertical profiles of streamwise velocity u, spanwise velocity v and turbulent viscosity k_m as non-dimensionized with the geostrophic velocity G, the geostrophic height h_{geo} and the rotor diameter D; valid for a geostrophic height of 500 m and a surface roughness length of 0.1 mm

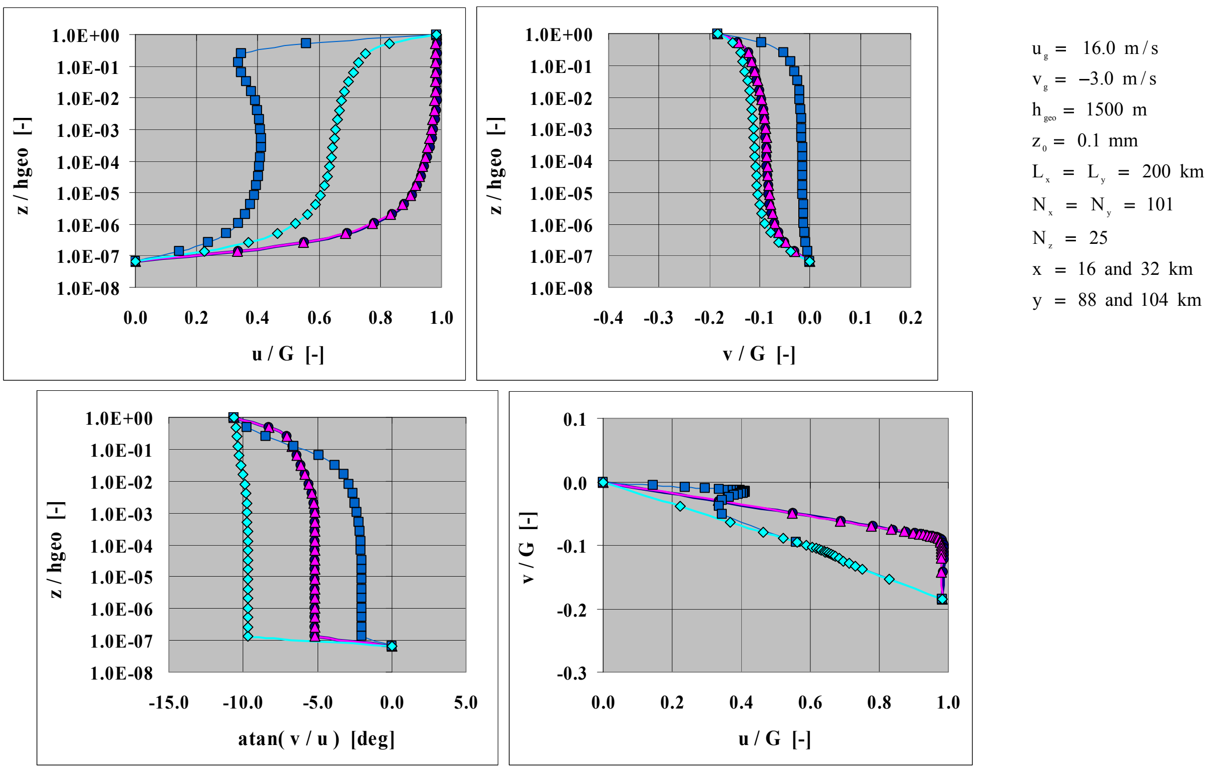
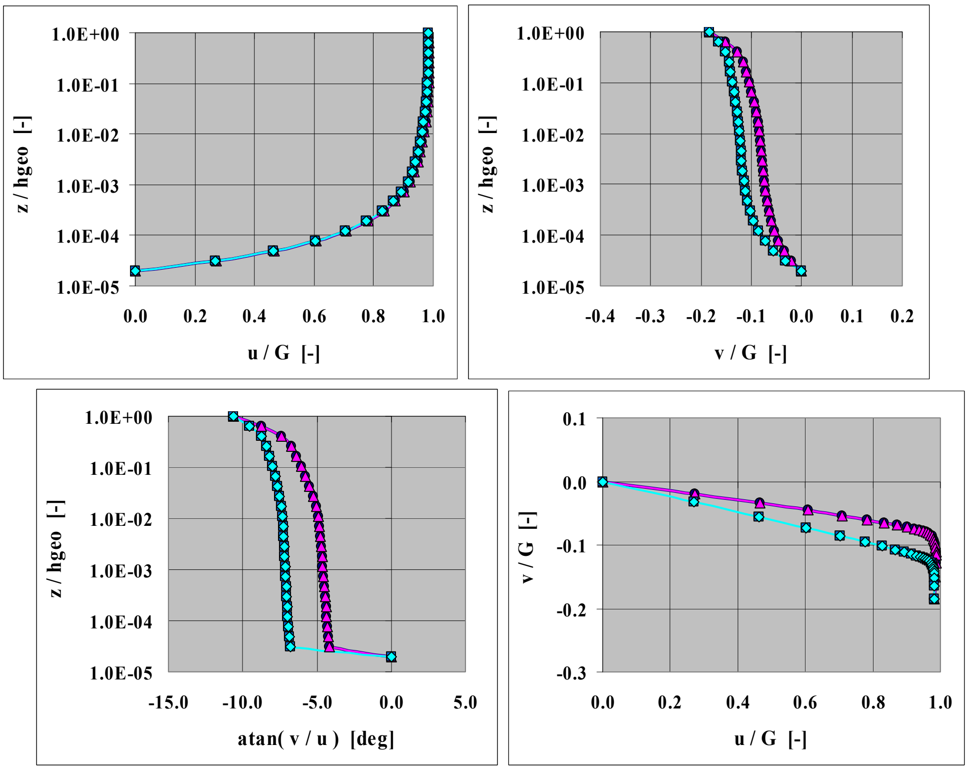
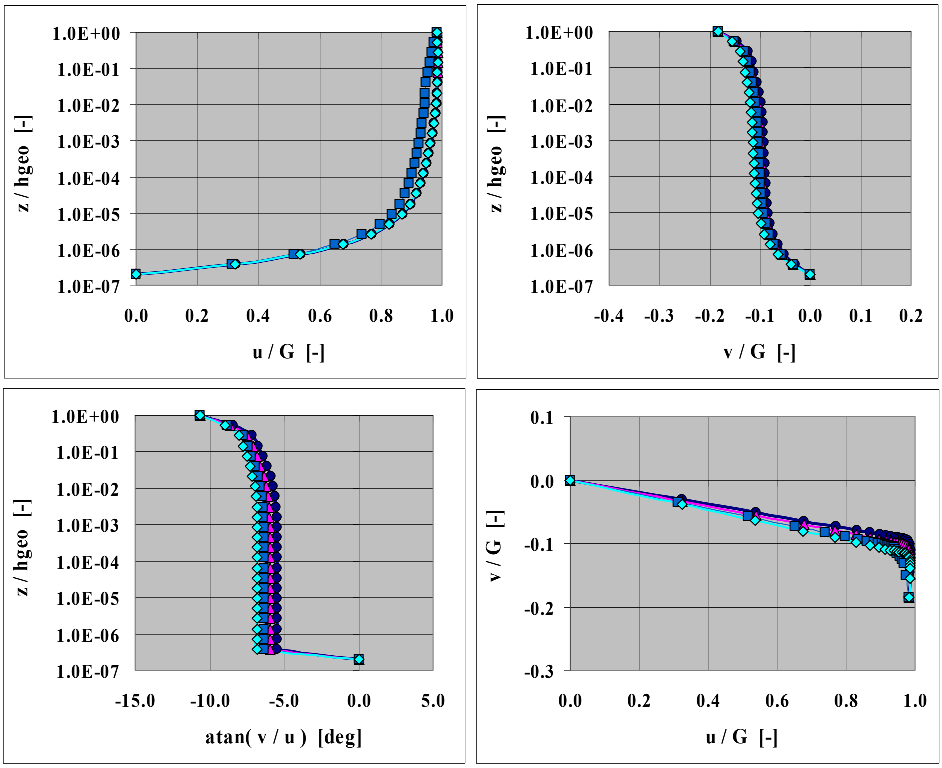


Figure 2: Vertical profiles for a geostrophic height of 1500 m and a surface roughness length of 0.1 mm; see caption of figure 1 for an explanation of the symbols



u_g = 16.0 m/s
v_g = −3.0 m/s
h_{geo} = 500 m
z_0 = 10 mm
L_x = L_y = 200 km
N_x = N_y = 101
N_z = 25
x = 16 and 32 km
y = 88 and 104 km

Figure 3: Vertical profiles for a geostrophic height of 500 m and a surface roughness length of 1 cm; see caption of figure 1 for an explanation of the symbols



u_g = 16.0 m/s
v_g = −3.0 m/s
h_{geo} = 500 m
z_0 = 0.1 mm
z_{hub} = 70 m
D = 100 m
A_{ffarm} = 1 km^2
$P_{nom,farm}$ = 5 MW
L_x = L_y = 200 km
N_x = N_y = 101
N_z = 25
s_x = −4, −2, 0 and +2 km

Figure 4: Vertical profiles upstream, near and downstream of a wind turbine for a geostrophic height of 500 m and a surface roughness length of 0.1 mm; see caption of figure 1 for an explanation of the symbols

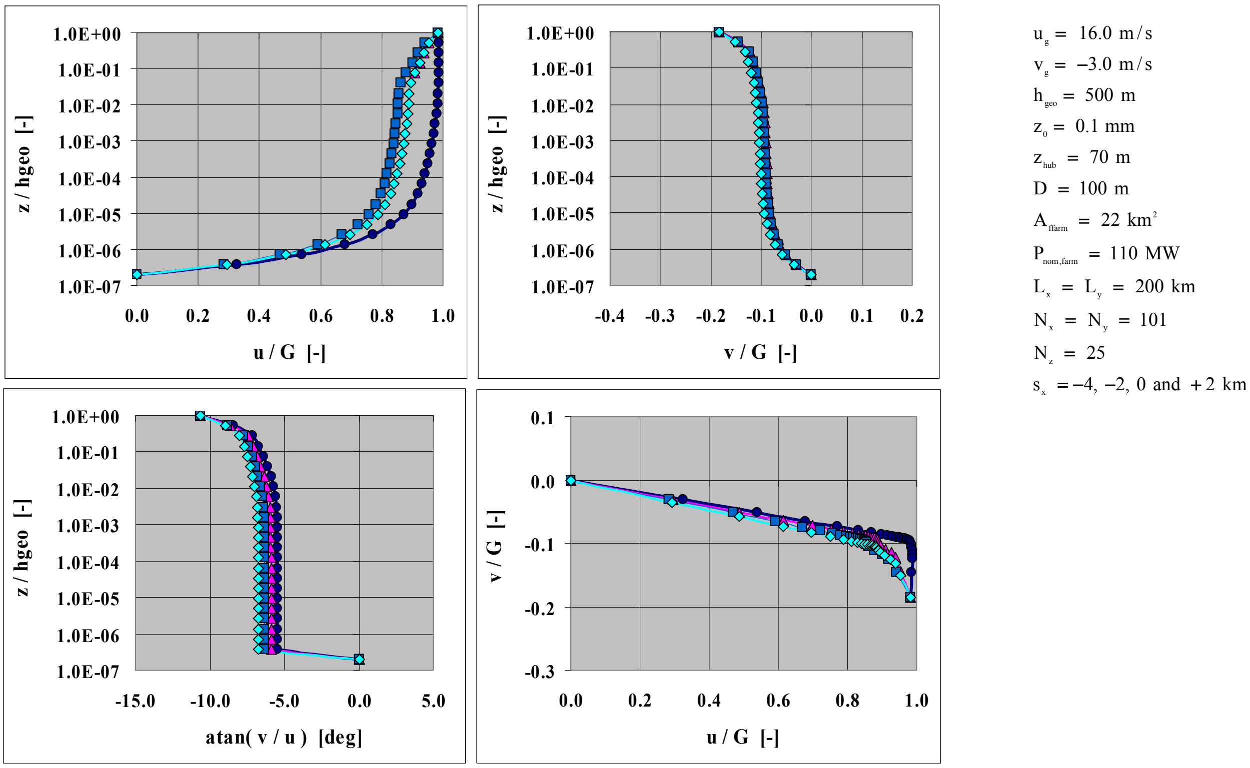


Figure 5: Vertical profiles upstream, near and downstream of a wind farm for a geostrophic height of 500 m and a surface roughness length of 0.1 mm; see caption of figure 1 for an explanation of the symbols

5. Impact of wind farm design parameters and meteorological parameters

Wind farm design parameters include separation distance from and layout (spacing, nominal power density) of the wind farm, and hub height and rotor diameter of the wind turbine. The impact of nominal power density is studied by changing the turbine separation distance in the hypothetical wind farm between 5 and 14 times the rotor diameter and keeping the geostrophic velocity at a constant value such that the hub-height velocity is halfway cut-in and nominal. Figure 6 shows that the relative initial velocity deficit (W_{ups} - W_{ini}) / W_{ups} increases with the nominal power density from 6% (turbine separation 14 rotor diameters) to 32% (5 rotor diameters), and that the relative velocity separation distance d_{rec} / L_{farm} is of the order of 20.

Meteorological parameters include geostrophic velocity, geostrophic height and surface roughness length. Figure 7 shows the impact of the geostrophic velocity for the hypothetical wind farm for hub height velocities near cut-in, halfway cut-in and nominal, near nominal, halfway between nominal and cut-out, and beyond cut-out. The relative initial velocity deficit (W_{ups} - W_{ini}) / W_{ups} is found to decrease with increasing geostrophic wind speed, and the largest absolute initial velocity deficits W_{ups} - W_{ini} (of in this case 1.2 m/s) occur when the hub-height velocity is halfway cut-in and nominal. Also the relative velocity recovery distance is found to increase with the geostrophic velocity, from 0 at low geostrophic velocities to a limit value near 40 at high geostrophic velocities.

6. Summary

Resolved profiles have been presented that show how most of the wind speed change occurs in the lower part of the boundary layer whereas most of the wind direction change occurs in the upper part. The profiles also show that the thinner the boundary layer or the larger the surface roughness, the larger the wind direction change. Also it has been shown that near a wind turbine with a rotor diameter of 100 m operating at a full load of 5 MW the velocity deficit is of the order of 5%, the wind direction change is increased with 1...2 deg, and the velocity recovery distance is 20 rotor diameters. And it has been shown that for a wind farm with 22 of these turbines these numbers are 15%, 2...3 deg, and at least 2 wind farm length scales, respectively.

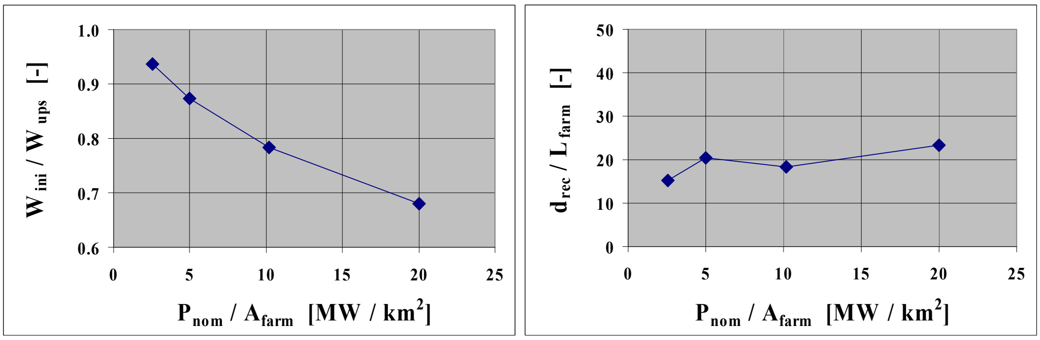


Figure 6: Initial downstream velocity W_{ini} relative to the upstream velocity W_{ups} and velocity recovery distance d_{rec} relative to the wind farm length scale L_{farm} as a function of nominal power density P_{nom}/A_{farm} for a wind farm in a geostrophic height of 500 m, a geostrophic velocity of 14 m/s, and a surface roughness length of 0.1 mm

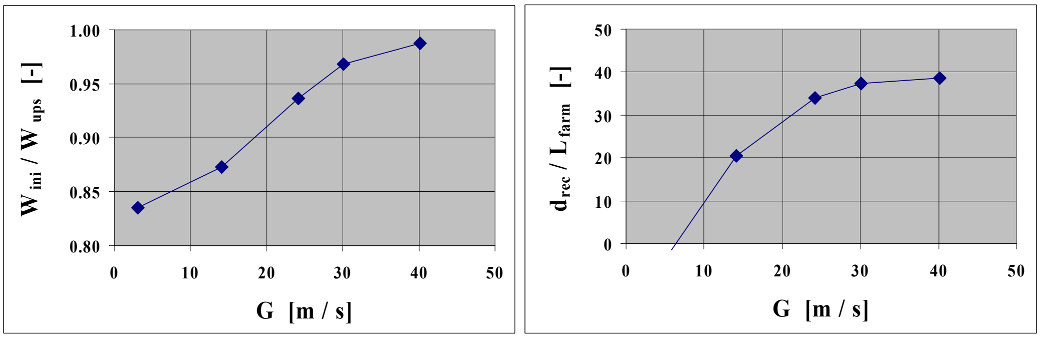


Figure 7: Initial downstream velocity and velocity recovery distance as a function of geostrophic wind speed G for a wind farm with a nominal power density of 5 MW/km^2; see caption of figure 6 for an explanation of the other symbols

Initial velocity deficits and velocity recovery distances have been presented that show the impact of nominal power density and geostrophic velocity for a wind farm which consists of 22 wind turbines with a nominal power of 5 MW. It has been shown that the initial velocity deficit relative to the upstream velocity decreases with increasing geostrophic velocity in general, and ranges from 6% (at a turbine separation of 14 rotor diameters) to 32% (at a separation of 5 rotor diameters) if the velocity at hub height is halfway cut-in and nominal. Also it has been shown that at this hub-height velocity the absolute initial velocity deficit reaches a maximum (of 1.2 m/s in the case of a nominal power density of 5 MW/km^2), and the velocity recovery distance relative to the wind farm length scale is of the order of 20. Finally it has been shown that the relative velocity recovery distance for other geostrophic velocities ranges between 0 (at low geostrophic velocities) and a limit value of the order of 40 (at high velocities).

Acknowledgements
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Modelling the effect of wind farming on mesoscale flow
Modification of the wind profile

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Summary

This work presents insights on how the wind profile in the planetary boundary layer is modified due to the presence of a wind farm, and the new method which has been developed for this purpose.

Motivation

The need for wind farm wake studies is increasing as offshore wind farms tend to be placed closer together over the years, as already illustrated by OWEZ and Q7-WF in the Netherlands or Horns Rev I and II in Denmark.

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Governing equations of the new model

Planetary boundary layer flow with wind farming:
Balance between convective forces, Coriolis forces, spanwise gradients of turbulent momentum fluxes, and wind turbine thrust.

$$\bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{v}\frac{\partial \bar{u}}{\partial y} = +f_\phi\left(\bar{v} - v_g\right) - \frac{\partial \overline{u'v'}}{\partial y} - \frac{\partial \overline{u'w'}}{\partial z} + \bar{f}_x$$

$$\bar{u}\frac{\partial \bar{v}}{\partial x} + \bar{v}\frac{\partial \bar{v}}{\partial y} = -f_\phi\left(\bar{u} - u_g\right) - \frac{\partial \overline{v'v'}}{\partial y} - \frac{\partial \overline{v'w'}}{\partial z} + \bar{f}_y$$

$$\frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} = 0$$

Velocity decomposition

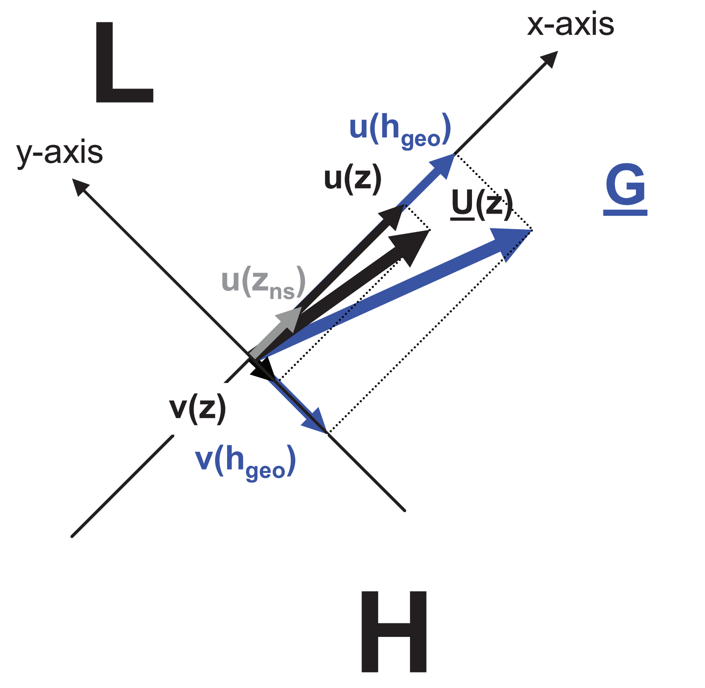
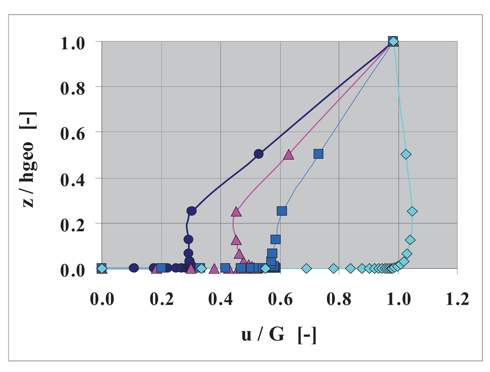


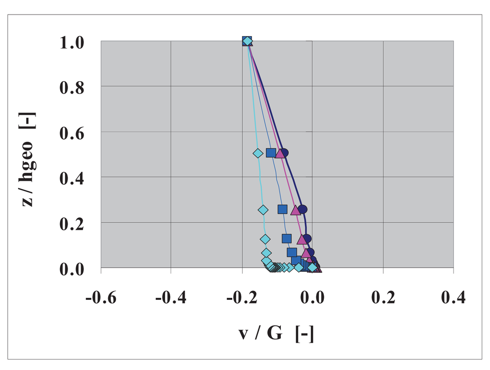
Illustration of the big wind deficit due to a wind farm

Profiles at downstream distances of 2, 6, 10 and 18 km

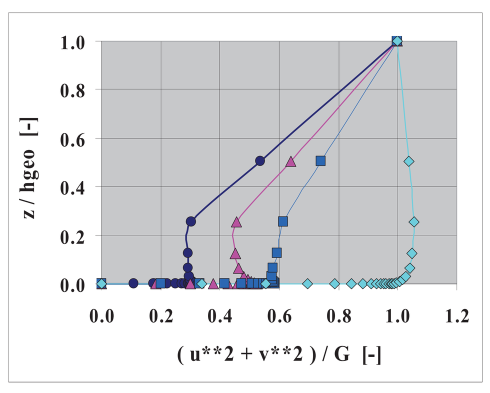
Streamwise wind speed



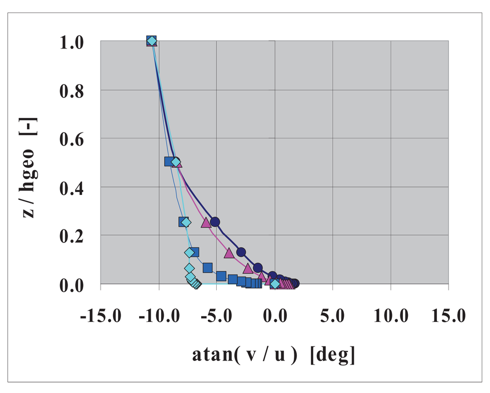
Spanwise wind speed



Total wind speed



Wind direction



Conditions

u_g = 16.0 m/s
v_g = −3.0 m/s
h_{geo} = 1500 m
z_0 = 0.1 mm
z_{hub} = 70 m
D = 100 m
A_{farm} = 22 km^2
$P_{nom,farm}$ = 110 MW
L_x = L_y = 200 km
N_x = N_y = 101
N_z = 25

Conclusions

- A wind farm has a considerable effect on both speed and direction of the wind.
- A wind farm modifies the wind profile from the bottom to the top of the planetary boundary layer.
- The initial wind speed deficit can be of the order of 70% of the upstream wind speed.
- The wind speed recovering distance can be of the order of 5 streamwise length scales of the wind farm.

Acknowledgment: This work was performed in the framework of the Dutch Ministry of Economic Affairs BSIK programme We@Sea, Project "Windenergiecentrale Noordzee - Parkinteractie" (We@Sea/BSIK 2005/002)