Assessment of wind turbine representation in upper ocean variability

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Introduction

Wind energy has been recognized as one of important resources of green energy which meets the increasing electricity demands in a very sustainable manner. Additionally, offshore wind energy has gained more attention due to its minimal impacts on physical environment. However, deploying array of multiple turbines in the ocean gives rise the need for assessment of interactions between these large manmade structures and external forces exerted on the structures, and how turbines influence the marine life and sediment dynamics. In this study, we present a modified simple two-dimensional ocean circulation model to investigate a number of physical processes including upper ocean hydrodynamics and mixing. In the present method the momentum equation are modified to include thrust force (for momentum equations) and structure-induced turbulence corrections (for the turbulence balance equations) as turbine-induced terms. Alternatively, this can be implemented for a large wind farm by modification of surface forcing variation at wind park covered area. To predict gravity waves, we assume a fully-developed sea (which rarely established in the real ocean) that makes it possible to use some emprical relations to estimate wave bulk parameters. The aforementioned methods can be extended and adapted for the wind-wave-current-turbine interactions.

Model Equations

The two-dimensional primitive equations of motion in Cartesian coordinates is expressed in equation (1) for model simulation domain presented in Figure 1.

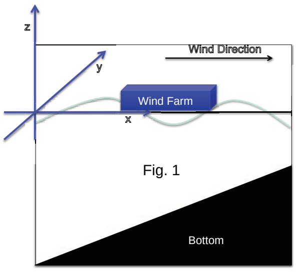


Fig. 1

1) Coriolis parameter.
2) Y-component of wave-induced Stokes drift.
3) Inverse of reference density.
4) Vertical gradient of Reynolds stress.
5) Horizontal eddy viscosity.
6) X-component of wave-induced Stokes drift.
7) Horizontal eddy diffusivity.
8) Density fluctuation.
9) Continuity equation.

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}-\overset{1}{f_{Cor}}\left(v+\overset{2}{v_s}\right)=-\overset{3}{\frac{1}{\rho_0}}\frac{\partial P}{\partial x}+\overset{4}{\frac{\partial (u'w')}{\partial z}}+\frac{\partial}{\partial z}\left(\overset{5}{A_m}\frac{\partial u}{\partial x}\right)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+w\frac{\partial v}{\partial z}+f_{Cor}\left(u+\overset{6}{u_s}\right)=-\frac{1}{\rho_0}\frac{\partial P}{\partial y}+\frac{\partial (v'w')}{\partial z}+\frac{\partial}{\partial z}\left(A_m\frac{\partial v}{\partial x}\right) \quad (1)$$

$$\frac{\partial \rho'}{\partial t}+u\frac{\partial \rho'}{\partial x}+w\frac{\partial \rho'}{\partial z}=\frac{\partial (\rho'w')}{\partial z}+\frac{\partial}{\partial z}\left(\overset{7}{A_h}\frac{\partial \overset{8}{\rho'}}{\partial x}\right)$$

$$\overset{9}{\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0}$$

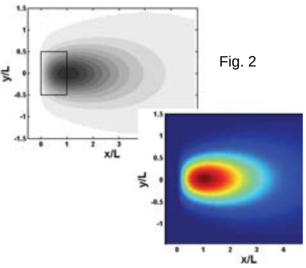


Fig. 2

Figure 2 indicates the shape of wind stress influenced by appearance of a large wind turbine with characteristic length of *L*. All details on how to parameterize farm-affected wind stress can be found in [1,3]. It should be noted that this parameterization is a rough estimate of wind stress which is not able to describe properly the wind farm wakes.

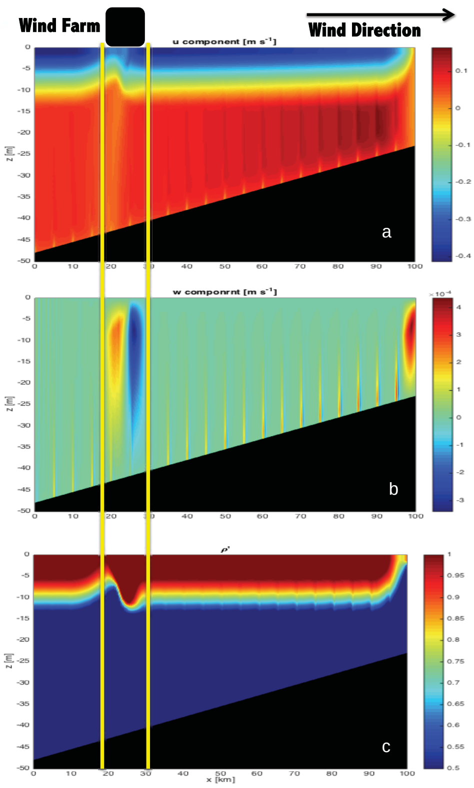


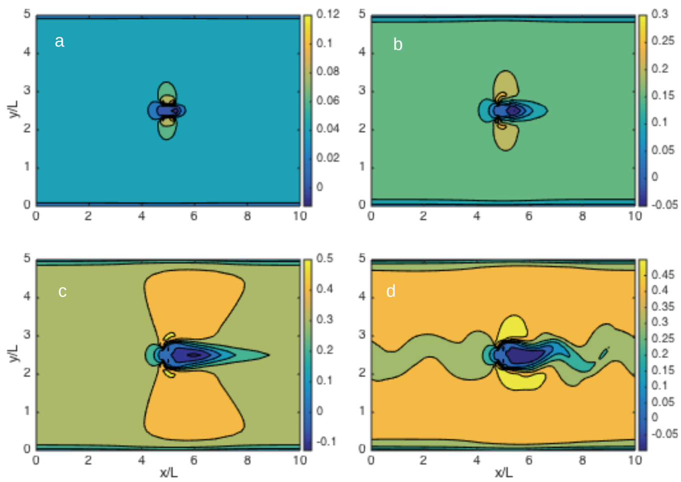
Fig. 3

Change of wind stress, spatial-temporal pattern, in the presence of an offshore wind farm influences substantially the wind-driven coastal upwelling process in a stratified water column. Figure 3 shows the early stage in the establishment of coastal upwelling in response to the farm-affected wind forcing and gravity wave contributions (here only Stokes drift [2,3]). The wind forcing induces an oscilatory motions across the pycnocline (Fig. 3-c below) resulting in change of hydrographic parameters in water column. Horizontal velocity shows further formation of onshore and offshore Ekman drifts at the bottom and surface, respectively.

The cross section plot of vertical velocity reveals formation of vertical cells around the offshore wind farm district. Establishment of such strong vertical upwelling and downwelling cells influeces substantially upper ocean mixing, and exchange processes at the sea surface sea surface by the means of increasing sea surface temperature and declining the sea surface elevation. This figure shows how hydrographic parameters and hydrodynamic quantities interact in response to farm-induced distortion. These disturbances penetrate vertically across the water column and weaken with depth.

Vertically Integrated Model

In this example, we use vertically integrated two-dimensional shallow water equations as explained in [3]. The possible impacts of atmospheric forcing change and upper ocean response time can be seen in Fig. 4. to highlight the required time for possible impacts. U-component of vertically integrated current illustrates nicely the wind wake effects by the means of increased and decreased flow dynamics around the wind park. This process can be explained by the (farm-modified) elevation of sea level (with different local drops and subsidence events) together with generated pressure gradients which push flow around the wind park. This generted pressure gradients under influence of wind forcing generate overturning flows downwind of farm. Continuing this procedure will result in formation of vortex street in farm wake district (Fig. 4-d).



Further Works

As it has been already mentioned, the prameterization of farm-affected wind forcing or assuming farm as a rigid body can not describe the wind farm wakes and inter-relation between farm elements. To resolve this problem, we can alternatively impose the farm effects in balance equations by perturbing it by a turbine-induced thrust force. This results in illustration of device induced turbulence perturbation in the model which neccessiate an appropriate representation for turbulence correction terms in energy equations. Simulation of this technique confirm its ability to predict more precisely both momentum and turbulent wake interactions at any spatial scales (not shown).

Summary

Due to large demand for efficient development of renewable energy resources such as wind farms, offshore wind industeries are gaining widespread attention, investment, and investigations among other types of reliable renewables. To make this energy more feasible, less expensive, and more popular, we need a comperhensive understanding of various underlying physics and important interacting mechanisms such as wind climotology in the offshore farm district. In this study, we ideally parameterized excitation of wind field in the farm located area with a significant reduction of wind stress in the downstream direction. This disturbance in the wind field as important forcing mechanism for upper ocean will substantially affect upper ocean (the whole water column in shallow water). To study this complicated interaction between disturbed wind forcing and upper ocean, we conducted two model simulation runs using finite difference-volume technique. In the vertical cross-section simulation, a vertical upwelling and downwelling cells have been established in the area of wind park. This strong vertical velocity events will influence significantly both upper ocean mixing and stratification. Second simulation based on vertically integrated shallow water equation shows generation of pressure gradients as driving force to deviate flow around the farm. Continuation of wind forcing and its interaction with offshore wind farm results in enhanced pressure gradient effects such that, in the extreme case, vortex street together with overturning flow will form on the farm wakes.

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References

[1] Brostrom G. (2008): On the influence of large wind farms on the upper ocean circulation, *Journal of Marine Systems*, 74, 585-591.

[2] M. Bakhoday-Paskyabi, I. Fer, A. D. Jenkins (2012), Surface gravity wave effects on the upper ocean boundary layer: modification of a one-dimensional vertical mixing model, *Cont. Shelf Res.*

[3] Bakhoday Paskyabi, et. al, (2012), Upper Ocean Response to Large Wind Farm Effect in the Presence of Surface Gravity Waves, *Energy Procedia*.