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Offshore Wind Farm Wake Effect on Stratification and Coastal Upwelling

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Abstract

In this study, the interactions between an offshore wind farm, upper-ocean currents, and stratification are examined under shallow water conditions from a two-dimensional modeling standpoint. The modeling results from two numerical simulation runs provide new insights on the formation of downwind vortex streets and the adjustment of coastal processes, such as upwelling and stratification. The distorted farm-induced wind deficits are calculated by the concept of single- and multiple-wake models. By assuming farm geometry as a large rigid rectangle, the numerical results of a shallow water model demonstrate the formation of vortex shedding wakes in the downwind of the wind farm. The slice model simulation runs, as the second numerical experiment, will address the coastal upwelling and geostrophic adjustment of density fronts in the presence of wind farm effects over a sloping bathymetry. We apply gravity wave effects using a wave-dependent aerodynamic roughness length when assuming the wind farm as an array of multiple turbines. Despite dynamical differences between simulation runs assuming farm as a rigid element and those considering farm as a cluster of single turbines, the results show some aspects of the farm-induced modulations on the pycnocline displacements and on the spatial-temporal evolution of the coastal upwelling. Although each simulation run has a unique scientific focus, the overall achieved numerical results are greatly able to improve the understanding of physical coupling between the wind farms and upper ocean dynamical processes.

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Keywords: Offshore wind farm; Coastal upwelling; Vortex street; Density frons; Shallow water equation; Wake model.

1. Introduction

Wind energy has been recognized as one of the important resources of green energy which meets the increasing electricity demands in a very sustainable manner. Additionally, offshore wind energy has gained more attention

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due to its minimal impacts on the physical environment. However, deploying multiple-turbine arrays in the ocean necessitates the need for the assessment of the potential links between these large man-made structures and upper-ocean dynamical processes such as upper-ocean turbulent mixing, surface gravity waves, currents, local scour, local sediment variations, and (offshore and onshore) Ekman drifts in the offshore site districts.

While the effects of the offshore wind farms on the oceanographic processes have been addressed extensively during the recent years, a few research studies have been conducted to provide the detailed analysis of such local and far-field influences theoretically, numerically, and observationally. Lass et al. 2008 [1] conducted field measurements of acoustic backscattering and currents to study the pile-induced turbulence and mixing. Their measurements were carried out at the Western Bridge of the Great Belt Fixed Link, Denmark. The results suggested the plankton growth, turbulence energy levels, particles' settling rates, and particles' suspension time as being quantities which are influenced substantially by the large wind farm. Broström 2008 [2] investigated numerically the formation of coastal upwelling with speeds greater than 1 m/day for wind speeds ranging between 5 to 10 $\mathrm{m\,s^{-1}}$ in a large wind farm district. He showed that the pycnocline displacement increases directly as a function of wind farm characteristic length associated with the internal Rossby radius. Bakhoday-Paskyabi and Fer 2012 [3] studied the relationship between the strength of upwelling and the farm size by including contributions from the surface gravity waves. They showed that waves (particularly Stokes drifts) are able to increase the magnitude of the pycnocline displacements.

To reduce the existing uncertainty in the modeling of the farm-ocean interactions, we first investigate two empirical wake models which enable us to adequately predict the wake spatial distributions downwind of each single wind turbine (Section 2). The formation of the vortex streets in the lee side of a large wind farm is then studied using a two-dimensional shallow water model. The formed vortices can induce vibrations in a broad range of frequencies to the farm (Section 3.1 and 4). Another two-dimensional vertical ocean model is used to investigate the change in the structure of the coastal upwelling and stratification caused by the appearance of a large wind farm. In all numerical investigations, the farm is assumed either as a rigid body, or an array of multiple turbines (Section 3.2 and 4). The velocity deficits used are then calculated from a multiple-wake model.

2. Wind-farm interaction

The wake of a single turbine is generated due to the movements of turbine blades leading to changes in the wind field and the ambient turbulence intensity in the downwind areas. These changes reduce the output energy and increase the fatigue damages and loads imposed to each single turbine. Furthermore, due to the substantial distortion of wind field by the multiple wakes, the upper ocean model predictions in the farm sites will be directly linked to the quality of the wake modeling. In this section, we present two linearized wake models [4]: (1) Jensen wake model; and (2) Larsen wake model.

2.1. Jensen wake model

This model describes a single wake distribution by assuming that the wake's diameter is expanded linearly relative to the radial distance behind the turbine. Figure 1-a and b visualize a single Jensen's wake as a function of wake decay coefficient, which is controlled by the atmospheric turbulence intensity (note that both the turbulence intensity and the decay coefficient grow behind the turbine).

By assuming the conservation of momentum in the wake district, the wind speed at the downwind of the turbine is given by

$$v = v_\infty + v_\infty\left(\sqrt{1 - C_T} - 1\right)\left(\frac{R_0}{R(x)}\right)^2 , \tag{1}$$

where v denotes the wind velocity at the downstream wake, v_∞ is the undisturbed wind velocity, R_0 is the turbine rotor radius, x is the radial distance (in the downwind area of the turbine) along the incoming wind direction, $R(x)$ is the wake diameter which is related to the diameter of the turbine via: $R(x) = R_0 + \beta x$, where β is a dimensionless constant called decay coefficient, and $C_T = \beta(1-\beta)$ is the turbine thrust coefficient. Figure 1-a