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Offshore Wind Wakes - the underrated impact on the marine ecosystem

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Abstract

The wind wake effect of offshore wind farms (OWFs) affects the hydrodynamical conditions in the ocean, which has been hypothesized to impact nutrient availability in surface waters and consequently marine primary production. However, this has not clearly been shown so far and little is known about the ecosystem response to wind wakes under the premisses of large OWF clusters. Here we show that the wind wakes of large OWF clusters in the North Sea provoke large scale changes in annual primary production with local changes of up to 10%, which occur not only in the direct vicinity of the OWF clusters but are distributed over a wider region. In addition, we found an increase in sediment biomass in deeper areas of the southern North Sea due to reduced current velocities. Our results show that the ongoing OWF developments can have a substantial impact on the structuring of coastal marine ecosystems.

INTRODUCTION

The North Sea is a shallow shelf sea system in which the interaction between bathymetry, tides and a strong freshwater supply at the continental coast foster a complex frontal system, which separates well mixed coastal waters from seasonally stratified deeper areas. The shallow coastal areas and sandbanks combined with stable wind resources make the North Sea an ideal area for renewable energy production and have made the North Sea a global hotspot for offshore wind energy production[1]. The lately negotiated European Green Deal to support the European target to phase out dependence on fossil fuels will further accelerate the development of offshore renewable energy[2] and a substantial increase of installed capacity (150GW by 2050[3]) is planned in the North Sea as a consequence to Europe´s strategy to be carbon neutral by 2050. The size and magnitude of already installed and in future planned offshore windfarm installation[4] has raised concerns about their impact on the marine environment[5] and scientific efforts have increased to understand and assess the implications of these large structures for the marine system. In addition to impacts on the regional atmosphere[6], multiple physical[7,8], biological[5,9] and chemical[10] impacts on the marine system have been identified. The underwater structures, such as foundations and piles relate to turbulent current wakes, which impact circulation, stratification, mixing and sediment resuspension[11–13]. Most studies conclude that the direct hydrodynamic consequences of the windfarm structures are mainly restricted to the area within the windfarms [14,15]. However, some speculate also, that the cumulated impacts of an increasing number of offshore installations might result in substantial impacts on the larger scale stratification[12,16]. Larger scale effects of offshore wind energy production well beyond the wind farm areas are introduced to the atmosphere by infrastructures above the sea level and the energy extraction itself[17]. Atmospheric wakes appearing in the lee of wind farms extend on scales up to 65km and beyond, in dependence of atmospheric stability, with a flow reduction of up to 43% inside the wakes[17] leading to upwelling and downwelling dipoles in the ocean beneath[18]. Previous modelling studies[18,19] showed that these dipoles are associated with vertical velocities in the order of meters per day and consequent changes in mixing, stratification, temperature and salinity. A first assessment of the large-scale integrated impact of atmospheric wakes from already existing OWFs on the hydrography of the southern North Sea revealed the emergence of large-scale oceanic structures with respect to currents, sea surface elevation and stratification[7].

For the marine ecosystem the effects of OWFs might or might not be severe, positive or negative. As Berkel et al. (2020)[15] explicate, the evaluation of ecosystem effects through BACI (before-after-control-impact) surveys are challenging due to the spatio-temporal variability of the natural system, regional and global trends, and the focus of investigations on selected fish species. In the literature we find, so far, a number of studies related to immediate impacts of

OWFs on marine fauna[5], such as the artificial reefs effect [20,21] or the impacts of acoustic disturbances on fish and marine mammals [22,23]. Indirect impacts are, however, likely even more important, more complex and more difficult to investigate. This includes consequences of restricted fisheries inside the OWFs[24] as well as the impacts of the above-described modulation of the physical environment on the structuring of the pelagic[25] and benthic[21] ecosystem. It is well known that modifications in mixing and stratification also impacts nutrient availability in the euphotic zone[26,27], however, the picture of the ecosystem impacts is less clear for some obvious reasons; i) The changes in nutrient concentration would enter a cause effect chain that translate into primary production and effectively enters the food chain. ii) In a dynamical system like the southern North Sea, which is characterized by strong tidal and residual currents, changes in the biotic and abiotic environment are exposed to advective processes. iii) The expected changes depend strongly on the prevailing hydrodynamic conditions, which makes it difficult to disentangle natural from inflicted changes. Other than observations, numerical modelling studies, indeed, allow for BACI studies as scenarios with and without the disturbance can be simulated [28]. In a previous modelling study, van der Molen et al. [28] proposed such an approach for an OWF at Dogger Bank, a relatively shallow, well mixed area of the North Sea using a relatively coarse ecosystem model in combination with a wave model. Their study, however, was restricted to single OWF, which was parameterized simply as a reduction in wind speed above the OWF.

Future OWF installations are planned to be way more extensive and the consequences of accelerated deployment for atmospheric dynamics and thermodynamics were shown to be substantial and large scale in the area of the North Sea[6]. The implications of these atmospheric changes for the future ocean dynamics are still unclear. The question on how and to what degree the emergent large-scale structural changes in atmosphere and ocean [6,7], under the premisses of large OWF clusters, might affect marine ecosystem productivity remains yet unanswered. Here we address this question while concentrating on the effects of atmospheric wakes on the ocean. For a future offshore wind installation scenario, we consider the atmospheric impact as simulated by high resolution atmospheric model[6] to force a fully coupled physical-biogeochemical model for the North Sea and Baltic Sea[29]. Different to earlier studies[7] we employ an atmospheric model including a dynamical parameterisation of OWFs, which takes into account the size of the windfarm and the number of turbines[6], and estimates impacts not only on the wind field but on the entire atmospheric physics. The experiment including OWFs (Exp. 1: OWF) follows the design given in [6] that considers all existing and planned OWFs by 2015 in the North Sea area (see Suppl. 1) and is compared to a reference simulation (Exp. 2: REF) without OWFs.

Average System Response to OWF

The scenario simulations provide evidence that increasing future OWF installations will significantly impact and restructure the marine ecosystem of the southern and central North Sea. Changing atmospheric conditions will propagate through ocean hydrodynamics and change stratification intensity and pattern, slow down circulation (Suppl. 2) and systematically decrease bottom shear stress. Our results confirm the direct ocean response identified by earlier studies to the alterations in the wind field (Suppl. 2) with clearly defined upwelling and downwelling dipoles in the vicinity of the OWF clusters as has been described in earlier studies[15,16]. However none of the earlier studies could show the systematic, large-scale, time integrated response of the ocean to large OWF clusters as they are planned to be implemented in the southern North Sea.

As a consequence of the substantial amount of energy that is extracted from the lower atmosphere[6] , the ocean responds with a clear and systematic change in stratification both in strength of stratification (Suppl. 3) and depths of the seasonal mixed layer. The latter was estimated to be, on average, 1-2 m shallower in and around the OWF clusters. Most clearly in the deeper stratified German Bight area and around the Dogger Bank region. For OWFs in mixed areas this effect is per definition not relevant and in frontal, less stratified areas the effect is less clear as the stratification becomes naturally interrupted by changes in the frontal position.

Apart from the effect on the stratification, our simulations show that the ocean responds with a significant decrease in the annual mean of the vertically averaged current velocities in the range of 0.003 m s^{-1} in large parts of the southern North Sea, but which can reach up to 0.009 m s^{-1} with maximum decrease at the OWFs at Dogger Bank (Fig. 1a). At the same time there are also local increases in mean current velocities in the German Bight area and, specifically between the OWF clusters in that area. These result locally in a change in current velocities of about 10% of the prevailing residual currents, which corroborates the findings by Chistiansen et al. 2021[7] for the impacts of existing OWFs in the German Bight area and shows that the large-scale circulation of the area will be significantly altered with potential consequences for sediment transport as shown below.

Ecosystem Impacts

In the southern North Sea, areas with particularly high primary production are co-located with the frontal belt off the coast and around Dogger Bank (Fig. 2a, insert). The majority of future OWF installations are planned in exactly those high productive areas, which are known to be ecologically highly important[30]. Our model results show that the systematic modifications of stratification and currents alter the spatial pattern of ecosystem productivity (Fig. 2a). Annual net primary production changes (netPP) in response to OWF wind wake effects in the southern North Sea show both, areas with a decrease and areas with an increase in netPP to up to 10%. Most obvious is the decrease in the centre of the large OWF clusters in the inner German Bight and at Dogger Bank, which are both clearly situated in high productive frontal areas, and an increase in areas around these clusters in the shallow, near coastal areas of the German Bight and at Dogger Bank. Additionally, we also find changes in netPP in areas further away from the OWF clusters, such as a decrease along the freshwater front off the German and Danish coasts and an increase at the central southern North Sea, which is typically seasonally stratified and shows lower productivity. Identifying the robustness of these pattern with respect to different weather conditions and interannual variations requires additional analysis and simulations. The direct response of the ecosystem at the OWF sites can be assigned to a response to the changed hydrodynamic conditions. This includes, on the one hand, the clearly defined upwelling and downwelling pattern (Suppl. 2), which have been hypothesised to play a major role for the changes OWFs provoke in the marine ecosystems [9]. Those patterns depend on the wind direction and can be expected to modify the nutrient exchange at the thermocline, as it has been shown for temperature and salinity[8], at and around the OWF clusters. On the other hand, the production changes are directly related to the changes in stratification. A closer look at the vertical distribution of netPP change (Fig. 2b) averaged over the areas with OWF installations (partitioned spatially into OWFs at strongly stratified and less stratified regions and temporally into spring and summer period) shows that i) OWFs in clearly seasonally stratified waters show an upward shift of the vertical production maximum, which occurs typically at the mixed layer depth in summer. This is a consequence of the shallower mixed layer depth, due to reduced wind mixing. This signal is more prominent in summer than in spring; ii) OWFs in less stratified and frequently mixed waters show a decrease in production in the upper 20m of the water column in spring and at the depth of the thermocline in summer.

Additionally, changes in netPP might translate into changes in trophic interactions. The changes in netPP are clearly converted into changes in phytoplankton biomass (Suppl. 4). However, the response in phytoplankton biomass is relatively small; on average below 1% both inside and outside the OWF clusters (Fig. 3) but can locally also reach up to 10% (Suppl. 4). An exception is the biomass change inside OWF clusters positioned in stratified areas, where the average response is about 2.4 % but with large variation. Interestingly these locations also show a relatively strong increase in zooplankton biomass (12%), which indicates that the local ecosystem is additionally structured by top-down control through increased grazing pressure[31]. In contrast, for the other regions (outside OWF clusters and OWF clusters in less stratified and mixed areas) the model estimates a slight average reduction in zooplankton biomass (<0.5%). In these regions it is difficult to conclude on the overall trophic response, since the average fractional change in biomass is very small and shows a large regional variation (Fig. 3).

Besides the changes in the pelagic ecosystem our model results highlight a substantial impact on sedimentation processes. The overall, large-scale reduction in average current velocities (Fig. 1b) results in reduced bottom shear stress to locally up to 10% (Fig. 4a). The reduced re-suspension of organic carbon from the sediments leads to increased carbon biomass in sediments in large parts of the southern North Sea (Fig. 4b), but specifically at and close to the OWF locations in deeper areas and at Dogger Bank. This is consistent with findings from van der Molen et al. 2013[28] for his case study for an OWF located on Dogger Bank. Their model indicated an associated reduction in light attenuation in the water column leading to a slight increase in primary production. In large parts of the southern North Sea light can be considered the major limiting factor for primary production in summer[26]. Our results confirm changes in light availability (Suppl. 4c) in the subsurface, however the pattern is strongly related to pattern of change in primary production, which indicates a dominant effect of phytoplankton self-shading. In addition, our results do not show that the reduction in resuspension is necessarily related to an overall reduction on particulate organic matter biomass. Considering the cause-effect chain that leads to higher-primary production under improved light conditions, but would in turn increase phytoplankton self-shading it is difficult to quantify this effect on longer time scales.

Consequences for higher tropic levels and management

Within this study, we estimated, for the first time, the so far underrated of the, by OWFs, changed atmospheric conditions on the large-scale features of the lower trophic levels of the marine ecosystem in the southern North Sea. The results highlight that, considering the extensive OWF installation plans for the area, the marine ecosystem responds very clearly to the changes in the atmosphere provoked by changes in stratification, advective processes and a systematic decrease in bottom shear stress. These changes can be expected to progress into higher trophic levels of the marine ecosystem. The southern North Sea is well known for supporting a diversity of marine fauna[32,33] and especially the near coastal areas are nursery grounds for many economically relevant fish stocks. The estimated changes in spatial distribution of primary production might impact the survival of fish early life stages in that area due to e.g. variations in the match-mismatch dynamics[34] with their prey. Understanding these changes is pivotal for a successful future fisheries management in the North Sea and could influence the identification and implementation of marine protected areas. Additionally, the estimated changes in organic sediment distribution and quantity could have an effect on the habitat quality for benthic species such as lesser sandeel (*Ammodytes marinus*) and other benthic species, which live in the sediments in the deeper areas of the southern North Sea[35], whose distribution have been shown to depend on the available food quantity and quality [36] as well as the prevailing bottom shear stress[37].

The quantification of the effects on species distribution and diversity remains a topic for future studies as the here used model is truncated at the secondary production level and does not allow for species specific estimates. A repetition of the simulation experiments with an E2E model approach[38]and multi-annual simulations are required to shed further light on the robustness of the estimated pattern, the transfer of the changes into the food web and its implications for ecosystem services and management. Additionally, further research on the combined effects of atmospheric wakes and anthropogenic mixing induced by the pile structures[16] in the ocean is necessary, as this might counteract the stabilizing effect of the wind wakes. Under the ambitious plans for OWF constructions in the North Sea[16] space becomes one of the major limiting resources for a large number of partly conflicting use interests[39]. Our results can serve support the unavoidable development of co-use management strategies under the given conditions.

METHODS

ECOSMO Model description and Setup

ECOSMO is a well-established, fully coupled marine ecosystem model for the North Sea and Baltic Sea area. The here used version of ECOSMO II has been presented in detail before [40] and contains in total 16 state variables that described the lower trophic components (phytoplankton and zooplankton) of the marine ecosystem as well as the major macro-nutrient cycles (nitrogen, phosphorus, silicon) relevant for the North Sea and Baltic Sea system. The sediment compartment is realized through a simple bottom layer which accumulates organic material. Benthic fluxes of the different nutrients are estimated separately in a non-Redfield manner to account for oxygen dependent chemical processes in the sediment. On the basis of the free-surface 3D baroclinic coupled sea-ice model HAM(burg)S(chelf)O(cean) M(odel)[41], the non-linear primitive equations are solved on a staggered Arakawa-C grid with a horizontal resolution of ~2km and a time step of 90 s. The vertical dimension is distributed on z-level coordinates with maximum 30 layers, with a higher resolution in the surface layer to represent ocean stratification and increasing level thickness in deeper layers. In total this adds up to 2516251 wet grid cells. The model uses a 2nd order Lax–Wendroff advection scheme that was made TVD by a superbee-limiter [42] that has been described in detail in an earlier study[43], which has been shown to adequately represent the frontal structures in the southern North Sea.

The overall model setup including forcing data is comparable to the setup used in[26] with two modifications. Freshwater discharges are provided by the mesoscale hydrological model (mHM)[44], while boundary conditions for temperature and salinity were provided by an additionally performed global simulation using the Max Planck Institute Ocean Model (MPI-OM)[45] in a higher resolution setup[46] forced with the NCEP/NCAR reanalysis[47].

Atmospheric forcing and Windfarm scenarios

A non-hydrostatic model COSMO-CLM with atmospheric grid resolution of ~ 2km (1100x980 grid cells) has been used to simulate the regional climate with and without OWFs in the North

Sea. It uses 62 vertical levels with 5 levels within the rotor area. To include the impact of OWFs in COSMO-CLM a wind farm parameterization[48,49] has been implemented that represents wind turbine effects as momentum sink and source of TKE. In this experiment, a theoretical OWF model based on theoretical National Renewable Energy Laboratory (NREL) 5 MW reference wind turbine has been used. It uses a wind turbine with a hub height of 90 m and rotor diameter of 126 m[50] . These turbines have a cut-in wind speed of 3 ms^{-1}, rated wind speed of 11.4 ms^{-1}, and a cut-out wind speed of 25 ms^{-1}. The atmospheric model used a wind turbine density of about $1.8x10^{-6}$ m^{-2}. Due to coarse atmospheric grid resolution (~ 2km), the average effect of the wind turbines within the grid box is estimated using the average grid box velocity. For both the experiments, with and without wind farms, initial and boundary conditions from coastDat3 simulations[51] were used. The latter were forced by the European Centre for Medium-Range Weather Forecast (ECMWF) ERA-Interim reanalysis[52]. A more detail description of experimental configuration, wind farm parameterization and a validation of the parameterization can be found in a previous study[48].

Strategy for using the models and data analysis

ECOSMO was forced by the COSMO-CLM simulations with and without OWF parameterization for the year 2010. The change in forcing is thereby not constrained to the change in the wind field but comprises change in all required forcing parameters including pressure, short wave radiation, 2m air temperature, humidity and precipitation. The simulations in 2010 are initialized by a 2-year long (2008-2009) spinup simulation also forced by COSMO-CLM (without OWF parameterization). Initial fields for physical state variables were retrieved from a previously conducted simulation of the model starting in 1995 with the same setup but atmospheric forcing from the COSMO REA6 reanalysis[53]. Ecosystem state variables were initialized from climatological values based on the World Ocean Atlas [54] .

Model data output has been postprocessed based on daily mean values available for all state variables as well as for biogeochemical fluxes and bottom shear stress. Potential energy anomaly (PEA)[55], the energy required to homogenize the water column provides a measure for the strength of stratification. As the mixed layer depth (MLD) we defined the depth at which the water temperature gradient reached at least 0.5 °C between two consecutive grid cells.

Author contribution

CS, UD conceived the study and designed the study setup. UD performed the model simulation with ECOSMO, data analysis and prepared the manuscript with contributions from all co-authors. NA performed the atmospheric model simulation and prepared the atmospheric forcing data for the ecosystem model. UD, CS, NA, NC contributed to data analysis and manuscript writing.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Competing interest

The authors declare no competing interests.

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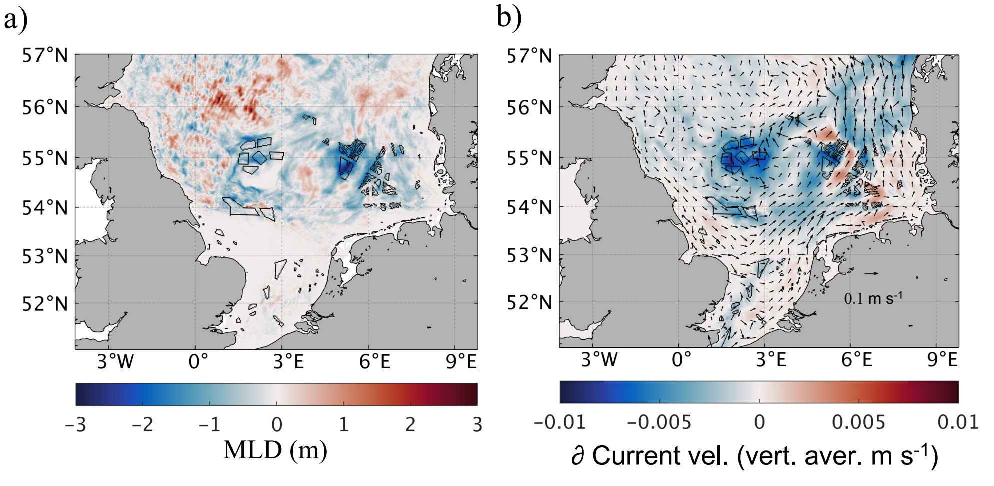

Figure 1 Annual mean ocean response to atmospheric changes due to OWFs. a) change mixed layer depth (MLD); b) vertically averaged current velocity for REF (arrows) and changes (OWF-REF) (color)

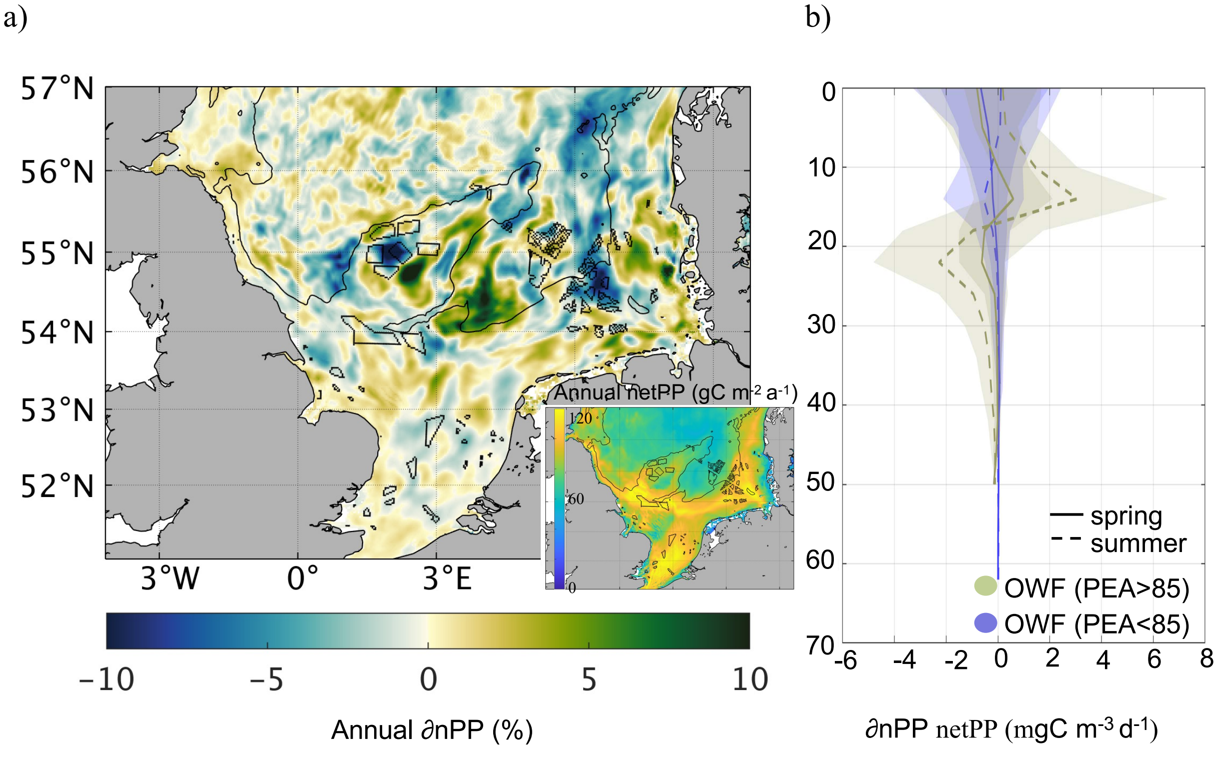

Figure 2 Estimated changes in annual net primary productions (netPP) a) relative change annual averaged net primary production 2010 (OWF-REF). Black line indicates potential energy anomaly of 85 J m^{-3} separating stratified from unstratified regions roughly separating seasonally stratified from mixed areas (insert: annual averaged netPP). b) vertical profiles of change (mean and standard deviation) in NPP at the OWF areas blue: less stratified and mixed areas (PEA<85); green: stratified areas (PEA>85) (solid lines: spring; dashed lines: summer)

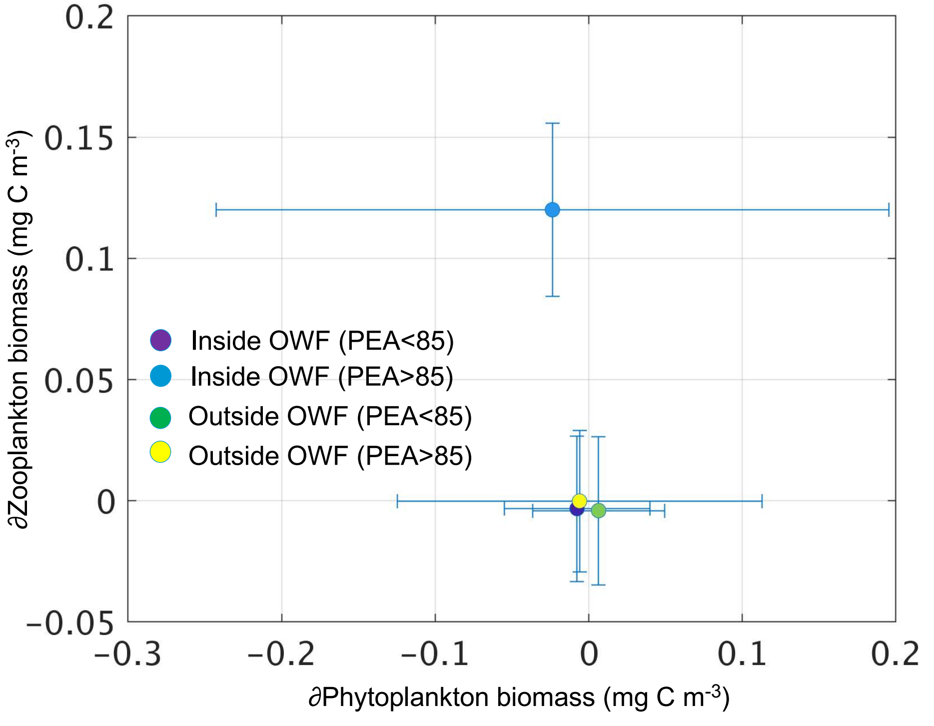

Figure 3 Fractional change ((OWF-REF)/REF) in annually and vertically averaged phytoplankton and zooplankton biomass. Mean and standard deviation for areas inside and outside the OWF clusters separated into stratified (PEA>=85) and less stratified and mixed areas (PEA < 85). Note, for the analysis areas deeper than 60m were excluded.

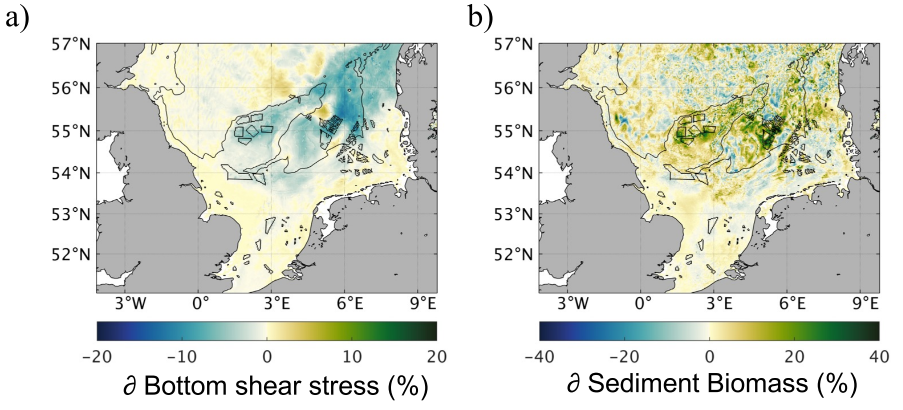

Figure 4 Annual mean response to atmospheric changes due to OWFs (OWF-REF). Relative change in annually averaged bottom shear stress (a); sediment organic carbon biomass (b). Black line indicates potential energy anomaly of 85 J m^{-3}.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Naturesubmsuppl.pdf