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Offshore wind farms are projected to impact primary production and bottom water deoxygenation in the North Sea

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The wind wake effect of offshore wind farms affects the hydrodynamical conditions in the ocean, which has been hypothesized to impact marine primary production. So far only little is known about the ecosystem response to wind wakes under the premisses of large offshore wind farm clusters. Here we show, via numerical modeling, that the associated wind wakes in the North Sea provoke large-scale changes in annual primary production with local changes of up to ±10% not only at the offshore wind farm clusters, but also distributed over a wider region. The model also projects an increase in sediment carbon in deeper areas of the southern North Sea due to reduced current velocities, and decreased dissolved oxygen inside an area with already low oxygen concentration. Our results provide evidence that the ongoing offshore wind farm developments can have a substantial impact on the structuring of coastal marine ecosystems on basin scales.

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The North Sea is a shallow shelf sea system in which the interactions 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 recently 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 (212 GW 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 the already installed (28 GW European offshore wind farm capacity by 2021[4]) and the planned offshore wind farm (OWF) installation[5] has raised concerns about their impact on the marine environment[6] 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[7], multiple physical[8,9], biological[6,10] and chemical[11] impacts on the marine system have been identified. The underwater structures, such as foundations and piles may cause turbulent current wakes, which impact circulation, stratification, mixing, and sediment resuspension[12–14]. Most studies conclude that the direct hydrodynamic consequences of the windfarm structures are mainly restricted to the area within the wind farms[15,16]. However, some speculate also, that the cumulative impacts of an increasing number of offshore installations might result in substantial impacts on the larger scale stratification[13,17]. 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[18]. Atmospheric wakes appearing in the lee of wind farms extend on scales up to 65 km and beyond, depending on atmospheric stability, with a wind speed reduction of up to 43% inside the wakes[18] leading to upwelling and downwelling dipoles in the ocean beneath[19]. Previous modeling studies[9,19] 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. Recently, Floeter et al.[20] provided empirical evidence for the existence of these upwelling/downwelling dipoles showing distinct structural changes in mixed layer depth and potential energy anomaly inside the wind wake area of OWFs in the summer stratified area of the southern North Sea. 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[8].

For the marine ecosystem the effects of OWFs might or might not be severe, positive or negative. As van Berkel et al.[16] explain, 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, as well as other anthropogenic impacts, such as changes in fishing effort, eutrophication, and noise levels, while the focus of investigations is on selected fish and seabird species. In the literature we find, so far, a number of studies related to immediate impacts of OWFs on marine fauna[6], such as the artificial reefs effect[21,22] or the impacts of acoustic disturbances on fish and marine mammals[23,24]. Indirect impacts are, however, likely even more important, more complex, and more difficult to investigate. This includes consequences of restricted fisheries inside the OWFs[25] as well as the impacts of the above-described modulation of the physical environment on the structuring of the pelagic[10] and benthic[22] 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 start a cause-effect chain that translates into changes in primary production and effectively alters the food chain; (ii) In a dynamic 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 a high-density suite of physical and biological observations, numerical modeling studies are the only means to build BACI studies as scenarios with and without the disturbance can be simulated[28]. In a previous modeling 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 hydrodynamics-ecosystem model in combination with a wave model. Their study, however, was restricted to a single OWF, which was parameterized simply as a reduction in wind speed above the OWF.

Future OWF installations are planned to be far more extensive[29] 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[7]. 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[7,8], 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 to the ocean. Mixing induced by the turbine foundations in the ocean was neglected. For a future offshore wind farm installation scenario, we consider the atmospheric impact as simulated by a high-resolution (~2 km) atmospheric model[7] to force a fully coupled physical-biogeochemical model for the North Sea and Baltic Sea[30]. Different to earlier studies[8] we employ an atmospheric model including a dynamical parameterization of OWFs, which takes into account the size of the windfarm and the number of turbines[7], 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 Akhtar et al.[7] that includes all existing and planned OWFs in the North Sea area based on information available in 2015 (see Supplementary Fig. 1) and is compared to a reference simulation (Exp. 2: REF) without OWFs. For our idealized scenario simulation, wind farm parameterization for 5 MW turbines and hub heights of 90 m are used, the rotor diameter was considered as 126 m. The density of installed turbines was chosen to be comparable to currently used densities for similar turbine types. For the spatial distribution of installed capacity all planned wind farm areas (planning status 2015) were used to distribute the turbines for the wind farm parameterization. The installed capacity for this scenario amounts to 120 GW, which is between the 2030 high scenario of 65 GW for the North Sea and the recently agreed commitment of the four countries Denmark, Netherlands, Germany and Belgium (Esbjerg declaration) to install a capacity of at 150 GW by 2050[31] in the North Sea. The EUs overall plan for the installed capacity in 2050 in the North Sea amounts to 212 GW. Hence, our simplified scenario corresponds approximately to the installed capacity reached in about 15 yrs, by 2037.

The scenario simulations provide evidence that the increasing amount of future OWF installations will substantially 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 and systematically decrease bottom shear stress. The model projects that wind wakes of large OWF clusters in the North Sea provoke large scale changes in annual primary production with local changes (increase/decrease) of up to 10%, while region-wide averages in estimated annual primary production remain almost unchanged. In addition, the results show an increase in sediment carbon in deeper areas of the southern North Sea with local increases of up to 10%, and reduced dissolved oxygen at the Oyster Grounds, which is an area where oxygen levels can occasionally fall below 3 mg l^{-1} [32].

Results and discussion

Average system response to OWFs. Our results confirm the direct ocean response identified by earlier studies[8,9] to the alterations in the wind field (Supplementary Fig. 2) with clearly defined upwelling and downwelling dipoles in the vicinity of the OWF clusters. 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[7], the ocean responds with a clear and systematic change in stratification, both in strength of stratification (Supplementary Fig. 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 (Fig. 1a). This effect occurred 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. Changes in mixed layer depth have been reported earlier as a consequence of offshore wind farm wakes due to the reduced wind induced mixing[8], but also due to the upwelling and downwelling dipoles[20]. Since the dipole structure is associated with both an uplift and a depression in mixed layer depth[20] and is variable in dependence of the wind direction (Supplementary Fig. 2), we hypothesize that the annual average response is mainly a consequence of the reduced wind mixing.

Apart from the effect on the stratification, our simulations show that the ocean responds with a substantial decrease in the annual mean of the vertically-averaged horizontal current velocities in the range of 0.003 m s^{-1} in large parts of the southern North Sea, but which can locally reach up to 0.0087 m s^{-1} at the OWFs at Dogger Bank and 0.0091 m s^{-1} in the seasonally stratified reach of the German Bight (Fig. 1b). In both of these areas this means a reduction of 15% of the prevailing residual current. 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 changes in current velocities of about ±10% of the prevailing residual currents, which corroborates the findings by Christiansen et al.[8], who studied the impacts of existing OWFs in the German Bight area by using an unstructured grid model and a very simple satellite-derived wind wake parameterization. This also shows that the large-scale circulation of the area will be strongly 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 highly productive areas, which are known to be ecologically highly important[33]. 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 (netPP) changes 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 of up to 10%. Most obvious is the decrease in the center of the large OWF clusters in the inner German Bight and at Dogger Bank, which are both clearly situated in highly 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. The latter might be fueled by nutrient supply from subsurface waters as a consequence of the upwelling and downwelling dipole as suggested in earlier studies[20]. Additionally, we also find changes in netPP in areas further away from the OWF clusters, such as a decrease along the fresh water front of the German and Danish coasts and an increase south-east of Dogger Bank at Oyster Grounds, which is typically seasonally stratified and shows lower productivity. Identifying the robustness of these patterns with respect to different weather conditions and interannual variations requires additional analysis and simulations. When integrated over a larger area, the estimated positive and negative changes tend to even

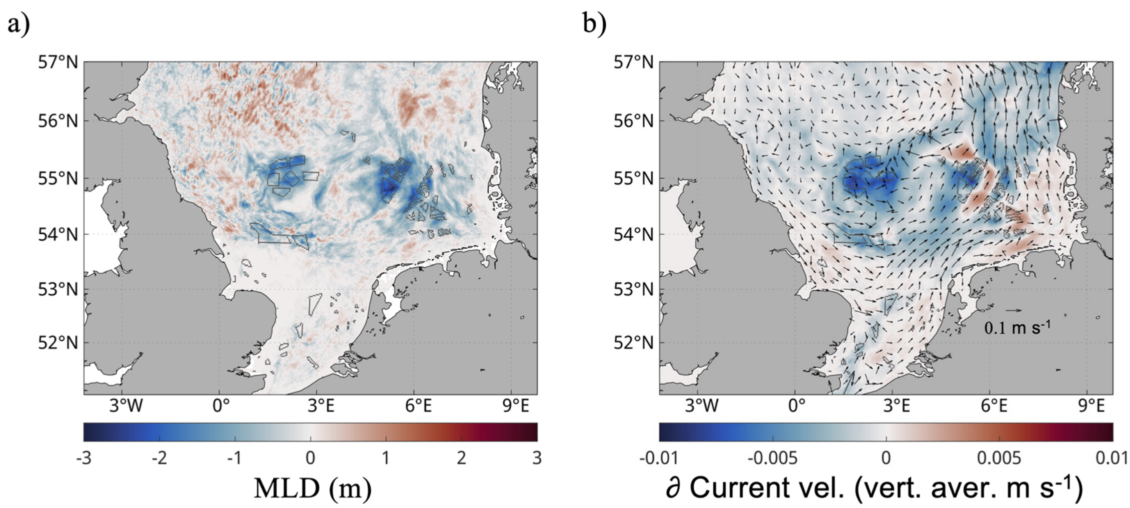

Fig. 1 Annual mean ocean response to atmospheric changes due to offshore windfarms. a Estimated change (OWF-REF) in mixed layer depth (MLD); **b** vertically averaged current velocity for REF (arrows) and changes (OWF-REF) (color). Gray polygons indicate location of offshore wind farms. (OWF: simulation experiment considering offshore wind farms; REF: reference simulation).

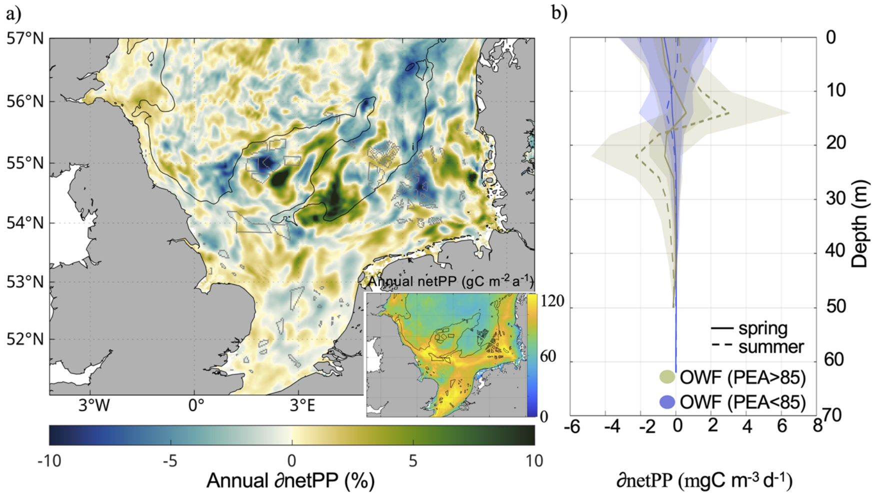

Fig. 2 Annual mean response of net primary productions (netPP) to atmospheric changes due to offshore wind farms. a Relative change in annual averaged net primary production for 2010 (OWF-REF). Black contour line indicates potential energy anomaly (PEA) of 85 J m^{-3} roughly separating seasonally stratified from mixed areas; gray polygons indicate location of considered offshore wind farms (insert: annual average of netPP simulated for 2010). **b** Vertical profiles of change (mean and standard deviation) in netPP inside the offshore wind farm areas; blue: less stratified and mixed areas (PEA < 85 J m^{-3}); green: stratified areas (PEA ≥ 85 J m^{-3}) (solid lines: spring; dashed lines: summer). (OWF: simulation experiment considering offshore wind farms; REF: reference simulation).

out. Regional averages for the whole North Sea (model area with longitude <9°E) as well as for the southern North Sea area (as in Fig. 2a) and the German Bight (latitude: 53.5–55.5°N; longitude: 4–9°E) only show reductions down to −0.5%, while the average reductions in netPP directly at the OWF locations adds up to −1.2 %. The direct response of the ecosystem at the OWF sites can be assigned to the changed hydrodynamic conditions. This includes, on the one hand, the clearly defined upwelling and downwelling patterns (Supplementary Fig. 2), which have been hypothesized to play a major role in the changes OWFs provoke in marine ecosystems[10,20]. Those patterns depend on the wind direction and can be expected to modify the nutrient exchange at the thermocline, as has been shown for temperature and salinity[9], 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 periods) shows that OWFs in clearly seasonally stratified waters experience 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. In contrast, OWFs in less stratified and frequently mixed waters show a decrease in production in the upper 20 m 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 (Supplementary Fig. 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 reach up to 10% locally (Supplementary Fig. 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 variations. 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[34]. In reality the increased zooplankton production at these locations

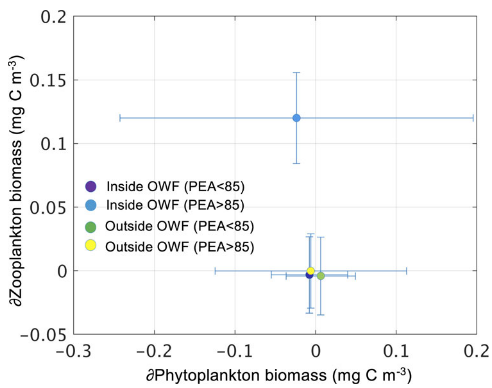

Fig. 3 Fractional change ((OWF-REF)/REF) in annually and vertically averaged phytoplankton and zooplankton biomass. Mean and standard deviation for areas inside and outside the OWF clusters separated based on the potential energy anomaly (PEA) into stratified (PEA ≥ 85 J m^{-3}) and less stratified and mixed areas (PEA < 85 J m^{-3}). Note, for the analysis areas deeper than 60 m were excluded. (OWF: simulation experiment considering offshore wind farms; REF: reference simulation).

might be mitigated by additional higher trophic levels feeding on zooplankton, which is not represented in the model used here. In contrast, 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 and seabed processes. The overall, large-scale reduction in average current velocities (Fig. 1b) results in reduced bottom-shear stress to up to 10% locally (Fig. 4a). The reduced resuspension of organic carbon from the sediments results in an increased amount of organic carbon in the sediments in large parts of the southern North Sea (Fig. 4b). This becomes specifically evident at and close to the OWF locations in deeper areas and at the Dogger Bank. The average increase in sediment organic carbon amounts to almost

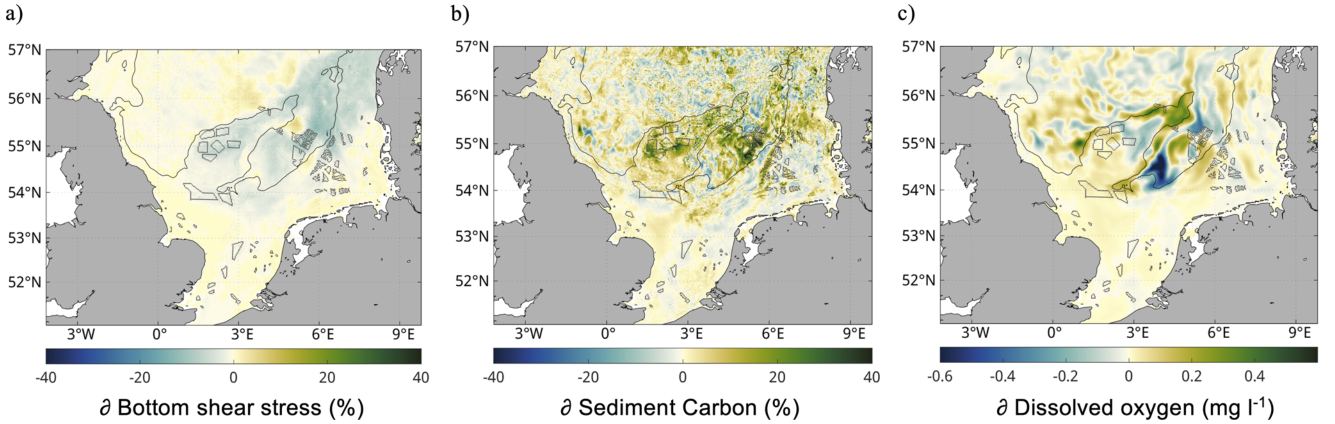

Fig. 4 Annual mean response of benthic processes to atmospheric changes due to offshore wind farms. a Relative change in annually averaged bottom shear stress; **b** relative change in annually averaged sediment organic carbon; **c** absolute change in dissolved bottom water oxygen (average July-September). Black contour line indicates potential energy anomaly of 85 J m^{-3}; gray polygons indicate location of considered OWFs. (OWF: simulation experiment considering offshore wind farms; REF: reference simulation).

10% directly at the OWF locations and 6% in the German Bight area. However, averaged over larger areas the effect is less pronounced with only a 0.2% increase North Sea wide. Our findings on reduced resuspension are consistent with findings from van der Molen et al.[28] for his case study of 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 (Supplementary Fig. 4c) in the subsurface, however, the pattern is strongly related to the 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 of particulate organic matter concentration in the water column. Considering the cause-effect chain that leads to higher-primary production under improved light conditions, but would in turn increase phytoplankton self-shading, the quantification of this effect on longer time scales remains to be studied in the future.

In addition to changes in sediment-carbon distribution the model indicates an impact of OWF on bottom water oxygen in the southern North Sea (Fig. 4c). Oxygen is a key biogeochemical component in marine ecosystems, and often considered as an indicator for ecosystem health[35]. Even though the highly dynamic North Sea is not known for extensive low oxygen areas, earlier studies reported the potential for low oxygen events in the central North Sea, more specifically at the Oyster Grounds[32,36]. The Oyster Grounds denotes a bathymetric depression, which partly limits the exchange with the surrounding water and supports the development of summer stratification. As a consequence, organic material tends to accumulate in bottom waters at the Oyster Grounds, which is associated with enhanced oxygen consumption. Observations in this area show that dissolved oxygen concentrations in bottom waters can occasionally fall below 3 mg l^{-1} [32], and also in our reference simulation dissolved oxygen in bottom water was below 4 mg l^{-1} in late summer and autumn. According to our simulation the Oyster Grounds is an area, which would be especially impacted by large-scale OWF installations. Due to increased primary production on the one hand, but also by the reduced advective currents and bottom shear stress the dissolved oxygen concentrations in late summer and autumn were further reduced by about 0.3 mg l^{-1} on average and up to 0.68 mg l^{-1} locally in our simulations. In other areas of the southern North Sea, the effect was estimated to be less severe, or even showing an increase in dissolved oxygen concentration, like e.g., along the edges of Dogger Bank.

Consequences for higher tropic levels and management. Within this study, we estimated the so far underrated effects of the changed atmospheric conditions by OWFs 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 leading to changes in ocean 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[37,38] and especially the near-coastal areas are nursery grounds for many economically relevant fish stocks. The estimated changes in the spatial distribution of primary production might impact the survival of fish early life stages in specific areas due to e.g., variations in the match-mismatch dynamics[39] with their prey or as a consequence of low oxygen conditions. Understanding these changes is pivotal for 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 that live in the sediments in the deeper areas of the southern North Sea[40]. Their spatial distributions might change as it has been shown to depend on the available food quantity and quality[41] as well as the prevailing bottom shear stress[42].

The quantification of the effects on species distribution and diversity remains a topic for future studies as the model used here is truncated at the secondary production level and does not allow for species-specific estimates. In addition, the high computational demand for running both models (atmosphere and ocean) on a high resolution currently limits our simulation to one year only, without an additional spinup period to allow for the system to adjust to the OWF-induced changes. The average physical response can be, at least partly (e.g., with respect to mixed layer depth and reduced residual currents), considered immediate and is mainly related to the reduced energy in the wind field. The ecosystem components, in contrast, might need a transition phase to establish a new ecosystem state under OWF influence. Still, the changes we see are a systematic response to the energy extraction from the atmosphere and will likely consolidate after a few years of simulation, but with interannual variations related to changes in the environmental conditions. A repetition of the simulation experiments with an "end-to-end" model approach[43] 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[17] 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[17] space becomes one of the major limiting resources for a large number of partly conflicting usage interests[44]. Our results can serve to support the inevitable 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 version of ECOSMO II used here has been presented in detail before[45] and contains a total of 16 state variables that describes 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 included 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)[46], the non-linear primitive equations are solved on a staggered Arakawa-C grid with a horizontal resolution of ~2 km and a time step of 90 s. The impacts of the OWF wind wakes were earlier found to be related to the internal radius of deformation[19], which is about 10 km in the North Sea area[47]. The smallest scales resolved by the model are twice the grid size (approx. 4 km). Hence, the internal radius of deformation is well resolved by the model. The vertical dimension is simulated with z-level coordinates with a maximum of 30 layers, with a higher resolution in the upper layers the surface to represent ocean stratification, and increasing level thickness in deeper layers (5 m for the first two layers; 4 m up to depths of 50 m; 6 m for depths between 50 and 92 m; 100 m; 120 m; 140 m; 160 m; 180 m; 200 m; 250 m; 300 m; 400 m; 500 m; 630 m). In total, this adds up to 2516251 wet grid cells. The model uses a second-order Lax–Wendroff advection scheme that was made TVD (total variation diminishing) by a superbee-limiter[48] that has been described in detail in an earlier study[49], and 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 Zhao et al.[26] but with a different set of open boundary conditions for temperature and salinity. The latter were provided by a global simulation using the Max Planck Institute Ocean Model (MPI-OM)[50] in a higher resolution setup[51] forced with the NCEP/NCAR reanalysis[52].

Atmospheric forcing and Windfarm scenarios. A non-hydrostatic model COSMO-CLM with atmospheric grid resolution of ~ 2 km (1100 × 980 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[7,53] has been implemented that represents wind-turbine effects as momentum sink and source of turbulent kinetic energy. In this experiment, a theoretical OWF model was used based on the theoretical National Renewable Energy Laboratory (NREL) 5 MW reference wind turbine. It uses a wind turbine with a hub height of 90 m and rotor diameter of 126 m[54]. 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 $1.8 \times 10^{-6}\,m^{-2}$. Due to coarse atmospheric grid resolution (~2 km), the average effect of the wind turbines within the gridbox is estimated using the average grid box velocity. For both the experiments, with and without wind farms, initial and boundary conditions from coastDat3 simulations[55] were used. The latter were forced by the European Center for Medium-Range Weather Forecast (ECMWF) ERA-Interim reanalysis[56]. A more detailed description of the experimental configuration, wind farm parameterization and a validation of the parameterization can be found in a previous study[7].

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 changes in all required forcing parameters including pressure, short wave radiation, 2 m air temperature, humidity, and precipitation. The simulations in 2010 were initialized using a 2-year long (2008–2009) spinup simulation also forced by COSMO-CLM (without OWF parameterization). Considering that the characteristic time scale of the North Sea is in the order of 1–3 years a two-year spinup is sufficient for initializing the simulation, especially since the initial fields for physical state variables were retrieved from a previously conducted simulation with a similar model setup but a different atmospheric and river forcing. The latter simulation started in 1995 with the same setup but atmospheric forcing from the COSMO REA6 reanalysis[57] and freshwater discharges provided by the mesoscale hydrological model (mHM)[58], which is a calibrated, grid-based hydrological model for Europe[59]. Ecosystem state variables were initialized from climatological values based on the World Ocean Atlas[60]. Since the atmospheric simulation is computationally very demanding, only one year of the simulation is currently available covering the full ocean model domain.

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[61], the energy required to homogenize the water column, provides a measure for the strength of stratification. For the definition of the mixed layer depth we used a temperature criterion suggested by de Boyer Montégut et al.[62] where the mixed layer depth is defined as the depths at which $\Delta T \geq 0.2$ °C with respect to the surface layer temperature. Figures were compiled with matlab using the cmocean colormap[63].

Reporting summary. Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The datasets generated and/or analyzed during the current study are publicly available at the world data center for climate (www.wdc-climate.de) under http://hdl.handle.net/21.14106/d116dd4f38f47f150e655ab9441601b34b312583.

Code availability

Model code access for the marine ecosystem model ECOSMO can be obtained upon request.

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Author contributions

C.S. and U.D. conceived the study and designed the study setup. U.D. performed the model simulation with ECOSMO, data analysis, and prepared the manuscript with contributions from all co-authors. N.A. performed the atmospheric model simulation and prepared the atmospheric forcing data for the ecosystem model. U.D., C.S., N.A., and N.C. contributed to data analysis and manuscript writing.

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Additional information

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