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# Current knowledge and key gaps in understanding of offshore wind farm impacts on the physical marine environment

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## Abstract

Offshore wind energy production is on the rise globally, projected to occupy significant areas in shallow shelf seas and moving into deeper waters as floating turbine technology is becoming more mature. However, knowledge about the potential impact of wind farms on the physical oceanography and lower trophic organisms is still severely limited. In this review, we assess the current state of knowledge on the effects and impacts of offshore wind farms on regional and local hydrography and circulation, nutrient distribution, phytoplankton and primary production, and sediment load in the water column during the operational phase of the wind farms and identify critical knowledge gaps. The body of literature on the topic has grown rapidly over the last years, but most studies focus on wind farms in relatively shallow (<60 m water depth) and mainly unstratified or seasonally stratified shelf seas, predominantly on the northern European shelf and around China. *In situ* observations are scarce, leading to heavy reliance on numerical models. As floating wind farms have become operational only very recently, few studies focus directly on their specific impacts. There is general understanding of local impacts on ocean physics, e.g. on turbulence, mixing and stratification due to flow past turbine foundations, or the potential of wind wake impacts on surface currents, up- and downwelling. Consequences for phytoplankton and primary production are much less clear and both physical and biogeochemical impacts on regional scales remain uncertain. There is a critical need for observational data for validation and targeted impact studies. Particularly characteristics and temporal and spatial scales of circulation and hydrographic changes and their effects and impacts on primary producers, vertical flux, and pelagic-benthic coupling are little understood especially in stratified and deep shelf regions. Given the rapidly accelerating growth of the offshore wind farm industry and expansion into deeper seas using floating technology, addressing these knowledge gaps is crucial for reliable environmental impact assessments and sustainable development of this still relatively new energy sector.

## Introduction

Offshore wind energy production plays a major role in the shift from fossil fuels to greener, sustainable industries. The first commercial offshore wind farm was commissioned off the coast of Denmark in 1991 with a total installed capacity of 5 MW. Development was slow until the early 2000s but accelerated since 2009 to just over 68 GW installed capacity by the end of 2023 (McCoy et al. 2024). The largest installed capacity, highest number of offshore wind farms, and greatest annual increase in capacity in 2023 (2.9 GW) was in China, followed by the UK (new capacity 1.1 GW). Other major actors are Germany and Netherlands in terms of current capacity, but other countries like Taiwan and Vietnam with 671 and 335 MW installed in 2023, respectively, are joining the market.

Plans by the European Union and the UK aim for a total capacity of 110 GW by 2030 (TCE 2022, European Commission, Directorate-General for Energy 2023). The total capacity of the global offshore wind energy pipeline (i.e. including all projects in planning, site control, permitting, financial close, and operating) at the end of 2023 amounted to over 453 GW, of which 35.6 GW were under construction (McCoy et al. 2024). Projects with floating installations amounted to just over 104 GW, of which 14.2 GW are planned operational by end of 2028. The world's currently largest floating wind farm, Hywind Tampen, consisting of 11 turbines with a total capacity of 88 MW, has become operational in 2023 and supplies electricity to the surrounding offshore oil and gas installations in the Norwegian North Sea. Pilot project wind farms are in place in UK waters (Hywind Scotland; Jacobsen and Godvik 2021) and off the coast of France in the Mediterranean Sea, and single floating turbines are installed in China, Japan, and Spain.

The push for offshore wind energy will require extensive areas with potential conflict with other users and impacts on ecosystems. There is limited space available in shallow, often unstratified or weakly, seasonally stratified shelf seas with strong tidal currents, where turbines can be mounted fixed to the bottom (depths of up to 60 m), such as the southern North Sea or the Yellow Sea, and challenges arise due to competing area use interests particularly with fisheries activities (ICES 2025). With the development of floating wind turbines, wind farms can be established in deeper regions with different stratification regimes, weaker tidal currents but possibly stronger geostrophic and/or topographically steered currents.

With the projected increase in numbers, capacity and area covered by offshore wind farms according to projects in pipeline, a better understanding of the impacts on the marine environment and ecosystems is urgently needed. Most studies and impact assessments so far focused mainly on higher trophic levels, i.e. fish, marine mammals, and seabirds, with several reviews now available regarding the impact on the

**Table 1.** Keywords used in the systematic literature search and number of results.

| Keywords | Number of search results | Number of relevant papers |
|---|---|---|
| floating AND "offshore wind farm*" | 337 | 3 |
| "offshore wind farm*" NOT floating AND hydrography | 3 | 2 |
| "offshore wind farm*" NOT floating AND stratification | 35 | 16 |
| "offshore wind farm*" NOT floating AND circulation | 43 | 12 |
| "offshore wind farm*" NOT floating AND ocean current* | 177 | 19 |
| "offshore wind farm*" NOT floating AND upwelling | 16 | 5 |
| "offshore wind farm*" NOT floating AND "water column" | 25 | 8 |
| "offshore wind farm*" NOT floating AND mixing | 194 | 13 |
| "offshore wind farm*" NOT floating AND turbulen* | 214 | 16 |
| "offshore wind farm*" NOT floating AND wave* | 402 | 15 |
| "offshore wind farm*" NOT floating AND nutrient* | 22 | 4 |
| "offshore wind farm*" NOT floating AND resuspension | 3 | 3 |
| "offshore wind farm*" NOT floating AND "suspended particulate" | 7 | 4 |
| "offshore wind farm*" NOT floating AND phytoplankton | 13 | 4 |
| "offshore wind farm*" NOT floating AND "primary producti*" | 13 | 5 |

Numbers as of 11 June 2025.

marine ecosystem as a whole or selected components (Methratta et al. 2020, Galparsoro et al. 2022, Wang et al. 2024). With the exception of few examples (e.g. Van Berkel et al. 2020, Farr et al. 2021), reviews rarely focus on oceanography, biogeochemistry and lower trophic levels, which, however, form the habitat and the base of any food web. Additionally, the number of papers increased rapidly over the last couple of years, and an updated overview is timely. In this paper, we therefore review the existing literature to assess the current knowledge and knowledge gaps regarding effects and impacts of offshore wind farms on local and regional oceanographic conditions (i.e. hydrography and hydrodynamics), nutrient distribution and availability, phytoplankton and primary production, and sediment load in the water column. We focus on impacts during the operational phase by turbine structures and alterations to the wind field. As we will show, the number of studies from floating wind farms is very limited due to the short period of time since the technology became available and operational. Most of the literature used here stems therefore from bottom-mounted wind farms.

We outline our approach in the next section, followed by a general overview of the available literature. We then present the current state of knowledge of offshore wind farm impacts on oceanography, nutrients, phytoplankton and suspended particles. We discuss the implications of our findings with regards to identified knowledge gaps and ecological consequences, and conclude with an overview of research needs and priorities, particularly in light of the anticipated future development and use of floating technology.

## Methods

We conducted a semi-structured literature search consisting of two approaches:

1. A systematic search of the peer-reviewed literature (see e.g. Pullin and Stewart 2006, similar to Farr et al. 2021, Watson et al. 2024) using the Clarivate Web of Science Core Collection search portal. We used focused keywords to identify potentially relevant papers, followed by assessment of paper title and abstract, if required introduction and methods section. Keywords and keyword phrases as well as numbers of search results and identified relevant papers are given in Table 1.

While the expression 'offshore wind farm' appears to be the most commonly used, some authors use slightly different terms. We therefore conducted additional searches with the expressions 'offshore windfarm*', 'offshore wind park*', 'offshore wind' AND (facility OR facilities), as well as 'offshore wind power' and 'offshore wind energy' in combination with specific keywords as in Table 1, which resulted in one additional relevant paper.

Using broad terms like 'offshore wind' did not differentiate general studies involving wind along the coast or similar, and therefore resulted in too high numbers of results requiring the further filtering described above. In general, the highest numbers of papers were associated with technical aspects of the wind farms (turbine design, load and fatigue, farm design, operational aspects), and papers investigating atmospheric conditions (e.g. mixing and upwelling in the atmospheric boundary layer, turbulence, impact of atmospheric stratification) outnumbered marine focused studies.

In total, the systematic search identified 53 unique, relevant papers.

2. As the Web of Science Core Collection does not include potentially relevant reports, theses, or papers in not-indexed journals, a general search on Google Scholar was conducted using similar keywords to the ones listed in Table 1. In addition, previously known papers and reports, and additional sources identified from reference lists and articles suggested on journal pages were included. The search pattern was continued until it became circular and no new relevant papers were identified.

Grey literature such as reports, books and theses were only included if adding additional insight beyond purely providing literature reviews, and if the reported results were not published in follow-up, peer-reviewed articles. Szostek et al. (2024) investigated the potential bias in reporting in grey and primary literature for OWF-related studies and (i) showed a bias towards negative impacts in grey literature, (ii) identified evidence gaps in both types of literature, (iii) warned of issues related to accessibility for both grey and primary literature and lack of peer-review for grey literature. Since many commissioned reports and the data they are based on are not publicly accessible, we did not perform a general search for such literature beyond the Google Scholar and reference list searches.

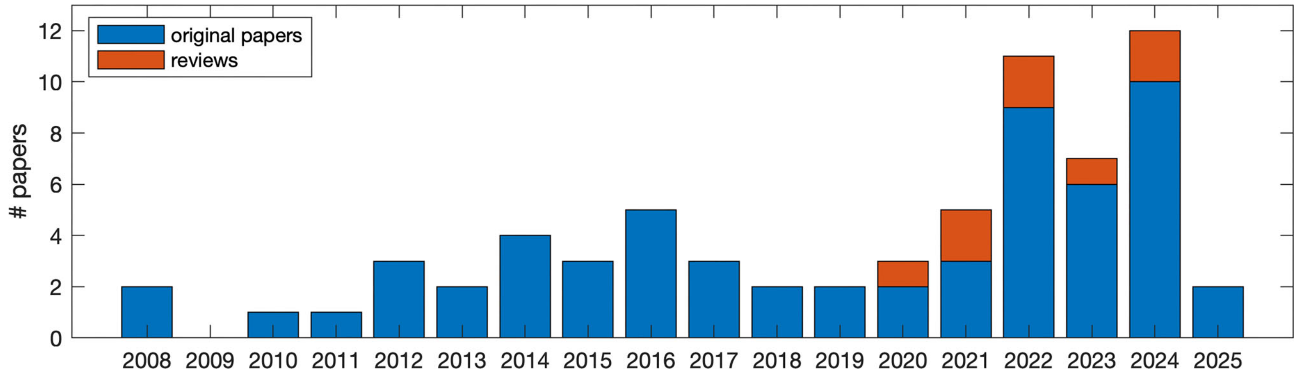


**Figure 1.** Number of papers by year (2025 includes papers up until 11 June).

This semi-systematic search identified a further 15 relevant papers.

In the choice of relevant papers and reports, we did not include studies conducted on the Great Lakes, scour around foundations (i.e. not looking into sediment load in the water column), or studies focused on the effects of hydrodynamic load, abrasion by sediment or similar stress on turbine structures. Studies into potential impacts of OWFs in areas where wind farms are planned but not established yet (e.g. Mediterranean Sea—Lloret et al. 2023, California coast—Dalsin et al. 2025) were not included either. Due to the explicit focus on impact of operational OWFs, studies of impacts and effects during construction or decommissioning were not considered. There is a large body of literature on the flow past obstacles and the generation of, e.g. von Kármán vortices and turbulence, using idealized fluid dynamics models and laboratory experiments. Here, we only include studies that directly apply to offshore wind related settings. Reviews were included only if they explicitly include one or more physical parameter and/or phytoplankton and provide new insight through synthesis, thus excluding reviews focussing purely on impacts on marine species or presentation of previously published findings.

For simplification, we will refer to 'papers' in the following and include both peer-reviewed articles, theses, and reports in the term.

## Literature availability

### General body of literature and bottom-mounted vs floating offshore wind farm studies

Given the only recent establishment of offshore wind farms, the body of scientific literature on environmental effects and impacts is clearly just starting to form, especially regarding the physical environment. Impact studies and assessments for charismatic species such as seabirds and marine mammals have been conducting already early in the development of the offshore wind industry. Physical effects have mostly centred around those relevant to structural integrity needs and challenges. The large discrepancy between search hits and low number of papers relevant to the issues investigated here (Table 1) is due to the large body of literature concerned with engineering questions and problems where, e.g. currents, waves, or sediments (in particular scouring) are investigated purely because of their impact on the turbine structure, life span, and efficiency. However, the increase in relevant papers especially in the last five years (Fig. 1) demonstrates a new urgency for better understanding of environmental impacts in light of the accelerating, massive expansion planned in large parts of the global coastal ocean.

Of the 68 identified relevant papers, 8 were reviews, 2 reports, 2 theses (1 PhD and 1 Master thesis), and 56 original articles. One paper investigated turbulence from a bridge pile but is included due to its relevance to wind turbine monopiles in the same region. Literature on floating offshore wind farms beyond the technical and engineering literature (an overview is provided by Hong et al. 2024a) is severely limited, which is expected given the limited time since their development. Only one peer-reviewed paper could be identified with measurements from a floating offshore wind farm (Hywind Scotland; Karlsson et al. 2022) but was not included in the overview due to its focus on hard-bottom fauna. The three identified relevant papers are either reviews or original studies on bottom-mounted turbines with application to floating offshore wind farms. A number of impact assessment studies were excluded due to their exclusive ecosystem focus and lack of inclusion of the physical environment (e.g. Lloret et al. 2022, 2023, Wawrzynkowski et al. 2025).

### Geographical focus by world region, water depth, and stratification regime

Of the 8 reviews, 6 had global focus, 1 was centred on the US Northeast coast (Mid-Atlantic Bight), and 1 look at the North and Baltic Seas. Of the original research papers, only one took a global perspective. The majority of research was performed in different parts of the North Sea with the German Bight standing out as the subject of over a quarter of all papers (Fig. 2). More recently, Chinese Seas became more prominent.

Almost all papers investigated bottom-mounted offshore wind turbines or farms in shallow shelf seas. Combined with the large percentage of papers focusing on the southern North Sea and German Bight, the depth ranges included in the studies was therefore very limited with over half of them addressing turbines in the depth range 21–40 m (Fig. 2). Only one study looked into a deep ocean region (800–2000 m; Raghukumar et al. 2023), although it was unclear from the paper at which depths (floating) turbines would be mounted. Some of the analytical or idealized numerical model papers employed theories that assume infinite ocean depths, whereas a large number of other idealized model papers did not specify a depth range at all. Very shallow depths were investigated in estuarine regions such as the Yangtze or the Pearl River estuaries (Cai et al. 2023, Hong et al. 2024b). Two papers addressed wind turbine

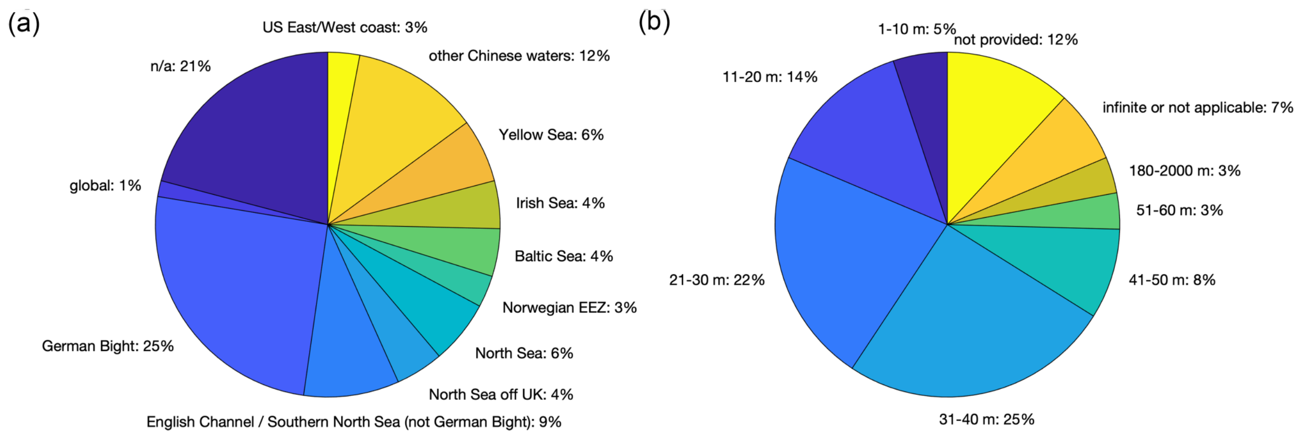


**Figure 2.** (a) Relative proportions of original papers (not including reviews) by geographical focus region and (b) maximum water column/wind turbine depth considered in the paper.

effects off the Norwegian coast at the previously proposed site for wind parks at Havsul and placed the modelled turbines in up to 30 m deep waters (Ponce De León et al. 2011, Segtnan and Christakos 2015).

Both geographic regions and depth ranges considered in the literature so far are severely limited. Particularly deeper shelf regions lack investigations; that includes the northern part of the North Sea but also other European shelf regions (e.g. the Atlantic shelf, the Mediterranean Sea), and deeper shelf regions globally. Examples of potential environmental impact assessments exist for some of these regions (e.g. Lloret et al. 2022, 2023, Dalsin et al. 2025, Wawrzynkowski et al. 2025); they need to be extended geographically and followed up by dedicated modelling and observational studies.

The geographic focus on shallow shelf regions is reflected in the stratification regimes considered in the literature with the majority of studies conducted in seasonally stratified waters like the German Bight (Table 2). Unstratified conditions are often encountered in the shallowest parts of the shelf or in estuaries, but also several idealized or analytical model studies did not consider stratification. The latter were also a large part of the papers that did not specify stratification state in their study; the other part were mainly satellite studies restricted to sea surface signals. Very few papers were placed in permanently stratified waters; these included studies looking into impacts on the deep, saline inflow to the Baltic Sea (Lass et al. 2008, Rennau et al. 2012), or impacts on upwelling systems (Raghukumar et al. 2023). Otherwise, papers explicitly stated that their models were set up with layered flow/stratified water column (e.g. Broström 2008, Bakhoday-Paskyabi 2015, Schultze et al. 2020) or observations were collected during summer stratified conditions (e.g. Floeter et al. 2022).

### Data sources and parameters addressed in the literature

The data sources used in the papers demonstrated the need for more *in situ* observations from both within and around offshore wind parks. Less than 20% of the papers were based solely on *in situ* observations, whereas more than half relied exclusively on numerical or analytical models and a further 10 papers combined models with *in situ* observations and/or satellite data (Table 2). Clearly, access to the wind farm areas is difficult to obtain but crucial for validation and evaluation of model performances and results. Satellite-based studies provide information of the sea surface state but need to be combined with models or *in situ* observations for further insight into water column processes.

Main drivers of potential effects and impacts by offshore wind turbines and farms are i) the structure of the turbines, and ii) the impact on the wind field both within the farm and downwind (wind wake). Especially in shallow shelf seas, tidal flow can be a third driver through its interaction with the turbine structures but is also affected both by the structures and the wind field changes (e.g. Cazenave et al. 2016, Ivanov et al. 2021, Christiansen et al. 2022, Austin et al. 2025). Many of the idealized or analytical modelling studies focused on structural effects, e.g. by investigating vortex generation or turbulence behind monopiles (e.g. Grashorn and Stanev 2016, Bailey et al. 2024, Pang et al. 2024), but in general both structure and wind wake-generated effects are fairly evenly covered (Table 2).

Table 2 shows the distribution of papers by parameters included in the analyses of effects and impacts. Prominent topics were stratification and water mass properties, turbulence and mixing, waves, and up- and downwelling. On the other hand, very few studies investigated impacts on nutrients (distribution, transport, flux) or phytoplankton and primary production, as already indicated by Table 1. Vertical flux was mostly included when discussing vertical water motion connected to turbulence and/or up- and downwelling. The gap becomes even more pronounced for stratified conditions and observational studies.

## Offshore wind farm effects and impacts on physical oceanography, particle load, nutrient supply, and phytoplankton

### Impact on mixing and stratification

It is well established that piles such as bridge piles or wind turbine foundations induce turbulence and mixing in a flow past these obstacles. Lass et al. (2008) demonstrated the emergence of eddies and von Kármán vortex streets and the subsequent change in salinity due to upward mixing of saline bottom waters and reduction of stratification in a stratified flow past a bridge pile at the entrance to the Baltic Sea. Just downstream, Rennau et al. (2012) modelled the potential impact of wind farm monopiles on dense bottom inflows into the Baltic Sea. They found a minor reduction of bottom water salinities un-

**Table 2.** Number of original papers addressing different drivers and affected parameters.

| | Driver | | Driver/affected parameter | Affected parameter | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Turbine structure | Wind wake | Tidal current | Turbulence/mixing | Waves | Water mass properties | Stratifi-cation | Up-/down-welling | Vertical flux | Nutrients | Resuspension/suspended particle load | Phyto-plankton |
| Overall (#60) | 42 | 30 | 31 | 17 | 18 | 17 | 22 | 17 | 10 | 4 | 15 | 10 |
| **By stratification** | | | | | | | | | | | | |
| stratified (#10) | 5 | 7 | 4 | 4 | 2 | 7 | 8 | 5 | 2 | 1 | 0 | 0 |
| seasonally stratified (#19) | 12 | 12 | 14 | 8 | 2 | 9 | 14 | 9 | 7 | 2 | 4 | 4 |
| unstratified (#9) | 7 | 3 | 4 | 4 | 4 | 0 | 0 | 0 | 0 | 1 | 6 | 3 |
| any (#3) | 1 | 2 | 0 | 1 | 0 | 1 | 0 | 2 | 0 | 0 | 1 | 1 |
| not specified (#19) | 17 | 6 | 9 | 0 | 10 | 0 | 0 | 1 | 1 | 0 | 4 | 2 |
| **By data source** | | | | | | | | | | | | |
| observations (#10) | 9 | 6 | 8 | 5 | 3 | 3 | 3 | 2 | 1 | 1 | 2 | 3 |
| model (#34) | 20 | 17 | 15 | 9 | 11 | 11 | 15 | 13 | 8 | 2 | 6 | 4 |
| model & observations (#6) | 5 | 3 | 4 | 2 | 1 | 2 | 4 | 1 | 0 | 1 | 1 | 1 |
| satellite (#4) | 3 | 2 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 3 | 1 |
| satellite & model or observations (#3) | 3 | 1 | 3 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 2 | 1 |
| observations, model and satellite (#1) | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| lab (#2) | 1 | 1 | 0 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

The total number of papers assigned per category is given in brackets.

der realistic offshore wind farm development scenarios that was within the ranges of natural variability, but cautioned that extensive development of the Western Baltic Sea could significantly alter bottom water properties with potential impact on ventilation of the Baltic proper.

Observations along transects through non-operative wind farms in the German Bight confirmed reduced stratification and a doming of the thermocline within the farms (Floeter et al. 2017). Schultze et al. (2020), also in the German Bight, were able to identify disturbance of the background temperature structure in weak temperature stratification due to a monopile wake using a Conductivity–Temperature–Depth sensor chain and time series data from a nearby fixed platform. Stratification was reduced by 35% at 250 m downstream but seemed to reestablish at 500 m. They suggested that with strong stratification, the signal would be within the natural variability. From large eddy simulations of different stratification scenarios, they estimated that offshore wind farms would need to be of the order of magnitude ∼100 km to prevent formation of stratification. Turbulence and mixing were focused on a narrow region downstream of the wind farm and background conditions were dominated by natural turbulence and mixing. Austin et al. (2025) used high frequency current and turbulence measurements in the tidal wake of a monopile in the Irish Sea to show the impact of friction with the sea floor on the velocity structure in the water column and the impact on turbulence and mixing. They suggested potential implications for formation/breakdown and strength of stratification and seabed mobility.

In shallow shelf seas, turbulence and mixing due to flow past wind turbine structures are often driven by tides. Carpenter et al. (2016) combined idealized modelling with observations to assess the importance of the tide-driven mixing on (seasonal) stratification in the German Bight. They found that the time scale of the breakdown of stratification by mixing was comparable to the summer stratification period, indicating potential impacts for the development of stratification in early summer. At current capacity in the German Bight region of the North Sea (as of November 2015), wind farm-induced mixing levels are low. With future scenarios where large parts of the German Bight would be filled with wind farms, this would change though leading to potentially signification reductions in stratification. Cazenave et al. (2016) found similar effects using an unstructured-grid numerical model for the Irish Sea and English Channel region where tidal flow past monopiles increases vertical mixing; in particular, this mixing leads to upward water movement downstream of the monopile and downward movement upstream. The subsequent decrease in stratification is noticeable in the far-field, coverage an area of ∼250 km$^2$ where unstratified regions do not show changes, but stratified regions are significantly affected. They, too, suggested potentially large impacts with future wind farm developments, and effects on nutrient distribution and ecosystems. Christiansen et al. (2023) tested different implementation methods and parameterizations to model the impact of turbine structures on currents, mixing, and stratification in the German Bight. They found different signals in deep vs shallow waters which were related to vertical density gradients and mixing rates in the water column. The monopile induced turbulence led to more vertically diffused density and horizontal velocity, causing positive anomalies in areas with strong vertical gradients and negative anomalies elsewhere. In shallow regions with stronger tidal flow, tides induced greater turbulence and dominated over wind-driven effects at offshore wind farm sites. Despite turbulent mixing being mostly local, temperature stratification weakened or even collapsed over larger spatial scales.

At the surface of the ocean, atmosphere-ocean interaction impacts sea surface temperature. Atmospheric mixing is influenced by offshore wind farms and might therefore alter heat exchange at the ocean-atmosphere boundary. Wang and Prinn (2011) suggested that offshore wind farms lead to surface air temperature cooling due to enhanced latent heat flux from the sea surface to the lower atmosphere driven by increased turbulent mixing from the wind turbines; this could indicate a decrease in sea surface temperatures. However, Deng et al. (2024), investigating atmosphere-ocean dynamics in the South China Sea connected with tropical cyclone development, found that the wind farm induced wind wake caused an increase in sea surface temperature through increased latent heat flux from the atmosphere to the ocean and reduced advection of colder surface waters into the region, thereby contributing to intensification of a tropical cyclone. These seemingly contradictory findings demonstrate the importance of regional and seasonal conditions and processes in altering the direction of impacts.

## Impacts on horizontal circulation (including tides)

Interaction of currents with offshore wind farm structures can lead to reduction of current speed. Christiansen et al. (2023)'s model experiments of the impact of turbine structures resulted in a reduction of depth-average current speeds within offshore wind farms and downstream, affecting the entire German Bight area. The changes were minor compared to the average tidal current speeds but accounted for ~10% of the mean current, comparable to the change to due wind wake effects (Christiansen et al. 2022a; 2022b). Carpenter and Guha (2024) derived similar reduction in an idealized model study investigating the blocking effect of offshore wind farms on the mean current and effect of different methods to implement friction by the turbines. There was large variability in current speed reductions depending on density and geometry of the turbines in the individual wind farms, where some configurations led to negligible effects. Observations of currents and turbulence near an offshore wind farm in the German Bight showed only weak signals in the currents but a stronger response in mixing and turbulence (Bakhoday-Paskyabi et al. 2018). This is similar to a model study by Hosseini et al. (2025) who used an unstructured-grid hydrodynamic model coupled to a wave model for the German Bight. They found a 5% reduction of monthly mean current speed (and significant wave height) by interaction with turbine foundations in weakly stratified spring conditions. Additionally, the wind wake led to an increase of turbulent kinetic energy and subsequently stratification close to the monopiles. Interestingly though, their model results showed a different pattern on regional scales where current speed and stratification slightly increased outside of the wind farm. Changes in current speed affect circulation and transport of material, including planktonic organisms. Chen et al. (2024) investigated transport and dispersal of scallop larvae on the US northeast shelf and suggested that monopiles generated a net offshore mesoscale flow around turbines which could enhance offshore transport of the larvae. Stratification played a major role in the flow modification.

## Impact on up- and downwelling

Several studies demonstrated how offshore wind farms alter the local and regional wind field based on airborne (e.g. Platis et al. 2018) and satellite measurements (e.g. Christiansen and Hasager 2005) and modelling (e.g. Akhtar et al. 2021), and described and quantified the wind speed reduction within and downwind of wind farms in so-called wind wakes. In their seminal paper, Broström (2008) provided analytical and idealized model results for the oceanic response to an offshore wind farm-generated wind wake. They found that wind speeds of 5–10 m $s^{-1}$ with sufficient reduction in the wake may generate up- and downwelling in a dipole pattern due to Ekman transport resulting in sea surface divergence and convergence in the wind wake. However, this requires the width of the wind wake to be at least the internal Rossby radius of deformation. The induced vertical movement was in the order 1 m $day^{-1}$, dependent on wind strength and farm size, and they suggested potential measurable effects on oceanic circulation and thus transport of nutrients. Further, they noted that their models did not include effects of interactions with the seafloor and a sloping bathymetry, where wind farms may provide additional forcing to a barotropic current system. Several modelling studies confirmed and extended Broström (2008)'s results, also demonstrating how the wind wake induced upwelling can affect coastal upwelling and stratification (e.g. Bakhoday-Paskyabi and Fer 2012, Bakhoday-Paskyabi 2015, Christiansen et al. 2022, Liu et al. 2023).

Modelling wind farm impacts in the German Bight, Ludewig (2015) found that winds needed to consistently blow from a constant direction with moderate speeds (5–10 m $s^{-1}$) for at least 8–10 h to induce an up-/downwelling dipole in the ocean; but then these up-/downwelling cells could span over approximately 30×30 km and vertical velocities reached up to 3–4 m $day^{-1}$, leading to significant excursions of the thermocline by up to 10 m and intensified vertical mixing. Christiansen et al. (2022a) applied an explicit wind wake formulation for the atmospheric forcing field to an unstructured-grid hydrodynamic model of the southern North Sea to investigate wind wake effects from all commissioned wind farms on summer stratified conditions. Results included a 5% reduction in surface ocean current speeds, which corresponded to up to 10%–25% of the interannual and decadal variability, reduced mixing rates leading to shallower mixed layer depths, counteracting the mixing effect from the turbine structures though at different spatial scales, and dipoles in sea surface elevation impacting up- and downwelling on scales that were comparable to climate change impacts. Although effects were difficult to distinguish from natural and interannual variability, structural changes in stratification following up-/downwelling and advective processes due to extensive offshore wind farm development might impact nutrient transport pathways and ecosystems. Tides could have potential to attenuate wind wake effects, depending on the alignment of the tidal ellipse with background currents and wind forcing (Christiansen et al. 2022b). The large natural variability especially in highly dynamic, tidally influenced systems, make detection of signals in observations often difficult. Nevertheless, Floeter et al. (2022) could identify up- and downwelling effect on the pycnocline in observations at two wind farms in the German Bight by contrasting operational and non-operational periods. They reported vertical excursion of the thermocline and changes in stratification connected to wind wakes and impacted by tides; however, they also cautioned that further assessment was required to confidently distinguish this signal from natural variability.

In a study located off the Norwegian coast, Segtnan and Christakos (2015) investigated the effect of wind wakes in a region with sloping bathymetry and dominated by a geostrophic coastal current. They found a reduction in the horizontal flow and a change vertical velocity which was not purely Ekman driven, confirming the suggestions by Broström (2008) and Bakhoday-Paskyabi and Fer (2012). In the shallow parts of their model, the surface Ekman layer reached to the sea floor, vertical mixing resulted in a barotropic ocean, and they suggested that the Coriolis effect should be insignificant for the horizontal scales under consideration, which would prevent formation of dipoles as in Broström (2008). In a different coastal setting with steep bathymetry off the coast of California, Raghukumar et al. (2023) modelled the effects of offshore wind farms of the size corresponding to the local Rossby radius and the scale at which coastal and wind stress curl-driven upwelling occurs in the region. The wind farms were simulated in much deeper waters than other studies, following the proposed establishment of floating farms in water depths of 800–2000 m. Their results indicated modest reduction in coastal upwelling inshore of the wind farms vs enhanced upwelling on the offshore side due to Ekman pumping. These changes in cross-shore upwelling structure exceeded natural variability and could affect water column properties and nutrient fluxes relevant for the local ecosystem.

## Impact on waves

Ocean surface waves are impacted by offshore wind farms through both interaction with the structures and changes in the wind field; reduction of significant wave height and wave energy within and downstream of offshore wind farms, with visible effects as far as 55 km, has been directly observed in the German Bight using airborne LiDAR measurements (Bärfuss et al. 2021). Using a tank set up in a laboratory, Miles et al. (2017) showed a reduction in wave height down-wave of a monopile due to interaction with the structure; at the same time, wave height increased immediately up-wave of the pile. Several studies used the SWAN (Simulating Waves Nearshore; Booij et al. 1999) model to investigate the wave field around offshore wind farms or include their effect on other parameters. Almost all studies were focused on the sea surface and did not account for potential stratification. Ponce De León et al. (2011) found a similar reduction down-wave and slight increase up-wave of a monopile as the laboratory results. They found that directionality of the incoming wave spectrum as well as diffraction and reflection influenced the reduction of wave height and wave energy, such that groups of monopiles like in offshore wind farms could lead to a blocking of wave energy propagation. Another factor to consider might be the type of turbine structure used: While most modelling studies investigated the effect of monopiles, Wang et al. (2021) used jacket-type foundations and found rather localized effects on waves (within and area of 4–5 times the diameter of the foundation structure) and currents (about 8 times the pile diameter). Van Der Molen et al. (2014) demonstrated that farm spacing and size (i.e. number of farms and area covered by them) determined the magnitude of the reduction in significant wave height; in all simulations, the largest reductions occurred within the farms though with limited far-field effects. Additional background wind field changes had minor effects but could attenuate the reduction in significant wave height. Christensen et al. (2013) conducted a parameter study of the relative importance of drag resistance due to the turbine structures, reflection and diffraction, and the change in the wind field for the wave conditions inside, around and downwind of an offshore wind farm. They suggested that drag resistance was small and thus negligible compared to the other effects; instead, reflection and diffraction by structures might have contributed a third and reduced wind shear due to the wind field change caused two thirds of the local reduction of wave height, whereas further downwind, reduced wind shear is the major driver. Maximum reduction of wave height was approximately 5% leading to a wave energy reduction of 10%; this is consistent with other studies. Christensen et al. (2013) explicitly cautioned though that their results apply to the wind farm size investigated in their study which was modelled after Horns Rev I off Denmark in the North Sea, approx. 5 × 5 km in size. Most studies focused on structure- or wind-driven changes of the wave field. Fischereit et al. (2022) found through coupled atmosphere-wave modelling that the wave-induced surface roughness contributed to a larger wind speed deficit within wind farms due to enhanced turbulent mixing, which, however, also led to a feaster breakdown and thus smaller area of the wind wake behind the farm. Larsén et al. (2024) had contradicting results and cautioned that better understanding of the atmosphere-wave-wake interactions are needed to ensure correct representation and parameterization in models.

## Impact on nutrient distribution and phytoplankton

As indicated in Table 2, studies directly addressing nutrients and phytoplankton or primary production are limited. We could identify only one study that sampled nutrients and chlorophyll *a* concentrations at an operational wind farm (Floeter et al. 2017) and one sampling chlorophyll a and phytoplankton abundance and community composition (Hong et al. 2024b). Floeter et al. (2017) conducted a summer survey in the German Bight, i.e. surface nutrient depleted conditions. They found slightly elevated silicate and phosphate concentrations within the wind farm, likely due to the enhanced vertical mixing by the foundations (see above) leading to reduced stratification and doming of the thermocline. Concurrent chlorophyll *a* samples did not show conclusive patterns and instead demonstrated large patchiness and variability. Hong et al. (2024b) analysed year-long observations of water quality indicators, including temperature, salinity, pH, transparency, dissolved oxygen, chlorophyll *a* concentration phytoplankton abundance and composition, from the Pearl River estuary in the South China Sea, a tidal system strongly influenced by freshwater runoff, monsoon seasonality and occurrence of tropical cyclones. They found a reduction in chlorophyll *a* concentrations within wind farms and compared to pre-construction levels; however, chlorophyll *a* concentrations were low in the wind farm region compared to outside the farm also before construction. They suggested that this is due to a natural barrier effect by small islands surrounding the regions and restricting circulation in the area; this effect was enhanced by the wind farms.

Floeter et al. (2022) and Plonus and Floeter (2024) suggested that offshore wind farm induced turbulence, vortices, up- and downwelling could affect primary production and generate phytoplankton patchiness. However, effects are complex due to the interaction with physical conditions influencing nutrient availability, sediment load impacting light levels, and uncertain impacts of wind farms on grazers (zooplankton) and thus unknown top-down controls on phytoplankton. Van Der Molen et al. (2014) employed a biogeochemical model to the southern North Sea with wind farms off the English coast. They found an increase in net primary production following reductions in suspended sediment concentrations and light extinction and resulting in reduced nutrient concentrations, increased secondary production and increased vertical export of organic matter to the seafloor. Øijorden (2016) with a similar model setup, also for the North Sea, found only slight changes in absolute production but changes in spatial distribution that were tied to stratification strength and mixed layer depth. Using an Ecopath model for the coastal Yellow Sea, Wang et al. (2019) also described increased primary production, but additionally found significant changes in trophic flow and ecosystem structure, highlighting the wider implications of potential changes at the base of the food web. Daewel et al. (2022) modelled a scenario with offshore wind farm capacity in the North Sea corresponding to anticipated levels reached in 2037. They suggested that while wind wake effects provoked local changes of ± 10% in annual primary production around wind farms and reduced dissolved oxygen levels in some regions, region-wide averages of primary production remained almost unchanged. However, changes in spatial patterns of primary productivity due to alterations or the large-scale circulation and nutrient supply from below might impact trophic interactions, and combined with changes in resuspension of sediment affect organic carbon export, lead to an increase in organic carbon in sediments in large parts of the southern North Sea and reduced bottom water oxygen concentrations in some trough regions.

### Impact on suspended particulate matter in the water column and resuspension

While a significant number of studies were conducted to investigate scour around wind turbine foundations due to the impact on structural stability and integrity, the body of literature considering sediment or suspended particulate matter in the water column is limited. Surface signatures or sediment load in the wake of offshore wind farms can be seen from satellite which has been utilized in several papers. Vanhellemont and Ruddick (2014) for example used Landsat 8 images of wind farm areas outside the Thames estuary and compared brightness spectra of wind farm wakes with those caused by ships. They found that the monopiles caused turbid wakes which were aligned with the tidal current. In the wakes, suspended sediment concentrations were significantly higher, and the wakes extended to about 30–150 in width and 1–10 km in length, depending on the time-integrated current since the last tidal reversal and the particle settling velocity. Due to the wake sizes, Vanhellemont and Ruddick (2014) suggested that there might be potential for persistent changes as well as implications for the underwater light field which could impact primary production and visual predation, and for sedimentation patterns. Bailey et al. (2024) combined satellite time series with *in situ* observations from the same site and demonstrated that suspended material was concentrated in the upper water column (surface and upper 10 m) in the wake but overall sediment load was not elevated. They suggested that the circulation patterns around the monopiles led to redistribution of material towards the surface instead of additional erosion from the seabed around the foundations. This was similar to findings by Cai et al. (2023) in the Yangtze estuary, but contrasted with results of an earlier study in the southern North Sea off the coast of Belgium where Baeye and Fettweis (2015) reported increased suspended particulate matter load stemming from the turbine foundations. Bailey et al. (2024) suggested that this is caused by difference in the sediment and current characteristics at the two sites. They also indicated that inter- and intraannual variability in sediment load in the wakes is consistent with variability outside of farm-influenced waters and concentrations during the operational phase had recovered to within the ranges of pre-construction observations. Brandao et al. (2023) had similar results with high natural variability in sediment load and complex environmental drivers leading to only few satellite scenes capturing wind farm-related sediment plumes off the Dutch coast, which also is consistent with variable detection of satellite-measured chlorophyll *a* signals in wind wakes by Yu et al. (2024). As suggested by Bailey et al. (2024), modelling studies also show patchiness in the distribution and deposition of sediment due to von Kármán vortices and submesoscale eddies (e.g. Ivanov et al. 2021). There have been several indications that sediment load over time is affected by filter feeders settling on the turbine structures, effectively altering water quality, carbon flux and nutrient distribution (e.g. Baeye and Fettweis 2015, Ivanov et al. 2021, Brandao et al. 2023) in addition to affecting primary production (Slavik et al. 2019). However, Huang (2022) found that turbid wakes caused by offshore wind farms in the eastern Taiwan Strait and extended to over 4 km likely contributed to a drastic decrease in sightings of humpback dolphins compared to pre-construction numbers, severely altering the dolphins' habitat. Ivanov et al. (2021) stressed the importance of positioning over farm size for the potential extent of sediment plumes and impacts on valuable habitats and biodiversity hotspots.

## Discussion and conclusions

### Physical impacts and ecological consequences in different environmental scenarios

The above presented current knowledge of potential impacts of offshore wind farms on the physical environment highlights the broad spectrum of effects in different settings but is also severely limited by the low diversity of the environments studied (Fig. 2). In Table 3, we present a summary of the main environmental conditions covered in the literature and the suggested impacts on the above reviewed parameters. While an increase of turbulence/mixing and vertical currents, a weakening of horizontal (surface) currents and a general decrease or delay in stratification are fairly well documented across different environments including various depth ranges, stratification states and tidal regimes, this detailed understanding is missing for the other parameters. Particularly deep regions, including coastal upwelling systems are understudied. Comparative modelling studies could help addressing some of the knowledge gaps by contrasting environmental scenarios.

**Table 3.** Summary of effects on oceanographic parameters across different environmental characteristics.

| Environmental conditions | | Affected parameter | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Turbulence/ mixing | Stratifi- cation | Horizontal currents | Vertical currents | Coastal upwelling | Wave height | Nutrient distribution | Phyto-plankton distribution | Primary production | Sediment load |
| | Shallow | ⇑ | ↓ | ↓ | ⇑ | x | ↓ | ↻↑↓ | ↻ | ↑? | ↻? |
| | Deep | ⇑ | x | x | ↑ | ↑↓ | x | x | x | x | x |
| | Stratified | ⇑↓? | ↓↑? | ↓? | ↑ | ? | x | ↑? | ↻↓? | ↑↓? | ? |
| | Un- stratified | ⇑ | −↓ | ? | ↑ | x | ↓ | ? | ? | ? | ? |
| | Tidal | ⇑ | ⇩ | ↓ | ? | x | ? | ? | ? | ? | ↻? |
| | Non-tidal | ↑ | ? | ↓ | ↑ | ? | ? | x | x | x | x |
| | Coastal upwelling | x | ↑↓ | ? | ↑↓ | ↑↓ | x | ? | x | x | x |
| | Nutrient poor | n/a | n/a | n/a | n/a | n/a | n/a | ↑? | ↻? | ↑↓? | x |
| | Nutrient rich | | | | | | | x | x | x | x |

⇑/⇓: clear increase/decrease
↑/↓: minor increase/decrease
↻: horizontal or vertical redistribution
?: unclear results
x: no results

Changes in physical parameters due to offshore wind farms will have ecological impacts on multiple levels. Altered stratification state or delay in stratification onset combined with increased mixing and vertical flux modify nutrient distribution, availability, and timing of nutrient replenishment in a depleted surface layer, thus impacting primary production (e.g. Øijorden 2016, Floeter et al. 2017, Plonus and Floeter 2024). Weakened or modified horizontal circulation affects transport, retention and thus distribution of dissolved and suspended material and planktonic organisms (e.g. Daewel et al. 2022, Bailey et al. 2024, Chen et al. 2024, Hong et al. 2024). Redistribution of sediments in the water column due to turbulence and mixing, and changes in circulation can impact a large range or organisms from primary producers to benthic filter feeders and marine mammals (e.g. Baeye and Fettweis 2015, Slavik et al. 2019, Huang 2022). Shifts in location and strength of coastal upwelling systems have potential to negatively affect primary and secondary productivity which could have far-reaching economic consequences (Raghukumar et al. 2023). While currently many of the effects on lower trophic levels seem to consist of a redistribution of organisms rather than a significant increase or decrease of biomass and/or productivity, detailed scenario studies for example regarding the effect of different bottom structure and substrate (e.g. hard- vs soft-bottom, gravel vs sand or mud) or background nutrient concentrations combined with hydrographic conditions are needed to assess the impacts especially on phytoplankton and primary production.

## Key knowledge gaps and recommendations for research

The existing literature provides a fairly good, consistent overview of effects of bottom-mounted offshore wind farms on physical conditions including stratification and hydrodynamics in shallow, unstratified or seasonally stratified shelf seas. Farr et al. (2021) concluded that impacts would likely be minor to moderate. However, Van Berkel et al. (2020) cautioned that a significant knowledge gap remains regarding regional effects and the identification of relevant spatial (and temporal) scales. The discussion in Miles et al. (2021) about potential effects on the northern US East coast highlights the lack of specific studies for regions relevant for offshore wind industry development outside the shallow northern European and Chinese shelf seas and the lack of information about the impact of regional conditions such as the Mid-Atlantic Cool Pool (Miles et al. 2021), the California coastal upwelling system (Raghukumar et al. 2023), or deeper shelf seas in general including the Norwegian shelf. Implications of different stratification regimes in deeper, not as much tidally influenced regions, sloping topography and topographically steered background currents, changes in latitude affecting the local Rossby radius, baroclinic vs barotropic conditions need to be explored.

A multitude of studies exists regarding the classic fluid dynamics problem of flow past an obstacle. Nevertheless, modelling monopiles in hydrodynamic models is challenging due to the scales required to resolve the interaction of the flow field with the pile, the turbulence, but also far-field effects. Studies such as Pang et al. (2024) nesting a computational fluid dynamics model in general ocean circulation models are highly interesting, but require validation against suitable observational data, which also is difficult to obtain. There is a

**Table 4.** Suggested topics and approaches to fill key knowledge gaps.

| Topic | Environmental setting | Methodological approach | Priority |
|---|---|---|---|
| Reduction/delayed onset of stratification | Shallow shelf, stratified/unstratified, varying tidal regimes | Observations (local to large-scale) | High |
| | | Modelling (local to large scale) | Medium |
| | Deep shelf (depth >60 m), potentially complex topography | Observations (local & regional) | High |
| | | Modelling (local to large-scale | High |
| | Continental slope and deep sea | Modelling (local to large-scale) | High |
| Effects of infrastructure design on turbulence, mixing and vertical flux | Shallow shelf, stratified/unstratified | Observations (process-scale) | High |
| | | Observations (local to large-scale) | High |
| | | Modelling (process-scale) | Medium* |
| | | Modelling (local to regional scale) | Low |
| | | Modelling (large-scale) | High |
| | Deep shelf, potentially complex topography | Observations (local to regional scale) | High |
| | | Modelling (process- to large-scale) | High |
| | Continental slope and deep sea | Modelling | Medium |
| Modification of horizontal circulation | Shallow shelf, stratified/unstratified, varying tidal regimes | Observations | High |
| | | Modelling (local to large-scale) | Medium |
| | Deep shelf, continental slope | Modelling (local to large-scale) | Medium |
| Shifts and strength of coastal upwelling systems | Deep shelf, continental slope | Modelling (local to large-scale) | Medium |
| Nutrient availability | Shallow shelf, stratified/unstratified | Observations (local to large-scale, throughout seasonal cycle) | High |
| | | Modelling (local to large-scale) | High |
| | Deep shelf, continental slope | Observations (local to large-scale, throughout seasonal cycle) | High |
| | | Modelling (local to large-scale) | High |
| Changes in phytoplankton abundance/biomass and primary productivity levels | Shallow shelf, stratified/unstratified, varying tidal regimes | Remotely sensed and *in situ* observations (local to large-scale) | Very high |
| | | Modelling (local to large-scale) | High |
| | Deep shelf, continental slope | Remotely sensed and *in situ* observations (local to large-scale) | Very high |
| | | Modelling (local to large-scale) | High |
| Impact of suspended particle load on light regime | Highly productive shallow shelf/coastal regions, stratified/unstratified, tidal/non-tidal | In situ observations (varying seafloor substrate, varying vicinity to river input, entire water column) | High |
| | | Modelling (local to regional scale) | Medium |
| Biogeochemical conditions (e.g. dissolved oxygen concentration, organic matter, carbon export) | Shallow shelf, stratified/unstratified, varying tidal regimes | Observations (local to large-scale, entire seasonal cycle) | High |
| | | Modelling (local to large-scale) | High |
| | Deep shelf | Observations (local to large-scale, entire seasonal cycle) | High |
| | | Modelling (local to large-scale) | High |

* High for floating turbines

critical need for more comprehensive observational datasets of ocean dynamics (currents, turbulence) and hydrography (vertical temperature and salinity profiles and horizontal coverage) from both close to the turbines, within the wind farms, and in the surrounding areas, covering different time periods, stratification states, and seasons over several years to properly assess the impact of wind farm related signals against natural variability.

The need for measurements and observations is even more dire for biogeochemical parameters and lower trophics (phytoplankton but also zooplankton). This review demonstrated the lack of observations and modelling studies, which strongly impacts our ability to assess consequences of changes in hydrography and circulation on nutrient distribution and availability, primary production and subsequent effects on marine ecosystems (Tweddle et al. 2018). This also applies to impacts on the role of marine ecosystems for carbon sequestration, especially in highly productive shelf regions, as understanding of potential changes of vertical flux and pelagic-benthic coupling due to turbine induced turbulence, changes in stratification or wind wake effects is severely restricted and basically not existent for deeper shelf regions. Reviews such as Farr et al. (2021), Rezaei et al. (2023), Danovaro et al. (2024), and Watson et al. (2024) demonstrate how primary producers, zooplankton and microbial activity so far have been neglected in most ecosystem impact assessments. A greater focus needs to be put on the connection between physical conditions and productivity at the base of the food web and the potential bottom-up impacts on the higher trophic levels including fish, marine mammals and seabirds. As offshore wind farm development extends into new regions covering larger areas, impact assessments have to take into account the variety of ecosystems and their functioning beyond temperate, mid-latitude shelf systems.

Table 4 provides an overview of suggested topics to address key knowledge gaps across different environmental settings. Scores of low or medium priority are based on the availability of relevant literature (see also Table 2) and consensus therein, or lower urgency. The need for (especially *in situ*) observations is high across all topics, but particularly so for biogeochemical parameters and lower trophics. The projected development of large-scale areal coverage of shelf seas with wind farms also urgently requires an integrated investigation and assessment of expected large-scale modifications of the physical system and the consequences on biogeochemistry and lower trophics.

### Future developments and impacts by floating offshore wind farms

As highlighted above, dedicated studies into the impact of floating offshore wind farms on the physical environment are currently lacking. The rapid development of the sector, however, requires robust knowledge for sustainable management. The priorities listed in Table 4 are valid across different types of offshore wind farms, with the exception of the effects of infrastructure design which has high priority for floating infrastructure: Interaction of currents with fixed-bottom structures such as monopiles, tripods or similar differ potentially significantly from those with structures extending only partially into the water column or moving elements like chains and cables. Austin et al. (2025) highlighted that the currently most wide-spread practice of simulating the effect of turbine structures by approximating them as cylindric monopiles implies a barotropic response. Floating structures, however, might cause baroclinic effects. Additionally, different designs of floating turbines (e.g. Hong et al. 2024a) will lead to different responses to ocean currents and tides depending on how deep they reach, their diameter, shape and drag. As these floating structures will be deployed in deeper, typically stratified shelf regions, impacts on stratification, vertical flux, e.g. of nutrients or organic matter, and retention in the surface mixed layer will vary depending on mixed layer depth and penetration depth of the structure.

Advancing offshore wind farms on greater scales into deeper regions also has the potential for far-reaching effects. Highly advective environments, strong and often topographically steered currents, and less compensatory effects of weaker tidal currents could promote fast transmission and or spreading of changes in physical and biogeochemical conditions. Disturbances caused by offshore wind farms might lead to generation and propagation of internal waves which could accelerate far-field impacts. Modelling studies prior to large-scale development and observational process- and long-term monitoring studies of effects from local to large-scale are crucial to avoid long-term negative impacts.

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## Data availability

The data underlying this article are incorporated in the article.

## References

Akhtar N, Geyer B, Rockel B, *et al.* Accelerating deployment of offshore wind energy alter wind climate and reduce future power generation potentials. *Sci Rep* 2021;**11**:11826. https://doi.org/10.1038/s41598-021-91283-3

Austin M, Unsworth C, Van Landeghem K, *et al.* Enhanced bed shear stress and mixing in the tidal wake of an offshore wind turbine monopile. *Ocean Sci* 2025;**21**:81–91. https://doi.org/10.5194/os-21-81-2025

Baeye M, Fettweis M. In situ observations of suspended particulate matter plumes at an offshore wind farm, southern North Sea. *Geo-Mar Lett*, 2015;**35**:247–55. https://doi.org/10.1007/s00367-015-0404-8

Bailey L, Dorrell R, Kostakis I, *et al.*. Monopile-induced turbulence and sediment redistribution form visible wakes in offshore wind farms. *Front Earth Sci* 2024;**12**:1383726. https://doi.org/10.3389/feart.2024.1383726

Bakhoday-Paskyabi M. Offshore wind farm wake effect on stratification and coastal upwelling. *Energy Procedia* 2015;**80**:131–40. https://doi.org/10.1016/j.egypro.2015.11.415

Bakhoday-Paskyabi M, Fer I. Upper Ocean response to large wind farm effect in the presence of surface gravity waves. *Energy Procedia* 2012;**24**:245–54. https://doi.org/10.1016/j.egypro.2012.06.106

Bakhoday-Paskyabi M, Fer I, Reuder J. Current and turbulence measurements at the FINO1 offshore wind energy site: analysis using 5-beam ADCPs. *Ocean Dyn* 2018;**68**:109–30. https://doi.org/10.1007/s10236-017-1109-5

Bärfuss K, Schulz-Stellenfleth J, Lampert A. The impact of offshore wind farms on sea State demonstrated by airborne LiDAR measurements. *J Mar Sci Eng* 2021;**9**:644. https://doi.org/10.3390/jmse9060644

Booij N, Ris RC, Holthuijsen LH. A third-generation wave model for coastal regions: 1. Model description and validation. *J Geophys Res Oceans* 1999;**104**:7649–66. https://doi.org/10.1029/98JC02622

Brandao ILS, Van Der Molen J, Van Der Wal D. Effects of offshore wind farms on suspended particulate matter derived from satellite remote sensing. *Sci Total Environ* 2023;**866**:161114. https://doi.org/10.1016/j.scitotenv.2022.161114

Broström G. On the influence of large wind farms on the upper ocean circulation. *J Mar Syst* 2008;**74**:585–91. https://doi.org/10.1016/j.jmarsys.2008.05.001

Cai L, Hu Q, Qiu Z, *et al.* Study on the impact of offshore wind farms on surrounding water environment in the Yangtze Estuary based on remote sensing. *Remote Sens* 2023;**15**:5347. https://doi.org/10.3390/rs15225347

Carpenter J, Guha A. Blocking effects on mean ocean currents by offshore wind farm foundations. *Phys Rev Fluids* 2024;**9**:103802. https://doi.org/10.1103/PhysRevFluids.9.103802

Carpenter JR, Merckelbach L, Callies U, *et al.* Potential impacts of offshore wind farms on North Sea stratification. *PLoS One* 2016;**11**:e0160830. https://doi.org/10.1371/journal.pone.0160830

Cazenave P, Torres R, Allen J. Unstructured grid modelling of offshore wind farm impacts on seasonally stratified shelf seas. *Prog Oceanogr* 2016;**145**:25–41. https://doi.org/10.1016/j.pocean.2016.04.004

Chen C, Zhao L, Lin H, *et al.* Potential impacts of offshore wind energy development on physical processes and scallop larval dispersal over the US Northeast shelf. *Prog Oceanogr* 2024;**224**:103263. https://doi.org/10.1016/j.pocean.2024.103263

Christensen ED, Johnson M, Sørensen OR, *et al.* Transmission of wave energy through an offshore wind turbine farm. *Coastal Eng* 2013;**82**:25–46. https://doi.org/10.1016/j.coastaleng.2013.08.004

Christiansen MB, Hasager CB. Wake effects of large offshore wind farms identified from satellite SAR. *Remote Sens Environ* 2005;**98**:251–68. https://doi.org/10.1016/j.rse.2005.07.009

Christiansen N, Carpenter JR, Daewel U, *et al.* The large-scale impact of anthropogenic mixing by offshore wind turbine foundations in the shallow North Sea. *Front Mar Sci* 2023;**10**:1178330. https://doi.org/10.3389/fmars.2023.1178330

Christiansen N, Daewel U, Djath B, *et al.* Emergence of large-scale hydrodynamic structures due to atmospheric offshore wind farm wakes. *Front Mar Sci* 2022;**9**:818501. https://doi.org/10.3389/fmars.2022.818501

Christiansen N, Daewel U, Schrum C. Tidal mitigation of offshore wind wake effects in coastal seas. *Front Mar Sci* 2022;**9**:1006647. https://doi.org/10.3389/fmars.2022.1006647

Daewel U, Akhtar N, Christiansen N, *et al.* Offshore wind farms are projected to impact primary production and bottom water deoxygenation in the North Sea. *Commun Earth Environ* 2022;**3**:292. https://doi.org/10.1038/s43247-022-00625-0

Dalsin M, Walter R, Mazzini P. Offshore wind farms could impact coastal marine heatwaves in eastern boundary upwelling systems. *Estuarine Coastal Shelf Sci* 2025;**313**:109102. https://doi.org/10.1016/j.ecss.2024.109102

Danovaro R, Bianchelli S, Brambilla P, *et al.* Making eco-sustainable floating offshore wind farms: siting, mitigations, and compensations. *Renewable Sustainable Energy Rev* 2024;**197**:114386. https://doi.org/10.1016/j.rser.2024.114386

Deng S, Chen S, Sui Y, *et al.* Intensification of an autumn tropical cyclone by offshore wind farms in the Northern South China Sea. *J Geophys Res Atmos* 2024;**129**:e2024JD041489. https://doi.org/10.1029/2024JD041489

European Commission, Directorate-General for Energy. *Communication from the commission to the European Parliament, the Council, the European economic and social committee and the committee of the regions, Delivering on the EU Offshore Renewable Energy Ambitions* 2023. (Technical Report No. COM(2023) 668, Document 52023DC0688,). European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:741:FIN&qid=1605792629666 (23 March 2025, date last accessed).

Farr H, Ruttenberg B, Walter RK, *et al.* Potential environmental effects of deepwater floating offshore wind energy facilities. *Ocean Coast Manage* 2021;**207**:105611. https://doi.org/10.1016/j.ocecoaman.2021.105611

Fischereit J, Larsen X, Hahmann A. Climatic impacts of wind-wave-wake interactions in offshore wind farms. *Front Energy Res* 2022;**10**:881459. https://doi.org/10.3389/fenrg.2022.881459

Floeter J, Pohlmann T, Harmer A, *et al.* Chasing the offshore wind farm wind-wake-induced upwelling/downwelling dipole. *Front Mar Sci* 2022;**9**:884943. https://doi.org/10.3389/fmars.2022.884943

Floeter J, Van Beusekom JEE, Auch D, *et al.* Pelagic effects of offshore wind farm foundations in the stratified North Sea. *Prog Oceanogr* 2017;**156**:154–73. https://doi.org/10.1016/j.pocean.2017.07.003

Galparsoro I, Menchaca I, Garmendia JM, *et al.* Reviewing the ecological impacts of offshore wind farms. *NPJ Ocean Sustain* 2022;**1**:1. https://doi.org/10.1038/s44183-022-00003-5

Grashorn S, Stanev EV. Kármán vortex and turbulent wake generation by wind park piles. *Ocean Dyn*, 2016;**66**:1543–57. https://doi.org/10.1007/s10236-016-0995-2

Hong S, McMorland J, Zhang H, *et al.* Floating offshore wind farm installation, challenges and opportunities: a comprehensive survey. *Ocean Eng* 2024;**304**:117793. https://doi.org/10.1016/j.oceaneng.2024.117793

Hong Y, Liu Z, Li S, *et al.* Benign water quality and phytoplankton status during the operation of Guishan offshore wind farm in the Pearl River Estuary, China. *Region Stud Mar Sci* 2024;**77** :103637. https://doi.org/10.1016/j.rsma.2024.103637

Hosseini S, Pein J, Staneva J, *et al.* Impact of offshore wind farm monopiles on hydrodynamics interacting with wind-driven waves. *Ocean Modell* 2025;**195**:102521. https://doi.org/10.1016/j.ocemod.2025.102521

Huang S. Unstated impacts of the green energy industry on the habitat of a coastal delphinid: turbid-turbulent wakes induced by offshore wind turbine foundations. *Aquatic Conserv Mar Freshw Ecosyst* 2022;**32**:1787–96. https://doi.org/10.1002/aqc.3888

ICES. *Workshop to Compile Evidence on the Impacts of Offshore Renewable Energy on Fisheries and Marine Ecosystems (WKCOMPORE)* . ICES Scientific Reports [PDF]. 2025;7:283. https://doi.org/10.17895/ICES.PUB.28759259

Ivanov E, Capet A, De Borger E, *et al.* Offshore wind farm footprint on organic and mineral particle flux to the bottom. *Front Mar Sci* 2021;**8**:631799. https://doi.org/10.3389/fmars.2021.631799

Jacobsen A, Godvik M. Influence of wakes and atmospheric stability on the floater responses of the Hywind Scotland wind turbines. *Wind Energy*, 2021;**24**:149–61. https://doi.org/10.1002/we.2563

Karlsson R, Tivefälth M, Duranovic I, *et al.* Artificial hard-substrate colonisation in the offshore Hywind Scotland Pilot Park. *Wind Energy Sci* 2022;**7**:801–14. https://doi.org/10.5194/wes-7-801-2022

Larsén X, Fischereit J, Hamzeloo S, *et al.* Investigation of wind farm impacts on surface waves using coupled numerical simulations☆. *Renew Energy* 2024;**237**:121671. https://doi.org/10.1016/j.renene.2024.121671

Lass H, Mohrholz V, Knoll M, *et al.* Enhanced mixing downstream of a pile in an estuarine flow. *J Mar Syst* 2008;**74**:505–27. https://doi.org/10.1016/j.jmarsys.2008.04.003

Liu K, Du J, Larsén X, *et al.* Spatiotemporal variations of ocean upwelling and downwelling induced by wind wakes of offshore wind farms. *J Mar Sci Eng* 2023;**11**:2020. https://doi.org/10.3390/jmse11102020

Lloret J, Turiel A, Solé J, *et al.* Unravelling the ecological impacts of large-scale offshore wind farms in the Mediterranean Sea. *Sci Total Environ* 2022;**824**:153803. https://doi.org/10.1016/j.scitotenv.2022.153803

Lloret J, Wawrzynkowski P, Dominguez-Carrió C, *et al.* Floating offshore wind farms in Mediterranean marine protected areas: a cautionary tale. *ICES J Mar Sci* 2023;**82**:fsad131. https://doi.org/10.1093/icesjms/fsad131

Ludewig E. *On the Effect of Offshore Wind Farms on the Atmosphere and Ocean Dynamics*. Vol. **31**. Cham, Switzerland: Springer International Publishing, 2015. https://doi.org/10.1007/978-3-319-08641-5

McCoy A, Musial W, Hammond R, *et al.* *Offshore Wind Market Report: 2024 Edition* (No. NREL/TP-5000-90525). National Renewable Energy Laboratory. 2024https://doi.org/10.2172/2434294

Methratta E, Hawkins A, Hooker B, *et al.* Offshore wind development in the Northeast US Shelf large marine ecosystem: ecological, Human, and fishery management dimensions. *Oceanography* 2020;**33**:16–27. https://doi.org/10.5670/oceanog.2020.402

Miles J, Martin T, Goddard L. Current and wave effects around wind-farm monopile foundations. *Coastal Eng* 2017;**121**:167–78. https://doi.org/10.1016/j.coastaleng.2017.01.003

Miles T, Murphy S, Kohut J, *et al.* Offshore Wind Energy and the Mid-Atlantic Cold Pool: a review of potential interactions. *Mar Technol Soc J* 2021;**55**:72–87. https://doi.org/10.4031/MTSJ.55.4.8

Øijorden I. *Influence of Offshore Wind Farms on Primary Production in the North Sea* [Master thesis]. University of Bergen. 2016.

Pang J, Ge J, Tao Y, *et al.* Simulating cross-scale flow dynamics around offshore monopile foundations with a GFD-CFD coupled model. *Ocean Eng* 2024;**312**:119200. https://doi.org/10.1016/j.oceaneng.2024.119200

Platis A, Siedersleben SK, Bange J, *et al.* First in situ evidence of wakes in the far field behind offshore wind farms. *Sci Rep* 2018;**8**:2163. https://doi.org/10.1038/s41598-018-20389-y

Plonus R, Floeter J. Identification of plankton habitats in the North Sea. *Ecol Evol* 2024;**14**:e70342. https://doi.org/10.1002/ece3.70342

Ponce De León S, Bettencourt JH, Kjerstad N. Simulation of irregular waves in an offshore wind farm with a spectral wave model. *Cont*

*Shelf Res*, 2011;**31**:1541–57. https://doi.org/10.1016/j.csr.2011.07.003

Pullin AS, Stewart GB. Guidelines for systematic review in Conservation and Environmental Management. *Conserv Biol* 2006;**20**:1647–56. https://doi.org/10.1111/j.1523-1739.2006.00485.x

Raghukumar K, Nelson T, Jacox M, *et al.* Projected cross-shore changes in upwelling induced by offshore wind farm development along the California coast. *Commun Earth Environ* 2023;**4**:116. https://doi.org/10.1038/s43247-023-00780-y

Rennau H, Schimmels S, Burchard H. On the effect of structure-induced resistance and mixing on inflows into the Baltic Sea: a numerical model study. *Coastal Eng* 2012;**60**:53–68. https://doi.org/10.1016/j.coastaleng.2011.08.002

Rezaei F, Contestabile P, Vicinanza D, *et al.* Towards understanding environmental and cumulative impacts of floating wind farms: lessons learned from the fixed-bottom offshore wind farms. *Ocean Coast Manag* 2023;**243**:106772. https://doi.org/10.1016/j.ocecoaman.2023.106772

Schultze L, Merckelbach L, Horstmann J, *et al.* Increased mixing and turbulence in the wake of offshore wind farm foundations. *J Geophys Res Oceans* 2020;**125**:e2019JC015858. https://doi.org/10.1029/2019JC015858

Segtnan OH, Christakos K. Effect of offshore wind farm design on the vertical motion of the ocean. *Energy Procedia* 2015;**80**:213–22. https://doi.org/10.1016/j.egypro.2015.11.424

Slavik K, Lemmen C, Zhang W, *et al.* The large-scale impact of offshore wind farm structures on pelagic primary productivity in the southern North Sea. *Hydrobiologia* 2019;**845**:35–53. https://doi.org/10.1007/s10750-018-3653-5

Szostek CL, Edwards-Jones A, Beaumont NJ, *et al.* Primary vs grey: a critical evaluation of literature sources used to assess the impacts of offshore wind farms. *Environ Sci Policy* 2024;**154**:103693. https://doi.org/10.1016/j.envsci.2024.103693

TCE. *Offshore Wind Report* [Technical report]. The Crown Estate. 2022. https://www.thecrownestate.co.uk/media/4378/final-published_11720_owoperationalreport_2022_tp_ 250423.pdf (28 March 2025, date last accessed).

Tweddle JF, Gubbins M, Scott BE. Should phytoplankton be a key consideration for marine management? *Mar Policy* 2018;**97**:1–9. https://doi.org/10.1016/j.marpol.2018.08.026

Van Berkel J, Burchard H, Christensen A, *et al.* The effects of offshore wind farms on hydrodynamics and implications for fishes. *Oceanography* 2020;**33**:108–17. https://doi.org/10.5670/oceanog.2020.410

Van Der Molen J, Smith HCM, Lepper P, *et al.* Predicting the large-scale consequences of offshore wind turbine array development on a North Sea ecosystem. *Cont Shelf Res* 2014;**85**:60–72. https://doi.org/10.1016/j.csr.2014.05.018

Vanhellemont Q, Ruddick K. Turbid wakes associated with offshore wind turbines observed with Landsat 8. *Remote Sens Environ*, 2014;**145**:105–15. https://doi.org/10.1016/j.rse.2014.01.009

Wang C, Prinn RG. Potential climatic impacts and reliability of large-scale offshore wind farms. *Environ Res Lett*, 2011;**6**:025101. https://doi.org/10.1088/1748-9326/6/2/025101

Wang H, Fang H, Chiang Y. Study on the coexistence of offshore wind farms and cage culture. *WATER*, 2021;**13**:1960. https://doi.org/10.3390/w13141960

Wang J, Zou X, Yu W, *et al.* Effects of established offshore wind farms on energy flow of coastal ecosystems: a case study of the Rudong offshore wind farms in China. *Ocean Coast Manage* 2019;**171**:111–8. https://doi.org/10.1016/j.ocecoaman.2019.01.016

Wang L, Wang B, Cen W, *et al.* Ecological impacts of the expansion of offshore wind farms on trophic level species of marine food chain. *J Environ Sci* 2024;**139**:226–44. https://doi.org/10.1016/j.jes.2023.05.0021001-0742

Watson S, Somerfield P, Knights A, *et al.* The global impact of offshore wind farms on ecosystem services. *Ocean Coast Manage* 2024;**249**:107023. https://doi.org/10.1016/j.ocecoaman.2024.107023

Wawrzynkowski P, Molins C, Lloret J. Assessing the potential impacts of floating Offshore Wind Farms on policy-relevant species: a case study in the Gulf of Roses, NW Mediterranean. *Mar Policy*, 2025;**172**:106518. https://doi.org/10.1016/j.marpol.2024.106518

Yu W, Guo P, Du J, *et al.* Detecting offshore wind farm-induced wind wake signatures on sea surface using MODIS data. *Front Mar Sci* 2024;**11**:146534. https://doi.org/10.3389/fmars.2024.1465634

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