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Assessment of system effects of large-scale implementation of offshore wind in the southern North Sea

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Title

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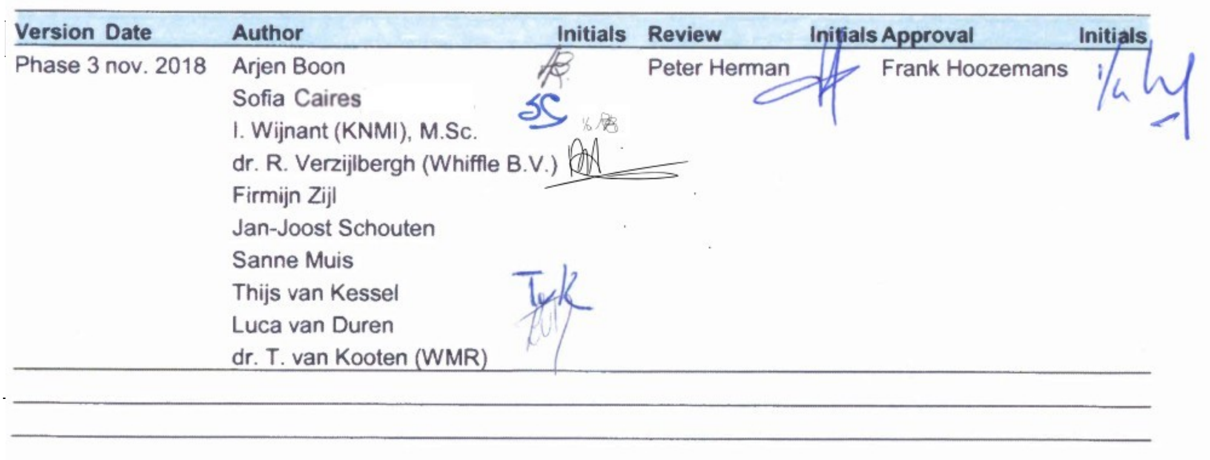
Summary

The possible upscaling in offshore wind for 2030 and even more so for 2050 in the southern North Sea is likely to have an impact on its functioning in very fundamental ways. Large-scale extraction of wind energy from the lower part of the atmosphere may affect local wind patterns, wave generation, tidal amplitudes, stratification of the water column, dynamics of suspended particles and bedload transport of sediment. Furthermore, the infrastructure will provide extra hard substrate, not only on the bed (in the form of scour protection) but also providing attachment opportunities for biota in the upper layers of the water column. Such changes to the physical functioning of the North Sea may have far-reaching consequences for the ecological functioning, such as changes to the total amount and the timing of primary production, food availability of filter feeders and higher trophic levels, and habitat suitability for many species. In this report the potentially most important effects of the possible upscaling in offshore wind in the southern North Sea and the most important knowledge gaps have been identified.



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Contents

Executive summary

Scenarios from PBL[1], aiming for 2050, foresee the construction of 12 to 60 GW of marine offshore wind capacity in the Dutch part of the North Sea. Neighbouring countries have comparable plans, possibly cumulating to several hundred GW of offshore wind farm capacity in the southern North Sea. Such massive deployment of offshore renewable wind energy devices may have effects on the wind, wave, current, sediment and water quality properties of the North Sea, which have knock-on effects on the North Sea ecology. Various recent studies point to offshore wind farm effects that transcend local boundaries and may have regional or even system-wide impacts.

Rijkswaterstaat, part of the Dutch ministry of Infrastructure and Environment, in concert with the Dutch ministry of Economic Affairs and Climate Policy, asked Deltares to develop a scoping study to the possible system effects of the large-scale development of offshore wind farms on the southern North Sea. This study adds to the currently implemented research programme (Wozep: the Dutch Governmental Offshore Wind Ecological Programme, 2016-2023) to the effects of offshore wind farms.

Based on available literature and expert judgement, the current report probes these possible regional and system-wide effects with a main focus on the physical and chemical properties of the southern North Sea, i.e. the meteorological conditions, waves and currents, suspended matter and nutrient concentrations, and seabed habitat changes. Based on these impacts, the likely consequences on the primary production, zooplankton and benthos are described. The possible knock-on effects of such changes on higher trophic levels (e.g. fish, birds, marine mammals) are also likely but are not treated in this report.

The following possible effects have been identified and prioritised according to their risks:
- Large-scale development of OWF may lead to (as yet poorly quantified) effects on the wind (and therefore waves) on the North Sea. There likely is a limit to how fast the atmosphere can replenish the energy that the OWF have harvested, either through transport from higher levels or from the area surrounding the OWF (with more OWF, less energy available there).
- The impact of wakes (wind shadows) on wave generation may be significant, and impact may still be present near the coast, e.g. with respect to density driven transport of suspended matter and nutrients in coastal areas directly influenced by river outflow.
- Tidal current blockage may have repercussions for tidal dynamics in the southern North Sea.
- Enhanced vertical mixing of the water column may lead to (local/regional and/or temporal) destratification and resuspension of SPM and nutrients and concurrent shifts in light climate.
- Feeding activities from epistructural fauna on the OWF foundations may significantly decrease phytoplankton densities around wind farms affecting in turn zooplankton densities.

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[1] *PBL: 'Netherlands Environmental Assessment Agency'*

- The “stepping-stone” effect of the OWF (increase of spatial distribution of hard-substrate species) may be serious and lead to genetic homogenisation and to the spread of species beyond their natural boundaries.

Directions for first steps to resolving major knowledge gaps are given, consisting of targeted combinations of remote and field measurements, experiments and major modelling exercises.

1 Introduction and approach

1.1 Introduction

In the Netherlands, the currently established capacity for offshore wind farms is near 1.000 MW. The roadmap 2030 (https://www.pbl.nl/publicaties/de-toekomst-van-de-noordzee) foresees the development of 3,500 MW of new offshore wind power in the wind farm zones "Borssele" (1,400 MW), "Hollandse Kust (zuid)" (1,400 MW) and Hollandse Kust (noord)" (700 MW) until 2023. Additional capacity is planned in the wind farms zones"Hollandse Kust (west)" (1,400 MW), "Ten noorden van de Waddeneilanden" (700 MW) and "IJmuiden Ver" (4,000 MW) until 2030, see Figure 1.1. Scenarios from PBL[2], aiming for 2050, foresee the construction of 12 to 60 GW of marine offshore wind capacity in the Dutch part of the North Sea alone. Also other countries surrounding the southern North Sea might build comparable capacities of large offshore wind farms, see Figure 1.2. Furthermore, over the last decades the turbines in the offshore wind farms have shown a significant scaling up of dimensions, which is likely to continue in the coming period. As a result, one of the scenarios is that around 2050, offshore wind farms will have been constructed on a large scale in the southern North Sea to harvest hundreds of GWs.

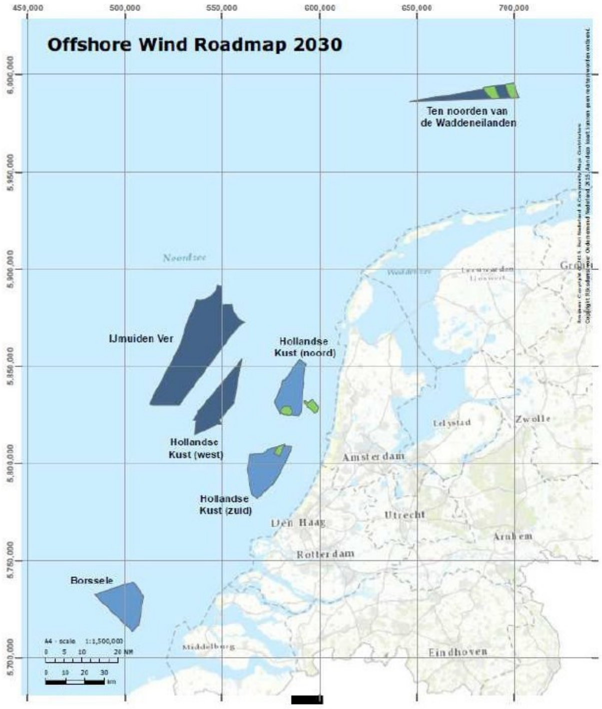

Figure 1.1 Dutch offshore wind roadmap 2030. Source: The Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland, RVO.nl), part of the Ministry of Economic Affairs and Climate Policy.

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[2] *PBL: 'Netherlands Environmental Assessment Agency'*

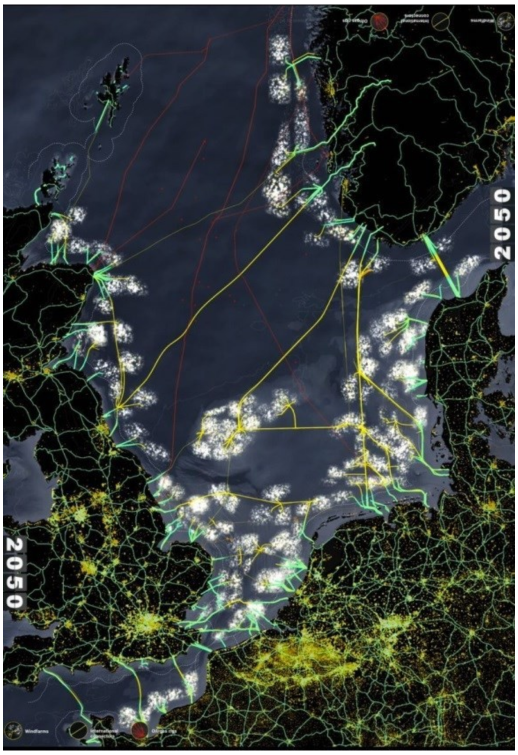

Figure 1.2 Vision of the North Sea wind farm development from the 2016 International Architecture Biennale Rotterdam (IABR) meeting (Maarten Hajer, Dirk Sijmons with H+N+S Landscape architects, Tungsten Pro, Ecofys for IABR 2016).

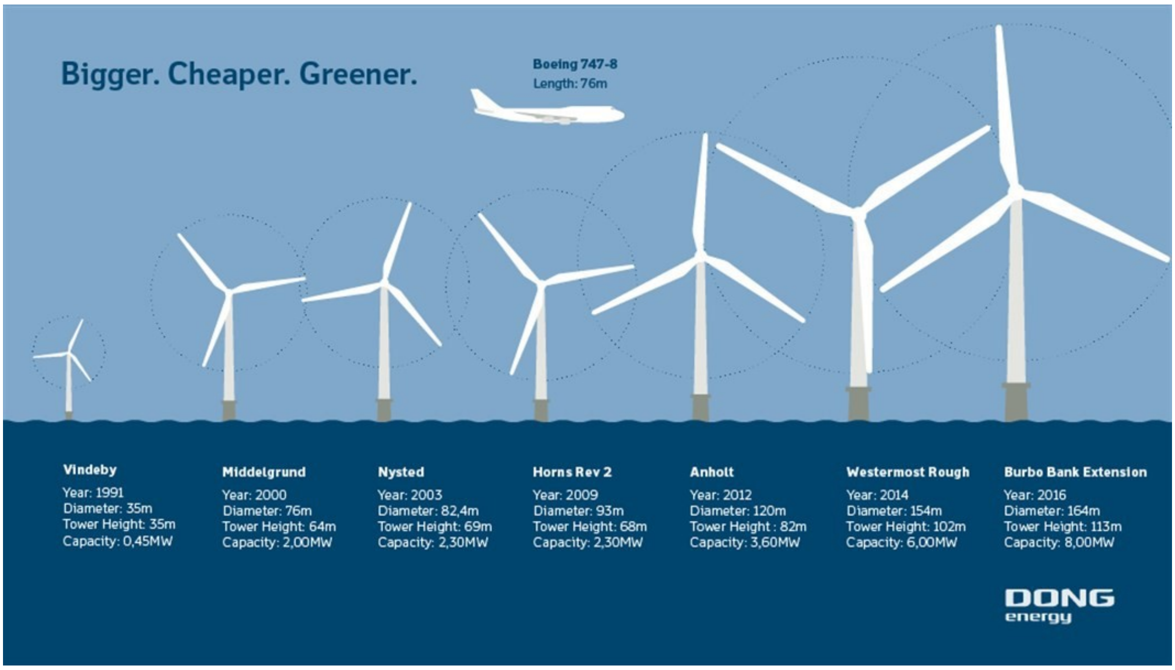

Figure 1.3 Growth of wind turbines over the last 25 years (https://orsted.tw/en/News/2017/08/DONG-Energy-celebrates-1000-wind-turbines-at-sea)

These ambitious (inter)national scenarios for more and larger wind farms in the North Sea are likely to have consequences for the ecosystem in the North Sea at scales and in ways that are currently not well understood. The large-scale impacts of such an extensive construction of offshore wind power on the hydrodynamic climate (waves, currents and surge), suspended matter and morphodynamics and thereby the ecological functioning of the southern North Sea is poorly known (Clark et al. 2014). Our current knowledge mainly focuses on wind farm specific, so near-field effects (Lindeboom et al. 2011, Bergström et al. 2014), with few studies venturing into the possible large-scale effects (van der Molen et al. 2014). Most probably, the cumulative effect will extend to more than simply the adding up of the effects of individual wind turbines or farms.

Within this context, Rijkswaterstaat, part of the Dutch ministry of Infrastructure and Water Management, in concert with the Dutch ministry of Economic Affairs and Climate Policy, asked Deltares – in cooperation with the Royal Netherlands Meteorological Institute (KNMI), Whiffle, and Wageningen Marine Research (WMR) - to identify and assess the cumulative effects of the possible large-scale deployment of OWF on the ecosystem of the North Sea. This study adds to the currently implemented research programme (Wozep: the Dutch Governmental Offshore Wind Ecological Programme, 2016-2023) to the effects of offshore wind farms

The current study answers this question by describing what we know about how wind farms interact with the North Sea meteorological, hydrodynamic and morphodynamic system and its ecology. From this description, the possible large-scale and cumulative impacts on system functioning are assessed in the above-mentioned scenario: a North Sea with significantly more and larger OWF. A particular point of interest is whether the cumulative effects approach so-called critical system limits: do the scenarios for large-scale OWF significantly change the North Sea ecosystem by impacting the physical system driving the natural North Sea functioning such as large changes in wind forcing, or changes to tidal functioning, and/or vertical mixing and destratification of the water column. Any significant change at this level is prone to have strong implications for food-web functioning and our dependence on the ecosystem’s structure and functioning, which affect the major ecosystem services and benefits such as biodiversity and fisheries.

The requested study was carried out in three phases:

- Phase 1 (the first version) comprised a qualitative schematization of (a) the factors that affect the Dutch part of the North Sea ecosystem and are likely to change as a result of more offshore wind energy farms and (b) how these factors depend on each other. The result was the basis for the further assessment in Phase 2.
- In Phase 2 (the previous version), a semi-quantitative estimate was made of these cumulative effects, describing also the state-of-the-art level of knowledge on these effects, major and prioritized knowledge gaps, possible system effects and first steps needed to enhance our knowledge on assessing (and modelling) these large-scale impacts of more and larger wind farms on the ecosystem of the Dutch part of the North Sea. The emphasis in this phase was on the physical impacts and implications for water quality, i.e. the effects on wind, waves, currents and tide, mixing of nutrients and suspended matter, lateral transport of suspended matter and sand, and ultimately primary production.
- Phase 3 (the current report) qualitatively described the transfer of physical-chemical

effects of the offshore wind farms on the biological components of the North Sea, focusing foremost on plankton and the benthos, with a view to possible effects on the higher trophic levels, such as fish, birds and marine mammals.

Note that this assessment does not include the possible effects of the (very uncertain) plans for the construction and presence of islands supporting offshore renewables.

1.2 Approach

This study follows an effect-chain approach. Our approach followed the set-up of a causal network of offshore wind farm effects from the main physical drivers (wind, waves, currents) to the abiotic and the biological components composing the (southern) North Sea ecosystem. A simplified version of this causal network is depicted below in Figure 1.4.

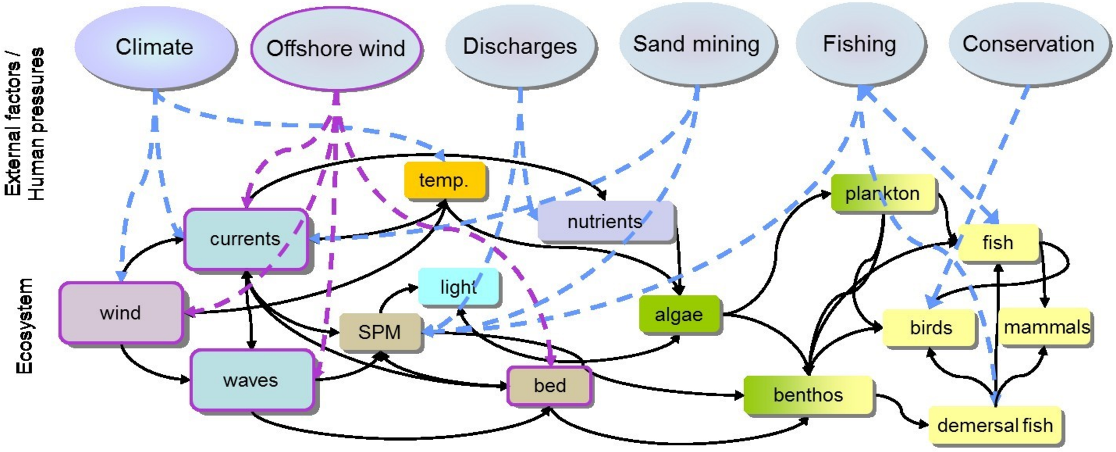

Figure 1.4 Simplified causal network for assessing large-scale offshore wind farm effects on southern North Sea ecosystem. Purple arrows indicate direct effect chains from offshore wind farms. Blue arrows indicate effect chains from other main drivers. Note that this and the other illustrative figures are not exhaustive but point to the main drivers and causal pathways.

This figure shows the important societal drivers in the top row of ovals (Climate, Offshore wind development, etc.), and the main physical drivers at the left (wind, currents and waves) directly influenced by offshore wind farms, together with light, temperature and nutrients driving the habitat and biotic components of the ecosystem. This figure is repeated for each different subsection in section 3, highlighting the most relevant causal pathways that are treated in that section. Note that not all societal drivers or pressures have been included in this simplified network; neither have all causal pathways been included. Other marine renewables (e.g. wave and tidal energy), shipping, aquaculture, oil and gas exploration and exploitation, coastal nourishments, coastal extensions, pollution, climate change, and military activities are also relevant societal drivers. For the sake of overview, we have omitted these from the above network for several reasons. Aquaculture is not (yet) a very relevant driver in the southern North Sea, and neither are other marine renewables. Shipping, military activities and gas and oil exploration and exploitation impact parts of the ecosystem such as fish, birds and marine mammals, but less so the primary production and benthos, or the main physical drivers affecting these ecological components. Coastal nourishments and coastal extensions do affect e.g. habitats, suspended matter, and currents. Still, we decided not to add them for the sake of overview. The cumulative effect of all marine and coastal human activities on the physical, chemical and biological components of the southern North Sea is a very relevant and important issue that deserves its own study but is not the topic of this report.

Inevitably, many causal pathways remain heavily simplified. Some likely less relevant pathways are not even mentioned. The reason for this is the myriad of feedback mechanisms that play a role in linking back to their main drivers, while dampening or strengthening the cause-effect relationship. To display these would lead to an unreadable picture; the texts in subsection 3 explain the causal pathways in much more detail.

Based on the expert judgement of scientists at Deltares, WMR, Whiffle and KNMI, the causal pathways were ranked, and the most relevant ones were selected. Internal quality control has assured the coverage of the main relevant issues.

1.3 Result outline

In the next chapters, the results of the assessment of the cumulative effects of possible large-scale implementation of offshore wind farms in the southern North Sea are presented. Each subsection roughly has the same set up, and includes:

1. An overview of the cause-and-effect relationships
2. A description of effects within, outside, and across OWF (system level); scaling up and the transition from near-field to far-field effects; accumulation of effects in time and space.
3. A semi-quantitative assessment of the effects; the assessment focuses initially on the relative impact and spatial extent of the effects; where possible, an assessment is made of the risk that system limits were crossed. Note that in all cases it was impossible to reliably quantify the effects; in some cases, we were able to quantify the variability of the extent of the effect. The assessment of the ecological effects is mostly qualitative, due to time restraints of the study and relatively high uncertainty levels in extent and direction of the net ecological effects.
4. The knowledge level on the effects. What do we already know? Where are the most important knowledge gaps and what should we do to gain that knowledge?

The results in this Phase 3 report are structured in four chapters (2 to 5), in which the following components are discussed:

- Chapter 2: Wind and waves
- Chapter 3: Tides and currents
- Chapter 4: Suspended matter and morphodynamics
- Chapter 5: Ecology

In the final chapter of this report, chapter 6, the results will be summarised and concluding remarks will be made on the topics of this study:

- What are the most important effects of larger and more OWFs on the North Sea?
- What is their chance of occurrence? Do they impose a risk?
- Can we quantify these effects?
- Where are the knowledge gaps and how best to gain missing knowledge?

2 Wind and waves

In Figure 2.1, the causal pathways that are assessed in this subsection are shown. The red arrows depict the main relevant system pathways discussed here.

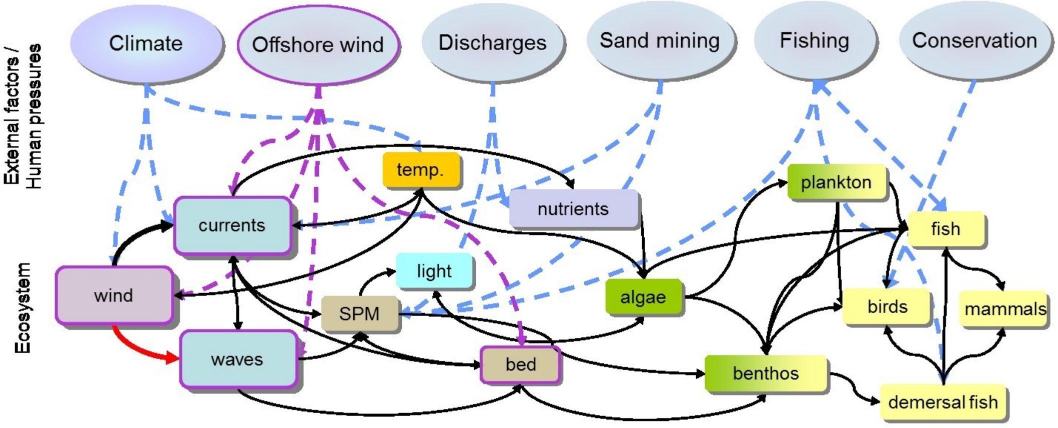

Figure 2.1 Simplified causal network for assessing large-scale offshore wind farm effects on southern North Sea ecosystem; the red arrows depict the main causal pathway discussed in this subsection.

Section 2.1 describes the interaction of turbines with the atmosphere, section 2.2 discusses the impact on waves.

2.1 Overview interaction turbines, wind and waves

2.1.1 Effects on wind in and around offshore wind farms

Wind farms interact with the wind in three different ways:

1. They harvest wind energy and thereby slow down the wind velocity at hub height (momentum sink).
2. They mix the atmosphere and increase the turbulence intensity (mixing).
3. They are obstacles deflecting the wind around them, which causes the wind to slow down upstream of the turbine and to speed up around the turbine (blockage).

Below, these effects are further explained.

Momentum sink

Wind farms extract kinetic energy from the wind flow, which creates a wake with lower wind speeds leeward of the wind farm (wind shadow). Downstream from the wind farm the wind speed will increase again to the local level of the undisturbed flow. How much time this takes and thus how far downstream the turbines the wind speed will return to the undisturbed flow, depends mainly on the ability of the atmosphere to mix (turbulent diffusion) with the flow at higher levels not affected by the wind turbines. And this, in turn, depends on the stability of the atmosphere (less stable, more mixing), the wind speed (more wind, more mixing) and the number of turbines (more turbines, more mixing). Off course there will also be energy replenishment at the boundaries with the “undisturbed flow” outside the wake (at all levels). At some point further leeward from the wind farm the kinetic energy is replenished. It is important to realize that:

- Wakes will extend further at 10 m height than at hub height (the wind speed recovers first at higher altitudes and then downward). At sea surface level wakes will extend even further.
- Wake effects occur downstream of a wind turbine or wind farm. That is why it is important to know the wind rose (distribution of wind direction and wind speed) and more specifically the prevailing wind direction.
- At 10 m height, the wake of a turbine will only become apparent at a certain distance behind the turbine (depending on the type of turbine and the wind speed). This is why at 10 m height, wake effects are probably absent at the first few upstream rows of turbines in a wind farm.

Mixing
As the rotor blades turn, air will be mixed, increasing the wind speed at the lowest part of the rotor and decreasing the wind speed at the highest part of the rotor. It is therefore possible that the wind speed at the lowest part of the rotor increases downwind of the turbine.

What happens below the rotor blades, e.g. at 10 m height or at the sea surface, depends on the stability of the atmosphere and the wind speed itself. If the wind profile is stable, there is less mixing. This means that the changes in the wind speed at higher levels will dissipate slowly (or not) to lower levels. If the change is felt at these lower levels, then only at a distance from the wind turbine or wind farm (see “stable atmosphere” example of Horns Rev 2 in Figure 2.4 (right) where the fog does not disappear immediately, but only in the far wake region)

In general, wind turbines will transform stable wind profiles into less stable or neutral wind profiles. Neutral/unstable wind profiles will remain neutral/unstable. In a stable atmosphere, temperature increases with height (which means limited mixing of the air between layers). In an unstable atmosphere, temperature decreases with height. Offshore, the sea surface temperature (below) and the air temperature (above) determine the stability. Figure 2.2 shows that in stable situations the wind changes less with height in the lowest part of the wind profile (closest to the sea) than in neutral/unstable situations. On the North Sea, the atmosphere is mostly neutral or unstable. Based on 1 year of measurements at Meetmast IJmuiden, Holtslag et al. (2016) concluded that the atmosphere is stable in 30% of the cases for wind speeds below 18 m/s. Sathe et al. (2011) draw a similar conclusion based on measurements at Offshore Windfarm Egmond aan Zee (OWEZ): for prevailing wind directions (long fetches) the atmosphere over the North Sea is mostly neutral or unstable. Figure 2.3 provides an artist impression of how the turbulent transfer of momentum from the higher speeds at higher levels (despite the extraction of momentum by the rotor) may lead to an increase in wind speed at the surface (Cui et al., 2015, Mittelmeier et al., 2017 and Remco Verzijlbergh, personal communication).

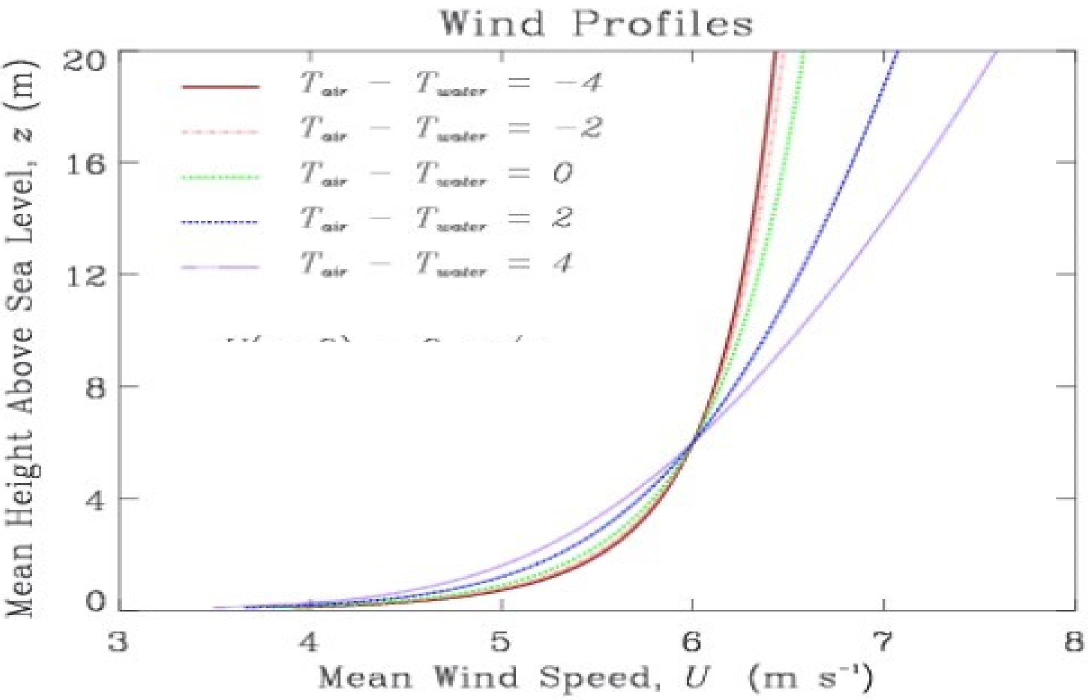

Figure 2.2 Example of variation of the vertical wind profile with the atmospheric stability. The purple line corresponds to a stable situation, the red line to an unstable situation and the green line to a neutral profile.

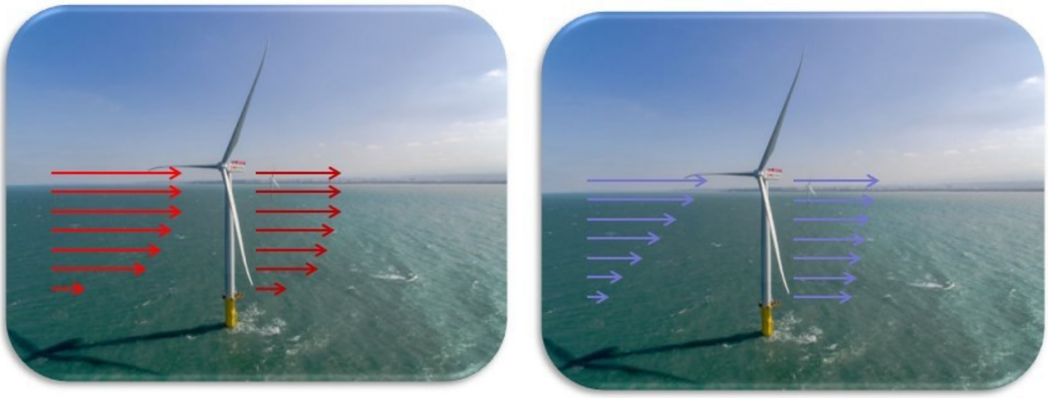

Figure 2.3 Artist impression of the effects of a wind turbine on the wind speed at heights from hub height to the lowest part of the rotor depending on the atmospheric stability. The left panel corresponds to a neutral stability situation, with, downwind of the rotor, a decrease in wind speed from hub height to the lower part of the rotor. The right panel corresponds to an atmospheric unstable situation, with a decrease in wind speed at hub height and an increase at the lower part of the rotor.

Figure 2.4 Left: Vattenfall's offshore wind farm Horns Rev 1 off the coast of Denmark on the 12th of February 2008 at 10:10 UTC. Right: DONG Energy's offshore wind farm Horns Rev 2 off the coast of Denmark on the 25th of January 2016 at 12:45 UTC.

Effects of wind turbines on shallow fog

Because wind turbines are mixers of the atmosphere they can generate or dissolve shallow fog layers. A famous example of wind turbines generating fog is shown in Figure 2.4, left. This event at Horns Rev 1 offshore wind farm on the 12th of February 2008 is known as "the Horns Rev Photo Case" and an analysis of this event is published in 2013 by Hasager et al. (2013)[1]: *"The special atmospheric conditions are characterized by a layer of cold humid supersaturated air that re-condensates to fog in the wake of the turbines. The process is fed by humid warm air up-drafted from below and adiabatic cooled air down-drafted from above by the counter-rotating swirl generated by the rotors. The wind speed is near cut-in and most turbines produce very little power. The condensation appears to take place primarily in the wake regions with relatively high axial wind speed and high turbulent kinetic energy".* Another photo case analysed by Hasager et al. (2013, fig. 2.4, right)[1] is a situation where wind turbines caused shallow fog to disappear (Horns Rev 2 on 25 January 2016 at 12:45 UTC): "*Key findings are that a humid and warm air mass was advected from the southwest over cold sea and the dew-point temperature was such that cold-water advection fog formed in a shallow layer. The flow was stably stratified, and the freestream wind speed was 13 m/s at hub height, which means that most turbines produced at or near rated power. The wind direction was southwesterly and long, narrow wakes persisted several rotor diameters downwind of the wind turbines. Eventually mixing of warm air from aloft dispersed the fog in the far wake region of the wind farm".*

It is not clear how often situations comparable to the one in of figure 2.4 occur on the North Sea. Figure 2.4 shows winter-situations:

- *Figure 2.4 left: this is a typical situation of very cold air gets advected over a warmer sea (an unstable situation without a low-level inversion therefore). There is hardly any wind, presumably from the east (because the advected air is so cold). On the southern North Sea, a situation like this can occur if there is a high-pressure area just north of the Netherlands. So the turbines mix in colder air from above, cool the water-warmed air below (made possible by low wind speeds so air near surface has time to warm up and gain moisture) and produce fog.*
- *Figure 2.4 right: this is a typical "large warm sector" situation and can also occur on the southern part of the North Sea. Very moist air is advected over cold sea water (so the atmosphere is stable), high south-westerly winds and shallow fog. The turbines cause the shallow fog to grow by introducing mixing between the stratified layers (outside of the turbulent wake the stratification prevents the shallow fog from growing). Eventually the wakes get so big that the drier warmer air from higher levels becomes dominant in the mix and the fog clears.*

So, based on these two examples, it seems that wind turbines are able to form or dissipate fog in winter-situations where there is either a large warm sector (warm moist air over cold water and high winds from the southwest) or very cold air (colder than the sea in winter) advected with a light easterly wind.

Situations like this will be rare and even if they happen, they will not have an effect on the sea surface temperature.

Blockage effect

Wind turbines are obstacles: the flow has to go around them causing it to slow down in front of the wind turbine and speed up along the sides of the wind turbine. The flow is diverted around the obstacle with an increased velocity due to conservation of mass. For a single wind turbine, this effect would manifest itself as a ring with increased velocity just outside the rotor swept area disk. Indeed, this phenomenon has been described in a number of experimental and numerical studies (Sarlak et al., 2016, Zaghi et al., 2016). An interaction with the turbine

rotor will start at hub height (generally between 80m height on land and 100m offshore) and dissipate to the (water or land) surface. At the first row(s) of wind turbines this effect will therefore not be noticed at sea surface level, but the effect of the obstacle (the foundation or other structure supporting the wind turbine) will be noticeable, since the effect propagates downward (and upward). Wessels (1983) has developed a method to correct wind speed and direction for flow around an obstacle (cylinder) and this method is used for corrections of measurements on meteorological wind masts. This effect will most likely be gone before the flow reaches the next turbine (at a distance of typically 7 times the diameter of the turbine rotor). Including the effect of the turning rotor blades on the flow makes the situation a lot more complicated. ECN part of TNO[1], has developed a flow model to calculate wake effects within a wind farm (parabolised Navier-Stokes code FarmFlow), and this is the “standard” model used for wind resource assessments (wake effects at hub height). FarmFlow is not designed for calculating wake effects at 10m heights. It is also not a weather model: it models the flow, not the atmosphere (including temperature and humidity). Large Eddie Simulation models are weather models on a high spatial and temporal resolution (100m, 1min) and can resolve these complicated wake effects. In the past few years LES-models have been coupled with wind turbine models: the effects of the turbines on the flow are parametrized with actuator-disk models.
In terms of the vertical wind speed profile, this can lead to an increase in the 10 m wind speed (compared to the free stream velocity), depending on other factors like surface roughness and atmospheric stability whether this effect will dominate over the momentum sink. For wind farms as a whole, or clusters of multiple wind farms, blockage effects can also play an important role. This will be described in the next section.

2.1.2 Interaction of effects and far-field effects

The major interaction between wind turbines and wind are, as stated previously, momentum sink (or extraction), mixing, and blockage. For an individual turbine, blockage is relatively unimportant. Depending on the state of the atmosphere, mixing or momentum extraction may dominate, and the wind speed at sea surface level may therefore either decrease (momentum extraction dominant) or increase (mixing dominant).

However, the interaction between multiple turbines and wind is scale dependent. As the size of the wind farm increases, several turbines will first start to interact with each other within the wind farm. Turbulent wakes behind individual turbines affect the efficiency of downstream turbines. This effect is well known and plays an important role in the design of wind farms (spacing and arrangement of the turbines relative to the dominant wind directions). Also, blockage becomes relatively more important, which affects the design of several wind farms relative to each other. Within individual wind farms, momentum extraction becomes more important as the wind farm and turbine size increases (with decreasing wind speeds downstream of the wind farms at sea surface level), and differences between upwind and downwind turbines become noticeable.

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[1] *ECN stands for Energieonderzoek Centrum Nederland, but since early this year (2018) ECN has become part of TNO (Toegepast Natuurwetenschappelijk Onderzoek) and is now called “ECN part of TNO”.*

When wind farms become very large, the efficiency of wind turbines depends dominantly on the rate of replenishment of the kinetic energy from higher atmospheric layers relative to the rate of extraction. There are two sources of kinetic energy for a windfarm: horizontal advection at hub height and vertical mixing. The input of kinetic energy by horizontal advection is, per unit of cross-wind length of the farm, fairly constant. That implies that with increasing length of the farm in the along-wind direction, this source becomes smaller and smaller when expressed per unit surface of the farm (and thus, with a fixed density of turbines per unit surface, per turbine). The vertical mixing of kinetic energy from higher to lower layers in the atmosphere therefore becomes the dominant source of energy in (very) large wind farms, where this vertical transfer is determined by the stability of the atmosphere. Any impact of such large wind farms on this vertical transfer of energy may affect wind speed at sea surface level on the lee-side of these wind farms, and thus have concomitant effects on significant wave height, and water column mixing.

A relevant, but highly debated impact of the large-scale development of (offshore) wind farms is that of the possible limits to the amount of kinetic energy transferred from higher atmospheric layers to the wind farm level. Several studies on large-scale land-based wind farms describe the limit of this vertical flux to order 1 W.m^{-2} (e.g. Adams and Keith, 2013; Miller et al., 2015). However, considerable spatial variation may occur, with much higher potential limit values of around 8 W.m^{-2} over the Northern Atlantic Ocean as an example (Possner and Caldeira, 2017). There are large uncertainties on the rate and mechanisms of vertical transport of kinetic energy, and current knowledge levels and modelling tools fall short on properly quantifying this vertical transfer.

There are two-way couplings between wind farms and the higher atmosphere that may enhance vertical energy transfer, but these are not sufficiently represented in existing models (Abkar and Porté-Agel, 2014). There remains considerable scientific uncertainty about the regional value of this vertical energy transfer limit for very large wind farms (Badger and Volker, 2017). At a global, scale, there is even more uncertainty about the interaction between wind farms and the global climate. There are many studies on the effect of wind farms on climate in general and temperature in particular (see e.g. Vautard et al., 2014 and Boettcher et al., 2015) but the results are not very conclusive.

However, considering that there is a risk of the large-scale wind power plans for the North Sea approaching this (highly debated) limit, and the possible regional knock-on effects on ecosystem functioning, it is a subject that merits further and more detailed measurements and modelling development (Dupont et al., 2018). Some of the approaches that may improve our knowledge levels and modelling tools are described below.

2.2 Interaction of OWF wind effects with waves

Wind farms can affect the waves in three ways (Alari and Raudsepp, 2012; Cooper and Beiboer, 2002; Rodrigues and Harris, 2012; Christensen et al., 2013):

1. Changes in wind speed directly affect the wave growth and indirectly the wave propagation, dissipation and interactions.
2. The foundation or other structures supporting the wind turbine will block the wave propagation leading to wave diffraction.

3. Local changes in the bathymetry and bed roughness due to the presence of the wind farm may affect the wave propagation and lead to changes in energy dissipation and distribution (focusing).

From these effects the more significant is the first, wind, effect. Waves are driven by the wind and changes in the wind directly lead to changes in the waves. The measure that is most commonly used to describe the waves, the significant wave height, depends linearly to quadratically on the 10m wind speed. Therefore, a change of 5% in the wind speed can lead to a change of 5 to 10% in the significant wave height.

In order to get a rough estimate of the effects of changes in the 10 m wind fields due to the wind farms in the waves in the Dutch coastal waters a number of idealized wave model computations have been carried out.
The following variables have been changed in the computations:

- Offshore wind farm development scenarios: 2018, 2023, 2035 and 2050;
- Unperturbed wind speed: 12 m/s and 25 m/s;
- Wind direction: -45°N, -22,5°N, 0°N, 22,5°N and 45°N; and
- Local (near-field) wind farm wind speed variation: -20%, -10%, and +10%.

The following Figures 2.8 - 2.10 show a selection of the results. As can be seen in the figures, the effects depend on the extension of the wind farm. Far-field changes of up to 5% can be observed in the coastal waves. The spatial effects of the wave model show effects up to somewhere around 80 km.

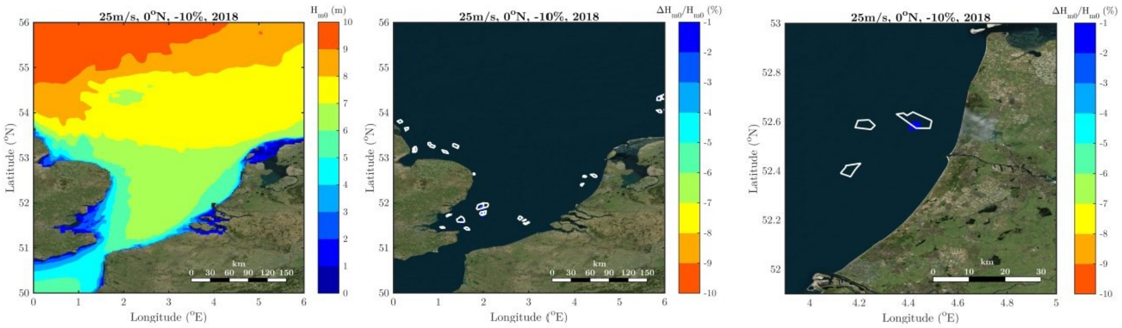

Figure 2.8 Model results for the computations with Offshore wind farm development scenarios 2018, Unperturbed wind speed 25 m/s, Wind direction 0°N and Local wind farm wind speed variation -10%. Left panel: Undisturbed significant wave height. Middle panel: Effect of the offshore wind farms on the significant wave height. Right panel: Zoom in of the middle panel (images from ongoing Deltares study).

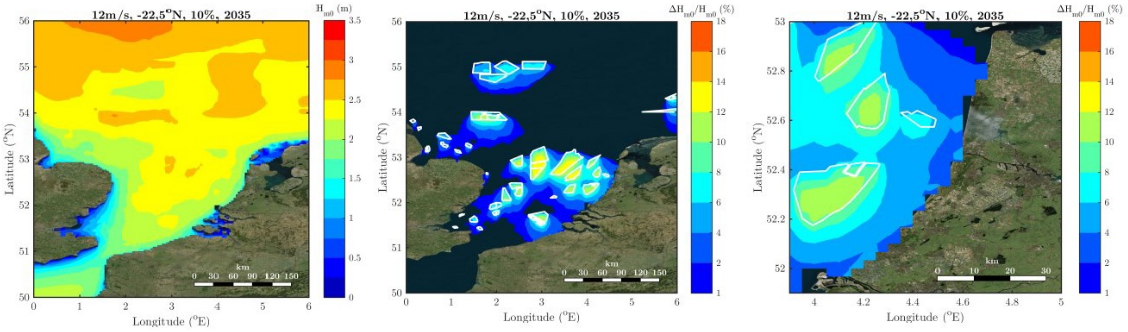

Figure 2.9 Model results for the computations with Offshore wind farm development scenarios 2035, Unperturbed wind speed 12 m/s, Wind direction -22.5°N and Local wind farm wind speed variation +10%. Left panel: Undisturbed significant wave height. Middle panel: Effect of the offshore wind farms on the significant wave height. Right panel: Zoom in of the middle panel (images from ongoing Deltares study).

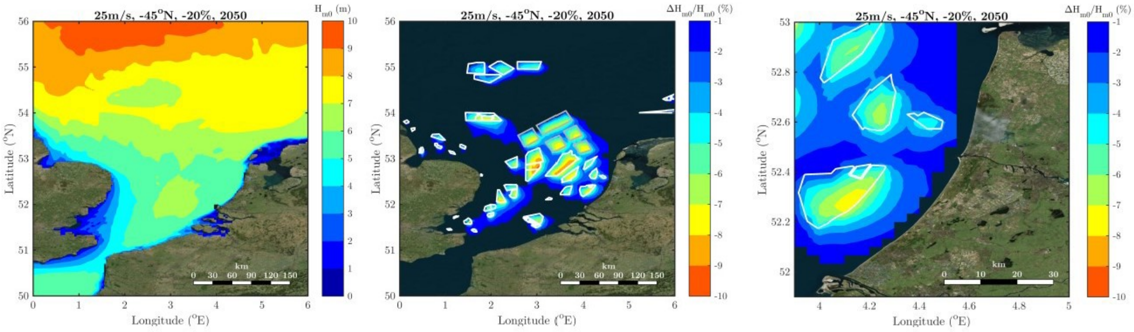

Figure 2.10 Model results for the computations with Offshore wind farm development scenarios 2050, Unperturbed wind speed 25 m/s, Wind direction -45°N and Local wind farm wind speed variation -20%. Left panel: Undisturbed significant wave height. Middle panel: Effect of the offshore wind farms on the significant wave height. Right panel: Zoom in of the middle panel (images from ongoing Deltares study).

These calculations are scenarios, not predictions, and may include various sources of uncertainties. One of these is the far-field effect of wind extraction on the wind.

In the case of one or a few scattered wind farms, the amount of energy extracted is small compared to the energy advected laterally, and at some distance in the wake of the wind farm the wind speed will be restored to the original wind speed. However, in case of very large wind farms, vertical energy transfer is dominant, and this may limit the total flux of energy, as mentioned above. In case of such energy limitation, wind speed in the farms and wakes will, on average, decrease. Quantification of the effect is, however, very unsure yet.

Effects of large-scale wind energy extraction on far-field wave propagation, and the concomitant impacts on climate and ecology may be significant and is one of the prioritised issues for further study.

2.3 Knowledge gaps and further steps

Measurements of wakes and turbulence
Four measurement techniques are available for improving our understanding of atmospheric processes at the wind farm level:

SAR: Synthetic Aperture Radar. Synthetic-aperture radar determines the 3D reflectivity from measured data. There are a number of wake effect studies based on satellite SAR-images (Christensen and Hasager, 2005; Hasager et al. 2015), detecting 3D wave reflectivity. Wind speeds at 10 m height can be derived from SAR-images when model wind directions are available and when the atmosphere is neutral (and the wind profile logarithmic). The wake has to be present at sea surface level for SAR to be able to measure it. However, since SAR results make use of modelled wind profiles for calculating the wakes at sea level, any error in the wind models will be reflected in the SAR results.

SAR images show wind farm wakes that can extend tens of kilometres, see Figure 2.5 and 2.6.

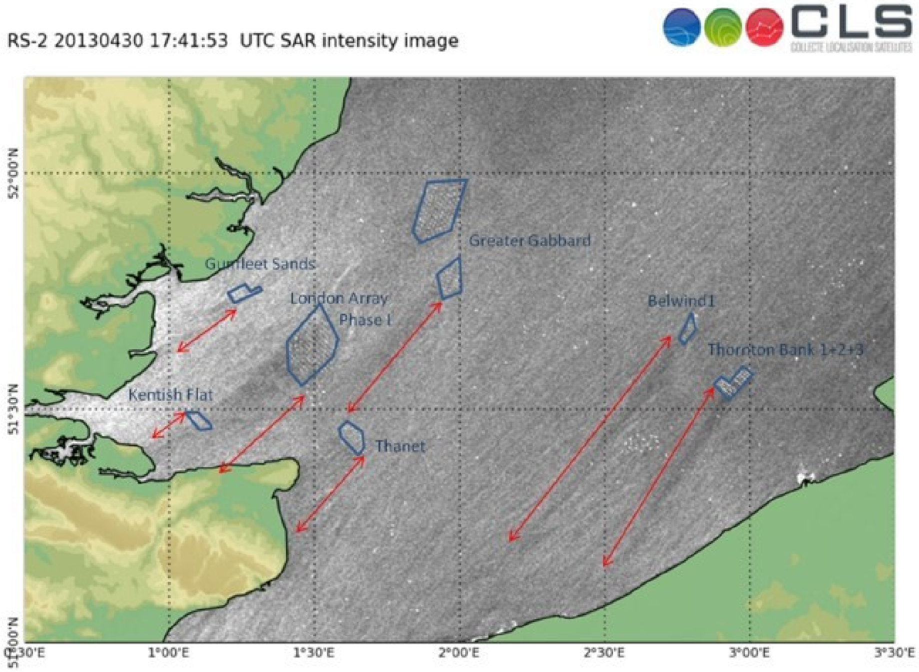

Figure 2.5 Image from a Synthetic Aperture Radar satellite of the southern North Sea on 30 April 2013 at 17:41 UTC. A number of wind farms (dark blue) off the coast of Belgium and the UK are visible, with wind farm wakes (red arrows) extending for tens of kilometres. Prevailing wind directions were from the Northeast. Figure taken from Hasager et al. (2015). Grey scaling illustrates wind effects at sea level.

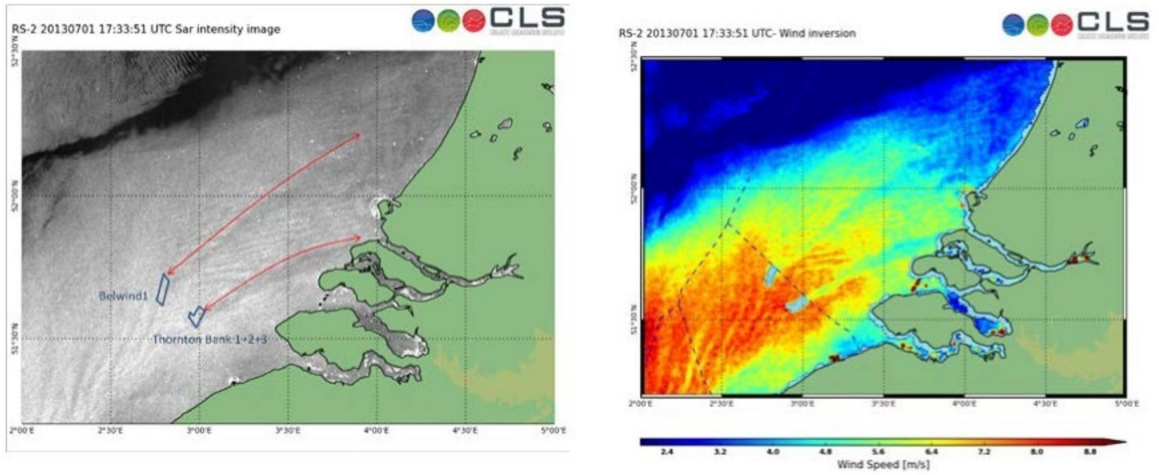

Fig. 2.6 Long wind farm wakes observed behind Belwind1 and Thornton Bank from RADARSAT-2 intensity map (left) and wind speed map (right), July 1, 2013. Figure taken from Hasager et al. (2015).

There are various techniques available to measure the wind field downwind of wind farms, such as scanning LiDAR and dual-doppler radar. Another option is the use of Aeolus measurements (wind profiles from satellites, see https://www.esa.int/Our_Activities/Observing_the_Earth/Aeolus). These data are crucial for validating the modelling of the far-wake leeside of wind farms, but there are still not nearly enough measurements available for wind farm wake effect studies.

Modelling of wakes and turbulence

Due to the lack of field data, wake effects are mostly studied with numerical models. These can be 'stand-alone' parametric models like the frequently used Jensen wake model (Shakoor et al., 2015), or parameterizations of wind turbines/farms in atmospheric models. There are many parametric wake models available in the literature depending on the characteristics of the turbine’s rotor (Frandsen et al., 2006; Paskyabi, 2015; Segtnan and Christakos, 2015), including extension to multiple wakes (González-Longatt et al., 2011; Christensen et al., 2013). Many parametric models exclude stability effects although wind speed reductions at hub height downwind of offshore wind farms tend to be larger in stable than in unstable conditions, and the lengths of wakes are longer (Platis et al., 2018). Such effects are, however, fully accounted for in Large Eddy Simulation (LES) models (Wu & Porté-Agel, 2012) which provide more accurate quantifications of wake effects. By using an LES model coupled to a large-scale weather model, one can perform turbulence resolving weather and climate simulations (Schalkwijk et al., 2015). When combined, a wind turbine parameterization in an atmospheric LES coupled to a large-scale weather model is able to simulate wind farms in realistic weather conditions. As an illustrative example, Figure 2.7 shows the 10m-wind speed from the operational atmospheric LES model used by Whiffle (http://www.weatherfinecasting.com/) for a typical day with south-westerly winds. One identifies a number of effects that have been described above: in general, we observe reduced wind speeds behind the wind farms. However, near the turbines that are positioned closest to the upstream part of the wind farm (i.e. southwest in this case) there is an increase in 10m wind speed. This can be attributed to the local blockage effect. In between the wind farms, a large-scale blockage effect 'tunnels' the wind and leads to increased 10m wind speed.

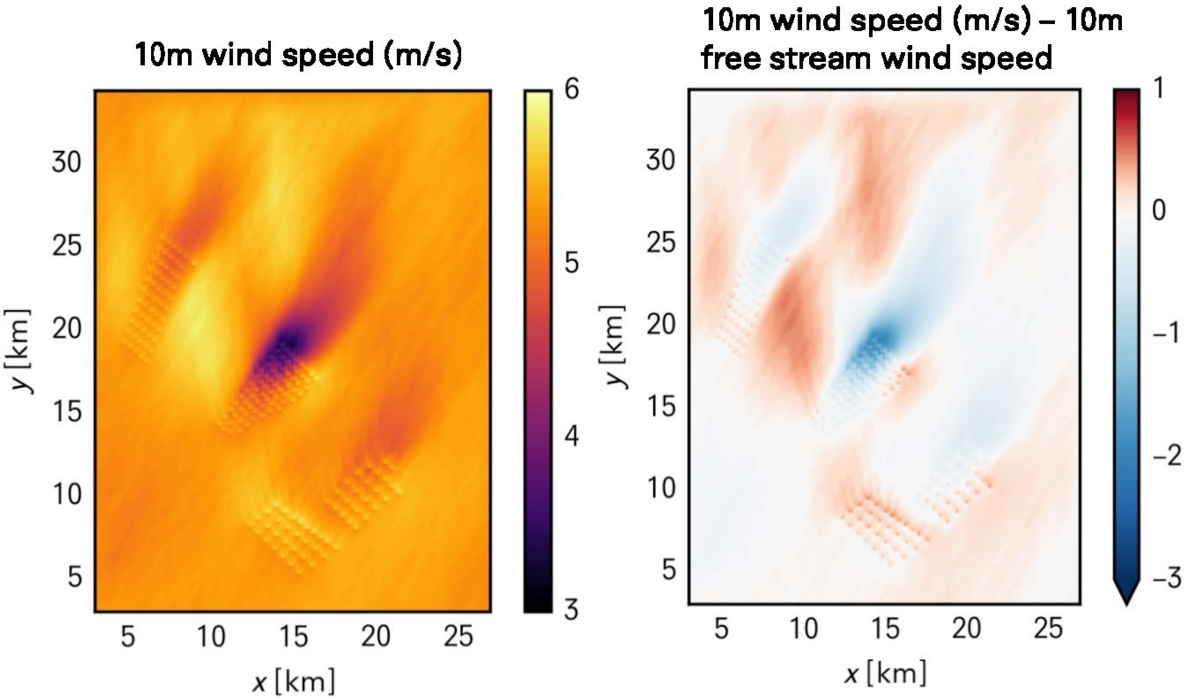

Figure 2.7 Wind speed on 10m height as produced by a large-eddy simulation of the Borssele wind farm zone on 2016-05-08. Left panel: Daily average wind speed. Right Panel: The difference between the 10m wind speed and the 10m free stream wind speed. ERA5 data were used for boundary conditions. The dots in the illustrations are the individual wind turbines (images from ongoing Deltares study).

However, as mentioned above, there are several shortcomings to using these models; there is a general lack of validation with field data, and there is a need to link the local results back to regional processes to understand if and how vertical transport of kinetic energy can be limiting. To resolve turbulence and turbulent exchange, LES models are necessary. But LES models assume a fixed geostrophic pressure, determining the vertical wind profile as a result from large-scale circulation, which is not influenced by friction with the Earth's surface: there is a one-way parameterisation, but the information from the LES model should be fed back to the regional model, a so-called two-way parameterisation. Another approach could be the inclusion of the large offshore wind farms in the regional models themselves. However, this approach deals with a large set of complex feedback loops that are currently too simplified to resolve the influence of the offshore wind farms on geostrophic pressure gradients.

Modelling wind and waves

There is a need for combined atmospheric and wave modelling on different spatial scales which can be achieved by coupling atmospheric mesoscale, LES and spectral wave models. Further data mining of satellite images is needed to validate these model results.

3 Tides and currents

In Figure 3.1, the causal pathways that are assessed in this subsection are shown. The red arrows depict the main relevant system pathways discussed here.

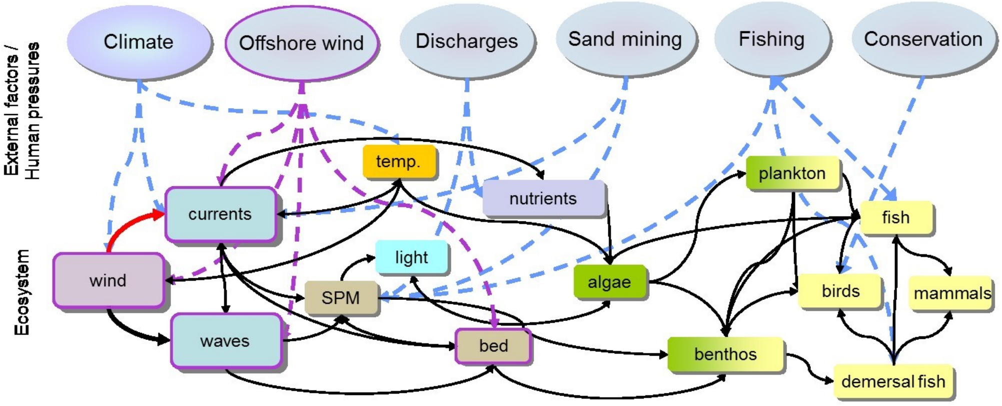

Figure 3.1 Simplified causal network for assessing large-scale offshore wind farm effects on southern North Sea ecosystem; the red arrows depict the main causal pathway discussed in this subsection

3.1 Overview cause-and-effect relations

The large-scale construction of offshore wind farms can impact the hydrodynamic processes in the North Sea (Clark et al. 2014). Large-scale wind farms can act on both the near- and far-field through different processes. The North Sea is a semi-enclosed shelf sea where tides and currents are important processes for vertical and horizontal mixing (e.g. Otto et al., 1990; Huthnance, 1991; Ducrotoy et al., 2000). Tidal currents may reach a speed of tens of cm.s^{-1} and generally dominate over flows driven by density or wind. Residual currents contribute to the cyclonic circulation pattern of the North Sea. These residual currents are driven by tidal residual currents together with wind-driven circulation and baroclinic effects.
During the summer the relatively deep parts of the North Sea are characterised by thermal stratification. This happens when increased solar radiation and increased air temperatures warm the upper layer of the water column, resulting in temperature differences from the bottom layer. In the shallower parts this stratification is prevented by tidal mixing and the turbulence created by the wind stress acting at the water surface and bottom friction. For major estuaries such as the Rhine, there is also salinity stratification due to the inflow of fresh water in coastal waters; the area in which a river has influence on the salinity of marine coastal waters is called a Region Of Freshwater Influence, ROFI. This ROFI has a large interannual and seasonal variability (De Boer 2008, Van der Hout et al., 2015) and is the only ROFI in the southern North Sea. Other rivers (e.g. Thames, Elbe) do have some influence in marine coastal waters, but their effects on salinity do not extend along the coast, because their discharge rates are much lower than that of the Rhine.

The main cause-and-effect relationship is the obstruction of flow which changes local flow velocities and can lead to an increase in vertical mixing, while the concomitant production of turbulence may also lead to an increase in the dissipation of tidal energy. These causal relationships may have near-field and far-field effects. Although these cause-effects relationships are not distinct, we treat these two effects separately in the sub-headings below.

3.1.1 Flow obstruction

Horizontal velocities have been shown to increase at the sides of each foundation and decrease on the leeside of the foundation (Clark et al, 2014). The impact decreases with distances but can extend for hundreds of meters (Cazenave et al., 2016). The changes in horizontal velocities are largest in the upper water column with differences of up to 5% of the peak velocities (Cazenave et al., 2016). The exact influence of a wind farm on currents is depending on the design (e.g. number of foundations and spacing) and the angle of incidence between the current and wind (Zhang et al., 2009). Vertical velocities are also influenced by the foundation with a downward flow upstream of the foundation and upward flow downstream of the foundation. The strongest effect is in the lower part of the water column (from 10 m depth to the seabed). Magnitudes of the vertical flow are ±0.1 $m.s^{-1}$ but over a limited extent (within 20 m of the foundation) before returning to zero over the majority of the transect. Stratified water will experience smaller vertical velocities than fully mixed waters due to the increased energy that is required to overcome the density gradient.

Vertical transport is enhanced when water flows along the foundations. In areas subject to seasonal stratification, this leads to an increased mixing of the water column and a decrease of stratification. Also, in both mixed and stratified waters, particulate matter in the lower water layer, especially the fines, may be transported upwards. In a study by Carpenter et al. (2016) the wind turbines near the tidal mixing front changed the hydrodynamics sufficiently to decrease stratification by 5–15%. Furthermore, despite the limited horizontal extent of these changes in flows at the foundations (less than 20 m) their impact on stratification is felt much more widely. Using an idealized modelling approach, Carpenter et al. (2016) showed that widespread construction of wind farms could impact the large-scale stratification. For present wind farms with a spatial scale of 10 km, the effect is limited, but it could become very significant when the farms are scaled up to ~100 km.

In a recent survey in a German OWF, high-resolution CTD (Conductivity, Temperature, Depth) data were collected, together with data on oxygen and chlorophyll-*a* (Floeter et al., 2017) around various OWFs in the German Bight, southern North Sea. These data provided empirical evidence that vertical mixing is indeed enhanced within OWFs in the summer- stratified North Sea. This leads to a “doming” effect on the thermocline and increased transport of nutrients from the deeper layers into the surface mixed layer. Measurements were carried out along a south – north transect in the “BARD” OWF in the German EEZ (see Figure 3.2).

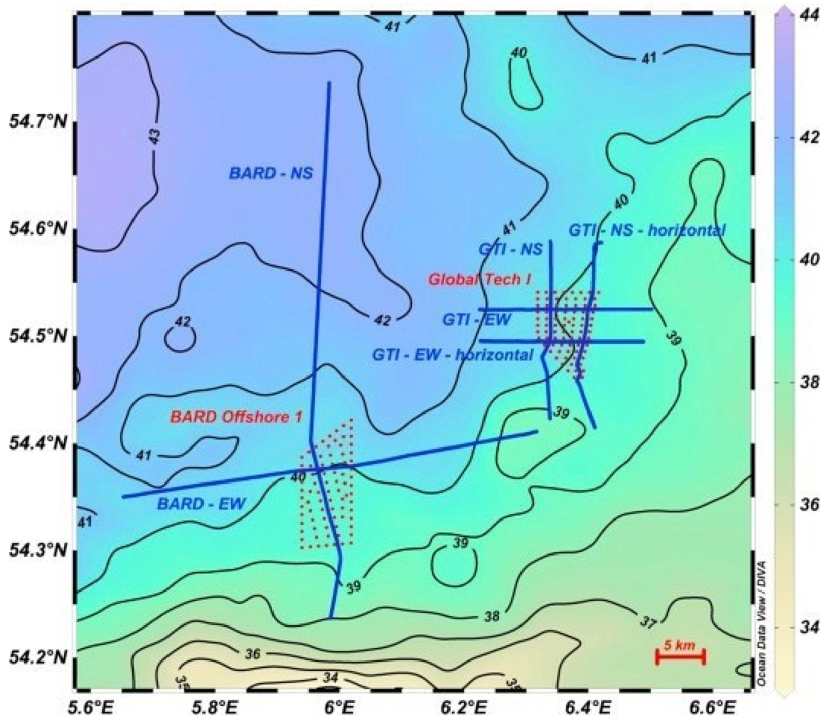

Figure 3.2: Location of the German OWF "BARD" in the German Bight, North Sea, and the transect investigated. The colour bar to the right indicates depth.

The total length of the transect was around 60 km, the section through the wind farm was around 10 km (see Figure 3.3). Within the wind farm the stratification index was markedly lower than outside. In this transect the effect on stratification appears to extend around 15 km beyond the wind farm in the direction of the current (Figure 3.3). These features could confidently be assigned to the presence of the OWFs present.

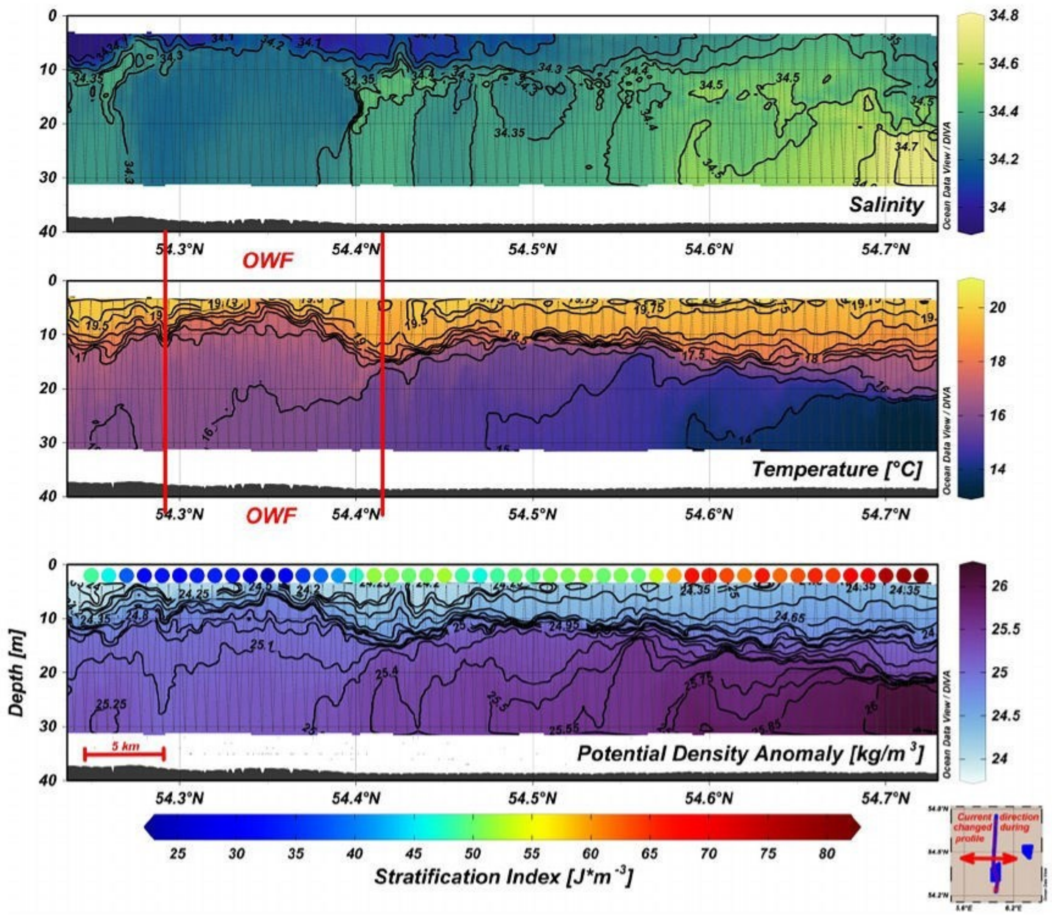

Figure 3.3 Top graph: salinity profile, middle graph: temperature profile and bottom graph stratification index along the south-north transect. Red lines in the middle graph indicate the boundaries of the BARD OWF (Floeter et al., 2017).

Such effects are expected to occur in areas that are intermittently or seasonally stratified, so mostly during the summer season (roughly from March to September). Areas that are permanently stratified are likely not easily mixed due to the strong stratification present. The assessment is that wind farms do not create enough turbulent energy to remove stratification in such areas. Which areas are intermittently and seasonally stratified in the North Sea is shown in Figure 3.4 below (Van Leeuwen et al., 2015).

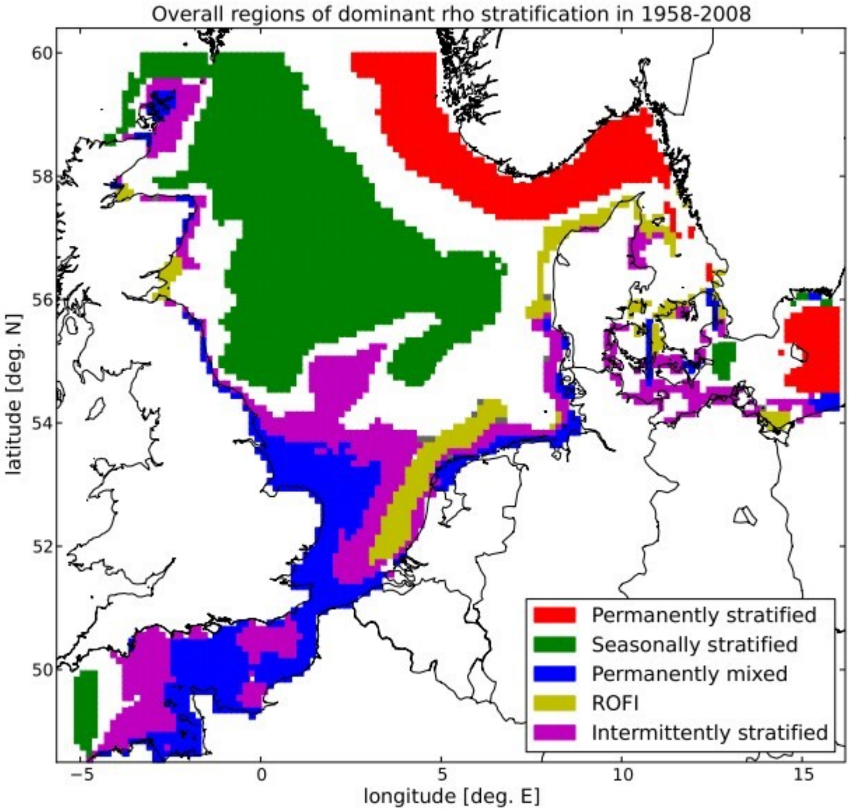

Figure 3.4. Time median results of the modelled, annual regions in the North Sea based on density stratification. Transparent areas indicate areas where the dominant regime occurs for less than 50% of the time (less visible due to minimal occurrence) (Van Leeuwen et al., 2015).

3.1.2 Tidal energy dissipation

Wind turbine foundations and the scour protection lead to the production of turbulence. High dissipation levels are generally observed close to the water surface and near the sea bed, which is explained by turbulence caused by wind drag and bottom friction of the tidal currents (Schultze et al., 2017). Carpenter et al. (2016) found that the turbulence induced by the wind farms is equal to 4-20% of the turbulence produced at the bottom (per surface unit). This will increase linearly with greater depths. This implies that the total energy that is extracted from the tides could be significant. Cazenave et al. (2016) showed that the construction of offshore wind farms in the Irish Sea can have large-scale impacts and change the amplitude of the tides at the coasts in particular (>2%), but also offshore (see Figure 3.5). Large effects are particularly found in the vicinity of the amphidromic points, which may reflect the limitations of the model boundaries or be the result of the absolute amplitude near these points being close to zero. Similar effects are found for the construction of tidal turbines (De Dominicis et al., 2017) with an increase in tides near the turbines, while far-field effects show decrease in tides in the order of 2 cm.

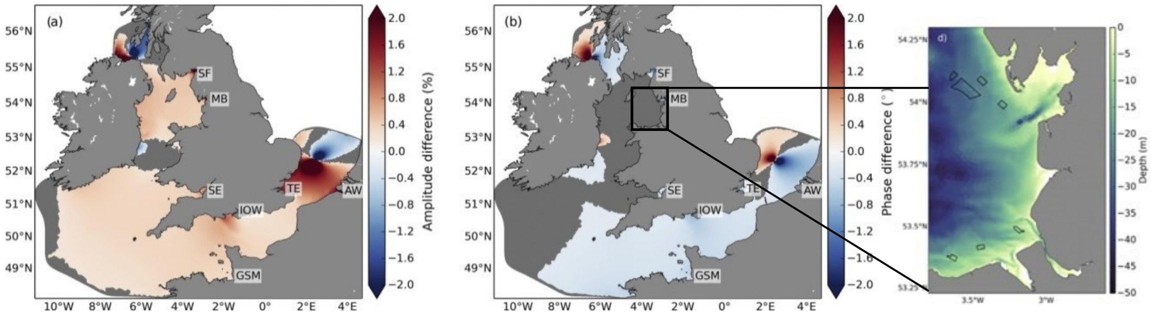

Figure 3.5 Far-field effects of a construction of a wind farm in the eastern Irish Sea (location shown in panel 3). Plots shows the difference in M_2 amplitude (panel a) and phase (panel 2) between a model with turbines and a model without turbines. The amplitude difference is expressed as a percentage of the amplitude for the model without turbines. Negative change indicates a decrease in amplitude with the introduction of the turbine foundations and vice versa. SF = Solway Firth, MB = Morecombe Bay, SE = Severn Estuary, GSM = Gulf of St Malo, IOW = Isle of Wight, TE = Thames Estuary, AW = Antwerp. Grey indicates a change of less than 0.2% in amplitude or 0.2° in phase.

3.2 Accumulation of effects

Because of the many feedback mechanisms and interconnections in the systems, it is difficult to assess whether these effects will accumulate and give an estimate of the overall impact of the construction of wind farms on the hydrodynamics in the North Sea. Many effects of the construction of offshore wind farms, such as changes in flow velocities and production of turbulence, will be near-field effects that act on a local scale. However, the local scale effects can propagate through the system and as such have a far-field effect, as illustrated by e.g. Cazenave et al. (2016) and De Dominicis et al. (2017).

Generally, the larger the number of offshore wind turbines the more tidal energy will be dissipated and hence the larger the impact on hydrodynamics. However, the impact on tidal amplitude can have large spatial variations. These regional variations are difficult to predict based on theory. A change in the location of the amphidromic point can result in large relative changes. Furthermore, the deeper the water, the larger the energy dissipation through production of turbulence (assuming equal flow velocity). Since the dissipation through bottom friction is lower in these areas, the relative impact of water depth is expected to be even larger. However, this assumes equal flow velocities, which in reality show large spatial variability and dependency on water depth. Since the production of turbulence scales with the third power of the typical flow velocity, this also gives rise to spatial variability in energy dissipation.

How hydrodynamic effects will accumulate may also depend on the location of the wind farm. For example, impacts are expected to be influenced by the break-up of stratification in areas, such as the region of freshwater influence (ROFI) of the Rhine and the northern parts of the North Sea characterised by temperature stratification. There an increase in vertical mixing due to wind turbines can destroy the stratification and alter the tidal currents.

Tides and wind act on a short time scale in the order of hours to days. Any changes in tidal energy dissipation will have an immediate impact on water levels. Effects on large-scale circulation patterns will act on larger time scale in the order of months to years and such effects might not have an immediate effect.

Literature suggests there could be large-scale changes in the hydrodynamics of the southern North Sea. These effects are especially notable considering the fact that these studies have analysed the effect of single wind farms. Interestingly, many large-scale human interventions in the Dutch part of southern North Sea, such as harbour extensions like Maasvlakte 2, closure of large estuaries like the Oosterschelde or changes to the coastline due to large- scale sand nourishments like the Sand Motor, have not (yet) resulted in any measurable effects on tides and currents to our current understanding. It is, therefore, difficult to imagine that the construction of a single wind farm in the Irish Sea could have a significant effect on large-scale tidal dynamics, as shown by Cazenave et al. (2016). As the authors write themselves, the largest changes in tides are found near the open model boundaries and near the amphidromic points where relative effects may blow up. These are reasons for caution in the interpretation. Nevertheless, various studies show that effects may occur far away from the wind farms and that impacts of individual foundations can be magnified when propagated through the systems. Therefore, based on our current review, we cannot rule out that the construction of large-scale wind farms may result in significant changes in tides and currents. There are large uncertainties and it is difficult to extrapolate the results from current studies due to very localized effects and many complex feedbacks in the system.

Since waves, wind, current and tides interact, there are many feedback mechanisms in the system. It is important to map these processes and show how changes in the hydrodynamics of the North Sea can propagate through the system and have cascading impacts on geomorphology and ecosystems. Tidal currents are one of the most important transport mechanisms in the North Sea. Changes in tidal currents can significantly alter the bed shear stress and, consequently, erosion/deposition processes. This will influence nutrient transport and affect ecosystem dynamics. Furthermore, the stratification and turbulent mixing is known to be important for carbon fixation, biomass distribution, and dissolved oxygen concentrations.

3.3 Knowledge gaps and further steps

The literature review reveals large gaps in the knowledge of the effects of large-scale construction and presence of offshore wind farms. The majority of studies focus on the effects of one particular wind farm, while few studies have assessed the far-field effects of the production of turbulence and the prevention/decrease of stratification. As such, there is sufficient understanding of how a single wind farm foundation may affect local currents, but there is a lack of knowledge of cascading effects and cumulative impacts of large-scale construction of offshore wind farms on hydrodynamics in the North Sea.

At the same time, the North Sea is one of most researched seas in the world. There is a thorough understanding of the North Sea system and the hydrodynamic processes that determine the tides and currents. There are several topics that require further research including the coupling of the hydrodynamics with water quality and ecosystems, the momentum exchange between atmosphere and ocean that is determined by the influence of waves on surface roughness, the exchange and transport between the shelf and oceanic water, and the production of turbulence and influence on the bottom drag. Nevertheless, the current state-of-the-art methodologies and knowledge are sufficient to investigate the hydrodynamic effects of large-scale development of wind farms in the North Sea. In principle all instruments needed to carry out an in-depth study are available.

Numerical modelling can be a valuable instrument to improve our understanding of the hydrodynamic effects of large-scale development of wind farms in the North Sea. The main requirements for the instrument include:

- Because the construction of offshore wind farms can result in far-field effects it is important that the model domain is sufficiently large and captures the entire North Sea. This will ensure that the boundaries are not affected by the wind farms.
- To quantify potential effects, it is also highly important that stratification and (residual) currents are accurately represented in the model. Because of the influence of salinity and temperature distributions, a 3D model with sufficient vertical layers is needed.
- Accurate parametrization of foundations in the model. Since the resolution of most models is insufficient to resolve the individual foundations, wind farms are commonly included as sub-grid structures.

We anticipate that the time frame needed for the development of knowledge is relatively short (6-12 months), because a new generation of models for the North Sea has been developed over the last years (Zijl et al., 2018). The 3D Dutch Continental Shelf Model - Flexible Mesh (3D DCSM-FM) could be used for an in-depth assessment of large-scale effects of wind farms. 3D DCSM-FM is based on the current operational 2D storm surge model used to forecast sea levels in the Netherlands (Zijl et al., 2013, 2015). However, in contrast to the current operational model, it uses a flexible mesh and has a varying grid resolution. The varying grid resolution makes the model computationally very efficient and allows for 3D modelling.
The model fulfils all requirements listed above. The domain covers the entire northwest European continental shelf between 15°W to 13°E and 43°N to 64°N. The grid size ranges from 1/10° in east-west direction and 1/15° in north-south direction in the deepest parts, down to 3/4' in east-west direction and 1/2' in north-south direction in the southern North Sea (Figure 3.6). The current 3D version of DCSM-FM implements 20 equidistant sigma-layers, which allows modelling of baroclinic processes.

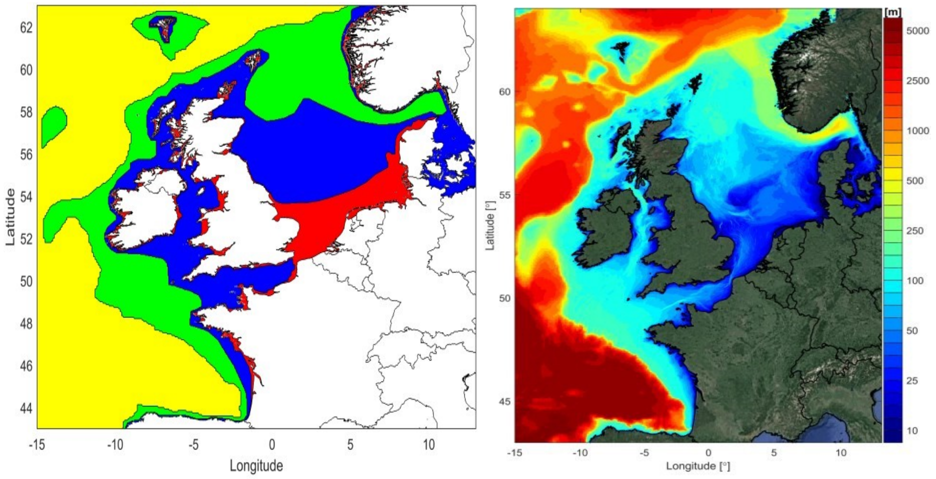

Figure 3.6 left: DCSM-FM model network with the colours indicating the grid size (yellow: ~4 nautical miles (nm); green: ~2 nm; blue: ~1nm; red: ~0.5 nm). Right: depth map of the model domain.

A detailed study of the impact of large-scale development of offshore wind farms would be composed of the following steps:

1. To validate the currents modelled with 3D DCSM-FM with a focus on residual current.

2. To validate the temperature and salinity fields modelled with 3D DCSM-FM, including stratification;
3. To include all large-scale wind farms that are planned in the model grid as sub-grid features;
4. To run 3D DCSM-FM with and without wind turbines
5. To identify changes in stratification, (residual) currents and tidal water levels.

On a longer time frame (1-5 years), many aspects of the model can be further developed to improve the accuracy and confidence in the results. One aspect in particular that could be improved is the coupling of the hydrodynamics with water quality and the transport of suspended particulate matter (clay, silt, algae etc.).

4 Suspended particulate matter, and morphodynamics

In Figure 4.1, the causal pathway that is assessed in this subsection is shown. The red arrows depict the main relevant pathways discussed here.

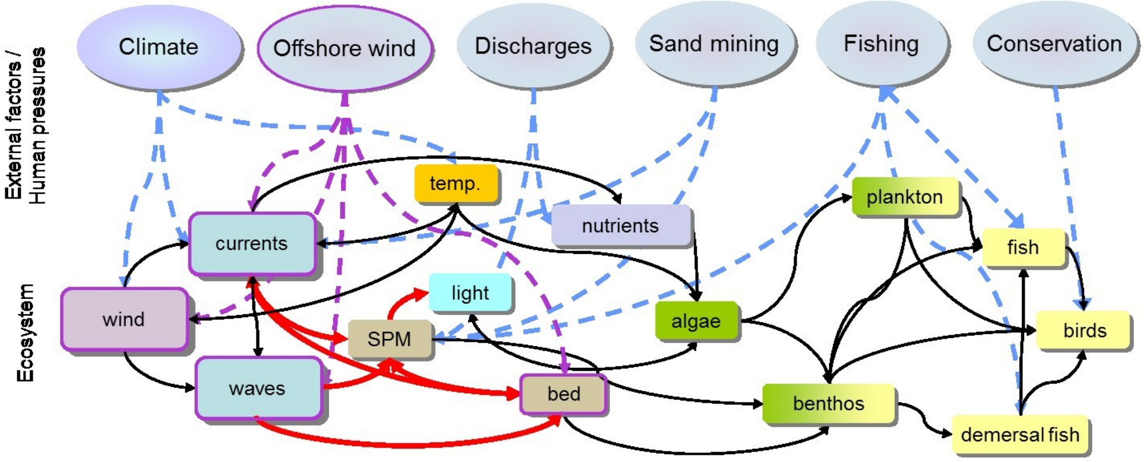

Fig 4.1 Simplified causal network for assessing large-scale offshore wind farm effects on southern North Sea ecosystem; the red arrows depict the main causal pathway discussed in this subsection.

4.1 Overview cause-effect relationships

There are various ways in which the large-scale construction of wind farms in the North Sea may influence suspended particulate matter (SPM), turbidity and seabed dynamics. These are linked to the main forces steering SPM dynamics, which may be influenced by the presence of wind farms. They can be categorised as follows:

- Wind and waves.
- Tides and currents.
- Bed shear stress, turbulence and mixing.
- Salinity and temperature stratification.
- Non-linear feedbacks, including ecological feedbacks (e.g. algae concentration).

The interactions of offshore wind farms with these steering factors have been discussed largely in the chapters 2 and 3 above. This chapter focuses on the indirect effects of waves, currents and mixing on the dynamics of suspended matter and the seabed, and water column nutrients. These factors are of main relevance for the steering of the primary ecological processes (algal production, benthic ecology).

In this domain, offshore wind farms have the following near-field and far-field effects:

- Bed shear stress and OWF foundation-induced turbulence affect the vertical distribution of suspended particulate matter (SPM).
- Currents, vertical mixing, and erosion/deposition processes influence the lateral transport of SPM.
- Bed shear stress impacts the erosion and deposition processes near and in the seabed, affecting bed forms and sedimentology.
- Long-term feedback mechanisms of changed bed forms on the hydrodynamics.

4.2 SPM dynamics

Changes in waves and currents result in changes in bed shear stress, which is an important parameter steering sediment erosion and deposition. A higher bed shear stress results in more resuspension of fines, whereas a lower bed shear stress results in more deposition. Also, the seabed composition is sensitive to changes in bed shear stress. The higher the local bed shear stress, the coarser the seabed composition. The seabed composition has feedbacks with the hydrodynamics via bed roughness and the occurrence of bed forms.

The changes in currents, waves and bed shear stress induce changes in turbulent mixing. The presence of the foundation (either monopile or jacket) of the wind farms introduces additional turbulence throughout the water column, whereas without such a foundation, the production of turbulence predominantly occurs near the bed (currents) and the surface (waves). Changes in (gradients of) vertical turbulent mixing affect vertical salinity, temperature and sediment concentration gradients. If the additional turbulence production is sufficiently strong, vertical stratification (e.g. temperature-induced) may be reduced. When this happens, the near surface concentration of SPM tends to increase markedly.

In the short term (days to weeks) the properties and local availability of fines vary little and effects are likely to be mostly caused by changes in hydrodynamic forcing. In the long term (months to years) local sediment quantity (e.g. seabed composition) and properties may also change through the presence of wind farms. Both time scales need to be considered in interaction to assess the upscaling of effects from the spatial scale of a single wind farm to the complete (southern) North Sea. These time scales should, furthermore, be considered in relation to the lifetime expectancy of a wind farm (i.e. some 30 years)

4.2.1 Direction and extent of the effect

Prior to quantification we first discuss the dominant processes for SPM dynamics in the water column:

- Horizontal SPM transport to and from the wind farm area.
- Settling and remixing, resulting in a vertical (re)distribution of SPM over the water column.
- Deposition and resuspension, i.e. the exchange of SPM between the water column and the seabed.
- The concentration of SPM in the area of interest.

Wind farms potentially interact with all three processes. Turbine foundations enhance vertical mixing (Floeter et al. 2017), which in turn enhances near-surface SPM levels if vertical SPM concentration gradients exist. In a situation that is already well-mixed, additional mixing won’t have any noticeable effect.

We have also seen that wind farms locally enhance current-induced bed shear stress in the wake of the foundations but may reduce it elsewhere within the wind farm area. Also, wave-induced bed shear stress tends to decrease. Most likely, there is an overall reduction of the average bed shear stress within the wind farm, resulting in a SPM concentration decrease.

So, there is a cascade of interactions, in which the near-surface SPM concentration is weakly to strongly related to the near-bed SPM concentration via the (im)balance between settling and vertical mixing; the near-bed concentration is determined from the (im)balance between deposition and resuspension. Assuming the settling velocity to remain unaffected (which is a first order approximation as this may be influenced by the distribution of organic matter), a higher bed shear-stress and a higher mixing will result in a higher near-surface SPM concentration and a lower bed shear stress and a lower mixing in a lower near-surface SPM concentration.

So, the overall impact may go both ways: different contributions (higher vertical mixing and a lower bed shear stress) may have different signs and the relative importance of the contributions may vary in space and time. For example, during storms the contribution of waves is dominant, during calm weather the contribution of tidal currents is dominant and during periods of stratification the vertical profile of mixing is dominant. Quantification of the impact of wind farms on SPM dynamics is therefore not straightforward.

To complicate matters further, apart from different processes there are also different time scales to consider. Shortly after construction the effect on SPM may be different from the long-term effect because of the long adaptation time scale for bed composition and bed level. Also, it is important to make a distinction between near-field and far-field effects, viz. the effects inside the wind farm(s) and the effects beyond their delineations. These different time scales are discussed below.

4.2.2 Transient effects versus long-term effects

Hydrodynamics adapt instantaneously to a new setting such as a wind farm. For sediment the response time is much longer, as both bed height and bed composition will adapt in response to the changed hydrodynamic forcing, notably with regard to changes in bed shear stress. The seabed will tend towards a new equilibrium which may require years to achieve, as the morphological response time scale is long in deep water where typical transport rates are quite modest. In case of enhanced bed shear stress, the wind farm will temporarily act as a sediment source whereas in case of reduced bed shear stress, the wind farm will temporarily act as a sediment sink. Also, the bed composition (mud content) is important: the higher the bed shear stress, the lower the mud content.

Related to this, a reduction in average bed shear stress will initially result in a proportional reduction in resuspension and SPM levels. However, as the mud fraction in the seabed gradually increases the resuspension flux is gradually restored to its original level prior to wind farm construction, so finally the (dynamic) equilibrium between deposition and resuspension is restored. Although the resuspension flux is restored, the distribution of the resuspension flux over time may be altered, as a higher mud fraction in the seabed results in higher concentration peaks during storms, unless the peak bed shear stress is substantially reduced by the wind farms. As deposition and resuspension may be distributed differently in time, this may result in periods with lower and higher SPM values compared to the base case without wind farms. Also, a higher mixing will result in a different distribution of SPM over the vertical: higher SPM levels near the surface and lower levels near the bed.

Because of the establishment of a new morphodynamic equilibrium, the wind farm areas will not have a significant net import or export of fine sediment in the end. Although wind farms do not consume or produce mud, as a transient process they may nevertheless act as a sink or source for sediment, as the seabed level and composition shift towards a new equilibrium after construction of a wind farm. A local sediment sink will result in a concentration decrease, whereas a local sediment source will result in a concentration increase.

A rough estimate of the magnitude of sink-source terms is a 0.25% absolute change in mud content over an active layer thickness of 0.3 m (i.e. a 10% relative change of a typical fines percentage of 2.5%). This results in a sink (in case of a decrease) or source (in case of an increase) of 1.2 kT/km^2 over a few years. With a projected wind park area of 3280 km^2, this would be equivalent with a potential order-of-magnitude sink or source term of 4 MT, which if distributed over a 10-year period is similar to the source term originating from sand mining (0,5 MT/year). This should be further investigated and quantified in more detail.

4.2.3 Far-field versus near-field effects

Far-field effects, i.e. outside the wind farm areas, can have two main causes:

1. Impact of sinks/sources
2. Adaptation of SPM level and vertical SPM distribution to differences in resuspension and vertical mixing

These causes originate from changes in SPM dynamics within the farm (near-field), triggered by changes in hydrodynamic forcing within the farm. With regard to point 1, sink/source effects only play a role in the transient phase, but they typically have an effect far beyond the boundaries of the wind farms (tens of km). With regard to point 2, the length scale for adaptation of the SPM vertical distribution is typically 1 to 2 tidal excursions (10 km), so the farm is virtually larger with some spill-over effects.

4.2.4 Preliminary conclusions

The interplay between the processes of settling and mixing, deposition and resuspension at the short and long term and in the near-field and far-field is visualised in Figure 4.2. These processes, which determine SPM dynamics, are influenced by changes in hydrodynamic forcing such as bed shear stress, mixing and horizontal transport. Therefore, also the SPM dynamics are likely to change. Quantification is not easy without the application of a numerical model, as both concentration enhancing and concentration reducing effects will occur at the same time.

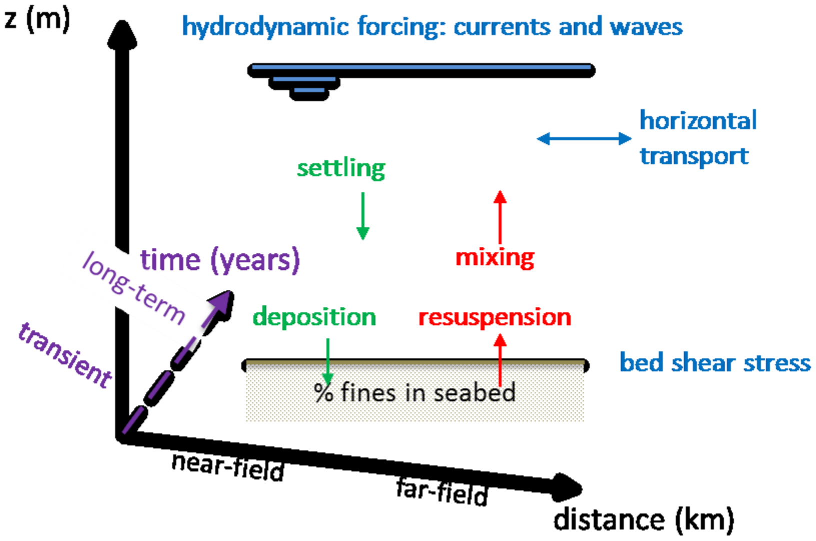

Figure 4.2 Illustration of processes important for fine sediment transport within space and time.

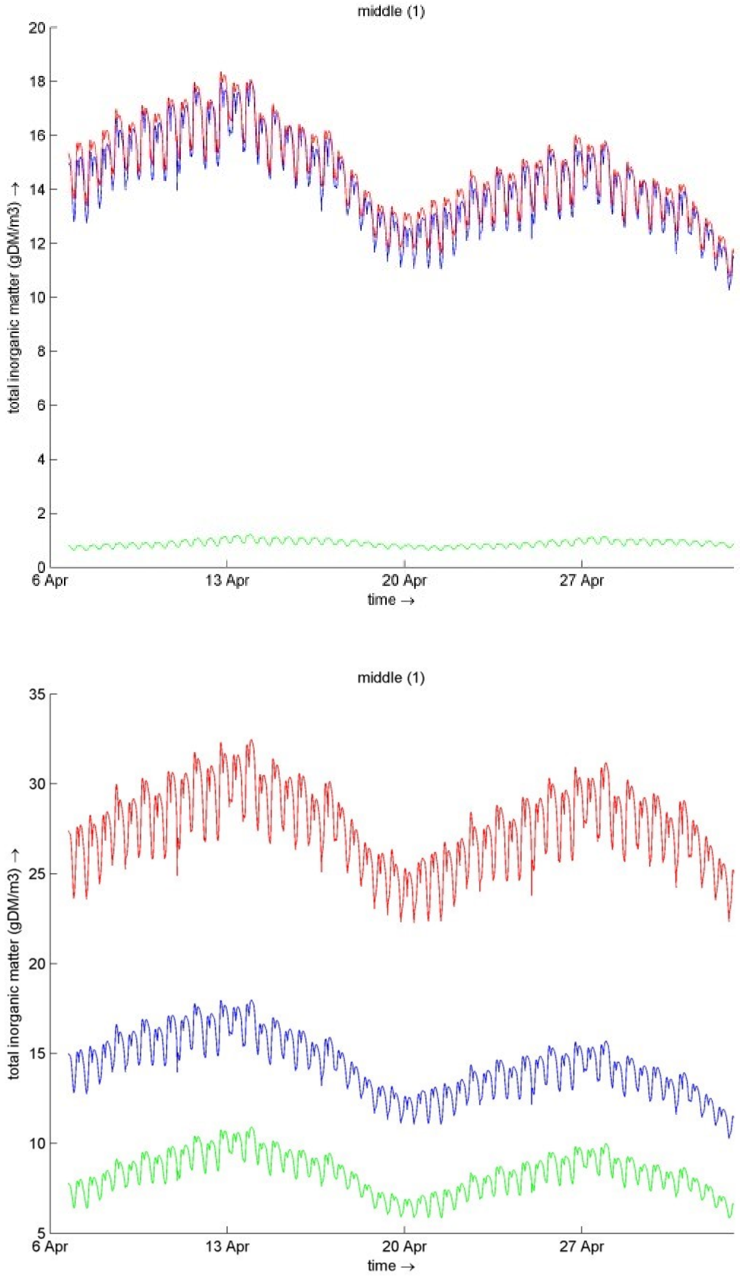

Figure 4.3 Illustration of effect of mixing (top) and resuspension (bed shear stress, bottom) on near-surface SPM concentration (mg/l). Blue line: reference. Red line: more mixing or more resuspension. Green line: less mixing or less resuspension.

The effects of changes in mixing and bed shear stress (i.e. resuspension) are illustrated in Figure 4.3. These results are obtained with a 1DV model for conditions similar to those encountered at the North Sea. From this figure it is clear that a) changes in mixing have an important influence on SPM levels, but only at low mixing intensities and b) changes in bed shear stress also have an influence on SPM levels, with higher shear stress values resulting in higher concentration levels. In the short term this effect is proportional, in the long term (not shown) the effect is smaller because of changes in bed composition as adaptation to the new OWF-including situation.

It is noted that there is an essential difference between SPM stratification and salinity or temperature stratification. On the one hand sediment stratification is more easily created (i.e. may occur at higher levels of vertical mixing) because of settling velocity. So, the impact is more important than for temperature and salinity stratification. On the other hand, after being mixed up sediment stratification re-establishes quicker than salinity or temperature stratification, which are not generated internally but need an external energy or salinity flux to unbalance the well-mixed state.

From the Environmental Impact Assessment on the effects of sand mining in the Dutch part of the North Sea it can be inferred that the potential influence of OWF on SPM transport can be significant, due to their (intended) location in areas with high SPM loads. The importance of the coastal river (ROFI: Region Of Freshwater Influence) in the cross-shore and longshore transport is large (Van Hout et al., 2015). Any changes in the stratification of this ROFI, its cross-shore extension or its distance from the shore may impact the transport of SPM from/towards the coast and along the coast towards the Wadden Sea.
If OWFs placed in or in the vicinity of the Rhine ROFI would influence salinity stratification, this could therefore also have an impact on the density-driven cross-shore SPM concentration gradients. A less pronounced stratification would reduce this gradient and may result in lower nearshore SPM levels but in higher offshore SPM levels. It may also affect the location of the near-shore zone of increased SPM concentrations along the Dutch coast.

4.3 Seabed morphodynamics

4.3.1 Bed composition

Bed shear stress is influenced by waves and tidal currents and is especially high in shallow areas as can be seen in Figure 4.4. In areas with relatively low bed shear stress, OWF can significantly influence this stress (increasing tidal currents around turbines foundations), causing resuspension of SPM and sediments that otherwise would remain near or in the seabed. Baeye & Fettweis (2015) suggest that bio-fouling and scour protection can act as a trap for mud, due to the locally reduced shear stress catching mud in the scour protection around the wind farm foundation during low tidal currents, which is then resuspended during increased tidal currents. Such release, resuspension or mixing up of SPM may also be the cause for the plumes visible in the wake of the Thanet OWF (Figure 4.5, see also Vanhellemont & Ruddick 2014). It should be noted that the plumes visible at Thanet are in an area with a relatively high SPM load. Here, the observed plume could be well related to this relatively high local SPM load that is mixed up to surface waters. However, the same plumes were also visible in Belgian waters (Figure 4.6, Baeye & Fettweis 2015), which are relatively poor in SPM load. Over time, increased resuspension and subsequent transport of fine sediment from the bed can lead to coarser bed sediment. Regarding the situation in Belwind OWF, it may well be possible that the same phenomenon exists in the Dutch OWF; at the time of writing this report, we did not know of any such observations.

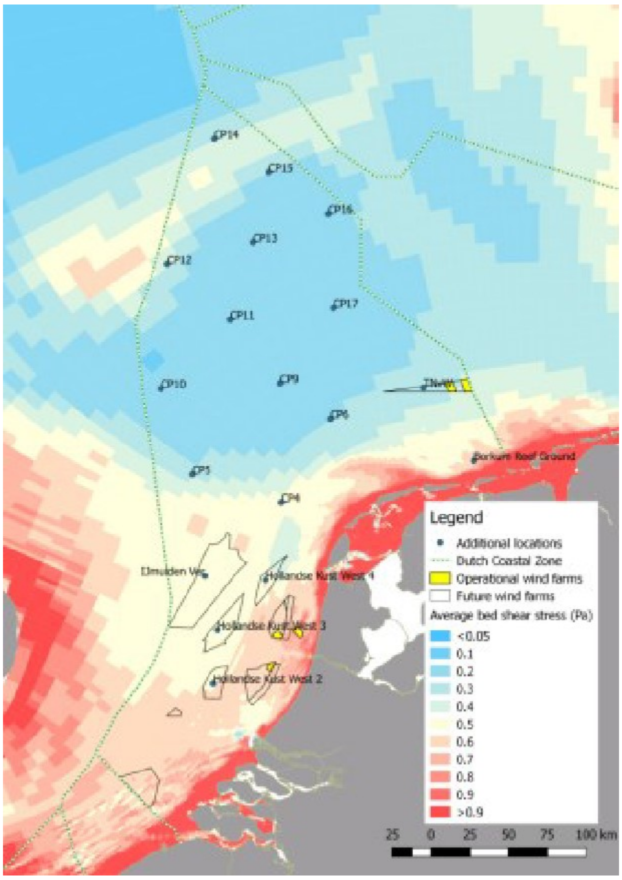

Fig. 4.4 Modelled bed shear stress in the southern North Sea (van der Kaaij et al., 2017).Note that the area planned for OWF “Borssele” is not assigned in this figure (bordering the Belgian part of the North Sea), and the areas called “Hollandse Kust West 2” and “4” are now named “Hollandse Kust South” and “North” respectively.

Fig. 4.5 SPM plumes in the wake of Thanet OWF. Source : https://earthobservatory.nasa.gov/images/89063/offshore-wind-farms-make-wakes.

Figure 4.6 SPM plumes in the wake of Belwind OWF (18-03-2014) around maximum flood current (Baye & Fettweis 2015).

4.3.2 Sand waves

On part of the Dutch continental shelf mobile sand waves occur (Damen et al., 2018). These sand waves develop under the influence of tidal currents. These features can range in height from less than 1.5 m up to 10 m and have a wave length of 100 – 1000 m. Under the influence of residual currents (asymmetrical tides) and waves these sand waves can move over the bed surface of the North Sea, with speeds of up to several metres per year in the Dutch part of the North Sea; further south this speed can go up to tens of meters.

The chances of offshore wind farms changing the sand wave dynamics outside the wind farm are not very likely. The shape and mobility of these sand waves are expected to be influenced mainly locally by the wind turbine foundations and scour protection. Within the wind farm, bed height and sedimentological changes are confined to the area directly around the foundation and scour protection, and do not extend further than a few hundred meters (Coates et al. 2014). There are no indications from studies that far-field effect of seabed morphology occur.

However, the formation and mobility characteristics of sand waves are mainly formed under the influence of tidal currents. From the previous chapter, it was assessed that tidal dynamics could be affected by OWFs; in that case sand wave formation and mobility could be affected as well. However, the expectation is that this effect will not be large and fall within the wider variation of mobility of sand waves in the Dutch part of the North Sea. Our ability to predict the height, speed and direction of sand waves has improved recently and this behaviour can now be modelled with a reasonable level of accuracy, given accurate information about the wave climate, hydrodynamic conditions and bed composition.

Hence, the direct impact of OWFs on sand waves is expected to be local near offshore wind turbine foundations and not to be significant at a larger scale. However, as the tidal and residual flow determines the characteristics of sand waves in the North Sea, and these tidal and residual flow forcings may be influenced by the large scale OWFs, it is advised to further investigate the impact on sand waves. If and when sand waves change position, their major relevance is in changing tidal dynamics, and the second-order effects of these tidal dynamics; this probably leads to a new balance in tidal dynamics and the formation and mobility of sand waves. It is this feedback mechanism that appears of most relevance in possible future environmental impacts.

4.4 Knowledge gaps and further steps

For a more thorough analysis and quantification of the effect of OWFs on SPM dynamics, it is recommended to re-run the existing SPM model of the North Sea with an updated hydrodynamic module, including the effects of wind farms on tide, currents, waves, bed shear stress and mixing, and the most recent insights on the spatial extension of the Rhine ROFI and SPM concentrations. This will give a first quantitative estimate of the impact on SPM. This model includes horizontal transport and the vertical processes of SPM settling, remixing and resuspension (including exchange with the seabed via deposition) and computes these fluxes on the different spatial and temporal scales discussed. Without such a model-based approach, quantification is dangerous as both concentration-enhancing and concentration-reducing effects play a role and the resulting net effect varies in space and time, depending on which effect is dominant at a given time and position. In addition, not only the present and local conditions determine this, but also the ambient conditions and the conditions in the past, as SPM dynamics typically are not in instantaneous equilibrium with hydrodynamic conditions but may show important lag (i.e. memory) effects.

The impacts of OWFs on sand waves are expected to be not very large; it might be more relevant to improve our understanding of the feedback mechanisms of sand waves on tidal dynamics.

5 Ecological impacts

5.1 Introduction

The following sections describe the impacts from the physical changes of large-scale offshore wind farms on the chemical and ecological components and processes. Summarised, these effects can be aggregated into four physical impact groups on the level of suspended matter, nutrients, temperature and substrate composition. These factors are dominant parameters affecting the lower trophic levels of the North Sea ecosystem: primary and secondary production, through plankton and benthos.

Section 5.2 describes the possible changes on water quality and primary production. Section 5.3 focuses on the impact on the secondary production level: heterotrophic plankton and macrobenthos. Any knock on-effects on fish, marine mammals and birds are treated shortly in section 5.4. A concluding section on risks, mitigation and research needs has been added in section 5.5.

5.2 Water quality and primary production

Figure 5.1 below illustrates the causal pathways that are assessed in this section. The red arrows depict the main relevant pathways discussed here.

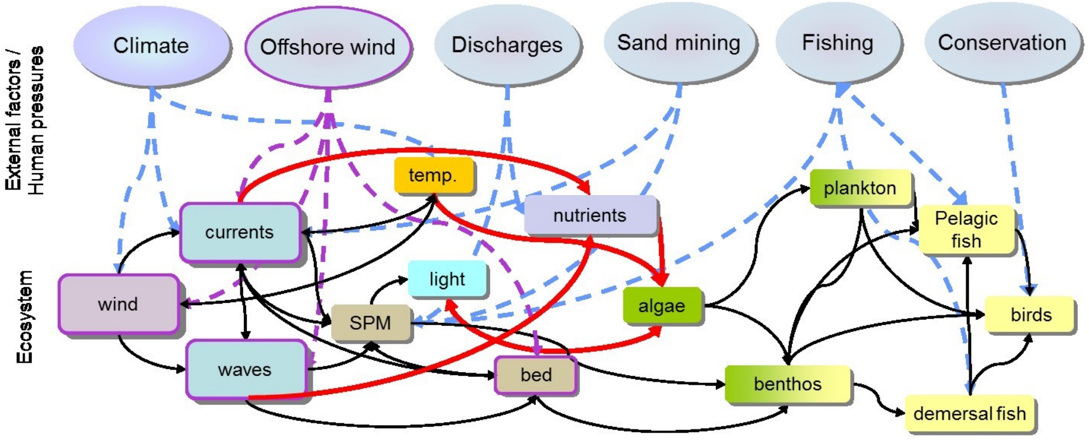

Figure 5.1 Simplified causal network for assessing large-scale offshore wind farm effects on southern North Sea ecosystem; the red arrows depict the main causal pathway discussed in this subsection.

5.2.1 Overview effects nutrients and water quality

1. Near to mid-field effects:
    a. Mixing of nutrients and SPM to the photic zone with impacts on extent and timing of primary production[2] in case of gradients of SPM in mixed waters.

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[2] *Not mentioned explicitly, but changes to water turbulence may change algal species composition, affecting (1) the quality of algae as a food source for algivores, (2) breakdown rates of algal detritus, and (3) the sedimentation of algal detritus to the seafloor.*

   b. Destratification, with the same effects as above, but at different spatial scales since the processes of stratification (temperature mostly) may play out at different spatial scales than simply mixing effects
2. Far-field effects:
   a. Large-scale SPM dynamics: impacts on primary production.
   b. Large-scale transport of nutrients; impacts on primary production.

5.2.2 Effects via nutrient dynamics

Two water quality parameters drive primary production in the North Sea: the availability of nutrients and the availability of light. In the North Sea, around 25% of the available nutrients enter the system from the Atlantic Ocean (a smaller part via the English Channel and the bulk via the connection between Scotland and Norway). Another 25% enters the system via the rivers and is mainly anthropogenic in nature and 50% are recycled internally (OSPAR Intermediate Assessment 2017, Pressures from Human Activities, Eutrophication[3]). It is unlikely that OWFs will influence the input of nutrients via the ocean or rivers. However, as OWFs are likely to influence stratification in certain areas as well as exchange processes between the bed and the water column there is certainly potential to influence the turnover of nutrients and hence the total availability of inorganic nutrients. To what extent there is an effect on remineralisation remains unclear, as this may be influenced by benthic biota and exchange processes. Since OWFs are likely to have some effect on currents and stratification, they will influence the transport of nutrients throughout the system, and therefore the spatial distribution, both horizontally and vertically.

One of the defining characteristics of the Dutch coast is the ‘coastal river’ of water with lower salinity and high nutrient concentrations, the Rhine ROFI. The horizontal extent (away from the coast) of this ROFI has a strong influence on nutrient and SPM transport. Stratification within the Rhine ROFI creates cross-shore transport of SPM and nutrients (De Boer et al., 2009). This in turn has a strong influence on the productivity in the coastal zone, specifically the zone with very high densities of shellfish (Huthnance et al., 2016). Relatively small changes in the way the ROFI can extend further out offshore or is ‘pressed’ against the shore may have large effects on the horizontal distribution of primary production.

In areas that are intermittently stratified, German studies have already shown that in the presence of OWFs stratification can be reduced or even suppressed altogether (Floeter et al., 2017). This will also have large implications for primary production. In areas with seasonal stratification, e.g. in the German Bight, primary production is reduced in summer as nutrients are used up quickly in the top layer (where phytoplankton has access to light) and the higher nutrient concentrations in the lower layers cannot reach the photic zone (Van Leeuwen et al., 2013, 2015). Destratification may well lead to higher levels of primary production in such areas. The fact that algae produced in the photic zone will also quickly reach the bed and be accessible to benthic filter feeders may alter turnover rates. However, it is difficult to predict the ecological consequences exactly without good ecosystem models.

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[3] *https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/pressures-human-activities/eutrophication/nutrient-inputs/*

The change in nutrient ratios over the past decades has already led to a marked change in species composition in the North Sea (Prins et al., 2012). OWFs are not likely to influence the influx of nutrients (through rivers and via the Atlantic) dramatically. However, OWFs may influence the reflux of nutrients from the bottom to the upper water layers, since the speed with which N and P are recycled in the benthic system may differ, OWFs may also have an influence on nutrient ratios. Changes in nutrient ratios and changes to light limitation relative to nutrient limitation may also result in changes in phytoplankton composition (Van Duren et al., 2017). Even if total primary production is not much affected, a change in composition may have impacts on grazers as the nutritional value of species varies.

5.2.3 Effects through changes in SPM dynamics

In the water column, light is attenuated by water itself, by dissolved material, by inorganic suspended material (SPM) and by suspended algae and dead organic material. SPM is generally the dominant factor. As wind farms are likely to alter SPM dynamics, the light attenuation will be affected. This in turn affects primary production. In general: more light attenuation results in lower primary production. Also: a higher SPM content in the water column tends to lead to a later onset of primary production, i.e. the spring bloom will shift to later in the year. This is caused by the fact that the spring bloom is also triggered by light availability. If light is attenuated more, it will take more ambient light to reach this threshold. This threshold will therefore be reached later in the year. This principle is illustrated in a model study in the Scheldt estuary (de Kluijver et al., 2013), a system that is predominantly light limited (Figure 5.2). In model runs with a reduced SPM concentration, primary production is significantly higher, but also the spring bloom starts earlier. In scenario runs with increased SPM levels the opposite can be seen.

The stratification regime will be a major influence on the way SPM resuspension in wind farms will impact primary production. In non-stratified areas, resuspension of fine sediment will quickly disperse the material throughout the water column, affecting light attenuation. In stratified areas this will be different. Fine sediment resuspended from the bed, will disperse through the lower layer, but will not mix into the top layer. Most stratified areas are relatively deep, and the bottom layer will be outside the photic zone anyway. As long as the SPM is contained in this layer, effects on primary production will be limited.

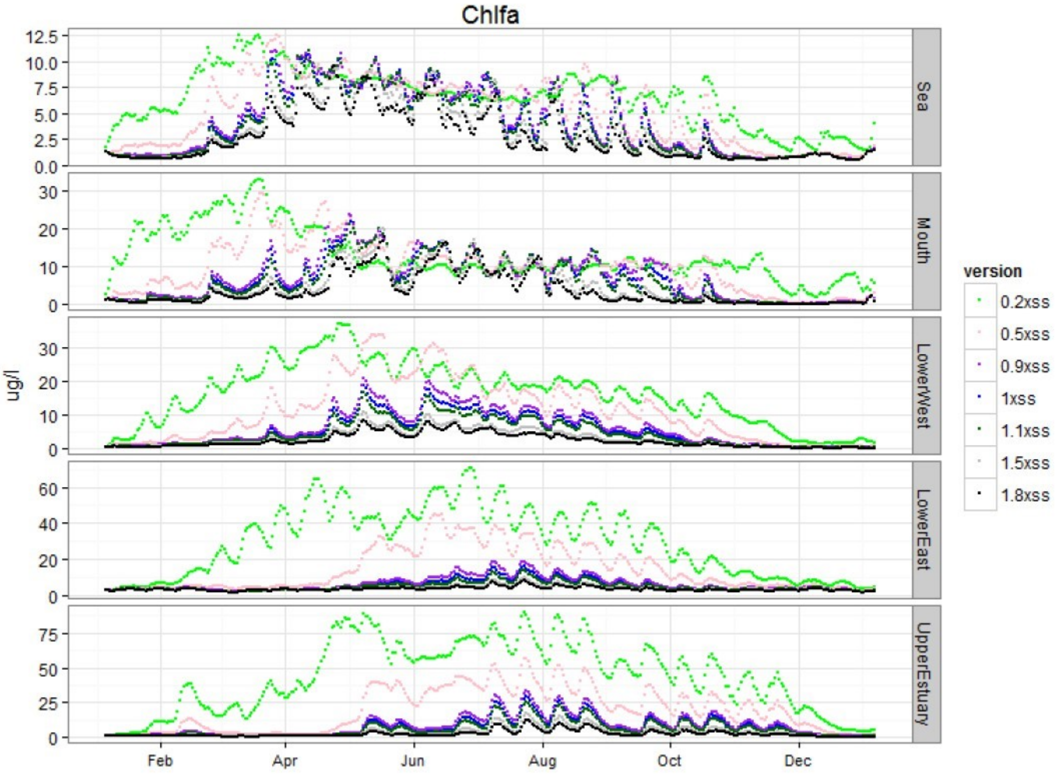

Figure 5.2: Modelled chlorophyll a concentration in the Scheldt estuary with different mud loads. The blue line is the reference situation, green is an 80% reduction in mud load, black is an 80% increase in mud load (de Kluijver et al., 2013).

5.2.4 Interactive effects of nutrients and SPM on primary production

Generally speaking fewer nutrients would imply less primary production and more SPM would also mean less primary production. However, the exact effect of adding or reducing nutrients or SPM may depend on the balance of limiting factors. In a strongly light-limited system, adding more nutrients will have limited effect on primary production. Conversely, if there are no available nutrients, a small increase in SPM is also not going to have a large effect. The North Sea is a light limited system in early spring, after which nutrients limit the primary productivity until late autumn. Due to the relatively high concentrations of suspended matter in the near-coastal areas, light limitation may play a more extensive role here. Increased SPM levels may prolong the light limitation and shorten the role of nutrients.

The ability to cope with either low nutrient levels or low SPM levels differs amongst species of phytoplankton. Some are adapted to cope with strong nitrogen limitation, while others are more adapted to phosphate limited conditions.

The effect of mixing and destratification will vary in time and space. In winter, when large areas are not stratified anyway and productivity is limited by day length and temperature, effects are likely to be minor. However, in spring and summer, for some areas added nutrients to the photic zone will enhance primary productivity, while in other areas added SPM concentration will decrease primary productivity. A priori it is impossible to predict the net effect. However, the current state of ecosystem knowledge and the current technological development of coupled physical-ecological models, does allow the initiation of appropriate modelling studies to gain quantitative insight into the net effects.

5.3 Zooplankton and benthos

Figure 5.3 illustrates the causal pathways that are assessed in this subsection. The red arrows depict the main relevant pathways discussed here.

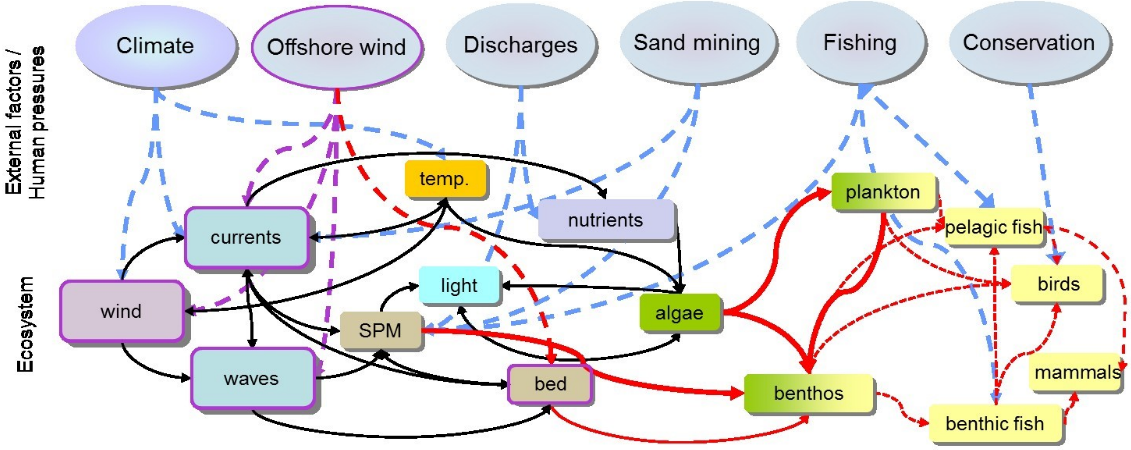

Figure 5.3 Simplified causal network for assessing large-scale offshore wind farm effects on southern North Sea ecosystem; the red arrows depict the main causal pathway discussed in this subsection.

5.3.1 Zooplankton

The impact of offshore wind farms on zooplankton can be established through:

1. Changes to sea surface temperature (SST): changes in temperature affect the onset of growth, abundance and composition of zooplankton.
2. Changes to the primary production: quantity, quality and timing of available food impact the peak and growth of zooplankton.
3. Competition between zooplankton and zoobenthos; reduction of available food (algae) due to filtering by epifauna on wind farm foundations

Changes to SST

Changes in zooplankton composition are regionally and locally related to changes in SST.

Two main groups of zooplankton can be discerned: species that remain planktic their whole lifetime, holozooplankton, and species that are planktic only in the early period of their life cycle (meroplankton) such as larvae of benthic organisms and fish (Fransz et al., 1991, Johns and Reid, 2001).

Since around 1960, CPR data have shown that climatically forced changes in the North Atlantic Oscillation (NAO) have triggered changes in sea surface temperature (SST) and affected changes in the abundance of the main copepod species *Calanus finmarchicus* and *Calanus helgolandicus* (Johns and Reid, 2001, Alvarez-Fernández et al., 2012). Beaugrand et al. (2014) modelled these changes based on the thermal tolerance of copepod (pseudo) species and found a strong correlation with observed monthly SSTs from 1958 to 2009. *Also, timing of the peak abundance has shifted forward in time due to SST rise over the last decades* (Beaugrand, 2003). These changes were thought to be triggered by climate- forced changes to water currents. Moreover, also intra-annual variability of water temperature was of influence on the onset of zooplankton growth (Suchy, 2014). The same was found for the meroplankton: *changes in composition and peak abundance were related to regional and local SST changes* (Lindley and Kirby, 2007).

Changes to primary production and trophic mismatch

Phytoplankton is the major food source for zooplankton; any changes in the total biomass and production, composition and timing of the phytoplankton growth is likely to affect zooplankton dynamics as well.

Since the availability and the quality of food is a major determining factor for the abundance of zooplankton in the growth season, any change to the total primary production and the composition of phytoplankton is likely to affect the total production of zooplankton. As is indicated in paragraph 5.2.4, changes in primary production are possible due to mixing of nutrients and suspended matter, and these are likely to affect the total production of zooplankton in a given area. *Total food availability, but also the quality (through phytoplankton composition) has been shown to have a major influence of the zooplankton growth* (Suchy, 2014).

Where phytoplankton growth is mainly determined by available light and nutrients, and zooplankton is governed importantly by *temperature*, changes at this level could in principle lead to *trophic mismatches* (Edwards and Richardson, 2004): prey and predator do not develop in the same time frame, leading to a reduced food availability for the predator with a reduced growth rate or abundance as a result. Where meteorological changes affect air and thus water temperature, or destratification occurs, such trophic mismatches may occur.

Another possible factor affecting zooplankton density is the *competition for phytoplankton with newly established shellfish or other filter-feeding organisms* that live on the foundation and scour protection. Overgrazing by shellfish in the Oosterschelde is now seen as the main cause for the decrease of primary production (Smaal et al., 2013), and may also limit the growth of zooplankton. Slavik et al. (2018) modelled a significant decrease in phytoplankton around offshore wind farms based on mussel biomass and filtration rates on the wind farm foundations.

5.3.2 Macrobenthos biomass and production

The impact of offshore wind farms on macrobenthic biomass and production can be established through:

1. Cessation of bottom trawling
2. Introduction of hard substrates with consequences for:
    a. Biodiversity and biomass
    b. Fouling and concomitant effects
    c. Availability and quality of organic matter (food)
    d. Seabed changes in dynamics and sedimentology

Cessation of bottom trawling

The cessation of trawling may enhance recovery of benthic communities within offshore wind farms.

Various studies have been conducted with regard to the effect of the cessation of bottom trawling on the macrobenthic diversity and production. At larger distances from the foundations and scour protection (> 100 m), some subtle changes have been found that cannot be attributed to the local influence of the wind farm's foundations; these changes have been attributed to the disappearance of beam trawl fisheries within the Belgian wind farms (Coates et al., 2016), as was also suggested in a German study in a non-fished area in the German Bight (Dannheim et al., 2014). Recent findings around Belgian wind farms also demonstrated a difference in community structure close by and far away (but still within the OWF) from the foundations (Degraer et al., 2016); changes in increased organic matter in and sedimentology of the seabed found near offshore wind farm foundations may be related to this (Coates et al., 2016)[4]. Also, samples from within C-Power OWF showed the presence of *Mytilus edulis* clumps and *Anthozoa sp.* in soft sediment samples; these species were (virtually) absent from reference locations outside the OWF (De Backer & Hostens in Degraer et al., 2018). According to the authors, this suggests that the reef effects of the OWF foundations are spreading beyond the direct influence sphere of the OWF foundations. However, no community level changes were documented within sandy sediments in Dutch wind farms Bergman et al. 2014. Also, recently, no differences in community composition within and outside Dutch wind farms were found (Leewis et al., 2018). Note that the results in the shallow, sandy and high-dynamic Dutch coastal zone are not necessarily representative for the effect elsewhere in the Dutch North Sea; a muddier environment in the southern North Sea did show differences in benthic macrofaunal composition between fished and unfished sites (Duineveld et al., 2007). Studies on effects of bottom trawling on benthos have shown that these effects are much stronger in low-dynamic than in high-dynamic environments (Rijnsdorp et al., 2017 and references therein).

Introduction of hard substrates
The introduction of hard substrate impacts the benthos through:

1. Increasing epifaunal biodiversity and biomass, introducing ecological stepping stones
2. Filter-feeding fouling organisms decreasing algal biomass
3. Changes in carbon flow to seabed
4. Changing seabed sedimentology around the scour protection or foundations of offshore wind farms

Epifaunal biodiversity and the stepping-stone effect

Local biodiversity increases due to the increase of formerly rare hard-substrate habitats in the North Sea and adding formerly absent intertidal hard substrate introducing new species. Distribution of fouling species is facilitated.

Recent North Sea studies of the growth and diversity of epifaunal organisms on offshore wind farms and platforms have been conducted by Vanagt et al. (2013), Krone et al. (2013), and Mesel et al. (2015). These studies show that biodiversity is substantially enhanced in sandy areas where previously no hard substrate was found. Such fouling organisms are also present on buoys, and the many wrecks littered throughout the North Sea. The construction of offshore platforms and wind farms has contributed to an increase in their distributions and

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[4] *Note that in Coates et al. (2016) the increased TOC and mud concentrations coincided with the presence of Lanice conchilega. Although not postulated in their paper, cause and effect could be reversed: L. conchilega causing increases in TOC and mud in the sediment instead of the reverse.*

numbers; species on the intertidal and subtidal hard substrate add up to around 80 unique species. The construction of offshore wind farms adds to this in two ways. First (and most foremost), they introduce a number of new species, typical for intertidal environments, including a number of non-indigenous species (NIS) (Coolen et al., 2015), and thus increase the per-sample species number (alpha-diversity). Second, due to the addition of subtidal hard substrate at a regional scale, they change the regional (beta-)diversity.

The distribution of these organisms is mainly mediated through the regional and local hydrography; larvae are transported through water currents from source to sink. The speed of transport and duration of the larval phase are important parameters in the (hydrographic) distance between two connected populations of a species. Coolen et al. (2017) studied the role of hard structures offshore such as wind farms and oil and gas exploitation platforms in the North Sea. The role these structures play in the distribution of hard substrate species is termed the stepping-stone effect: each structure can act as a sink and source of these species and with decreasing distance between the structures the spatial distribution of species can be facilitated. They found a clear stepping-stone effect of these structures in the North Sea. Any additional wind farm will enhance this stepping-stone effect, which may lead to more comparable species compositions and a lower species genetic diversity. When offshore wind farms are placed near locations where species' distribution is hindered by hydrodynamic boundaries, this could lead to an additional spread of non-endemic species (Adams et al., 2014).

Epifaunal biomass

Offshore wind farms supply an increased surface on which fouling organism can grow.

Slavik et al. (2018) modelled the increase of biomass of mussels growing on current and projected offshore wind farms in the southern North Sea (epistructural mussels), see Figure 5.4. Scour protection around piles adds to hard substrate, but lower in the water column, with an estimated addition of over 100 km^2 hard substrate, including cable crossings etc.
They calculated an increase of 42 kilotons, compared to an existing epibenthic mussel biomass of 96 kilotons, a ca. 50% increase. Importantly, the epistructural mussels grow at different locations from the existing epibenthic mussels, see Figure 5.5. Although mussels are a dominant species on these structures, other species, such as *Metridium senile* (frilled anemone) will add significantly to this biomass (Van der Stap et al., 2016).

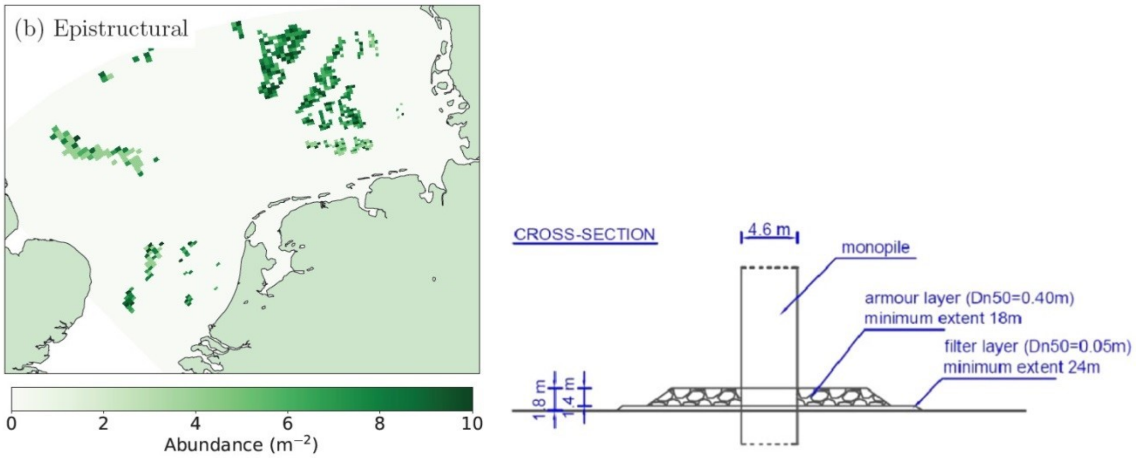

Figure 5.4 Left: modelled abundance of mussels on OWF piles. Right: dimensions of monopoles scour protection (Slavik et al., 2018).

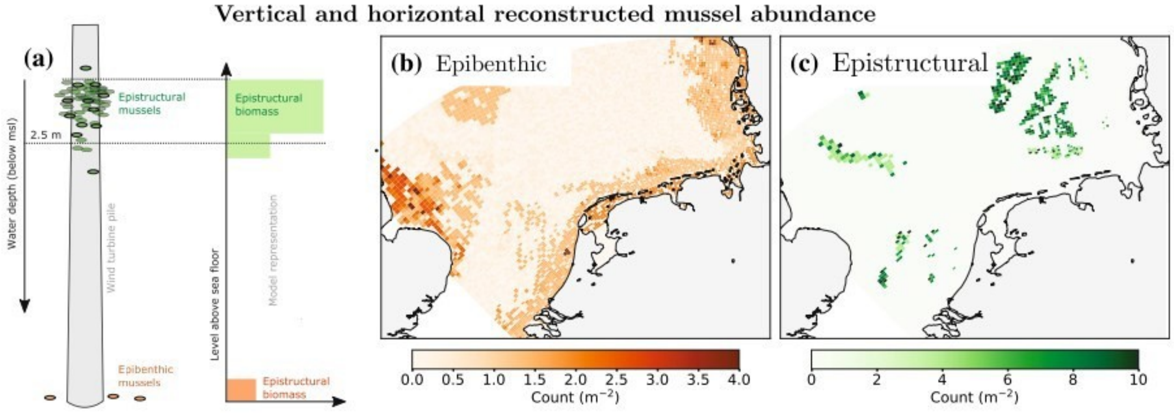

Figure 5.5 (a) Vertical representation of epibenthic and epistructural M. edulis as observed (left) and in the model space (right). Epibenthic mussels are homogeneously distributed in the lowermost model layer. Epistructural mussels are equally distributed in all model layers above 2.5 m depth, and proportionally in the model level encompassing the 2.5 m depth contour. No mussels are considered in the intermediate layers. (b) Reconstructed abundance of M. edulis at the sea floor, estimated from the presence and count data and sediment habitat mapping; (c) Abundance on wind turbine piles, estimated from scaling individual pile monitoring observations to the coarse model grid (Slavik et al., 2018).

In a zero-sum situation (without changes to primary production (PP)), this increase in biomass will lead to reductions in biomass of other organisms. In the case of changes to PP, such reductions can be compensated (increase in PP) or aggravated (decrease in PP). Which organism groups will show a lower biomass is difficult to say, this would require setting up local food web models.

<u>Decrease of algal biomass though filtering by epifaunal organisms</u>
Epifaunal organisms remove algal biomass from the water column through their filtering activities.

Since a large part of these mussels and other epistructural organisms acquire food by filtering, an impact on algal biomass in the upper water column can be expected. Also, they have a function in nutrient regeneration and particulate carbon flow; the organic matter ingested is only partly converted to biomass, the rest is digested and excreted as nutrients and organic matter (faecal pellets). These effects were modelled by Slavik et al. (2018), see Figure 5.6. The model predicts levels of grazer biomass in wind farms that apparently can exert a grazing pressure higher than the turn-over time of the algae. This leads not only to a suppression of algal biomass in the wind farm areas, but also to a top-down control of primary production. As a consequence, the limiting factor for primary production in the immediate vicinity of the wind farm is grazing rate, rather than nutrient limitation. The excess nutrients, when transported out of the range of influence of the grazer population can lead elsewhere to a boost in primary production. Clearly, regional effects of both increases (prolonged bloom) and decreases of primary production resulted from the model, extending to up to 50 kilometres outside the wind farms.

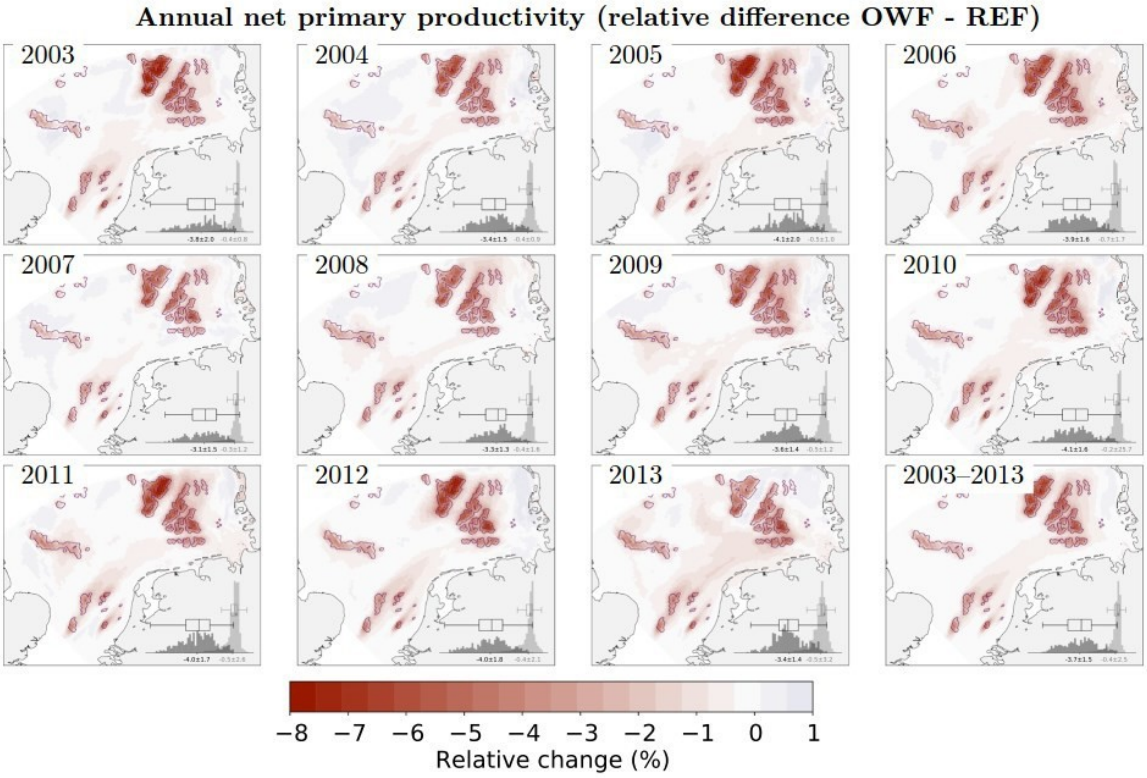

Figure 5.6 Simulated relative difference of annual net primary productivity 2003–2013 between simulations with and without epistructural mussels, calculated as 100(OWF-REF)/REF (Slavik et al., 2018).*

Since the effects are regionally different, gradients in productivity occur, reaching a maximum reduction in annual net primary productivity of 8%. The projected wind farms modelled in Slavik et al. (2018) are not yet the projected wind farm construction around 2050; extrapolating the results of Slavik et al. (2018) gives a significant and substantial spatial change in primary productivity amplitude and patterns throughout the southern North Sea.

<u>Changes in carbon flow to the seabed</u>

Changes in the primary production in and around offshore wind farms will affect the productivity and diversity of the macrobenthos, since the benthos is depending on it for its food.

High biomass and production of the macrobenthos in the shelf sea environment has been related to the favourable food supply to the benthos, which is related to primary production, and mediated by settling in areas with reduced current speeds such as the Frisian Front and the Oyster Grounds (Creutzberg et al., 1984).

Within wind farms, the filtering activities of epifauna on the foundations may create more local shunts of detrital particles to the seabed. This was hypothesised by Coates et al. (2014, 2016) as the cause for the increased organic matter concentrations they found in the seabed near the foundations of a Belgian offshore wind farm. Such localised changes could, if scaled up, lead to significant changes in macrobenthic diversity and production within wind farms, with spill over effects on demersal fish. Also, biological material falling from the foundation due to scour and wave action may locally increase organic matter abundance on and in the seabed (Vanaverbeke et al. 2018).

Seabed dynamics and sedimentology

Foundations and scouring protection around wind farms change local morphology and sedimentology close to wind farm foundations affecting regional benthic diversity and biomass.

As explained above, the large-scale construction of offshore wind farms may cause large- scale changes in physical forcing and food supply. This may have an influence on the diversity and biomass of soft-sediment macrobenthos beyond the near-field effects outside the direct influence of offshore wind farms. Such changes will, however, not be easily documented by small-scale studies such as those carried out recently (Coates et al, 2014), and are in many cases confounded by the effects of the release from bottom fishing pressure (see e.g. the earlier mentioned studies by Reubens et al. (chapter 4 in Degraer et al., 2016), Duineveld et al., 2007, Bergman et al., (2014), Glorius et al., (2016) and Leewis et al,. 2018). Such a large-scale effect could come about through cumulative, small-scale effects of grazing of algae, and shunting of detritus by hard-substrate epifauna, and mixing of water layers in combination with concomitant cumulative effects on suspended matter concentrations and decrease of wave and tidal energy affecting large-scale deposition and erosion effects. Such effects would be influenced by changes in the distribution and intensity of bottom fishing, climate change, and (planned) aquaculture and nature restoration projects.

One of the related pathways that may affect macrobenthic community composition and production is the long-term potential recovery of benthos within wind farms through benthic trawling cessation and local changes in TOC fluxes, and sediment composition, leading to local increases in sensitive bio-engineering species such as tube building worms like *Lanice conchilega* and oysters (*Ostrea edulis*, *Crassostrea gigas*), which may affect regional recruitment and recolonization processes. Such local changes may thus lead to ‘spill-over’ effects. Moreover, their influence on changing the physical and chemical seabed characteristics was hypothesised to be substantial (Rabaut et al., 2007, Lunt et al., 2017), affecting sedimentary carbon and nutrient cycling, and is to some extent now established to be a local effect in a Belgian OWF (Vanaverbeke et al., 2018). Also, the reintroduction of oysters and variable hard substrate types (to enhance growth of hard substrate fauna) within OWF may lead to comparable processes.

5.4 Higher trophic levels

Changes in zooplankton and benthos affect higher trophic levels, i.e. fish, birds, and marine mammals.

The changes to the system at the level of primary and secondary trophic levels are likely to influence the higher trophic levels, i.e. fish, marine mammals and birds. The direction and magnitude of these effects are very hard to assess, since even the direction and magnitude of the effects on the lower trophic levels are uncertain. Furthermore, they may be direct effects of physical and chemical ecosystem changes to fish, marine mammals and birds. Changes in SPM loads may affect feeding success of diving birds, hunting on sight (Baptist and Leopold, 2010).

Knock-on effects of zooplankton changes to higher trophic levels can be expected. (Hufnagl et al., 2017, Payne et al., 2008) analysed the failing recruitment of herring and found a good correlation with the decreased availability of important larval herring prey copepod species, although also hydrographic changes shifting frontal areas and increased warm-water predatory species such as sardines and anchovy may have contributed to the failed herring recruitment. Arnott and Ruxton (2002) found comparable relationships between sandeel recruitment and the (NAO-forced) temperature and density of *Calanus sp*. Since both herring and sandeel are important stock species for other fish and marine mammals (Gilles et al., 2016) as well as for several seabird species, any changes in their abundance and distribution possibly affect further higher trophic levels.

Some studies in the southern North Sea wind farms point to changes at higher trophic levels. Degraer et al. (2012) showed differences in flatfish feeding patterns within and outside wind farms. In a more recent study (Degraer et al., 2016), such patterns were also found for the lesser weever and dab, linking their feeding habits to prey species typical for wind farms hard substrates. Whether the availability and ingestion of local prey species will provide profits for these species and lead to a higher survival of the individuals living around wind farms has not been established. Bergström et al. (2013) found increases in piscivorous fish near the piles in an offshore Swedish wind farm in the Baltic Sea. Within the Dutch wind farm OWEZ, increased densities in sole, whiting, and striped red mullet were found compared to outside the wind farm (Lindeboom et al., 2011). The upscaling of wind farms in the southern North Sea will provide more feeding opportunities for fish, but whether this will lead to higher survival rates is unknown.

Increasing fish densities within wind farms may lead to increased presence of seals and porpoises within wind farms. Individuals have been spotted swimming in wind farms, and seal tagging revealed individual seals swimming and foraging in UK and Dutch wind farms (Russell et al., 2014). However, this study did not assess a structural increase in the presence of seals within offshore wind farms in comparison to areas outside, but the seals did visit the OWF, presumably for foraging (confirmed by S. Brasseur, pers. comm.).

The same reasoning holds for harbour porpoises and birds: they could profit from increased fish and shellfish presence in wind farms. Cormorants have been found to actively forage within Dutch wind farms, using the platforms for drying their wings (Hartman et al., 2012). Other birds, such as gannets, avoid the wind farms and are thus not likely to profit, they may even lose habitat by avoiding OWF. Any changes in the distribution of fish may lead to changes in the distribution of their predators, and large-scale presence of wind farms in the southern North Sea thus has the potential to change the large-scale distribution of marine mammals and birds. Whether marine mammals and birds profit from an increased presence of fish and shellfish remains to be studied.

5.5 Conclusions ecological impacts

The impacts of the large-scale development of offshore wind farms on the ecology of the (southern) North Sea can theoretically be extensive and significant. The uncertainties about the direction and extent of the net effect are large. Various effects, such as an increase in SPM and nutrients in the top water layers may counteract each other and make intuitive prediction of the net result extremely difficult. Based on expert judgement, some tentative differentiation in risks can be given. Priority risks from the ecological viewpoint are expected to be the following:

- Destratification within, and downstream of wind farms may lead to significant changes in the timing and spatial distribution of primary production, having knock-on effects on secondary production (zooplankton and benthos).
- Feeding activities from epistructural fauna on the offshore wind farm foundations may significantly decrease phytoplankton densities around wind farms affecting in turn zooplankton densities.
- Changes in significant wave height leeward of offshore wind farms extend over tens of kilometres and may also affect the upper water layer mixing. In coastal areas, where depth is less than 10 meters, such changes in wave heights may impact density driven transport of suspended matter and influence the ROFI, affecting fresh water and nutrient distribution with impacts on primary production and shellfish production.
- The stepping-stone effects from the offshore wind farms may be serious and lead to genetic homogenisation and to the spread of species beyond their natural boundaries. This specifically holds for non-endemic species that are found in the intertidal zone of offshore wind farm foundations. The many structures currently present in the North Sea (buoys, platforms, but also vessels) already contribute to these processes, but in contrast to wind farms, they have no intertidal zone (Van Duren et al., 2016). Also, for subtidal species, the additional hard substrate in offshore wind farms may provide stepping stones that tip the balance.

Other effects such as changes to the composition and production of sediment macrobenthos are mostly expected to be local, and may extend beyond offshore wind farm boundaries, partly due to the effects described in the bullets 1 and 2 above. Furthermore, the effect of tidal current blockage by OWF may have repercussions for tidal dynamics in the southern North Sea. Although the way in which such changes to tidal range near and further away from amphidromic points may occur is not entirely clear and thus somewhat controversial, but the far-field effects in combination non-linear behaviour of these dynamics are perceived as a potential medium risk. The stepping stone effects of the offshore wind farms may lead to genetic homogenisation and to the spread of species beyond their natural boundaries. This specifically holds for non-endemic species that are found in the intertidal zone of offshore windfarm foundations.

The many structures currently present in the North Sea (buoys,platforms, but also vessels) already contribute to these processes, but in contrast to wind farms have no intertidal zone (Van Duren et al., 2016). Also, for subtidal species, the additional hard substrate in offshore wind farms may provide stepping stones that tip the balance. Changes in the timing of primary production due to SPM increases may cause a trophic mismatch between the phytoplankton and algivores such as zooplankton and benthic larvae whose dynamics are importantly temperature driven. These effects cannot be assessed currently due to major knowledge gaps on the presence, composition, spatial distribution and (interannual) variability of zooplankton in the Dutch part of the North Sea; only large-scale CPR data give some insight in compositional changes of macro(holo)zooplankton species in the larger North Sea (Beaugrand et al,. 2014).

Low risks are those of local effects on bed morphology and sedimentology, SPM resuspension effects around offshore wind farms (creating the so-called plumes) if not related to destratification and impacts on sand waves.

As already pointed out, the uncertainties in determining the direction and extent of the effects are large. It is crucial to better understand the physical and chemical drivers of primary production, as this forms the basis of the food web. We consider this the main knowledge gap. Related to the prioritised effects above, the main knowledge gaps and how the knowledge can be improved are the following:

1. Field studies on the phytoplankton composition, biomass and production around offshore wind farms in concurrence with the studies to mixing and destratification events, and nutrients and SPM concentrations (following studies such as Floeter et al. 2017). Such data should be used for calibrating models such as the DCSM that is in development at Deltares.
2. The above effects on secondary (zooplankton and shellfish) production also remain a field in dire need of measurements and modelling.
3. The clearance rates and thus algal grazing of epistructural species should be better measured and their effect on algal densities assessed in experiments, and in the field. Such data should be used to build and validate depletion models such as those in Slavik et al. (2018).
4. Zooplankton as a subject of study, either of holozooplankton or of meroplankton in the southern North Sea (and adjacent areas) is virtually absent. Our knowledge gaps here are major and a structural sampling program is needed to start filling even the most basic knowledge gaps.
5. The spatial distribution of the genetic makeup of epistructural species needs to be further investigated in combination with hydrodynamic modelling to assess the risk of spread of non-endemic species.

As pointed out above, any significant changes in the processes at the base of the food web, prioritized in this list, may have consequences for higher trophic levels and for community composition. Therefore, the basic changes in the food web have received the highest priority, assuming that they may guide to further possible changes in the ecosystem. In this approach, knowledge development is first oriented at system level. It will direct field measurements, experiments and modelling of the coupled physical-ecological system, but also identify areas of possible further-reaching effects at higher trophic levels.

6 Synopsis

This chapter reviews the earlier chapters, organises the described cause-and-effect relationships, highlights the perceived major risks, and integrates the various knowledge gaps and steps ahead for developing our knowledge on the impacts of large-scale constructions of offshore wind farms.

6.1 Feedback mechanisms

Feedback mechanisms are the processes by which information of an effect is ‘fed back’ into the causal chain. As an example, morphodynamics have a feedback effect on the hydrodynamics: when changes in current speed and/or direction occur, sandy sediments react by erosion or deposition of sand and morphology (and sedimentology) changes. As a result, local hydrodynamics are changed, and this interaction then works towards a local equilibrium. Such feedback mechanisms commonly are antagonistic: they weaken each other so a balance can be found. Other feedback mechanisms can be synergistic: they enforce each other causing a cascade of interacting effects away from any equilibrium.

An important conclusion of this study so far is that we have not identified any synergistic feedback mechanisms that could lead to derailments of the physical processes. However, we have to stress the high level of uncertainty in the impact assessments in this study and cannot link any well-founded accuracy to this assertion.

6.2 Risk assessment and prioritisation

The following possible effects have been identified and prioritised according to their risks:

- Interactions OWF with wind: effects are commonly assessed as being local, but a large-scale development of OWF may lead to (as yet poorly quantified) effects on the vertical transfer of energy from the higher atmosphere to the OWF, impacting wind and waves.
- Effect of OWF on waves through wind: the impact of reduction of wind speed on wave generation may be quite significant, and scenarios show that effects on wind in the order of magnitude of 20% have far-field effects on waves over tens of kilometres. SAR images seem to confirm these effects. Such changes in wave heights may impact density driven transport of suspended matter and influence the ROFI, affecting fresh water and nutrient distribution with impacts on primary production and shellfish production.
- Interaction of OWF with currents: vertical mixing in and around OWF is an established phenomenon, that in accumulation may lead to destratification and resuspension of SPM and nutrients. Although these effects are, in contrast to the foregoing impacts more near-field than far-field, large-scale OWF or OWF clusters may cumulatively destratify waters that would otherwise be stratified in the area. This may affect the redistribution of nutrients into the surface (light) layer, as well as the access of benthic filter feeders to phytoplankton, and therefore non-linearly change the primary production and the food web.
- Feeding activities from epistructural fauna on the offshore wind farm foundations may significantly decrease phytoplankton densities around wind farms affecting in turn zooplankton densities, as well as nutrient regeneration and primary production.

Medium risks are the changes brought about by offshore wind farms to (soft) sediment macrobenthos and temporal mismatch between phytoplankton production (due to changes in SPM concentrations) and the growth onset of zooplankton and benthic larvae (temperature controlled). Furthermore, the effect of tidal current blockage by OWF may have repercussions for tidal dynamics in the southern North Sea. Although the way in which such changes to tidal range near and further away from amphidromic points may occur is not entirely clear and thus somewhat controversial, but the far-field effects in combination non-linear behaviour of these dynamics are perceived as a potential medium risk. The stepping stone effects of the offshore wind farms may lead to genetic homogenisation and to the spread of species beyond their natural boundaries. This specifically holds for non-endemic species that are found in the intertidal zone of offshore wind farm foundations. The many structures currently present in the North Sea (buoys, platforms, but also vessels) already contribute to these processes, but in contrast to wind farms have no intertidal zone (Van Duren et al., 2016). Also, for subtidal species, the additional hard substrate in offshore wind farms may provide stepping stones that tip the balance.

Low risks are those of local effects on bed morphology and sedimentology, SPM resuspension effects around offshore wind farms (creating the so-called plumes) if not related to destratification and impacts on sand waves.

6.3 Knowledge development: data and modelling

As said several times before, large uncertainties surround the assessment of the (cumulative) impacts on the North Sea physics of the possible large-scale developments of OWF. Various types and sources of uncertainties can be identified (Milner-Gulland & Shea, 2017), such as process uncertainty (system variability), observation uncertainty (measurement related), structural uncertainty (knowledge related), and linguistic uncertainty (concept related).

We have, in general, a good knowledge basis for hydrodynamic and meteorological processes in the North Sea. The most important challenge is in the proper representation of how OWF deployment interacts with these physical processes. A single wind turbine is very small in comparison with the domain of study. Modelling approaches thus require very high resolution to properly study the wind turbine and its interaction with the physical process, whereas at the other hand the large scale of OWF deployment requires large model domains even extending beyond the North Sea area.

In order to solve these problems, we need a combination of observational and modelling studies; data collecting, and model development and validation will need to be used interactively to further our understanding of system functioning and fill the observational gaps. Model approaches at different levels of spatio-temporal resolution will be needed, where in particular the problem of proper integration of these different models is posed. Data and observations will need to reflect these needs in model development, and provide the level of detail, as well as full spatial coverage, needed for model validation. Data collection should also consider remote sensing techniques and local data gathered by the OWF industry.

Currently, the main development pathways for improving our understanding of the effects of the possible large-scale development of OWF in the southern North Sea are linked to the main risks identified in earlier sections of the report and mentioned above:

i. Combined atmospheric and wave modelling on different scales up to resolutions of 100 m by 100 m which can be achieved by coupling atmospheric mesoscale, LES and spectral wave models. Further data mining of satellite images is needed to validate these model results. Local data on wakes of offshore wind farms are strongly needed.
ii. Develop a hydrodynamic model for assessing effects of OWF on tidal dynamics, based in the flexible mesh model for the Dutch continental shelf (DCSM), and using appropriate parameterization of the wind farms.
iii. Re-run the existing SPM and water quality model of the North Sea with an updated hydrodynamics, including the effects of wind farms on tide, currents, waves, bed shear stress and mixing, nutrient dynamics, primary and secondary production. For calibration and validation, a monitoring campaign needs to be set up around offshore wind farms focusing on vertical mixing/destratification events, SPM and nutrient concentrations, phytoplankton abundance and composition, primary and secondary production, and algal grazing of epistructural species.

All steps are relatively easy to carry out, since for all aspects, the basis (or an important part thereof) has already been developed. Hence, important progress for these parts can be made on a relatively short time frame (within a year). The combined wind and wave modelling will be the largest challenge, since there are many unknowns that still need to be identified and quantified.

Another, more difficult step would be to re-use the outcomes of the different models and actually integrate the various possible effects on wind, waves, hydrodynamics and morphodynamics.

Additionally, it is advised to start up a zooplankton sampling campaign (preferably concurrent with the existing phytoplankton monitoring program at the Dutch part of the North Sea), since there is no structural data on this species group linking effects of phytoplankton to the higher trophic levels. These data are crucial if we are to improve our understanding of how effects on algal biomass and primary production can propagate to the higher trophic levels of fish, birds and marine mammals. The inclusion of meroplankton would benefit our understanding of how benthic larvae and recruitment may be affected by changes in food availability, and changes in sediment morphology, sedimentology and detritus input.

References

Abkar, M. A., F. Porté-Agel. 2014. Mean and turbulent kinetic energy budgets inside and above very large wind farms under conventionally-neutral condition. Renewable Energy 70: 142-152.http://dx.doi.org/10.1016/j.renene.2014.03.050

Adams, A.S. and D.W. Keith. 2013. Are global wind power resource estimates overstated? Environ. Res. Lett. 8 015021

Adams, Thomas P.; Miller, Raeanne G.; Aleynik, Dmitry; Burrows, Michael T.; Frederiksen, Morten 2014. Offshore marine renewable energy devices as stepping stones across biogeographical boundaries. In J Appl Ecol 51 (2), pp. 330–338. DOI: 10.1111/1365-2664.12207.

Alari, V. and U. Raudsepp, 2012: Simulation of wave damping near coast due to offshore wind farms. *Journal of Coastal Research, 28*(1), 143-148. doi: 10.2112/JCOASTRES-D- 10-00054.1.

Alvarez-Fernandez, S.; Lindeboom, H.; Meesters, E. 2012. Temporal changes in plankton of the North Sea: community shifts and environmental drivers. In *Mar. Ecol. Prog. Ser.* 462, pp. 21–38. DOI: 10.3354/meps09817.Arnott, S. A.; Ruxton, G. D. (2002): Sandeel recruitment in the North Sea: demographic, climatic and trophic effects. In Mar. Ecol. Prog. Ser. 238, pp. 199–210. DOI: 10.3354/meps238199.

Badger and Volker, 2017. Efficient large-scale wind turbine deployment can meet global electricity generation needs, PNAS, 114 (43), http://www.pnas.org/content/pnas/114/43/E8945.full.pdf.

Baptist, M.J.; Leopold, M.F. 2010. Prey capture success of sandwich terns *Sterna sandvicensis* varies non-linearly with water transparency. Ibis 152(4): 815-825

Baeye, Matthias; Fettweis, Michael 2015. In situ observations of suspended particulate matter plumes at an offshore wind farm, southern North Sea. In *Geo-Mar Lett* 35 (4), pp. 247– 255. DOI: 10.1007/s00367-015-0404-8.

Beaugrand, Gregory 2003. Long-term changes in copepod abundance and diversity in the north-east Atlantic in relation to fluctuations in the hydroclimatic environment. In Fisheries Oceanogr 12 (4-5), pp. 270–283. DOI: 10.1046/j.1365-2419.2003.00248.x.

Beaugrand, Grégory; Goberville, Eric; Luczak, Christophe; Kirby, Richard R. 2014. Marine biological shifts and climate. In *Proceedings. Biological sciences* 281 (1783), p. 20133350. DOI: 10.1098/rspb.2013.3350.

Bergman, Magda J. N.; Ubels, Selma M.; Duineveld, Gerard C. A.; Meesters, Erik W. G. 2015. Effects of a 5-year trawling ban on the local benthic community in a wind farm in the Dutch coastal zone. In *ICES Journal of Marine Science* 72 (3), pp. 962–972. DOI: 10.1093/icesjms/fsu193

Bergström, L.; Sundqvist, F.; Bergström, U. 2013. Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community. In Mar. Ecol. Prog. Ser. 485, pp. 199–210. DOI: 10.3354/meps10344.

Bergström, Lena; Kautsky, Lena; Malm, Torleif; Rosenberg, Rutger; Wahlberg, Magnus; Åstrand Capetillo, Nastassja; Wilhelmsson, Dan 2014. Effects of offshore wind farms on marine wildlife—a generalized impact assessment. In Environ. Res. Lett. 9 (3), p. 34012. DOI: 10.1088/1748-9326/9/3/034012.

Boettcher, M, P. Hoffmann, H.-J. Lenhart, K. H. Schlünzen and R. Schoetter, 2015: Influence of large offshore wind farms on North German climate, Meteorologische Zeitschrift, 24 (5) 465–480.

Carpenter JR, Merckelbach L, Callies U, Clark S, Gaslikova L, Baschek B 2016. Potential Impacts of Offshore Wind Farms on North Sea Stratification. PLoS ONE 11(8): e0160830. https://doi.org/10.1371/journal.pone.0160830

Cazenave, P. W., Torres, R., & Allen, J. I. 2016. Unstructured grid modelling of offshore wind farm impacts on seasonally stratified shelf seas. Progress in Oceanography, 145, 25-41.

Christensen, E. D., M. Johnson, O. R. Sørensen, C. B. Hasager, M. Badger and S.E. Larsen, 2013: Transmission of wave energy through an offshore wind turbine farm. *Coastal Engineering, 82*, 25-46. doi: 10.1016/j.coastaleng.2013.08.004

Christiansen, M. B., C. B. Hasager, 2005: Wake effects of large offshore wind farms identified from satellite SAR, Remote Sensing of Environment, 98 (2–3), 251-268, https://doi.org/10.1016/j.rse.2005.07.009.

Clark, S., Schroeder, F. & Baschek, B. 2014. The Influence of Large Offshore Wind Farms on the North Sea and Baltic Sea - A Comprehensive Literature Review, HZG Report 2014-6, https://www.hzg.de/imperia/md/content/hzg/zentrale_einrichtungen/bibliothek/berichte/hzg_reports_2014/hzg_report_2014_6.pdf

Coates, Delphine A.; Deschutter, Yana; Vincx, Magda; Vanaverbeke, Jan 2014. Enrichment and shifts in macrobenthic assemblages in an offshore wind farm area in the Belgian part of the North Sea. In Marine Environmental Research 95, pp. 1–12. DOI: 10.1016/j.marenvres.2013.12.008.

Coates, Delphine A.; Kapasakali, Danae-Athena; Vincx, Magda; Vanaverbeke, Jan 2016. Short-term effects of fishery exclusion in offshore wind farms on macrofaunal communities in the Belgian part of the North Sea. In Fisheries Research 179, pp. 131–138. DOI: 10.1016/j.fishres.2016.02.019.

Coolen, Joop W.P.; Bos, Oscar G.; Glorius, Sander; Lengkeek, Wouter; Cuperus, Joël; van der Weide, Babeth; Agüera, Antonio 2015. Reefs, sand and reef-like sand: A comparison of the benthic biodiversity of habitats in the Dutch Borkum Reef Grounds. In Journal of Sea Research 103, pp. 84–92. DOI: 10.1016/j.seares.2015.06.010.

Coolen, J.W.P. 2017. North Sea Reefs - Rocky reefs in the southern North Sea. Ph.D. Wageningen University, Wageningen, The Netherlands.Cooper, B. and F. Beiboer, 2002: Potential effects of offshore wind developments on coastal processes. Report by ABP marine environmental research ltd (abpmer) (pp. 127).

Creutzberg, F.; P. Wapenaar; G. Duineveld and N. Lopez Lopez 1984. Distribution and density of the benthic fauna in the southern North Sea in relation to bottom characteristics and hydrographic conditions. In Rapp. P.-v. Réun. Cons. int. Explor. Mer 183, pp. 101– 110.

Cui, Y., L. Li, Y. Liu and L. Gao, 2015: Wind turbine wake vertical distributions considering different inflow shear indices, *International Conference on Renewable Power Generation (RPG 2015)*, Beijing, 2015, 1-6, doi: 10.1049/cp.2015.0490

Damen, J. M.; van Dijk, T. A. G. P.; Hulscher, S. J. M. H. 2018. Spatially Varying Environmental Properties Controlling Observed Sand Wave Morphology. In J. Geophys. Res. Earth Surf. 26 (4), p. 433. DOI: 10.1002/2017JF004322.

Dannheim, Jennifer; Brey, Thomas; Schröder, Alexander; Mintenbeck, Katja; Knust, Rainer; Arntz, Wolf E. 2014. Trophic look at soft-bottom communities — Short-term effects of trawling cessation on benthos. In Journal of Sea Research 85, pp. 18–28. DOI: 10.1016/j.seares.2013.09.005.

De Boer, G. J. 2008. On the interaction between tides and stratification in the Rhine Region of Fresh water Influence. Ph.D. thesis TU Delft

De Boer, G. J., Pietrzak, J. D., and Winterwerp, J. C. 2009. SST observations of upwelling induced by tidal straining in the Rhine ROFI. Continental Shelf Research 29, 263-277.

De Dominicis, M., Murray, R. O. H., & Wolf, J. 2017. Multi-scale ocean response to a large tidal stream turbine array. Renewable Energy, 114, 1160-1179.

De Kluijver, A., Chatelain, M. S. J., and Stolte, W. 2013. "Long-term vision Schelde Estuary; primary production modelling," Rep. No. 1207720-001-ZKS-0004. Deltares, Delft.

Degraer, Steven; Brabant, Robin; Rumes, Bob (Eds.) 2012. Environmental impacts of offshore wind farms in the Belgian part of the North Sea. Learning from the past to optimise future monitoring programmes. RBINS. Brussels.

Degraer, Steven; Brabant, Robin; Rumes, Bob; Vigin, Laurent (Eds.) 2016. Environmental impacts of offshore wind farms in the Belgian part of the North Sea. Environmental impact monitoring reloaded. Royal Belgian Institute of Natural Sciences, OD Natural Environment, Marine Ecology and Management Section. Brussels.

Ducrotoy, J. P., Elliott, M., & de Jonge, V. N. 2000. The North Sea. *Marine Pollution Bulletin*, *41*(1-6), 5-23.

Duineveld, Gerard C. A.; Bergman, Magda J. N.; Lavaleye, Marc S. S. 2007. Effects of an area closed to fisheries on the composition of the benthic fauna in the southern North Sea. In ICES Journal of Marine Science 64 (5), pp. 899–908. DOI: 10.1093/icesjms/fsm029.

Dupont, E., R. Koppelaar, H. Jeanmart. 2018. Global available wind energy with physical and energy return on investment constraints. Applied Energy 209: 322-338. https://doi.org/10.1016/j.apenergy.2017.09.085

Edwards, Martin; Richardson, Anthony J. 2004. Impact of climate change on marine pelagic phenology and trophic mismatch. In Nature 430 (7002), pp. 881–884. DOI: 10.1038/nature02808.

Floeter, J., van Beusekom, J. E. E., Auch, D., Callies, U., Carpenter, J., Dudeck, T., Eberle, S., Eckhardt, A., Gloe, D., Hänselmann, K., Hufnagl, M., Janßen, S., Lenhart, H., Möller, K. O., North, R. P., Pohlmann, T., Riethmüller, R., Schulz, S., Spreizenbarth, S., Temming, A., Walter, B., Zielinski, O., and Möllmann, C. 2017. Pelagic effects of offshore wind farm foundations in the stratified North Sea. *Progress in Oceanography* **156**, 154-173.

Frandsen, S., R. Barthelmie, S. Pryor, O. Rathmann, S. Larsen, J.Højstrup, M. Thøgersen, 2006: Analytical Modelling of Wind Speed Deficit in Large Offshore Wind Farms. Wind Energ., 9, 39–53.

Fransz, H. G.; Colebrook, J. M.; Gamble, J. C.; Krause, M. 1991. The zooplankton of the north sea. In Netherlands Journal of Sea Research 28 (1-2), pp. 1–52. DOI: 10.1016/0077-7579(91)90003-J.

Gilles, A.; Viquerat, S.; Becker, E. A.; Forney, K. A.; Geelhoed, S. C. V.; Haelters, J. et al. 2016. Seasonal habitat-based density models for a marine top predator, the harbor porpoise, in a dynamic environment. In Ecosphere 7 (6), e01367. DOI: 10.1002/ecs2.1367.

Glorius, Sander; van Hal, Ralf; Kaag, Klaas; van der Weide, Babeth; Chen, Chun; van Kooten, Tobias 2016. Benthic development around a gas platform in the North Sea -: a small scale closure for fisheries: a trait based approach. Den Helder: Wageningen Marine Research.

González-Longatt F., P. Wall and V. Terzija, 2011: Wake effect in wind farm performance: Steady-state and dynamic behavior, Renewable Energy, doi:10.1016/j.renene.2011.08.053.

Hartman, J.C., K.L. Krijgsveld, M.J.M. Poot, R.C. Fijn, M.F. Leopold, S. Dirksen 2012. Effects on birds of Offshore Wind farm Egmond aan Zee (OWEZ) - An overview and integration of insights obtained. Bureau Waardenburg, NoordzeeWind report nr OWEZ_R_233_T1_20121002, pp. 148.

Hasager, C. B., P. Vincent, J. Badger, M. Badger, A. Di Bella, A., Peña, Volker, P.; Badger, J.; Di Bella, A.; Palomares, A.; Cantero, E.; Correia, P. M. F.2015: Using satellite SAR to characterize the wind flow around offshore wind farms. Energies, 8(6), 5413–5439. http://doi.org/10.3390/en8065413

Hasager, C.B.; Rasmussen, L.; Peña, A.; Jensen, L.E.; Réthoré, P.-E., 2013: Wind Farm Wake: The Horns Rev Photo Case. *Energies* 2013, *6*, 696-716.

Holtslag, M. C., W. A. A. M Bierbooms, and G. J. W. van Bussel, 2016: Wind turbine fatigue loads as a function of atmospheric conditions offshore. *Wind Energ.*, 19: 1917–1932. doi: 10.1002/we.1959.

Hufnagl, Marc; Payne, Mark; Lacroix, Geneviève; Bolle, Loes J.; Daewel, Ute; Dickey-Collas, Mark et al. 2017. Variation that can be expected when using particle tracking models in connectivity studies. In Journal of Sea Research 127, pp. 133–149. DOI: 10.1016/j.seares.2017.04.009.

Huthnance, J. M. 1991. Physical oceanography of the North Sea. *Ocean and shoreline management*, *16*(3-4), 199-231.

Huthnance, J., Weisse, R., Wahl, T., Thomas, H., Pietrzak, J., Souza, A. J., Van Heteren, S., Schmeltzer, N., Van Beusekom, J., Colijn, F., Haigh, I., Hjøllo, S., Holfort, J., Kent, E. C., Kühn, W., Loewe, P., Lorkowski, I., Mork, K. A., Pätch, J., Quante, M., Salt, L., Siddorn, J., Smyth, T., Sterl, A., and Woodworth, P. 2016. Recent Change—North Sea. In "North Sea Region Climate Change Assessment" (M. Quante and F. Colijn, eds.).

Johns, D. G.; Reid, P. C. 2001. An overview of plankton ecology in the North Sea. SahFos (SEA2 Technical Report 005 - Plankton).

Krone, Roland; Gutow, Lars; Joschko, Tanja J.; Schröder, Alexander 2013. Epifauna dynamics at an offshore foundation--implications of future wind power farming in the North Sea. In *Marine Environmental Research* 85, pp. 1–12. DOI: 10.1016/j.marenvres.2012.12.004.

Leewis; L; Klink; D, A.; Verduin; C, E. 2018. Benthic development in and around offshore wind farm Prinses Amalia Wind Park near the Dutch coastal zone before and after construction (2003-2017). A statistical analysis. Eurofins.

Lindeboom, H. J.; Kouwenhoven, H. J.; Bergman, M. J. N.; Bouma, S.; Brasseur, S.; Daan, R. et al. 2011. Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. In Environ. Res. Lett. 6 (3), p. 35101. DOI: 10.1088/1748- 9326/6/3/035101.

Lindley, J. A.; Kirby, R. R. 2007. Long-term changes in the meroplankton of the North Sea. In ICES CM A:16, pp. 1–10.

Lunt, J.; Reustle, J.; Smee, D. L. 2017. Wave energy and flow reduce the abundance and size of benthic species on oyster reefs. In Mar. Ecol. Prog. Ser. 569, pp. 25–36. DOI: 10.3354/meps12075.

Mesel, Ilse de; Kerckhof, Francis; Norro, Alain; Rumes, Bob; Degraer, Steven 2015. Succession and seasonal dynamics of the epifauna community on offshore wind farm foundations and their role as stepping stones for non-indigenous species. In Hydrobiologia 756 (1), pp. 37–50. DOI: 10.1007/s10750-014-2157-1.

Miller, L.M., N. A. Brunsell, D.B. Mechem, F. Gans, A.J. Monaghan, R. Vautard, D.W. Keith, A. Kleidon. 2015. Two methods for estimating limits to large-scale wind power generation. PNAS 112: 11169–11174. http://www.pnas.org/cgi/doi/10.1073/pnas.1408251112

Mittelmeier, N.; Allin, J.; Blodau, T.; Trabucchi, D.; Steinfeld, G.; & Rott, A. 2017. An analysis of offshore wind farm SCADA measurements to identify key parameters influencing the magnitude of wake effects, Wind Energ. Sci., 2, 477–490, https://doi.org/10.5194/wes-2-477-2017.

Otto, L.; Zimmerman, J. T. F.; Furnes, G. K.; Mork, M.; Saetre, R.; & Becker, G. 1990. Review of the physical oceanography of the North Sea. *Netherlands journal of sea research*, *26*(2-4), 161-238.

Paskyabi, M. B., 2015. Offshore Wind Farm Wake Effect on Stratification and Coastal Upwelling. Energy Procedia, 80, 131 – 140 (12th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2015).

Payne, M. R.; Hatfield, E. M. C.; Dickey-Collas, M.; Falkenhaug, T.; Gallego, A.; Groger, J. 2008. Recruitment in a changing environment: the 2000s North Sea herring recruitment failure. In ICES J Mar Sci 66 (2), pp. 272–277. DOI: 10.1093/icesjms/fsn211.

Platis, A.; Siedersleben, S. K.; Bange, J.; Lampert, A.; Bärfuss, K.; Hankers, R.; & Neumann,T. 2018: First in situ evidence of wakes in the far field behind offshore wind farms, Scientific Reports, 2163 (2018), doi:10.1038/s41598-018-20389-y.

Possner, A.; & K. Caldeira. 2017. Geophysical potential for wind energy over the open oceans. PNAS 114: 11338–11343. http://www.pnas.org/cgi/doi/10.1073/ pnas.1705710114 Prins, T. C.; Desmit, X.; & Baretta-Bekker, J. G. 2012. Phytoplankton composition in Dutch coastal waters responds to changes in riverine nutrient loads. Journal of Sea Research 73, 49-62.

Rabaut, Marijn; Guilini, Katja; van Hoey, Gert; Vincx, Magda; Degraer, Steven 2007. A bio-engineered soft-bottom environment: The impact of Lanice conchilega on the benthic species-specific densities and community structure. In Estuarine, Coastal and Shelf Science 75 (4), pp. 525–536. DOI: 10.1016/j.ecss.2007.05.041.

Rodrigues, G. R. & J. Harris, 2012. Nearshore wave damping due to the effect on winds in response to offshore wind farms. *Coastal Engineering Proceedings, 1*(33), 55. doi: 10.9753/icce.v33.waves.55

Russell, Deborah J. F.; Brasseur, Sophie M. J. M.; Thompson, Dave; Hastie, Gordon D.; Janik, Vincent M.; Aarts, Geert 2014. Marine mammals trace anthropogenic structures at sea. In Current biology : CB 24 (14), R638-R639. DOI: 10.1016/j.cub.2014.06.033.

Rijnsdorp, Adriaan D.; Eigaard, Ole R.; Kenny, Andrew; Hiddink, Jan Geert; Hamon, Katell; Piet, Gerjan 2017. Assessing and mitigating impact of bottom trawling. Benthis FP7 Final Report.

Sarlak, H.; Nishino, T.; Martínez-Tossas, L. A.; Meneveau, C.; & Sørensen, J. N. 2016. Assessment of blockage effects on the wake characteristics and power of wind turbines. *Renewable Energy*, *93*, 340–352. http://doi.org/10.1016/j.renene.2016.01.101

Sathe, A.; Gryning, S.-E.; & Peña, A. 2011. Comparison of the atmospheric stability and wind profiles at two wind farm sites over a long marine fetch in the North Sea. Wind Energy, 14 (6), 767-780.

Schalkwijk, J.; Jonker, H.J.J.; Siebesma, A.P.; & Meijgaard, E. van 2015. Weather forecasting using GPU-based large-Eddy simulations,” Bull. Am. Meteorol. Soc., 95 (5), 715–723.

Schultze, L. K.; Merckelbach; L. M.; Carpenter, J. R. 2017. Turbulence and mixing in a shallow shelf sea from underwater gliders. Journal of Geophysical Research: Oceans, 122(11), 9092-9109.

Segtnan, O.H. & K. Christakos 2015. Effect of Offshore Wind farm Design on the Vertical Motion of the Ocean. Energy Procedia, 80, 213 – 222 (12th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2015).

Shakoor, R.; Hassan, M. Y.; Raheem, A.; Wu, Y. K. 2016. Wake effect modeling: A review of wind farm layout optimization using Jensen's model. *Renewable and Sustainable Energy Reviews*, *58*, 1048–1059. http://doi.org/10.1016/j.rser.2015.12.229

Slavik, Kaela; Lemmen, Carsten; Zhang, Wenyan; Kerimoglu, Onur; Klingbeil, Knut; & Wirtz, Kai W. 2018. The large-scale impact of offshore wind farm structures on pelagic primary productivity in the southern North Sea. In Hydrobiologia 148 (2), p. 215. DOI: 10.1007/s10750-018-3653-5.

Smaal, A. C.; Schellekens, T.; van Stralen, M. R.; & Kromkamp, J. C. 2013. Decrease of the carrying capacity of the Oosterschelde estuary (SW Delta, NL) for bivalve filter feeders due to overgrazing? In Aquaculture 404-405, pp. 28–34. DOI: 10.1016/j.aquaculture.2013.04.008.

Suchy, Karyn Dawn 2014. The response of crustacean zooplankton production to variations in food quantity, quality, and primary production in coastal marine ecosystems. Ph.D. University of Victoria.

Vanhellemont, Q; Ruddick, K. 2014. Turbid wakes associated with offshore wind turbines observed with Landsat 8. Remote Sensing Env. 145: 105-115.

Vautard, R.; Thais, F.; Tobin, I.; Bréon, F.-M.; Lavergne, J.-G.D. de; Colette, A.; Yiou, P.; Ruti, P.M. 2014. Regional climate model simulations indicate limited climatic impacts by operational and planned European wind farms. Nat Commun 5:3196. doi: 10.1038/ncomms4196, https://www.nature.com/articles/ncomms4196.

Van der Kaaij, Theo; van Kessel, Thijs; Troost, Tineke; Herman, Peter; van Duren, Luca; Villars, Nicky 2017. Modelondersteuning MER winning suppletie- en ophoogzand Noordzee 2018 – 2027. Modelvalidatie (1230888-002).

Van der Molen, Johan; Smith, Helen C.M.; Lepper, Paul; Limpenny, Sian; & Rees, Jon 2014. Predicting the large-scale consequences of offshore wind turbine array development on a North Sea ecosystem. In Continental Shelf Research 85, pp. 60–72. DOI: 10.1016/j.csr.2014.05.018.

Van der Stap, Tim; Coolen, Joop W. P.; & Lindeboom, Han J. 2016. Marine Fouling Assemblages on Offshore Gas Platforms in the Southern North Sea: Effects of Depth and Distance from Shore on Biodiversity. In PloS one 11 (1), e0146324. DOI: 10.1371/journal.pone.0146324.

Van Duren, L.A.; Gittenberger, A.; Smaal, A.C.; Van Koningsveld, M.; Osinga, R.; Cado van der Leij, J.A.; & De Vries, M.B. 2016. Rijke riffen in de Noordzee – Verkenning naar het stimuleren van natuurlijke riffen en gebruik van kunstmatig hard substraat. Deltares rapport 1221293-000.

Van Duren, L. A.; Van Kessel, T.; Troost, T. A.; Blauw, A. N.; Kramer, L.; Van Gils, J. A.; Craeymeersch, J. A. M.; & Herman, P. M. J. 2017. "Scenariostudies ter ondersteuning van de MER-Zandwinning 2018-2027," Rep. No. 1230888-000-ZKS-0018. Deltares, Delft.

Van Hout, C.M., Gerkema, T., Nauw, J.J., & Ridderinkhof, H. 2015. Observations of a narrow zone of high suspended particulate matter (SPM) concentrations along the Dutch coast. Cont. Shelf Res. 95: 27-38.

Van Leeuwen, S. M., van der Molen, J., Ruardij, P., Fernand, L., & Jickells, T. 2013. Modelling the contribution of deep chlorophyll maxima to annual primary production in the North Sea. Biogeochemistry 113, 137-152.

Van Leeuwen, S., Tett, P., Mills, D., & van der Molen, J. 2015. Stratified and non-stratified areas in the North Sea: Long-term variability and biological and policy implications. J. Geophys. Res. 120, 4670-4686.

Vanagt, T.; van de Moortel, L.; Faasse, M. A. 2013. Development of hard substrate fauna in the Princess Amalia wind farm. eCoast. Oostende, Belgium (2011036).

Vanaverbeke, Jan; Braeckman, Ulrike; Borger, Emile de; Mavraki, Ninon; Toussaint, Elise; Voet, Helena et al.: Interactions between biological and physical effects modify local biogeographic cycling processes in offshore wind farms. Poster EMBS Ostende 2018

Wessels H. R. A., 1983: Distortion of the wind field by the Cabauw meteorological tower. KNMI Scientific Report 8 3- I 5, De Bilt, The Netherlands. http://bibliotheek.knmi.nl/knmipubWR/WR83-15.pdf.

Wu, Y. T., & Porté-Agel, F., 2012: Atmospheric turbulence effects on wind-turbine wakes: An LES study. *Energies*, *5*(12), 5340–5362. http://doi.org/10.3390/en5125340

Zaghi, S., Muscari, R., & Mascio, A. Di., 2016: Assessment of blockage effects in wind tunnel testing of wind turbines. *Journal of Wind Engineering and Industrial Aerodynamics*, *154*, 1–9. http://doi.org/10.1016/j.jweia.2016.03.012

Zhang, W., Xia, H., & Wang, B. 2009. Numerical calculation of the impact of offshore wind power stations on hydrodynamic conditions. In Advances in Water Resources and Hydraulic Engineering (pp. 1143-1150). Springer, Berlin, Heidelberg.

Zijl, F., Verlaan, M., & Gerritsen, H. 2013. Improved water-level forecasting for the Northwest European Shelf and North Sea through direct modelling of tide, surge and non-linear interaction. Ocean Dynamics, 63(7), 823-847.

Zijl, F., Sumihar, J., & Verlaan, M. 2015. Application of data assimilation for improved operational water level forecasting on the northwest European shelf and North Sea. Ocean Dynamics, 65(12), 1699-1716.

Zijl, F., Veenstra, J., & Groenenboom, J. 2018. The 3D Dutch Continental Shelf Model - Flexible Mesh (3D DCSM-FM): setup and validation. Deltares report 1220339.