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# Summary

A previous desk study has shown that a possible future large-scale increase in offshore wind farms in the North Sea may have ecosystem effects on the North Sea (Boon et al. 2018; commissioned by RWS and the Ministry of Economic Affairs). This concerns either effects that are not currently occurring, or that are not yet relevant on the scale of the North Sea ecosystem but may become relevant in the future. To gain timely insight in these processes, Wozep has initiated the current research, which builds on the 2018 desk study. Wozep focuses primarily on the effects of offshore wind on species with protected status. An important question is therefore: to what extent do effects of offshore wind farms affect these species through the physical processes, the growth of algae and further through the food chain?

In the present study, this question is approached both top-down and bottom-up. The top-down approach assesses the top predators (birds, marine mammals) and analyses how and to what extent these species can be influenced by changes in the food web. The bottom-up approach uses a number of integrated numerical models (modelling suite) to examine how changes in currents and fine sediment dynamics influence the growth of phytoplankton and how this subsequently affects higher layers in the food web. A new modelling suite has been tested in this bottom-up approach. Three scenarios have been calculated with this. A “reference scenario” without the presence of wind farms in the North Sea, a “2020 scenario” containing the wind farms that are already present and a hypothetical upscaling scenario, based on the forecast of the wind industry in 2050. The aim was to get a first impression of the order of magnitude of bottom-up changes, and in which parts of the North Sea these will be larger or smaller

The top-down part of this present study was aimed at comparing model approaches to assess the impact of changes at the base of the food web on birds and marine mammals. Individual-based models (IBMs) have been identified as the most promising way forward. These are relatively complex models that contain information about the behaviour, reproduction and physiology of individuals in relation to the environment. To date, none of the available IBMs for relevant species have been applied to such management scenarios. There are no off-the-shelf models available for relevant species. IBMs require a significant amount of basic data. First, information about behaviour and physiology of target species. Second, they need extensive information about the spatial and temporal distribution of their food (the food landscape). Both data categories are very species-specific. It is advisable to start developing IBMs for a limited number of species.

The bottom-up model results indicate that increasing offshore wind in the North Sea to levels of the current expectations of the wind industry around 2050 (approximately 60 GW for the Dutch EEZ and more than 200 GW for the international North Sea) can indeed have demonstrable effects on fundamental ecosystem processes. These coupled models are still in a development phase, so results should be treated with caution. However, the main changes shown are caused by changes in stratification (layering of the water column). These physical processes that have already been properly validated with existing data and they appear to be very robust. This indicates that further research into the ecosystem effects of wind farms is certainly warranted. Although individual model components still need to be improved and require further validation, this set of models appears to be a very useful tool for these kinds of issues.

Based on existing knowledge of processes and model runs carried out for the North Sea, we have identified six regions that have different physical characteristics and respond differently to the hypothetical upscaling scenario (see Figure 4.1). These are: 1) the Central German Bight, where on the one hand effects of changes in stratification that promote the growth of algae are observed and on the other hand increased silt concentrations in the upper water layers that inhibit algae growth and delay the spring bloom, 2) the English coast and western parts of the Dutch Continental Shelf, which generally show limited effects, mainly inhibition of algae growth due to increased concentrations of suspended matter (SPM), 3) the Central Southern North Sea where substantial effects can be seen due to increased mixing, increases in primary production and delay in onset of stratification and the beginning of the spring bloom, 4) the Holland Coast and Rhine region of freshwater influence (ROFI) where we see some influence on the salinity stratification and a decrease in primary production as a result of increases in fine sediment concentrations in the upper water layers. In this part of the North Sea also appears to have an effect on the transport of silt along the coast and towards the Wadden Sea., 5) The German and Danish coastal areas which have limited and mixed effects and are in many respects comparable to the British coastal areas and 6) the Dogger Bank. This is a shallow area in the central part of the North Sea that is weakly and irregularly stratified. Despite the shallowness, the resuspension of fine sediment is relatively limited and subsequent effects on primary production are limited and variable.

Based on these results, recommendations have been formulated for follow-up research. It is useful to start quickly with the construction of species-specific IBMs. We recommend starting with one marine mammal and one bird species for which a lot of basic information is already available. There are several studies available in which different individuals equipped with GPS transmitter to monitor behaviour as well as environmental parameters are involved. The results of these studies should provide the basic information needed for building these IBMs. Regarding the bottom-up models, there are a few important areas for improvement. In particular, the parameterisation of wind wakes behind wind farms must be improved. These are currently not yet properly incorporated in the model and this can have an influence on processes such as mixing and fine sediment dynamics. Modelling the growth of grazers, such as mussels, on the turbines will also provide more insight into changes in the food web. In future developments, this food web approach will be expanded to gain insight into the impact of the effects of wind farms on the food landscape for species with a protected status. One of the issues that should receive attention in the short term is to gain a better understanding of the effects of wind farms on the transport of fine sediments northward along the Holland coast as well as its subsequent impact on fine sediment import into the Wadden Sea.

The modelling suite as used in the present study is currently still under development and should not yet be used to assess potential effects of realistic scenarios for direct policy support. The intention is that these models will be used as such in the future, provided of course that they are sufficiently reliable. This allows us to determine safe upscaling levels and optimal configuration of wind farms, with minimal negative impact on the North Sea.

# Samenvatting

Eerder verkennend onderzoek heeft uitgewezen dat een eventuele toekomstige grootschalige toename van offshore windparken op de Noordzee, mogelijk ecosysteemeffecten kan hebben op de Noordzee (Boon et al. 2018; in opdracht van RWS en het ministerie van EZK). Dit betreft ofwel effecten die momenteel nog niet optreden, ofwel nog niet relevant zijn op de schaal van het Noordzee-ecosysteem, maar mogelijk bij toekomstige opschalingsniveaus wel. Om hier tijdig inzicht in te hebben heeft Wozep voorliggend onderzoek gestart, dat voortbouwt op de verkenning van 2018. Wozep richt zich primair op effecten van Wind op Zee (WoZ) op soorten met beschermde status. Belangrijke vraag is dus: in hoeverre werkt het effect van WoZ via de fysische processen, de groei van algen en verder via de voedselketen door op deze soorten?

In voorliggende studie wordt deze vraag zowel top-down als bottom-up benaderd. De top-down benadering redeneert vanuit de toppredatoren (vogels, zeezoogdieren) en analyseert hoe en in welke mate deze soorten via veranderingen in het voedselweb kunnen worden beïnvloed. De bottom-up benadering kijkt via een aantal gekoppelde rekenmodellen (modellentrein) hoe veranderingen in stroming en slibdynamiek de groei van algen beïnvloeden en hoe dit vervolgens naar hogere lagen in het voedselweb doorwerkt. In deze bottom-up benadering is een nieuwe modellentrein getest. Hiermee is een aantal scenario's doorgerekend. Een "referentiescenario" zonder aanwezigheid van windparken in de Noordzee, een "2020-scenario" met daarin de windparken die nu reeds aanwezig zijn en een hypothetisch opschalingsscenario, gebaseerd op verwachtingen van de windindustrie in 2050. Doel was om hiermee een eerste indruk te krijgen van de ordegrootte van bottom-up veranderingen, en in welk deel van de Noordzee deze groter of kleiner zullen zijn.

Het top-down deel van dit voorliggende onderzoek was gericht op het vergelijken van modelbenaderingen om de impact van de veranderingen aan de basis van het voedselweb op vogels en zeezoogdieren te kunnen beoordelen. "Individual-based models" (IBM's) zijn geïdentificeerd als de meest veelbelovende weg vooruit. Dit zijn relatief complexe modellen, die informatie bevatten over gedrag, reproductie en fysiologie van individuen in relatie tot de omgeving. Op dit moment is nog geen van de beschikbare IBM's voor relevante soorten toegepast op dergelijke beheerscenario's. Er liggen geen kant-en-klaar bruikbare modellen op de plank voor belangrijke soorten. IBM's hebben een aanzienlijke hoeveelheid basisdata nodig. Ten eerste betreft dit informatie over gedrag en fysiologie van doelsoorten. Ten tweede hebben ze uitgebreide informatie nodig over de ruimtelijke en temporele verspreiding van hun voedsel (het voedsellandschap). Beide datacategorieën zijn zeer soort-specifiek. Het is verstandig om te beginnen met ontwikkelen van IBM's voor een beperkt aantal soorten.

De bottom-up modelresultaten geven aan dat opschaling van offshore wind in de Noordzee tot niveaus van de huidige verwachtingen van de windindustrie rond 2050 (ongeveer 60 GW voor de Nederlandse EEZ en meer dan 200 GW voor de internationale Noordzee) inderdaad aantoonbare effecten kan gaan hebben op fundamentele ecosysteemprocessen. Deze gekoppelde modellen bevinden zich nog in een ontwikkelfase zodat resultaten met voorzichtigheid gebruikt moeten worden. Echter, de belangrijkste aangetoonde veranderingen worden veroorzaakt door veranderingen in stratificatie (gelaagdheid). Juist deze fysische processen zijn al behoorlijk goed gevalideerd met bestaande data en die blijken behoorlijk betrouwbaar. Dit geeft aan dat verder onderzoek naar de ecosysteemeffecten van windparken zeker noodzakelijk is. Hoewel individuele modelcomponenten op een aantal punten nog wel verbeterd en verder gevalideerd moeten worden, lijkt deze modellentrein een goed bruikbaar instrument voor dit soort vraagstukken.

We hebben op basis van bestaande kennis van processen in de Noordzee en uitgevoerde modelruns in de Noordzee zes regio's geïdentificeerd, die verschillende fysische kenmerken hebben en verschillend reageren op het hypothetische scenario (zie Figuur 4.1). Dit zijn: 1) de Centrale Duitse Bocht, waar enerzijds effecten worden waargenomen van veranderingen in gelaagdheid (stratificatie) die groei van algen bevorderen en anderzijds verhoogde slibconcentraties in de bovenste waterlagen die de algengroei remmen, 2) de Britse kust en westelijke delen van het Nederlands Continentaal Plat, die in het algemeen beperkte effecten laten zien, voornamelijk remming van algengroei door verhoogde concentraties zwevend stof (SPM), 3) de Centrale Zuidelijke Noordzee waar zeer grote effecten te zien zijn, door verhoogde menging, toename van primaire productie en vertraging in het begin van de voorjaarsbloei, 4) de Hollandse Kust en Rijnregio van zoetwaterinvloed (ROFI) waar we enige invloed zien op de zoutstratificatie en een afname van de primaire productie als gevolg van toenames in fijn sedimentconcentraties in de bovenste water lagen. In dit deel van de Noordzee lijkt ook een effect te zijn op het transport van slib langs de kust en richting de Waddenzee., 5) De Duitse en Deense kustgebieden die beperkte en gemengde effecten hebben en in veel opzichten vergelijkbaar zijn met de Britse kustgebieden en 6) de Doggersbank. Dit is een ondiep gebied in het centrale deel van de Noordzee dat beperkt en onregelmatig gestratificeerd is. Ondanks de ondiepte is de opwerveling van slib relatief beperkt en zijn effecten op primaire productie beperkt en enigszins variabel.

Op basis van deze resultaten zijn aanbevelingen geformuleerd voor vervolgonderzoek. Het is nuttig snel een begin te maken met het construeren van soort-specifieke modellen voor een zeezoogdier en voor een vogelsoort waar al veel basisinformatie van beschikbaar is. Er is een aantal onderzoeken uitgevoerd waarin verschillende individuen uitgerust met GPS-zender om zowel gedrag als omgevingsparameters te volgen. De resultaten van deze studies dienen als input voor de te bouwen IBM's. Met betrekking tot de bottom-up-modellen zijn er een paar belangrijke punten voor verbetering. Met name het verbeteren van de parameterisering van wind-zoggen achter windparken moet worden doorgevoerd. Die zitten momenteel nog niet goed in het model en dit kan een invloed hebben op processen zoals menging en slibdynamiek. Ook het modelleren van de groei van grazers, zoals mosselen, op de turbines, zal meer inzicht geven in veranderingen in het voedselweb. In toekomstige ontwikkelingen zal deze voedselwebbenadering worden uitgebreid om zicht te krijgen op de doorwerking van effecten van windparken op het voedsellandschap voor soorten met een beschermde status. Eén van de zaken die op korte termijn aandacht moet krijgen in beter inzicht in de effecten van windparken op het kust-langs transport van slib richting het noorden en de mogelijke doorwerking op import van slib in de Waddenzee.

De modellentrein zoals die in voorliggende studie gebruikt is bevindt zich momenteel nog in een onderzoeksfase en is nog niet geschikt voor het doorrekenen van realistische scenario's voor directe beleidsondersteuning. Intentie is dat dit in de toekomst, bij voldoende betrouwbaarheid wel die toepassing gaat krijgen. Hiermee kan advies gegeven worden over veilige opschalingsniveaus en optimale configuratie van parken, met minimale negatieve impact op de Noordzee.

# Contents

# 1 Introduction

## 1.1 General context: Wozep

Wozep (the *Wind Op Zee Ecologisch Programma*) is an integrated research programme to reduce the knowledge gaps regarding the possibly negative environmental effects of offshore wind farms (OWFs) on the North Sea. A number of topics concentrate on the direct impacts on priority species such as birds and bats (collision risks), habitat loss of seabirds, effects of noise (specifically during construction) on marine mammals and effects of electromagnetic fields on benthos and fish. A recent scoping study indicated that there may be effects of offshore wind on the functioning of the ecosystem and knock-on effects on the marine food web, through indirect (physical and ecological) processes (Boon et al. 2018). This study indicated that 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.
This scoping study did not attempt to quantify the potential effects, but did identify that particularly the effect of destratification (already measured in two German offshore wind farms (Floeter et al. 2017)) and effects of fine sediment dynamics on primary production are likely to occur and should be prioritised in future research.

This current project is the first attempt to quantify potential changes in the ecosystem through a coupled set of physical and ecological models and assess the impact of these changes for several species of high conservation status (birds and marine mammals).

## 1.2 Rationale

The ecosystem is the complex interacting system of elements from physics, biogeochemistry and biological populations ranging from bacteria and viruses to marine mammals. More or less autonomous external factors that cannot be influenced directly, such as climate change, as well as local human activities affect the ecosystem (Figure 1.1). Influences may be direct, such as fishing that directly impacts fish, but very often human pressures indirectly influence the ecosystem through the physics and subsequent biological effect chains. Offshore wind, the human impact central in this study, has direct impacts on birds (e.g. through collisions) but may also indirectly impact the food chain, through changes in the physical and chemical conditions in the system.

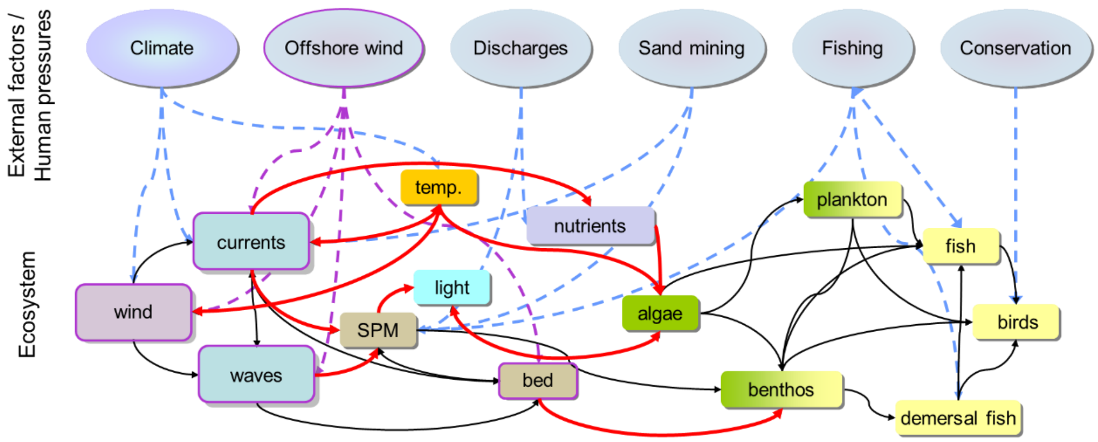


*Figure 1.1 Illustration of the effect chain, illustrating the pathways of direct and indirect effects of offshore wind on the ecosystem.*

At present such effects of offshore wind are probably only important on a small scale, or perhaps not at all. However, the scoping study indicated that with the potentially large upscaling we may see after 2030, such effects may exert a major impact on ecosystem functioning in the North Sea.

The main goal of the current project is to identify the pathways through which species of high conservation status can be affected by a large upscaling of offshore wind. The study gives a first assessment of the size of these effects as well as an indication which parts of the North Sea are most susceptible to such changes. The links between the physical functioning of the North Sea (currents, waves, stratification, fine sediment dynamics) and the higher trophic levels (birds, mammals) are extremely complex. The aim of this research is to assess whether the identified processes are relevant and where priorities for further research (measuring, modelling, monitoring) should lie.

## 1.3 Combined approach (bottom-up and top-down)

Most conservation targets relate to apex predators, such as birds, marine mammals and some larger fish such as rays and sharks. We currently lack the scientific knowledge and the modelling tools to assess directly how changes in currents or fine sediment eventually may affect such species. This project therefore followed a three-tier approach:

### 1.3.1 Bottom-up approach

This part of the project applied a state-of-the-art suite of numerical models to assess potential changes in hydrodynamics, sediment dynamics, light attenuation, primary production and secondary production. Three scenarios were assessed:

- a reference scenario without any wind farms
- a “2020” scenario with the currently present wind farms
- a hypothetical future scenario with a large upscaling of offshore wind farms in the southern North Sea.

The primary aim of this part of the research is to assess the following questions:

- Is large upscaling of offshore wind likely to cause changes in the lower parts of the food web that are large enough to cause knock-on effects on higher trophic levels?
- If such changes occur, which processes are most relevant?
- Which parts of the North Sea are most vulnerable for what type of effects?

### 1.3.2 Top-down approach

This part of the research estimates the vulnerability of several species (birds, marine mammals) with a high conservation status for changes in environmental conditions that can be caused by large-scale development scenarios for offshore wind. This part aimed at delivering the most appropriate methodologies to better quantify such effects.

### 1.3.3 Synthesis

This is the current document in which the results of the top-down and the bottom-up approaches are summarised and synthesized. A separate report will provide recommendations on an approach to fill the most pressing knowledge gaps. This recommendations report will be based on the joint position paper by Deltares, NIOZ and Wageningen Marine Research (Herman et al. 2019).

## 1.4 Report Lay-out

Chapter 2 describes the methodology and the results of the bottom-up approach. This comprises separate sections of the hydrodynamic modelling, the fine sediment models and the water quality and ecological models. Chapter 3 describes the top down approach, including the ecosystem changes and their potential effects, potential research lines and their suitability for application to the central questions and the recommended approach. Chapter 4 presents the general conclusions both in terms of the way ecosystem effects impact different elements of the food web and how different areas of the North Sea respond to the implementation of wind farms. It also outlines the most pressing gaps in our knowledge that currently restrict our ability to decide on the best possible lay-out of future wind farms, that minimise negative impacts on the system. Finally, it summarises the next steps we recommend, in filling these knowledge gaps.

# 2 Summary of the model results (bottom up approach)

## 2.1 Model description and scenario choices

### 2.1.1 Description of the modelling suite and approach

For the hydrodynamic modelling, the 3D Dutch Continental Shelf Model – Flexible Mesh (3D DCSM-FM) is used, which was developed in recent years as part of Deltares' strategic research. The main purpose of 3D DCSM-FM is to have a versatile model that can be used for studies on the Northwest European Continental Shelf, including the North Sea and adjacent shallow seas, such as the Wadden Sea. It aims to combine state-of-the-art capabilities with respect to modelling of water levels (tide and surge) as well as (residual) transport phenomena. The latter is crucial for application in water quality and ecological modelling. By combining this, the model is ideally suited for this study. The earlier exploratory study (Boon et al. 2018) had indicated that effects on stratification are likely (at least in some parts of the North Sea) in and around wind farms. Such effects can be very far reaching for ecological processes (Ruardij et al. 1997, Große et al. 2016, Flores et al. 2017). The new DCSM-FM model is known to be extremely good at simulating this process (Zijl et al. 2018, Zijl et al. 2020).

With a grid size of at least 900m, the piles of the OWFs are too small to explicitly include in the model schematization. Therefore, a sub-grid approach is used. In this approach, a quadratic sink term is included in the horizontal momentum equations. The energy extracted from the main flow in this manner is at the same time reintroduced as a source term in the equation for turbulent kinetic energy (k).

The locations of the offshore wind farms are specified in the hydrodynamic model by means of a polygon along its boundaries. In each computational cell within this polygon the appropriate sink and source terms are computed considering the pile density (number of piles per unit of area) and mean pile diameter. As presented in Table 2.1, different values for turbine density and pile diameter are used for areas that are operational, under construction or planned.
Since the wind forcing applied, does not yet include the impact of OWFs on the meteorological conditions, this has been included in a simplified manner by reducing the near surface wind speeds within the wind farms by 10%. Other meteorological forcing parameters, such as air temperature and relative humidity, are left unchanged. Wake effects and directional changes of the wind are not considered. Further details about the set-up and the parameterisation of wind farms in the model can be found in Zijl et al. (2021).

Coupled to the hydrodynamic model we have run models to assess the effects of wind farms on fine sediment dynamics and on nutrient transport and primary production. Running the water quality and ecology models at the full resolution of the hydrodynamic model takes about 2 weeks calculation on a 20-core cluster. To carry out tests for both the fine sediment model and the water quality and ecology model, we also constructed a much coarser grid on which calculations can be done much faster. This also provides a good first impression of results, but experience from the past has taught us that model resolution can be a crucial factor, particularly in fine sediment modelling. The results of the coarser resolution models have to be assessed with caution.
Because this was the first time that we ran the fully coupled model (including hydrodynamics, fine sediment dynamics and ecological processes) we did encounter some teething problems that have led to delays. Consequently, we have not managed to include the full set of results from the fine sediment model in the ecological model.

The fine-scale ecological runs have therefore used a well-calibrated sediment field from an older model, used to assess the effects of sand mining in the coastal zone (Van der Kaaij et al. 2017). This means that in those runs only the effects of the changes in hydrodynamics (stratification, changes in currents and therefore transports of nutrients) are taken into account, not the concomitant effects of the changes in fine sediment dynamics. To get some first ideas about the combined effects, some extra runs with the coarser models have been carried out in which the sediment fields used in the ecological model were proportionally increased or decreased, according to the results from the fine sediment model.

A limited modelling study from Germany has also highlighted that the growth of mussels and other epifauna on the turbine supports can in future affect primary production (Slavik et al. 2018). In this study we have also had a first attempt to include the effect of mussel filtration on chlorophyll and primary production, by including mussel growth in the model and analysing the feedback on the distribution of primary production and chlorophyll.

### 2.1.2 Scenario choices

The currently described model analyses have been carried out with the meteorological data from 2007. Although this is quite a few years ago and since then, there have been changes in the system such as the construction of “Maasvlakte II”, we have chosen this year because we had a lot of older model results available from previous models that were very well calibrated and validated. It therefore provided good comparison material for results with a new system.
In the studies we performed three types of scenarios:

- A reference scenario without any wind farms
- A “2020” scenario with the wind farms that were operational or nearly operational in 2020
- A hypothetical upscaling scenario

The latter is a scenario based on currently available targets of the offshore wind industry for 2050, distributed over available space in such a way that we can learn as much as possible from it. This is a purely theoretical scenario for research purposes, not a proposal for a realistic future scenario. A full description of the rationale can be found in Zijl et al (2021). Wind farms we defined in areas not yet designated as search areas, were located in areas with diverse physical circumstances, e.g. areas with strong seasonal stratification, areas on frontal systems, areas in permanently mixed areas and areas on relatively steep bathymetrical gradients.

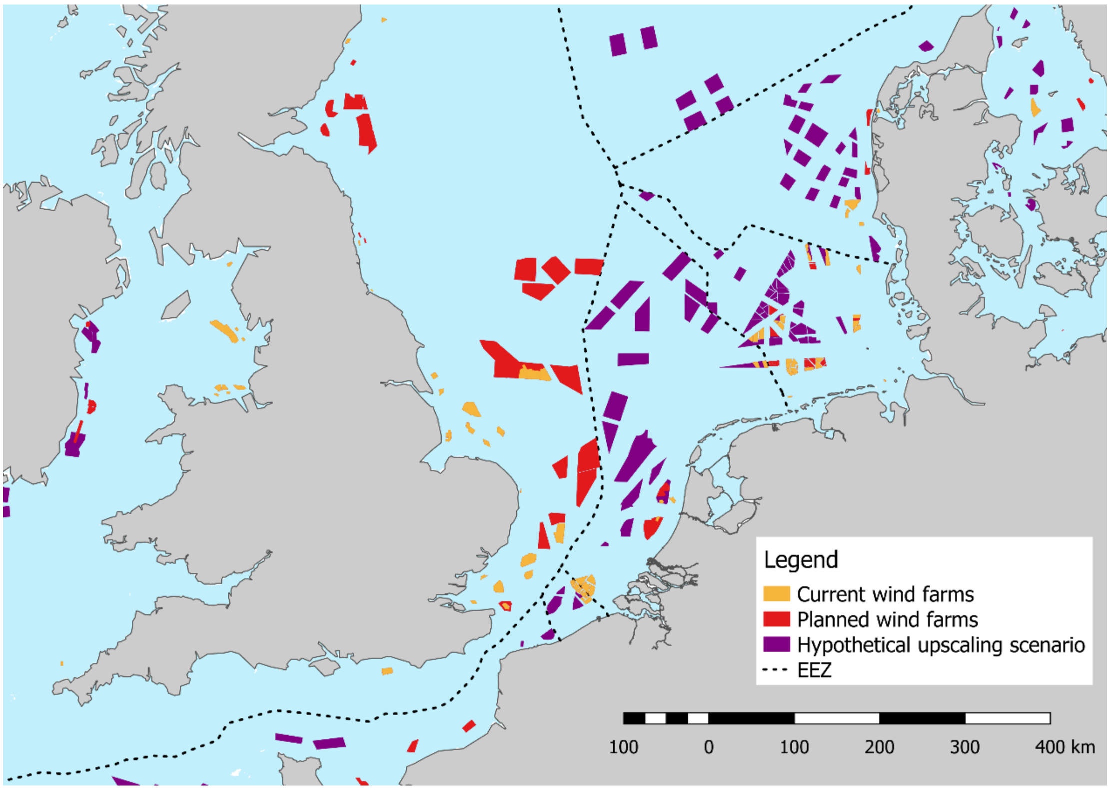


*Figure 2.1 Hypothetical upscaling scenario used in this study. The orange coloured farms represent the "2020" scenario", i.e. the currently operational ones. Red areas are already designated as wind farm in a process of being developed, the purple ones were either defined as "search areas for wind energy" by national governments and others were chosen by us.*

A few user factors have been taken into account (locations of N2000 areas and shipping routes). This did not compromise the primary goal: understanding the sensitivity of various parts of the North Sea for changes caused by the introduction of large-scale offshore wind energy.

The lay-out (in terms of area size, spacing of turbines, size of turbines) of currently operational farms and farms under construction is known. For future farms we had to make assumptions. The rationale for these assumptions can also be found in Zijl et al. (2021). The spacing and sizes of the turbines, used in the upscaling scenario is shown in Table 2.1:

*Table 2.1 Dimensions and spacing of the turbines in operational, under construction and future wind farms.*

| | Stem density (piles/km$^2$) | Stem diameter (m) |
|---|---|---|
| **Operational** | 3.15 | 5 |
| **Under construction** | 0.85 | 8 |
| **Future** | 0.67 | 12 |

### 2.1.3 Validation

The reference scenarios of the hydrodynamic model, the fine sediment model and the ecological model have been validated with available datasets. A general problem with most datasets is that often data are only available for the upper layers of the water column. This applies to current data, temperature and salinity, suspended matter, nutrients and chlorophyll. At present processes such as primary production, are not routinely measured.

A number of different data sources have been used, including remote sensing data, as well as in situ measurements from monitoring programmes, such as MWTL. The relevant MWTL measuring stations utilised for validation of model components are indicated in Figure 2.2.

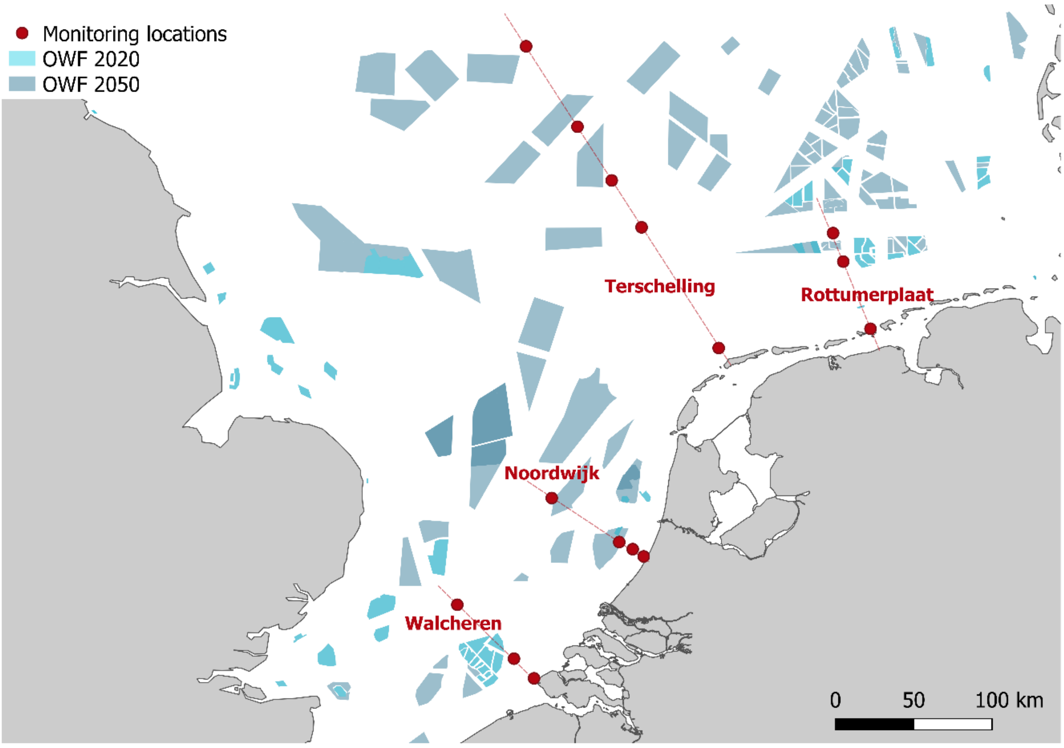


*Figure 2.2 Locations of MWTL monitoring stations that have been used to validate the fine sediment model and various water quality and ecological parameters.*

## 2.2 Model performance - reference scenario

### 2.2.1 Hydrodynamics

The hydrodynamics model had already been tried and tested before the Wozep project started. For the reference scenario several years of hydrodynamics results were available, i.e. not just for 2007. The model shows that offshore temperature stratification occurs and that nearshore (particularly near the outflow of the Rhine and Elbe) salinity stratification occurs (Figure 2.3).

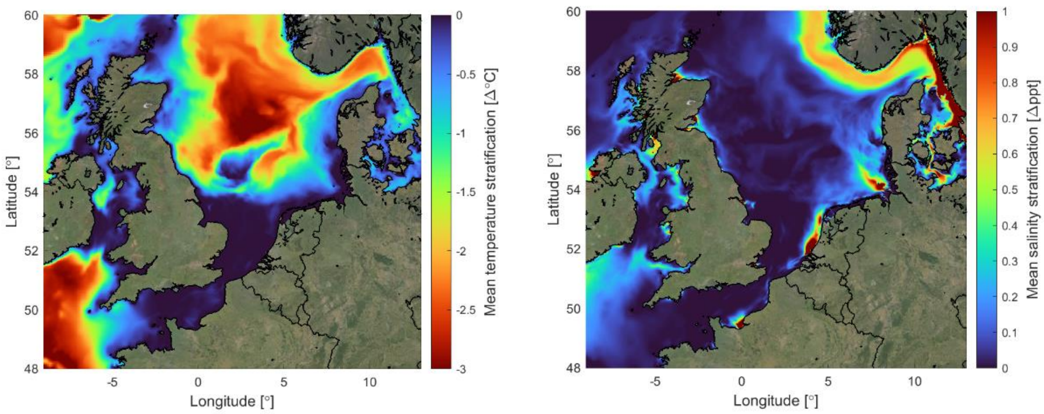


*Figure 2.3 Left annual mean temperature difference between the top and the bottom layer. Right: annual mean salinity difference between top and bottom layer.*

There are very few areas in the North Sea with data on temperature and salinity near the surface and near the bed. One measurement site is located on the Oyster Grounds, quite central in the southern North Sea. Model data and measured data regarding temperature match extremely well (Figure 2.4).

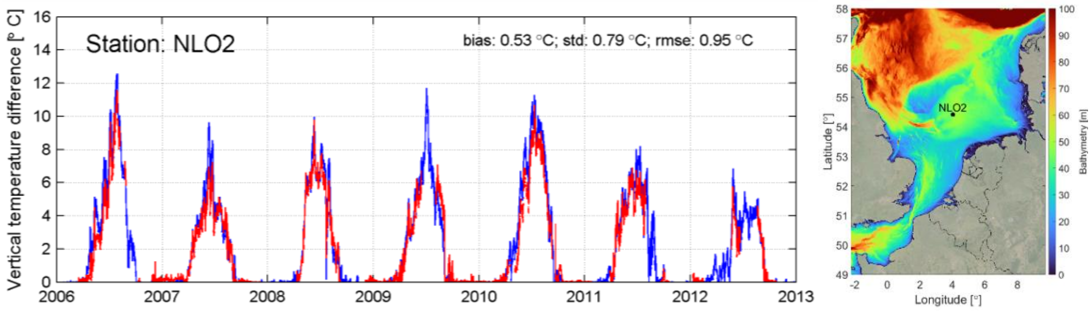


*Figure 2.4 Timeseries of measured (red) and modelled (blue) vertical stratification at station NL02.*

The model also shows patterns of residual currents and gives information about the amplitude and phase of the tide as well as residual currents (Zijl et al. 2021).

### 2.2.2 Fine sediment dynamics

In order to model the transport and resuspension of fine sediment, this module is coupled to the hydrodynamics model and to a wave model. Often waves are more important for the resuspension of particulate material than tidal currents. Waves are predominantly driven by wind. For the numerical modelling of waves, the third-generation shallow water wave model SWAN (Simulating WAves Nearshore; http://swanmodel.sourceforge.net/) is used (for further details see Zijl et al. 2021). In the scenarios with wind farms, the wind fields were assumed to decrease *within the wind farms* by about 10%. This resulted in an average reduction of wave heights of approximately 8%. This first model study on the effects of wind farms primarily focussed on the effects in the water. We did not model the reduction of wind velocities in the wakes of the wind farms. Model results from Large Eddy Simulation (LES) studies and spatial aperture radar images have indicated that the wakes of wind farms can cover a large area, but are strongly dependent on wind direction (Boon et al. 2018). Reductions in far field wakes are in the order of magnitude of 1-2% (Boon et al. 2018 and pers. comm. Sofia Caires). A better parameterisation of wakes in wave and hydrodynamic models is important for future work, and may also have some impact on our conclusions, particularly in shallow areas where waves are relatively important. Very recent work with research airplanes, has shown that the wakes of wind farms are strongly variable and depend on atmospheric stability and spacing of turbines (Cañadillas et al. 2020). The distance over which wind speed recovers up to 95% can vary between a few km to 50-60 km in very stable conditions, when the atmosphere is stratified.

In general, the patterns of SPM (suspended particulate matter) that were modelled in the reference scenarios, reproduced the patterns observed by MWTL measurements and remote sensing very well. However, there still is a bias in the absolute values. The model predicts values that are too low (Figure 2.5).

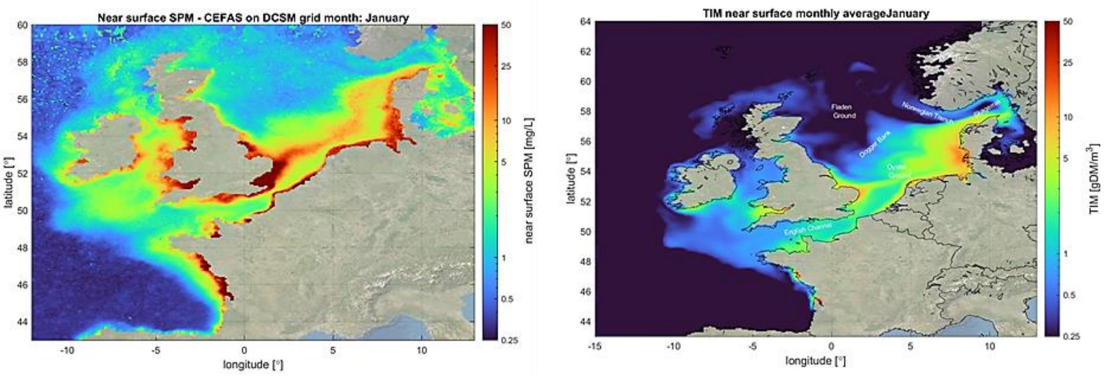


*Figure 2.5 Left Surface SPM values for January (source CEFAS satellite imagery). Right: modelled SPM concentrations in January.*

The absolute differences are largest in areas with high SPM concentrations, the relative differences are fairly similar over the whole domain. This is an issue that needs attention in future calibration. For the current study the results are suitable to compute relative effects in wind farm scenarios but are not yet suitable to use in ecological models.

### 2.2.3 Water quality and ecology

The water quality and ecology model needs to incorporate SPM to get the light climate correct, as well as nutrient loads (from rivers and atmospheric deposition) and the growth and mortality of algae. This model includes 4 categories of algae (diatoms, flagellates, dinoflagellates and *Phaeocystis*). Each of the first three groups have 3 ecotypes: one adapted to low nitrogen concentrations, one adapted to low phosphate concentrations and one adapted to low light levels. In the standard model growth of shellfish is included on the bed (mussels, *Mytilus edulis*) and the American razor clam (*Ensis leei*).

Overall, the model reproduces the temporal patterns of major nutrients, chlorophyll-a and $O_2$ well at the MWTL monitoring locations and the ICES data statistics (Figure 2.6). Dissolved inorganic N (DIN) winter concentrations are overestimated at the most northern observation points, most likely due to an overestimation of nutrient inflow at the offshore boundary and mixing in the deeper areas.

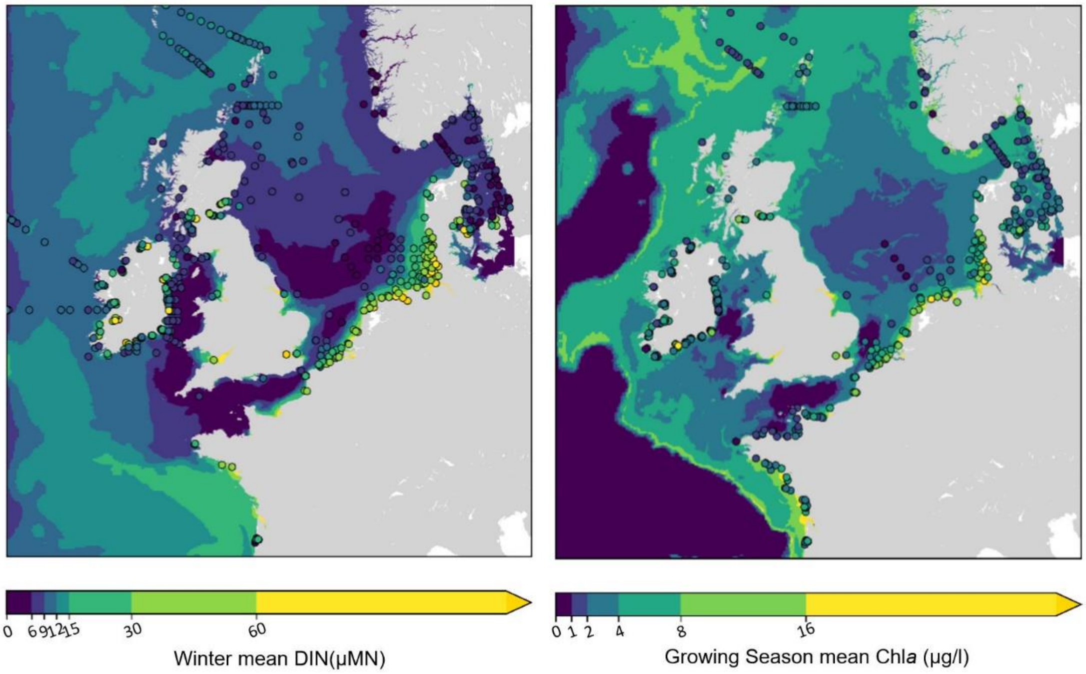


*Figure 2.6 Left Comparison of simulated (2007) winter-mean DIN and growing season-mean chlorophyll-a to ICES data statistics (2006-2014). Mean reported values at ICES monitoring locations are indicated by colored dots. Growing season = March-September.*

In general, the data regarding the timing of the spring bloom from the central North Sea measuring stations (the “Terschelling transect” Figure 2.2) compare quite well with the modelled data of nutrients and chlorophyll-*a*. In the south (particularly the offshore stations on the “Noordwijk transect”), the increase of $NO_3$ concentrations at the end of the summer starts too early in the season in the model, leading to an overestimation of summer phytoplankton biomass.
Along the Noordwijk transect, the model reaches P limitation in the summer, while this is not observed in the field, and overestimates $NO_3$ concentrations (close to depletion in the observations). Similarly, along the Terschelling transect, $NO_3$ depletion is well reproduced by the model, but summer $PO_4$ concentrations are constantly underestimated. The simulated phytoplankton biomass being very consistent with measurements, and winter nutrient levels well reproduced by the model, it seems that the N:P ratio of nutrient uptake by phytoplankton may be underestimated.
These issues will need to be addressed in follow up research. However, the generally observed patterns appear to be good enough for these initial scenario studies on effects of wind farms, particularly as in general relative differences will be assessed.

## 2.3 2020 scenario

### 2.3.1 Hydrodynamics

The 2020 scenario indicated that there were some changes in temperature stratification observed in current wind farms in the German Bight and very minor effects in salinity stratification in the Dutch farms under the influence of the Rhine plume. In nearly all cases the differences between top and bottom layers decreased, indicating reduced stratification.

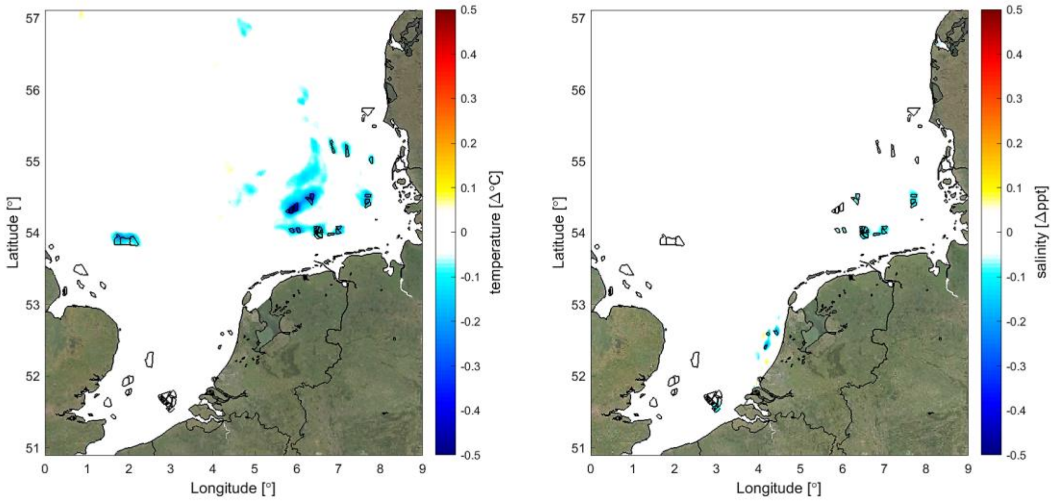


*Figure 2.7 Absolute change in annual mean of vertical temperature difference (left) and absolute mean in annual salinity difference (right) – 2020 scenario.*

Due to the fact that turbines exert drag on the flow, currents are slowed down inside the wind farms. This does have some effect on the residual flows. In this scenario effects on stratification and on residual currents are restricted to the wind farms and the immediate vicinity. We have not yet carried out model validation exercises on wind farm effects, but the farms where the model predicts destratification coincide with the farms where a German team of scientists has indeed measured destratification (Floeter et al. 2017).

### 2.3.2 Fine sediment dynamics

Effects of wind farms on fine sediment concentrations may be caused by the combination of three effects:

- the amount of suspended matter may change, e.g. extra resuspension from the seabed due to increased hydrodynamic forces on the bed or reduced resuspension due to reduced wave action)
- the composition of suspended matter may change
- the vertical distribution of suspended matter may change, e.g. due to increased mixing, particularly in stratified areas

Bed shear stress determines deposition and resuspension. The balance between deposition and resuspension determines whether a wind farm acts as a net sediment sink or net sediment source. Vertical mixing is determined by a combination of bed shear stress, turbulence around the piles and wind stress at the water surface. The vertical distribution of SPM may change caused by changes in both vertical mixing and settling velocity (hence sediment composition).

With regard to SPM concentrations, model results indicate that surface concentrations increase with about 10-20% at most locations within the wind farms, in contrast with near-bed concentrations, which decrease with 5-15% at most (but not all) locations (Figure 2.8).

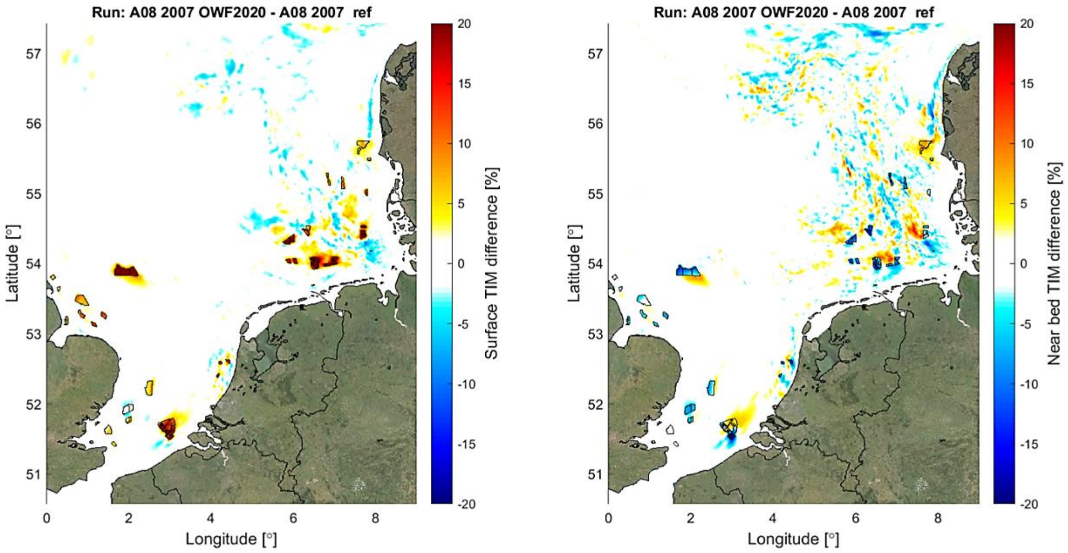


*Figure 2.8 Left: relative difference (in %) of SPM concentrations in the surface layer. Right: Changes in SPM concentration in the near-bed layers.*

Increased concentrations in the surface layers will reduce light levels and can influence primary production. As with the modelled hydrodynamic effects, changes are minor outside the immediate vicinity of the wind farms.

Along the Dutch coast there is a net residual current northward. This is an important mechanism of transport for fine sediment along the coast. Checks on fluxes of fine sediment along transects perpendicular to the coast in the model results, revealed some minor reductions in most areas (generally less than 1%).

### 2.3.3 Water quality and ecology

The 2020 scenario showed small differences with the reference scenario. Differences occurred nearly exclusively in the areas that show either temperature and/or salinity stratification (Figure 2.9). The same holds true for differences in nutrients. Overall the fine-scale model gives very similar results to the courser scale model. In the coarser scale model, the location of the wind farms is easier to recognise (Figure 2.11-left).

These model runs (Figure 2.9 and Figure 2.11-left) show only the ecological effects that are caused by the changes in stratification and changes in currents. On average we see an increase in primary production in the vicinity of the wind farms, due to the enhanced mixing and more nutrients being available in the upper layers. In these runs the effect of changes in turbidity are not taken into account. In order to get a first assessment of the combined effects of changes in hydrodynamics and sediment, the sediment field used to force the water quality and ecology model was locally changed by a factor derived from the changes in the coarse grid SPM model in the 2020 scenario relative to the reference scenario (Figure 2.10). The difference between a model without and with changes in fine sediment are shown in Figure 2.11. This shows that within and around the wind farms, where SPM concentrations in the top layers are elevated due to the enhanced mixing, primary production is reduced in comparison to the scenario runs where sediment effects are not taken into account. Due to the reduced primary production within the wind farm areas there are more nutrients available further away from the wind farms, where primary production is slightly enhanced. Particularly these far-field effects are relatively minor. They are in the order of less than 5 percent change and further outside of the wind farms there is no clear direction of change, some areas show small increases, others similar sized decreases.

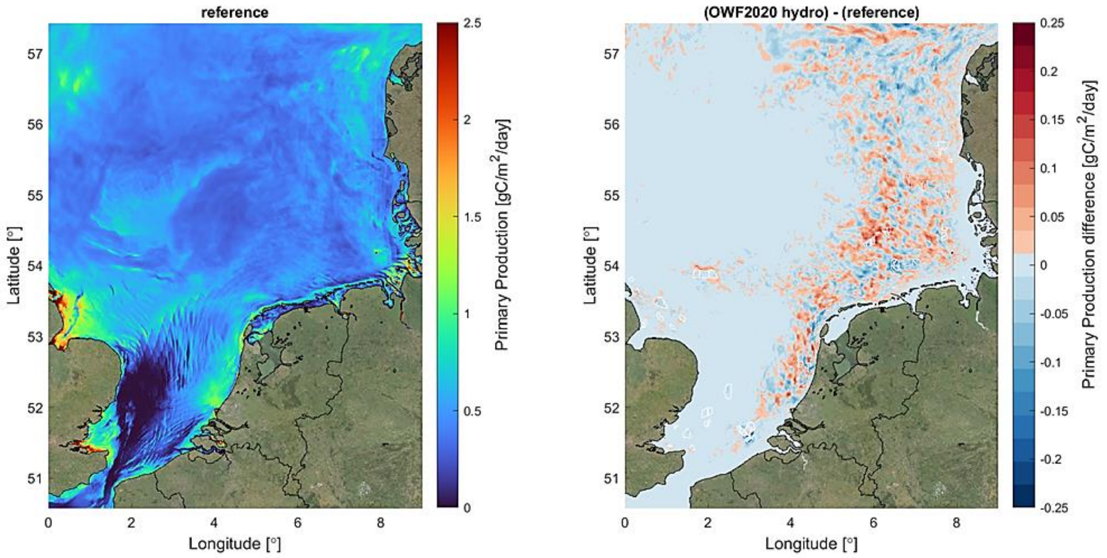


*Figure 2.9 Left: average primary production over 2007 in the reference run. Right: difference between average primary production simulated in the OWF2020 hydro scenario and in the reference run for 2007.*

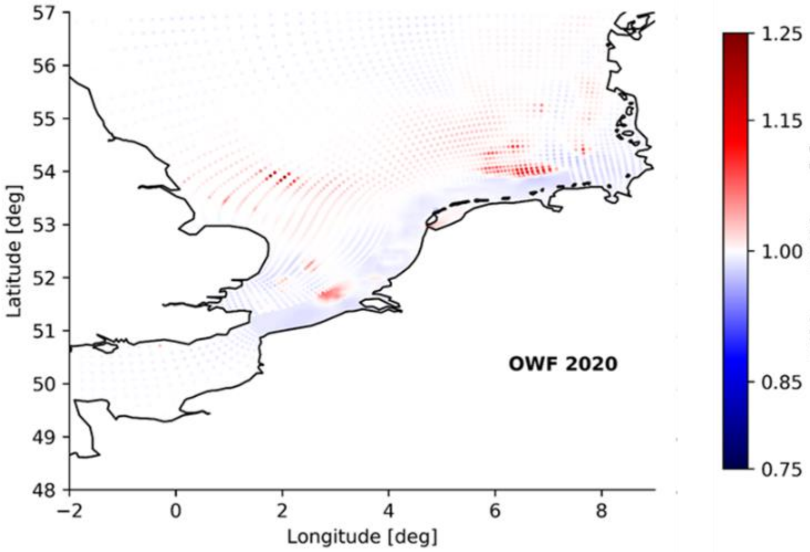


*Figure 2.10 Factors by which locally fine sediment concentrations were increased or decreased, based on the results of the fine sediment model run of 2020, divided by the reference run.*

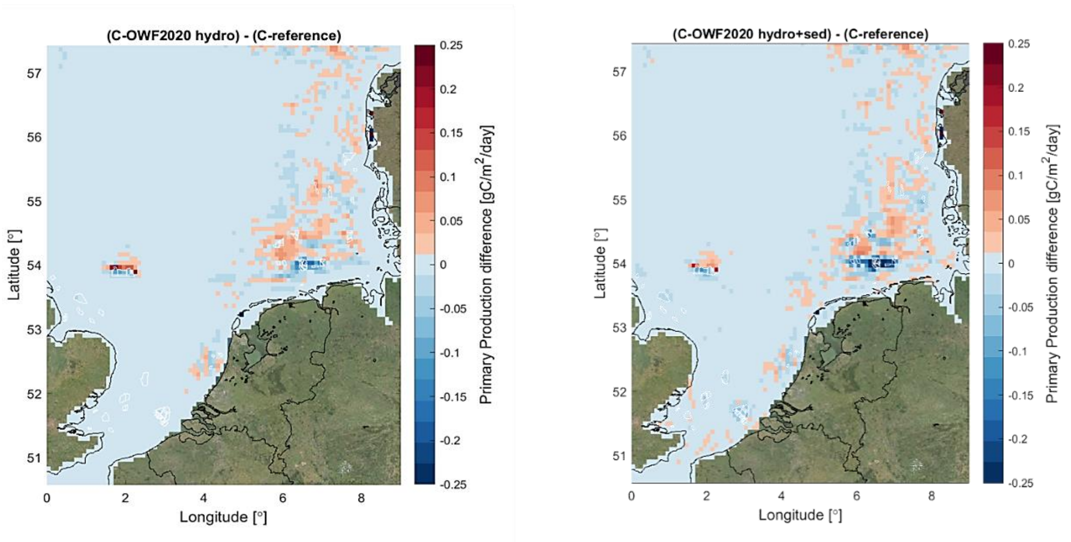


*Figure 2.11 Left: Course grid model results of the 2020 scenario minus the reference scenario. Right: Same scenario results with relative changes in fine sediment taken into account.*

## 2.4 Upscaling scenario

### 2.4.1 Hydrodynamics

The hypothetical upscaling scenario shows far more significant effects on temperature and salinity stratification (Figure 2.12).

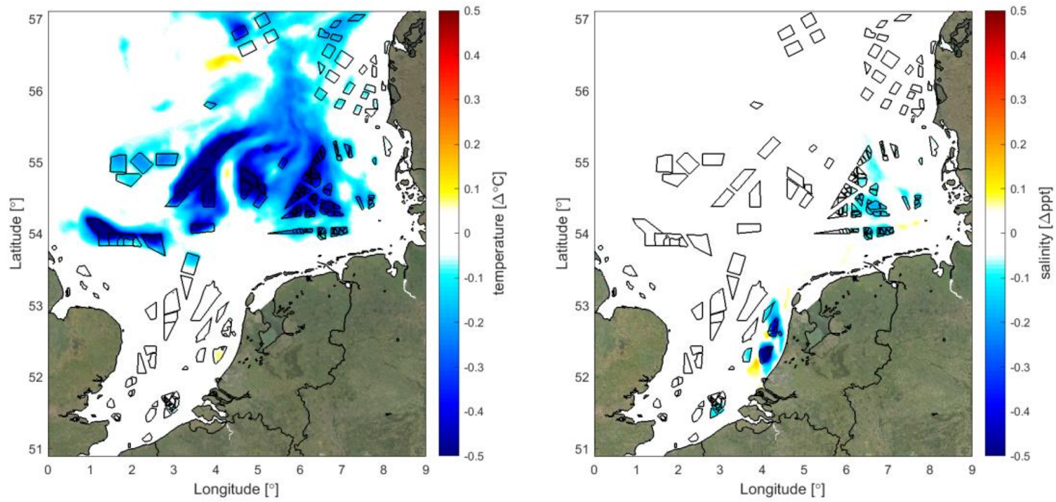


*Figure 2.12 Left: Absolute change in annual mean of vertical temperature difference. Right: Absolute change in annual mean of vertical salinity difference.*

In this scenario there are a number of wind farms in the central southern North Sea that are in a regime with pronounced seasonal temperature stratification (Van Leeuwen et al. 2015). These are the dark blue areas in the left panel in Figure 2.12. Changes in the central southern North Sea and in the farms in the German Bight are accompanied by a reduction of surface temperature of 0.2 – 0.5 °C. In this scenario the effects of destratification are not restricted to the immediate vicinity of the wind farms but are visible in areas well beyond the farms. Some effects in temperature stratification are visible well over 100 km away from any wind farms.

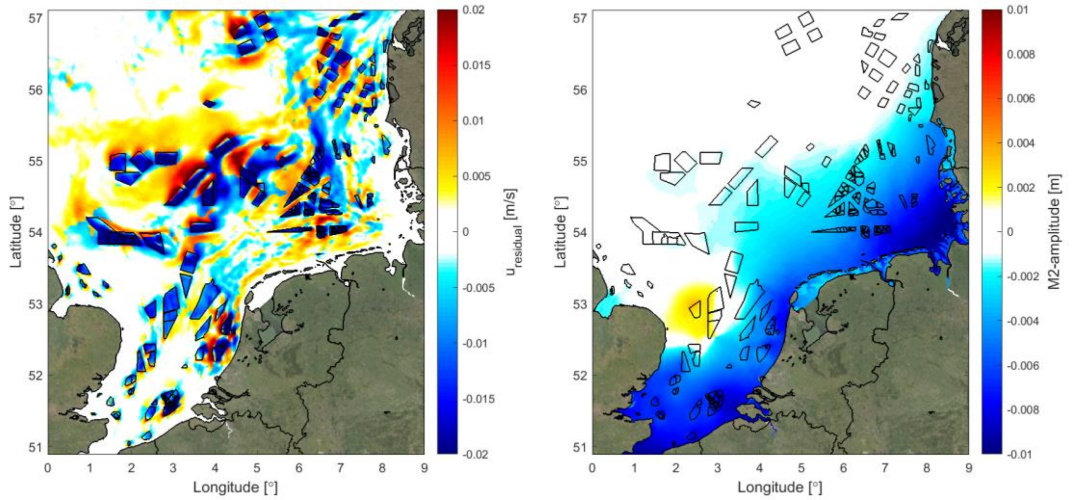


*Figure 2.13 Left: Absolute changes in residual velocity magnitude in the upscaling scenario. Right changes in the amplitude of the main component of the tide.*

Strong effects of changes in residual flow velocities are visible predominantly in and immediately around wind farms. Depending on the orientation of the farms with respect to the main direction of the tidal flow, residual velocities are decreased by several centimetres per second within the farms and increases of similar magnitudes are observed immediately outside the farms. This may not seem much in comparison to peak tidal velocities, however, in residual flow velocities this is substantial. It will have an effect on local transport rates of fine sediments and nutrients. However, further analyses of the larger scale transport patterns indicated that effects on these were limited (Zijl et al. 2021). The upscaling scenario also causes a reduction in tidal amplitude (Figure 2.13-right panel). The strongest effect is modelled in the ‘corner’ of the German Bight where the reduction in amplitude is around a centimetre.

### 2.4.2 Fine sediment dynamics

In the SPM model results of the upscaling scenario we see in most wind farms substantial effects on SPM concentrations in the upper and lower water layers (Figure 2.14).

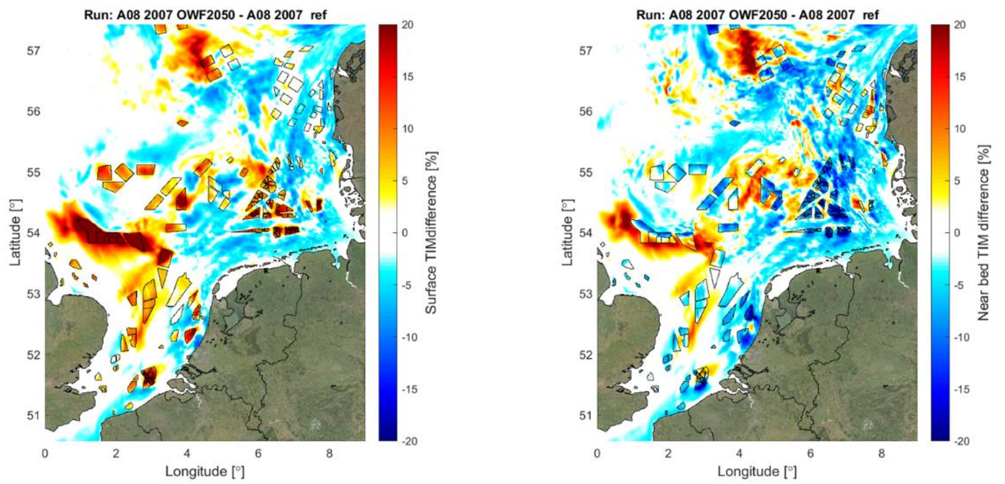


*Figure 2.14 Left: changes in fine sediment concentrations near the surface. Right: Changes in fine sediment concentrations near the bed. Both figures show the percentage difference between the upscaling scenario and the reference scenario, annual averages.*

In the near-surface layers nearly all wind farms show an increase in fine sediment concentration. In the near bed layers, it is quite variable. In many wind farms there is a reduction in near-bed concentrations but in some (particularly in some of the English farms south-west of the Dogger Bank) parts of the wind farms also show an increase near the bed. The effects are also affected by the season, with clearly higher increases in fine sediment concentrations in the top layers in spring and summer than in other times of the year.

Particularly in the Holland Coast and close to the Dutch Wadden Coast, fine sediment concentrations are on average lowered near the bed and outside the wind farms also often in the top layers. This is due to changes in bed shear stress as well as changes in vertical and horizontal mixing around the Rhine region of freshwater influence (ROFI). This appears to reduce the northward transport of fine sediment and (although the latter was in the current study not quantified) will also affect the influx of fine sediment into the Wadden Sea. In this model run the reduction in sediment flux across the transect near Texel amounted to about 10%. Due to the fact that the fine sediment model still needs some fine-tuning, the absolute amount of reduction in transport needs to be treated with caution. As reduction in transport appears to be consistent with the observations in changes in bed shear stress and changes in the mixing in the Rhine ROFI, some reduction in transport can be expected.

### 2.4.3 Water quality and ecology

The effects of wind farms on primary production in the upscaling scenarios is quite substantial. The increased mixing appears to boost primary production in the central southern North Sea. Particularly in the areas around the Oyster Grounds increases in primary production can be over 60%, in areas that stretch over 50 km beyond wind farms. The effect is obvious looking at annual average levels (Figure 2.15), but even more pronounced in the spring period (Figure 2.16). In spring increases can be more than 75% relative to the reference scenario.

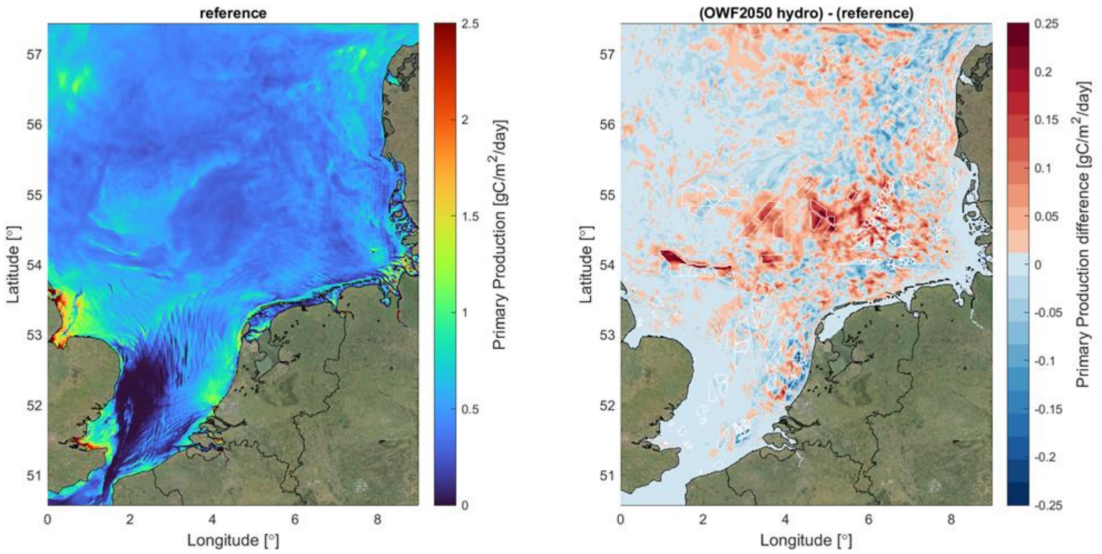


*Figure 2.15 Left: average primary production over 2007 in the reference run. Right: difference between average primary production simulated in the upscaling scenario and in the reference run.*

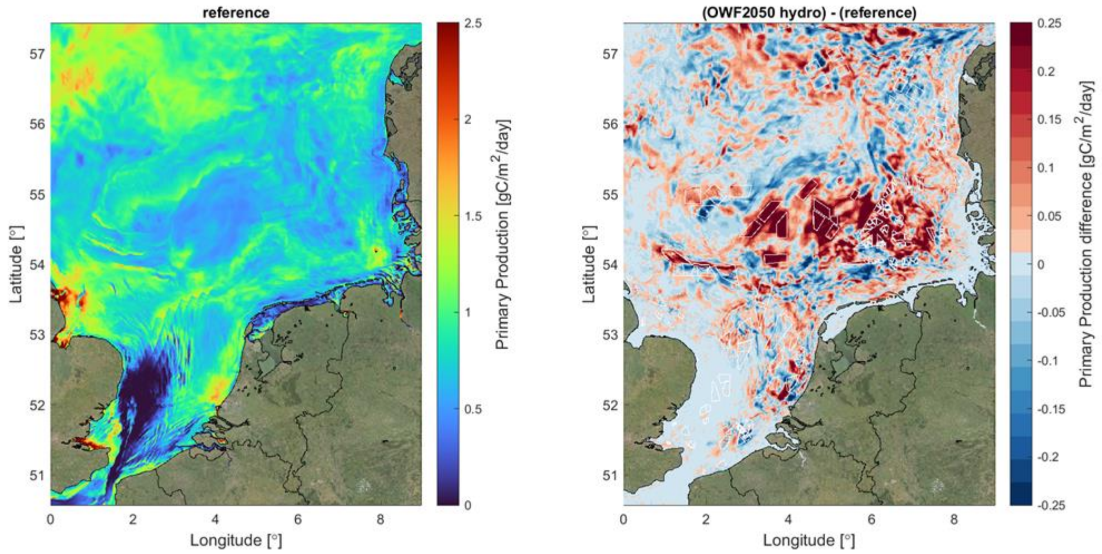


*Figure 2.16 Left: average spring primary production over 2007 in the reference run. Right: difference between average spring primary production simulated in the upscaling scenario and in the reference run.*

Again, the results from the fine-scale model do not yet take the wind farm effects of fine sediment into account. Also, for the upscaling scenario we performed comparison runs on the courser grid model and modified the sediment field based on the relative changes in the SPM model (i.e. upscaling scenario divided by the reference scenario). The patterns of increases and decreases are shown in Figure 2.17.

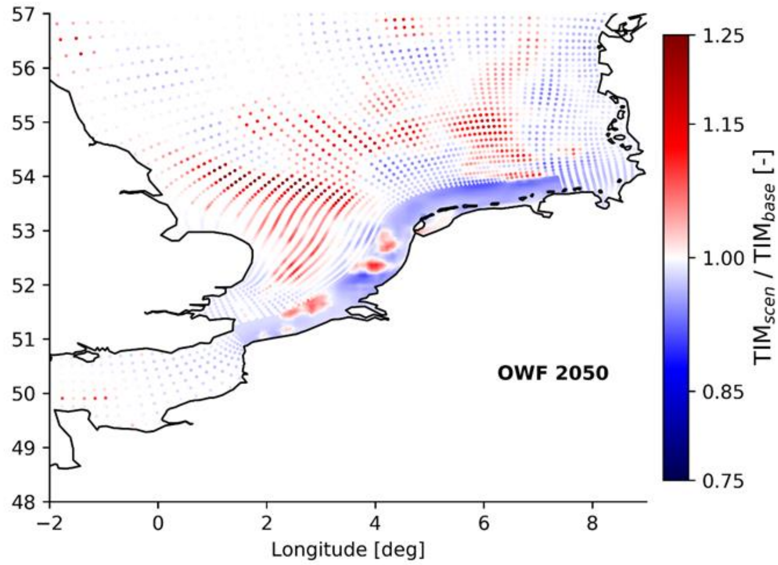


*Figure 2.17 Factors by which locally fine sediment concentrations were increased or decreased, based on the results of the fine sediment model upscaling scenario, divided by the reference run.*

Comparing the results from the model run with only the hydrodynamics effects to those where the fine sediment was included, a few things are significant. In the central southern North Sea, we still see a significant increase in primary production over a large area, despite the fact that in this area fine sediment levels in the upper layers were enhanced. In the farms in the German Bight, the effects of only the hydrodynamics are patchy, but on average cause an increase in primary production. If the effects of fine sediments are taken into account this effect is reversed.

In the German Bight the effect of reduced light levels are dominant, In the Central North Sea the effects of increased nutrient availability in the upper water levels is dominant.

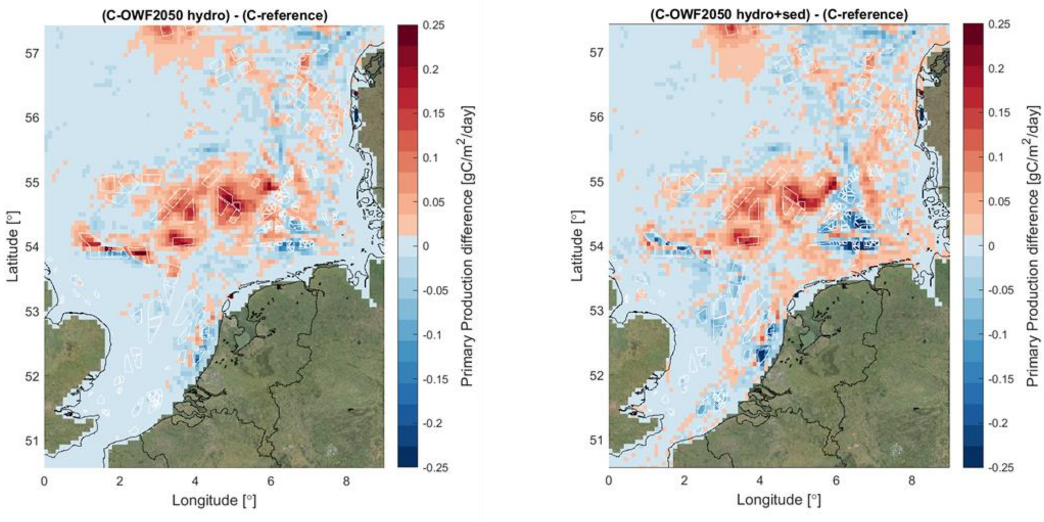


*Figure 2.18 Left: course grid model results of the upscaling scenario minus the reference scenario, with only the changes in hydrodynamics taken into account. Right: same scenario results also with relative changes in fine sediment taken into account.*

Apart from changes in the amount of primary production, in some areas we have also observed a shift in the timing of the spring bloom. Comparing two locations, one in the Dutch coast in an area with little temperature stratification (OWF1, Figure 2.19) and one in a British farm in the central Southern North Sea with strong effects on temperature stratification (OWF2, Figure 2.19) we see different effects.

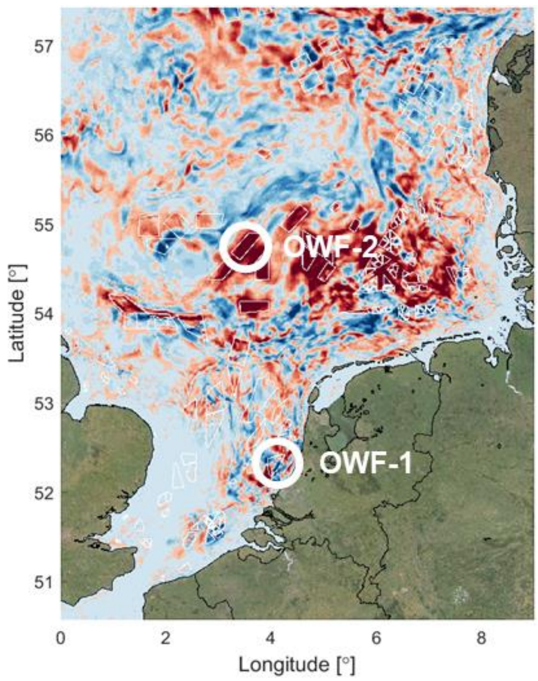


*Figure 2.19 Locations where temporal patterns are compared.*

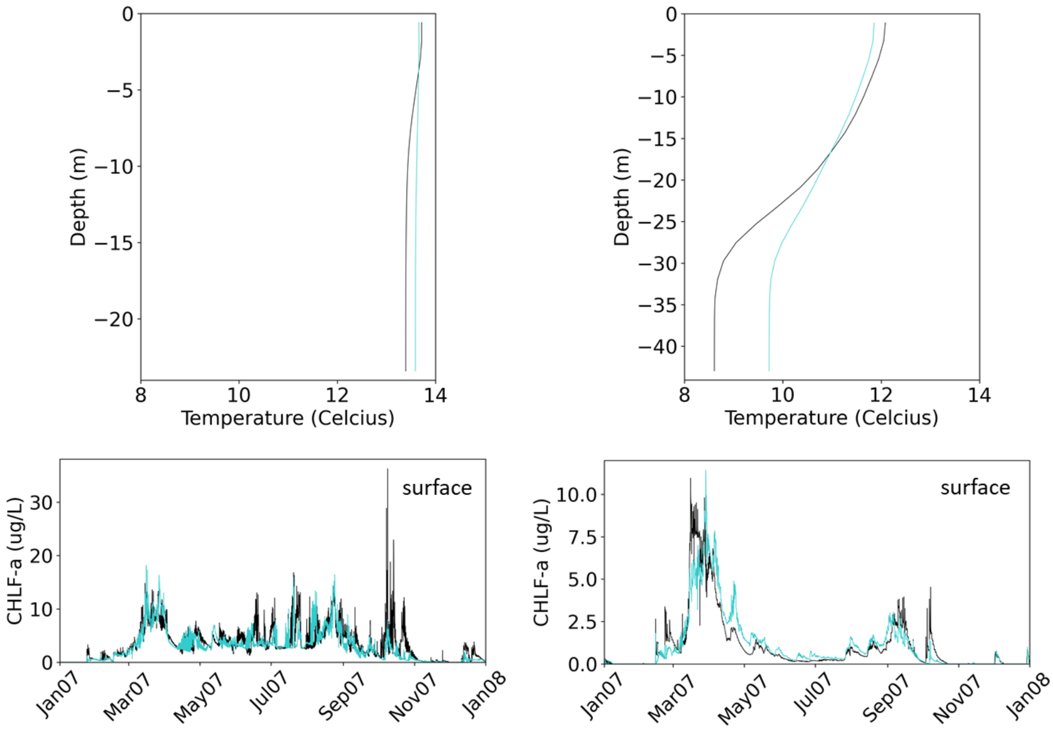


*Figure 2.20 Left: vertical temperature profiles in the reference scenario (black lines) and the upscaling scenario (blue lines) and below this the concentration of chlorophyll-a over time, at OWF1 (Dutch coast location). Right: As left figure, but at the stratified location in the central Southern North Sea (OWF2).*

In Figure 2.20 we can see that the temporal patterns in the not stratified part match between the reference and the upscaling scenario. In the stratified location, there is a time lag with the onset of the spring bloom in the upscaling scenario by a couple of weeks. This time lag is a consequence of the fact that increased mixing due to the presence of turbines not only diminishes the level of stratification, but also delays the onset of stratification. Prior to the onset of stratification algae are mixed freely throughout the water column and spend a significant amount of time outside of the photic zone, where there is not enough light for photosynthesis. Once stratification sets in, algae in the upper layers receive more light and the spring bloom can kick off, until the nutrients in the upper layer are utilised. So, a change in the onset of stratification can lead to a delay in the timing of the spring bloom. This has only been analysed for the fine grid model runs based on hydrodynamics only. Increased fine sediment in the upper layers can increase this effect. The first tests on the coarse grid including effects on fine sediments dynamics, show that this appears to be the case for the German Bight area, where the delay in spring bloom is largest.

### 2.4.4 Effect of filtration by mussels on turbines

The DELWAQ model allows incorporation of the growth of grazers such as shellfish in the model. On the seabed this is a standard effect to take into account. The dynamic energy budget (DEB) model to simulate growth of shellfish requires certain model parameters that are specific for the species as well as for the location. In the first attempt at incorporating mussels in the upper water layers we used the standard parameter set that is used for the Wadden Sea, an area that has average SPM concentrations orders of magnitude higher than the upper layers of the North Sea. In the model the mussels died off, which is clearly not the case in the field, where mussels grow very well in the upper 5 metres of the water column on the turbine monopiles (Degraer et al. 2013). This clearly requires further calibration of mussel parameters suitable for this environment.

## 2.5 General interpretation of model results

The first model results indicate that ecosystem effects in present wind farms are limited (effects are there but are local). The upscaling scenario showed more pronounced effects, particularly in areas that see seasonal stratification. Particularly in these areas in the central southern North Sea (south of the Dogger Bank, around the Oyster Grounds), effects can reach far beyond the limits of the wind farms and interaction between wind farms occurs over hundreds of kilometres. Despite the fact that there are uncertainties associated with such (new) model scenarios, there is certainly sufficient ground to continue this with follow up research.

### 2.5.1 Uncertainties

We did not manage to get fully coupled SPM and ecological models running and effects of fine sediment were only assessed using a relative increase or decrease based on the coarse scale SPM models, which certainly is something that needs to be addressed in the near future. The largest uncertainties occur in the central German Bight. The effects of increased nutrient availability due to mixing is counteracted by increased SPM concentrations in the upper layer. In the current first assessment in the German Bight it looks like fine sediment effects are outweighing the effects of increased nutrient availability, but this needs closer examination.
Another clear source of uncertainty is the fact that we have not incorporated wake effects in the wind. We only reduced the wind stress within the wind farms. Reduced wind fields may reduce waves and therefore reduce wave-induced mixing, which in turn may affect stratification. We expect this effect to be relatively minor, but as it can extend over large areas it may still be relevant.

### 2.5.2 Further validation required

The models need further validation. Not just in the basic processes (e.g. stratification processes in the Rhine ROFI area) but also further validation of the effects of wind farms. At the moment we have a first qualitative validation, as we model destratification in the German Bight, where this has actually been measured. This needs further quantification and also quantification of effects is required in other wind farms in physically different locations.

# 3 Top down approach

The focus of this approach was primarily on seabirds and marine mammals (Van der Meer and Aarts 2021). These species groups are most widely researched due to the important and often precarious conservation status. At the start of the project the possibilities were investigated to include sharks, rays and skates. Unfortunately, for these species there is quite a lack of fundamental autecological knowledge and a lack of habitat related data, so these were left out of further considerations. However, with more background knowledge, elasmobranchs should be included in future studies.

## 3.1 Ecosystem changes and their potential effects on higher trophic levels

Probably the most important ecosystem effects on higher trophic levels are driven by factors in the food web, either directly – because food availability may change, or indirectly, because certain feeding areas become accessible or inaccessible. This can lead to density dependent effects, such as limits to population growth and size (i.e. carrying capacity) or avoidance of areas with high density of conspecifics, despite high prey availability. Particularly the ecosystem changes moderated by changes in stratification are likely to affect the vertical distribution of food. This will affect marine mammals that often gather food near the bed in a different way than e.g. terns, gulls or gannets that are more restricted to the upper water layers. Various environmental factors that may be affected by offshore wind can also have a direct impact on the distribution of these species. If there are differences in stratification, this will likely mean there are in differences in temperature in the top and bottom layers. Temperature is of course an important factor for warm blooded species, but temperature differences can also have an effect on the energy budget of species that regularly dive below pycnoclines, such as seals. Also, characteristics of the sea bed can have an effect on the distribution of birds and marine mammals.

## 3.2 Assessing and predicting the effect of environmental change on birds and marine mammals

There are a number of different types of models available that can be used to investigate the relationship between individual species and changes in their environment. Three major types were identified:

- Demographic
- Species distribution models
- Individual Based Models (IBM)

Of these three types, the IBM ones are the most suitable for this type of research (Van der Meer and Aarts 2021).

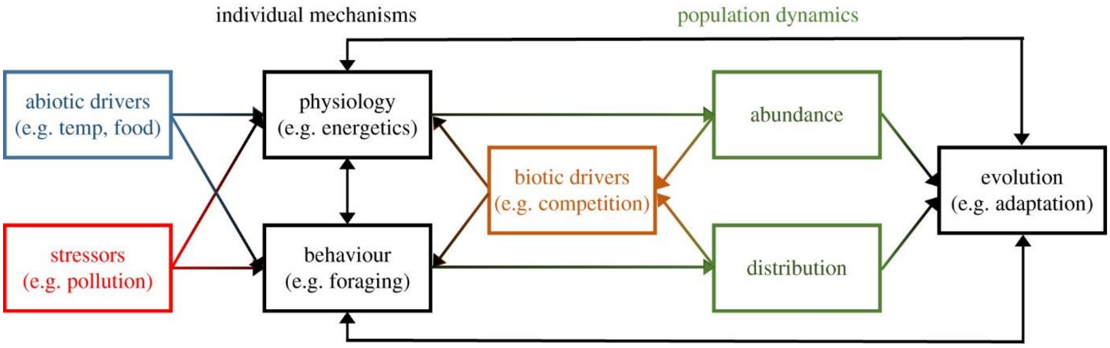


*Figure 3.1 Conceptual standardized mechanistic approach for predicting animal population dynamics in response to spatially explicit abiotic drivers (blue) and multiple stressors (red). Individual mechanisms (black) interact to drive shifts in population abundance and distribution (green), and biotic drivers (orange) cause feedbacks between population dynamics and individual mechanisms. (Johnston et al. 2019)*

There are a few IBM models for relevant North Sea species, notably gannets and marine mammal species. These models generally assume that three elements are working on individuals: physiology, behaviour and evolution. For studies on the timescale of the introduction of windfarms (a few decades) evolution is generally not relevant as many of the relevant species have long life spans. However, none of these models have as yet been applied for specific management scenario studies, such as effects of future offshore wind scenarios.

## 3.3 Requirements for IBM models

The IBM models all have in common that they need to be based on substantial datasets. Data required include:

- Detailed species specific and individual-level data on behaviour (such as movement) and physiology. Such data could best be collected using animal-borne data loggers (e.g. GPS-trackers, accelerometers and temperature sensors).
- Accurate representation of their environment, especially spatially explicit information on the dynamics of their prey is required, i.e. information on the changes in their food landscape.

Fish and larger invertebrates, such as squid, are the major constitutes of the food landscapes of birds, marine mammals as well as of sharks and rays. Currently, most fish surveys are carried out once (or twice) each year and provide a relative measure of abundance (since catchabilities are often unknown).
Estimates of absolute abundance are needed to calculate possible density dependent effects on the population dynamics of the apex predators. These estimates need to be coupled to measurements on “profitability” of locations, taking not only absolute prey abundance into account, but also the proportion of available prey that is obtainable to these apex predators. Multiple surveys each year are needed to quantify changes in distribution, abundance and energy content.

# 4 Synthesis

The ultimate aim of the Wozep programme is to gain insight in the knowledge gaps regarding the effects of large-scale implementation of offshore wind on vulnerable natural values. The targets for e.g. Natura 2000 are therefore important, hence the strong focus on apex species, such as birds and marine mammals. The literature review on appropriate top-down approaches has revealed the pathways by which higher trophic levels can be influenced by changes in physical forcing and in functions at lower trophic levels. A clear path has been designed for modelling the vulnerability of birds and marine mammals to the changes caused by wind farm deployment. This needs further development, as there are currently no off the shelf, ready to use suitable models available. These models also require significant data input, not all these data are available.

The bottom-up modelling approach has given the first insights into the potential effects of upscaling of offshore wind in different parts of the North Sea. Although these results cannot yet be translated directly into effects on the food landscape for apex predators (such as presence of fish), they do give a good indication that significant changes can be expected and that these changes differ per region. This was the very first attempt at investigating these effects using the new fully coupled ecosystem model of the North Sea. These models still need further work and certainly validation. At present these models are research instruments, not tools that are ready for predictions and policy decision support. However, despite technical hiccups, inherent to the use of entirely new modelling tools, the first conclusions (careful as we have to be with them) certainly warrant following up.

## 4.1 First conclusions

The ecosystem modelling results have given clear indications that ecosystem-scale changes in stratification, currents, fine sediment and productivity of different trophic levels are likely with large upscaling of offshore wind. These are likely to have knock-on effects on higher trophic levels through various pathways. These pathways are directly linked to the energy budgets of these apex species.

### 4.1.1 Effects through changes in water column mixing and benthic – pelagic transport

The most clear-cut pathway by which effects at lower trophic levels are going to influence higher trophic levels is the effect of increased water column mixing. This has a direct and significant impact on primary production. The first model results indicate that in certain areas increases or decreases in the order of magnitude of 0.25 $gC/m^2/day$ are possible. These larger changes occur in areas in the central southern North Sea, where normal annual averages range around 0.5 $gC/m^2/day$. So, such effects are certainly potentially significant. In a few limited areas the models also predict decreases, of a similar magnitude. These decreases are limited to some wind farm locations and their immediate vicinity and only occur in areas close to the coast, with generally higher rates of primary production. Hence the absolute decrease is similar, but proportionally the effects are less.

Increased mixing will transport more food and oxygen towards the bed. The Oyster Grounds in the central southern North Sea is typically an area with stable summer stratification that often coincides with low oxygen levels (Peeters et al. 1995). This can be limiting for benthic communities. Benthic communities are likely to benefit proportionally more from the increased production than pelagic grazers such as zooplankton. This means that predators that predominantly feed on benthic prey will be affected differently than species (e.g. bird species such as terns) that feed relatively close to the surface and feed on small planktivorous fish.

### 4.1.2 Effects through changes in temperature and / or habitat

Temperature is one of the main ecological drivers. It affects oxygen uptake due to changes in metabolism (Varó et al. 1991), species distribution (Neumann et al. 2009), swimming behaviour and speed in fish (Batty et al. 1991) and plankton (Gill and Crisp 1985) and many other different ecologically important processes. The hydrodynamic model showed that in the upscaling scenarios surface temperatures were affected by 0.2 – 0.5 °C. The figures shown in section 2.4.1 are annual averages. As stratification occurs here in summer and is broken up in winter, the differences in summer are higher (can be up to 1 °C). Such changes may have an effect on the distribution of certain species and needs further investigation in future.
Future changes in temperature are also expected due to climate change (Harley et al. 2006). Both climate change and OWFs can affect the distribution of temperature, but the underlying processes and the spatial extent differ. OWF-effects are far more localised and due to mixing, while climate change acts on much larger spatial scales and is due to increased air temperatures. Models such as these, can be used to assess the interactive effects.

The presence of turbines and scour protection offers different settlement habitat. Physical habitat formation and changes in biodiversity have not been specifically addressed in this study but are the subject of various other projects (Degraer et al. 2013, Lengkeek et al. 2017, Raoux et al. 2017). Future work needs to address these effects in conjunction with the ecosystem effects, such as the changes in primary production patterns in the North Sea. Specifically, the fact that offshore wind turbines offer substantial ‘alien’ settlement habitat for normally benthic species in the upper part of the water column, which will locally affect nutrient recycling and particle dynamics, is something that will need future attention.

### 4.1.3 Effects through changes in competition in lower trophic levels

The whole complex of new hard substrate being available at the bed and in the water column, as well as changes in near-bed oxygen levels and food supply towards the bed is likely to change the relative importance of various carbon pathways through the marine food web (Duffill Telsnig et al. 2019, Ehrnsten et al. 2019). Such changes can fundamentally alter the functioning of a system. Even though not all these changes will be detrimental e.g. for species of high conservation interest or for ecosystem services, such as fisheries, there are likely to be winners and losers. Although the implementation of a dynamic energy budget model of blue mussels was not immediately successful within this research, investigating trophic relationships with such models is likely to yield more insight into these pathways and therefore into ultimate effects.

## 4.2 Locations sensitive to ecosystem effects

A clear result of this first study is that offshore wind affects the different areas in the North Sea physically in different ways, which ultimately results in different ecological effects. Based on this first study, we can differentiate roughly five different areas where physical and ecological effects differ (Figure 4.1).

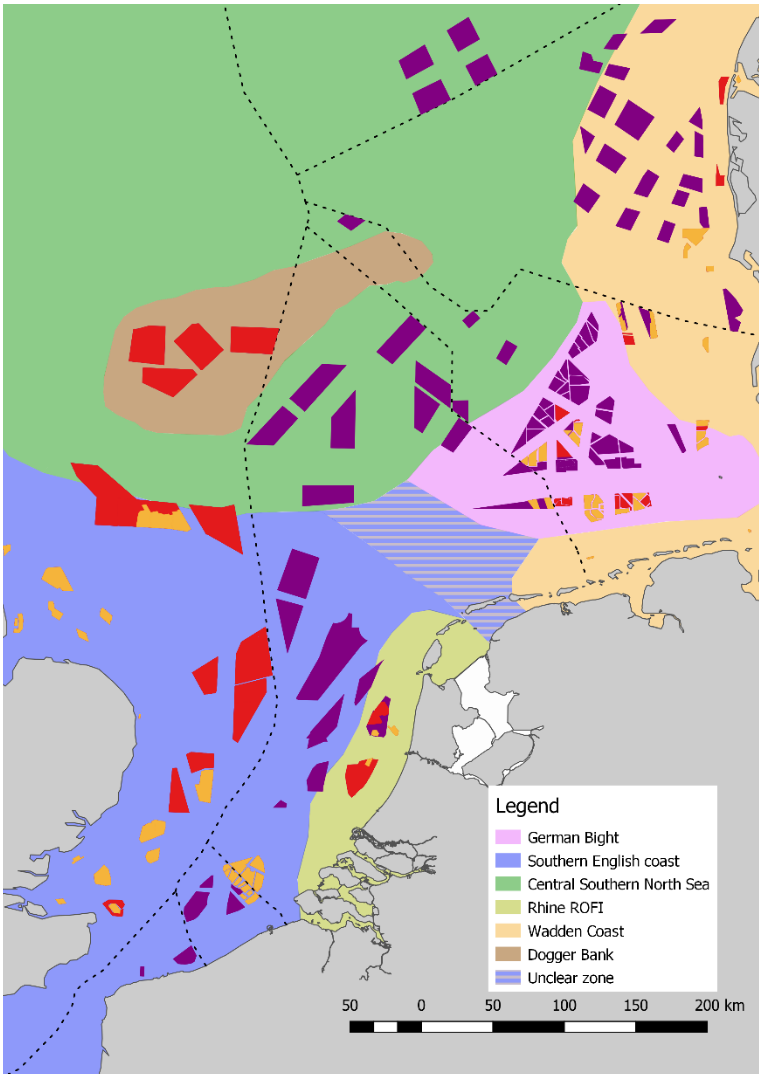


*Figure 4.1 Areas with different ecosystem effects in the North Sea*

### 4.2.1 Central German Bight

This area is characterised by regular but not very strong stratification. Temperature stratification is dominant, but also salinity plays a role here. This is an area where there are strongly opposing effects of wind farms. On one hand, increased availability of nutrients can boost primary production, however, increased SPM levels in the upper layers can also reduce this. The model runs with the adapted SPM fields suggest that SPM effects are significant and in some sub-areas dominant. This clearly needs further quantification with the fully coupled model system and well calibrated and validated SPM fields. In this area, the spring bloom is severely delayed due to both the effect of reduced stratification and enhanced fine sediment in the upper layers.

### 4.2.2 UK Coast and western most areas of the Dutch Continental Shelf

These are the areas that are fully mixed. Changes in stratification do not occur here. Particularly close to the Thames estuary the system is extremely turbid and hence very low in productivity. Certainly, in absolute terms, any increase in SPM in the top layers does not decrease productivity much further. Further away from the Thames estuary, increased turbidity does reduce production.

### 4.2.3 Central Southern North Sea

This area is regularly stratified, and some areas are always seasonally stratified due to temperature. Even the areas with relatively strong seasonal stratification see clear effects from wind farms. This area is most strongly impacted by wind farm effects and the effects reach well beyond the immediate wind farm perimeters. The area is low in SPM concentrations in the upper layers. Wind farms appear to increase the concentration, but this does not cancel out the effects of increased nutrient availability in the upper layers. In this area the net effect is an increase in primary production. Although there is an overall increase in the primary production, onset of phytoplankton growth in spring appears to be a bit later in these areas.

### 4.2.4 Holland coast and Rhine ROFI

This is an area with high nutrient availability and without temperature stratification, but some salinity stratification. It is a highly dynamic area with strong residual currents. In this area primary production is more light-limited than nutrient-limited. Nutrient availability in upper layers is high due to riverine input. The net effect is that higher fine sediment concentrations in the upper layers decrease primary production, but increased mixing does not enhance productivity. The changes in mixing in this area (in horizontal and vertical direction) are likely to have some effect on the transport of sediment along the Dutch coast. This effect needs further quantification. It is likely that this effect is partly influenced by the windfarms located in the Rhine ROFI. To what extent this is also influenced by farms further to the west (in the UK coast and the westernmost part of the Dutch EEZ) will need to be investigated.

### 4.2.5 German and Danish Wadden coast

This area is in most ways similar to the UK coastal area. It is generally not stratified, or only very occasionally. It is high in nutrients but due to high SPM concentrations it is light limited and not very productive. Effects of wind farms on SPM concentrations in the upper layers and on productivity are minimal. There is no clear delineation between this zone and the UK Coastal zone, hence the blue/orange hatched area is indicated as “unclear zone”.

### 4.2.6 The Dogger Bank

This is a relatively isolated shallow area surrounded by the seasonally stratified area. It has a unique composition of ecological communities. Sufficient light penetrates to the bed for primary production, hence this is one of the few areas in The North Sea where microphytobenthos occurs. The stratification regime of the Dogger Bank is unclear, some areas occasionally have some (not very strong) temperature stratification. The bed consists predominantly of medium sand and course-grained material, so even though waves easily reach the bed, resuspension of fine sediment from the bed is limited. The resulting effects of offshore wind farms on the Dogger Bank on primary production are limited and spatially varying. In some areas there is a small net increase in other areas a small net decrease.

## 4.3 Gap between top-down and bottom-up

This study was initiated to elucidate indirect effects of wind farms on species with high conservation status. The first steps indicate that such effects are likely. The changes in primary production are such that these will eventually translate into effects on higher trophic levels. However, we currently lack sufficient insights in the various pathways through the food web to link the bottom up effects we can determine deterministically to the apex predators. At the moment there are a few main missing links between bottom-up and top-down, and that is zooplankton and fish. The bottom-up models have yielded results indicating that changes in zooplankton are likely because of:

- Changes in locations of high primary productivity
- Changes in timing of primary productivity (in certain areas)
- Changes in competition with the benthos

Changes in competition with “new” benthos higher up in the water is also likely and will be followed up with successive model research. Changes in zooplankton imply changes in food availability for planktivorous fish, such as sandeel, herring, sprat, mackerel, anchovy and smelt, which in turn are all important prey items for various seabirds as well as marine mammals.

It is in principle possible to include zooplankton in the “bottom-up” deterministic modelling approach, by including DEB models for a few key species, such as a few typical copepod species. A similar approach is not useful for fish. Future work should seek to align modelling of the basis of the food web with approaches to model fish populations. Fish are among the best-documented organisms of the sea, and data-driven approaches can be promising, besides existing models in fisheries research. The deterministic bottom-up models and the scenario results on effects of offshore wind, can be input to such fish models and assess the changes in the food landscape for higher trophic levels that is required by the IBM’s for species of high conservation status.

## 4.4 Next steps

The current research focussed strongly on the development of models (both the bottom-up and the top-down approach). Models are very useful tools to investigate potential future situations, that at present do not exist. However, deterministic models are of limited value if they are not properly validated and the IBM models that are recommended for the higher trophic levels require significant amounts of input data. Future work therefore cannot rely on models only, but needs observations and in some cases process measurements as well (Herman et al. 2019, Van der Molen and Soetaert 2021).

Three main issues have been identified that limit the current applicability of the models for predictions:

1. The analysis focused mostly on the sea surface; further analysis of changes in the vertical structure are possible for many variables and more data are required to validate the models near the bed
2. Some likely important interactions/processes have not yet been (successfully) included, most notably: a) the effect of changes in suspended sediment concentration on the under-water light regime and primary production, b) atmospheric wakes of wind farms, and c) mussel growth on turbines and their effect on biogeochemical cycling
3. Changes due to several effects of wind farms (wind deficit, friction, biofouling) on the hydrographical and biogeochemical environment have only been simulated together, making it difficult to understand their individual contributions to the over-all effects.

A full description of recommended follow up research can be found in Vander Molen and Soetaert (2021). Below is a short summary of the most important points.

### 4.4.1 Short term steps

Some issues will be tackled in the short term. Fully online coupling of the SPM and water quality models will immediately improve the modelling of the combined effect of SPM and suspended algae on the light climate. Also, a better parameterisation of mussels growing on the turbine supports is likely to give a first impression of the effect of “benthic grazers in the water column” and its impact on nutrient cycling and the feedback effects on primary production.

There are more datasets available than the ones used to validate models, including some that include temperature, salinity, chlorophyll and current velocity data distribution over the vertical water column. However, more measurements of such parameters are required.

An important step will also be a closer investigation of the relationship between environmental characteristics and the response of the environment to the presence of wind turbines. The current first assessment appears to indicate that the strongest effects occur in areas with very pronounced stratification regimes. This needs to be investigated further and in conjunction with other parameters such as depth, bed composition, distance from the coast etc. Another issue that needs to be addressed with a certain amount of urgency is the effect of wind farms on transport of fine sediment. It is very likely that at least some level of reduction in transport will occur, along the Holland Coast, towards the Wadden Sea, but the magnitude needs further quantification. Which individual wind farms contribute to this reduction, cannot be determined with this single scenario. However, it is obvious that the biggest contributions will be caused by wind farms in the Holland Coast, Belgium and possibly the UK, some of which are already under construction or are scheduled to be built in the next decade.

For the top down approach, it has become clear that it will not be possible in the short term to develop IBM models for all species that have high conservation status or where internationally agreed conservation targets exist. The advice is to concentrate on a few key species, for which already a lot of data are available and for which already certain individuals are fitted with individually based loggers. Most likely candidates are seals (either harbour seal, *Phocaena phocaena* or the grey seal, *Halichoerus grypus*), and for birds lesser black-backed gull (*Larus fuscus*) and sandwich tern (*Thalasseus sandvicensis*). Particularly for these species there are a lot of data available regarding their behaviour and physiology and their prey requirements are well known. An important step will be to start collecting information regarding the dynamics and the spatial distribution of their prey, to gain insight in their food landscape.

### 4.4.2 Longer term work

Of high priority but probably not resolved immediately is the issue of better parameterisation of the wind wakes of wind farms and the better coupling of atmospheric and hydrodynamic models. There are projects running (e.g. by KNMI and WHIFFLE) that are trying to elucidate the effects of significant upscaling of offshore wind on the wind climate. Bringing the two sides together is clearly important but will not be achieved next year. However, based on the knowledge of the meteorologist community it should be possible to make a first order parameterisation of these wake effects and their impact on the wave climate.

The current ecosystem models use a relatively simple approximation to parameterise the drag the turbine supports exert on the currents. It requires more fine scale research on processes within wind farms to improve this and include effects of increased drag due to epifauna and the effects of e.g. filtration by epifauna and behaviour of faeces and pseudofaeces on the fine sediment dynamics within wind farms. Some of these fine-scale processes will be tackled in recently awarded NWA projects, but it will be a few years before these results are directly applicable.
We saw that the current bottom-up models require long calculation times. Having access to larger computers clearly helps to speed things up, but in future we need a suite of different model approaches, including simple, fast models to investigate particular processes.

Regarding longer term work for the top-down work we will have to start making the connection between the expected changes in carbon flows from the base of the food web to the primary prey species of the birds and marine mammals.

## 4.5 Fields of application

### 4.5.1 Impacts of wind farms and impacts of other factors

Apart from the changes caused by wind farms, there will be changes that are the consequence of other factors, illustrated in the top line of drivers in Figure 1.1. Long-term processes such as climate change and ocean acidification already have an effect. These effects are likely to become more prominent over the next few decades. The same is true for factors such as changes in nutrient run-off from land (e.g. as a consequence of WFD measures) as well as changing use of marine space (reduced fishing, increased offshore aquaculture and changes in sand mining and coastal nourishments). These factors are likely to interact with each other. Observations and monitoring can observe the changes, but as many factors act simultaneously on the system, analysing cause and effect is not easy. Models offer this possibility as with such instruments, not only effects of wind farms can be simulated, but also scenarios of climate change and other processes. Numerical models, not only the bottom-up ones, currently under development, but also models simulating effects on fish and higher trophic levels, can be used to tease apart the effects and assess the contribution of individual drivers.

### 4.5.2 Research and advice

Ultimately models (both from the bottom-up approach as well as the top-down approach) can be applied to assess the consequences of realistic scenarios and assess the impact of e.g. different wind farm lay-outs in order to minimise negative impacts. In future models can be important decision support tools. This will require further development and certainly validation of the models. The current application of these models is as a research tool, in order to understand the system and understand which processes are important in driving ecosystem change.

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